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Advancing Ecological Understanding and Sustainable Management of Small Pelagic Fish

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ABSTRACT

Small pelagic fish (SPF) are critical to the trophodynamic structure and function of marine systems and support some of the most valuable and socially important fisheries worldwide. Their "boom and bust" population dynamics, shifts in distribution, and importance as forage resources for other fish stocks place unique challenges to assessing and managing SPF. In response to these challenges, an international working group was formed in 2019 to foster collaboration aimed at closing key knowledge gaps in the ecology and sustainable management of SPF. Here, that group reviews progress made over the last ~10 years and identifies priorities for the next stage of coordinated international collaboration. Key research needs include: (i) enhancing monitoring programs to capture shifts in SPF distribution and incorporating new technologies, from molecular tools and digital imaging to biophysical and ecological modelling, (ii) improving data sharing to better understand life-history bottlenecks and cross-regional population dynamics, (iii) advancing process-based studies on oceanic and trophodynamic interactions to clarify the ecological roles of SPF as both predators and prey, and (iv) conducting bioeconomic and risk analyses to assess the vulnerability of fishing-dependent human communities to environmental and fish population fluctuations. A key pathway forward involves integrating mechanistic ecological knowledge, ecosystem and bioeconomic modelling, and social-ecological frameworks into real-time, adaptive, and equitable management approaches. This integration will be essential for developing resilient, ecosystem-based

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fisheries management capable of anticipating tipping points, accommodating non-stationary population dynamics, and ensuring sustainability under future climate and socio-economic uncertainties.

1 | Introduction

Small pelagic fish (SPF) are key to the trophodynamic structure and function of many aquatic food webs, transferring energy from lower to upper trophic levels (Pikitch et al. 2012; Ruzicka et al. 2024). They are the dominant prey for place-based foragers, such as seabirds and marine mammals, and can also be important to the diet of highly migratory, predatory fishes (Cury et al. 2011; Engelhard et al. 2014; Pikitch et al. 2014). SPF also make up 25% of global catches (FAO 2022; Hilborn et al. 2022), with Peruvian anchovy (*Engraulis ringens*) being the largest fishery worldwide (FAO 2022). Catches of SPF are critical for global food security, particularly in low- to middle-income countries (Robinson et al. 2022). These catches are now heavily strained by fishmeal production fueling burgeoning aquaculture that mostly feeds developed countries (FAO 2022). The population dynamics of SPF are characterized by massive and often rapid environmentally-driven fluctuations in biomass and shifts in geographical distribution (Checkley Jr. et al. 2009), changes which, for most fisheries, can be exacerbated by overexploitation (Gaines et al. 2018). Therefore, understanding the dynamics of SPF stocks is critical to providing science-based advice for sustainable, ecosystem-based management that can account for the multiple roles these fishes play in social-ecological systems.

International collaborative research on SPF was spearheaded by the launch of the GLOBEC Small Pelagic fish and Climate Change (SPACC) Program in 1994. SPACC was designed to understand how climate-induced changes in physical and biological processes impacted the population dynamics of SPF. SPACC included several major themes: long-term changes in ecosystems, retrospective analyses, comparative population dynamics, reproductive habitat dynamics, and economic implications of climate variability. The accomplishments of that 12-year program were described by Checkley Jr. et al. (2009). The SPACC program was followed by a 10-year gap in international programs specific to SPF despite extensions of long-term field time series, advances in numerical modelling of stocks and ecosystems, applications of new techniques (i.e., artificial intelligence, molecular and genetic analyses), conceptual developments in understanding of SPF population dynamics, and evidence of unprecedented effects of climate change. Fostered by discussions at international symposia held in Nantes, France (Peck et al. 2014) and Victoria, Canada (Alheit and Peck 2019; Alheit et al. 2019), a new international platform (the International Council for the Exploration of the Seas (ICES)—North Pacific Marine Science Organization (PICES) WG43/WGSPF) was created in 2019 to promote knowledge exchange, compile consistent databases, and coordinate global analyses.

Prior to the first meeting of this international working group, members ranked research priorities. From over 30 responses, seven topics emerged along with key questions and proposed solutions (Table 1) that could be organized within three different themes (Figure 1). In 2024, the group reviewed the first 4 years of collaboration in La Paz, Mexico, where the SPACC working group first met 30 years earlier. These discussions were fueled by (i) presentations and exchanges at the most recent international symposium on SPF (Lisbon, Portugal, November 2022), (ii) the results of 27 studies published in two symposium volumes (Peck et al. 2024; Rooper et al. 2024), and (iii) completed and ongoing analyses conducted by group members. These three sources of information were truly global as they included contributions from groups working in both the Northern (institutions represented by the group of authors here) and Southern (Peru, South Africa, Chile, Brazil, Australia) hemispheres. It should also be noted that the majority of participants were ecologists and scientists providing management advice and that the social sciences (e.g., economists, experts in community dialogue and engagement) were under-represented. As the global working group enters its second, four-year phase, a list of priority actions has been compiled (Figure 2) and justified here, on which the international community can focus to continue advancing scientific understanding and enable sustainable, ecosystem-based management of SPF. This paper justifies those priority actions by offering a review of recent accomplishments.

2 | Advancing Knowledge of Ecological Processes

2.1 | Better Understand Life Cycle Closure and Bottlenecks

Life cycle closure is a prerequisite for the persistence of populations, and this continues to be an important research subject for SPF because significant knowledge gaps exist regarding the underlying spatial and temporal mechanisms influencing population dynamics (Lowerre-Barbieri et al. 2017; Moyano et al. 2023) to better predict recruitment and to refine management strategies (Petitgas et al. 2010; Siple, Koehn, et al. 2021; Koenigstein et al. 2022; Payne et al. 2022). Advances have been driven by the accumulation of long-term data for some species and regions, but notable disparities in data and knowledge persist across species and Large Marine Ecosystems (Peck et al. 2021), especially concerning essential life processes such as migrations, identification of nursery areas, and stock mixing (Catalán et al. 2025). A recent example of the importance of long-term data was the discovery of changes in spawning migration behaviour of Atlantic herring due to intensive fishing that disrupts social learning (Slotte et al. 2025).

Efforts to enhance understanding of SPF life cycles would significantly benefit from utilizing data collected from existing surveys and those emerging from innovative technologies, such as genetics, acoustics, predator-inferred distributions, and isotopes (Gunther et al. 2024; Andersson et al. 2024; Maathuis et al. 2024; Catalán et al. 2025). For example, strategic placement of continuous echosounder monitoring stations, such as along migration corridors to nearshore nursery and feeding areas (Maathuis et al. 2024), can provide new process understanding on the reliance of SPF on shallow-water habitats that are difficult to sample. These measurements

TABLE 1 | Horizon scan of main topics, questions and potential solutions in the research of SPF based on the opinion of 32 scientists collected before the launching of the ICES-PICES working group in 2019.

Topic	Main questions	Main solutions
Climate change	How climate variability affects SPF distributions and productivity.	Potential adaptive management strategies and enhancement of socio-economic resilience.
Population dynamics	Better understanding of mortality, recruitment, and spatial patterns.	Improving data collection and modelling for better prediction and management.
New methods/technologies	Questions revolved around advancements in assessment and monitoring technologies.	To increase the adoption of these technologies for more accurate and efficient data gathering.
Modelling	Comparing phenotypic and evolutionary responses, and how SPF are depicted in ecosystem models.	Some solutions included integrating modelling approaches to better predict SPF responses to environmental changes.
Stock assessment	How to integrate Ecosystem-Based Fisheries Management (EBFM) principles.	Refining assessment models to incorporate ecological and environmental factors/processes.
Socio-ecology-economics	How to integrate the socio-economic considerations with ecological data.	Several solutions based on multi-disciplinary approaches to fisheries management were proposed.
Trophic studies	Main questions concerned the role of SPF in trophic networks and energy transfer.	General solutions included enhancing trophic studies to inform ecosystem-based management strategies.

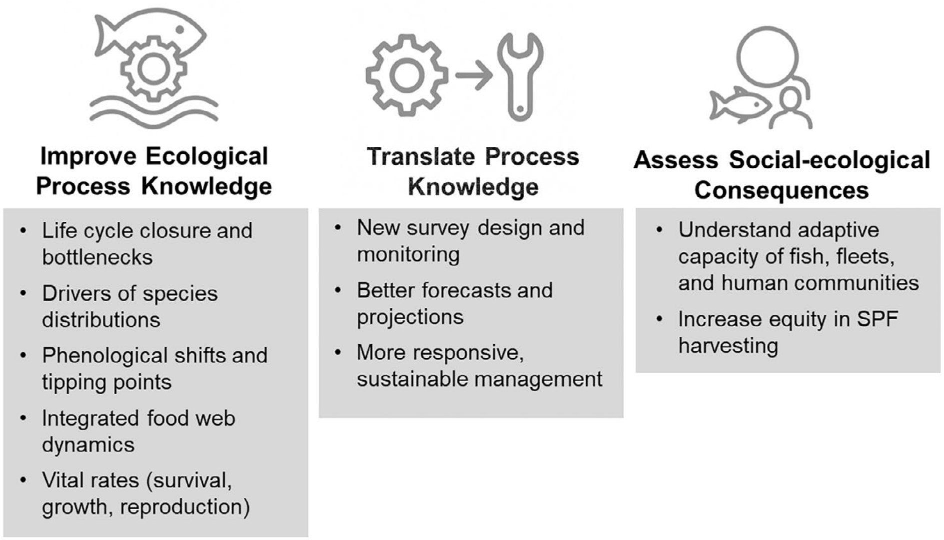

FIGURE 1 | Research themes and activities put forward by the international (ICES-PICES) working group on small pelagic fish in 2019.

can provide estimates of abundance when correlated with shallow-water sampling (e.g., passive fishing gear used in intertidal areas such as fyke nets (Rademaker et al. 2024)) and, in the longer-term, changes in habitat use that could be due to density-dependent mechanisms or signal habitat degradation. The integration of these methodologies, along with enhanced interdisciplinary cooperation, stands as the most promising path for a comprehensive understanding of habitats essential throughout ontogeny and gaining a more holistic view of the processes impacting SPF life-cycle closure (Catalán et al. 2025). Understanding the factors governing the dynamics of reproduction of SPF is particularly important to gauging reproductive resilience (Lowerre-Barbieri et al. 2017) and factors affecting life cycle closure.

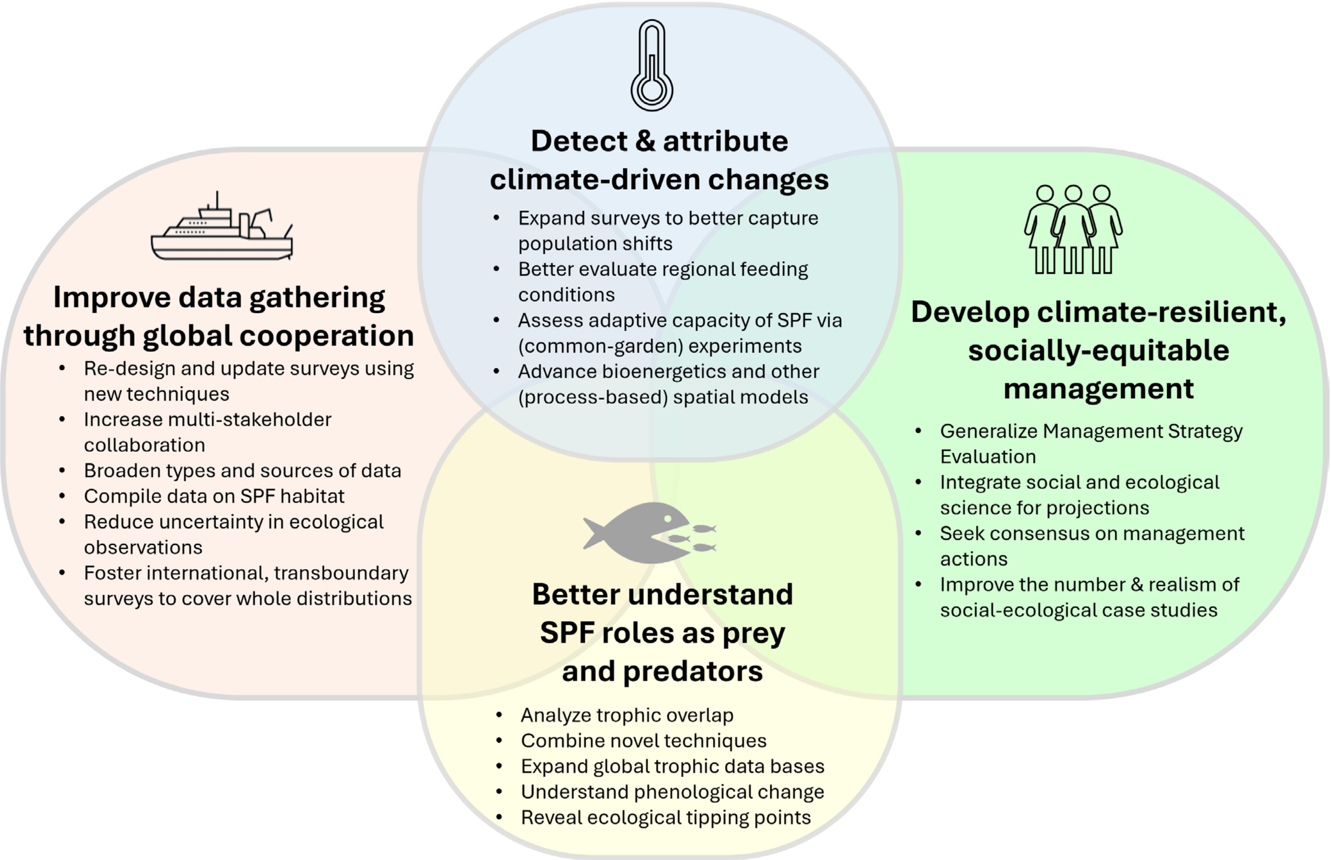

FIGURE 2 | Recommendations for future activities advancing science-based advice on small pelagic fish within complex social-ecological systems.

2.2 | Better Predictions of Species Distributions

Spatial distributions of SPF species are strongly influenced by the physical and biogeochemical ocean environment, but also in less predictable ways by stock size (e.g., density-dependence), linked to cyclical patterns in population dynamics. Several areas provide promise for improving the capacity to predict spatial shifts in SPF and reinforce robust management actions in response to shifts. For example, a combination of juvenile fish data from transboundary surveys, together with genetics and larval dispersal modelling, concluded that a northward expansion of Bay of Biscay anchovy (*Engraulis encrasicolus*) within the English Channel (Van Der Kooij et al. 2024) is likely under warming and density dependence. In another example, isotopic and microchemical measurements made on otoliths have helped uncover new aspects of population structure, mixing, and migration patterns (Arai et al. 2023). These data can help improve species distribution models (SDMs) to predict local extinctions, especially when there are barriers to movement or when species are at their ecological limits and are projected to shift latitudes (Baker et al. 2022).

Recent ensemble SDM approaches that merge estimates of spatial distribution from groups of models having different structures and assumptions better communicate uncertainty and can improve robustness (Rodrigues et al. 2023). The careful incorporation of SDMs into ecosystem models, together with the use of regional, downscaled climate models and ensemble modelling approaches, enables testing of new hypotheses related to spatial ecology (e.g., larval dispersal, survival, and meta-population connectivity). Such approaches can advance projections of SPF distribution under climate change in the context of shifts in physical conditions and response to climate (Muhling et al. 2020; Gibson et al. 2022). Moreover, the outputs of SDMs can inform short-term forecasts to improve fisheries management, such as expansion or contraction in fishing areas, and support assessment of allowable catch (Hsu et al. 2021). Understanding uncertainties in ecological observations, such as imperfect sampling and process errors in SDMs (Brodie et al. 2022), is crucial when applying models based on empirical data to management questions. It is recommended to incorporate diverse life history information into SDMs by, for example, including information on ontogenetic differences in essential habitat (e.g., Frans et al. 2017) and carefully selecting spatial and environmental co-variates.

2.3 | Understanding Phenological Shifts and Tipping Points

Recent studies have documented phenological shifts coinciding with decadal changes in somatic growth or survival, such as work on juvenile Japanese jack mackerel (*Trachurus japonicus*) by Takahashi et al. (2024) and European anchovy (*Engraulis encrasicolus*) by Ferreira et al. (2024). These are examples of non-linear dynamics in marine ecosystems that can potentially result in tipping points to alternative stable states within which the near-term recovery of SPF stocks may be unfeasible (Large et al. 2013; Kelly et al. 2015; Hunsicker et al. 2016). For example, the Kuroshio Current ecosystem switches from a sardine- to an anchovy-dominated community above a threshold temperature for optimal growth of early life history stages (Takasuka et al. 2007). Although detecting and forecasting thresholds and tipping points remains challenging for marine systems, new tools and frameworks are emerging (Lynch et al. 2022; Blöcker et al. 2023). Required is an understanding of ecosystem pressure-response relationships (Large et al. 2013) and how these relationships might change over time (i.e., non-stationarity; Litzow et al. 2019; Asch et al. 2022; Ma et al. 2023). For example, climate variability and extremes can lead to changes in fish distribution and phenology and, therefore, mismatches between predators and prey (Durant et al. 2019; Ferreira et al. 2023). A recent example is research by Ferreira et al. (2024) revealing the physical (oceanographic, upwelling strength) and biological (abundance of an intraguild predator) drivers associated with a dramatic, decadal shift to higher recruitment and fisheries catches of European anchovy in north-western Iberian (Canary Current) waters.

Advances in understanding population- and ecosystem-level changes will lead to improved science advice to promote resilient fisheries. Ecosystem studies that examine the extent to which species and communities are synchronous or disparate in their responses to environmental changes provide important information relevant to stock status and management reference points, ecosystem status, as well as the validity of assumptions for models of trophodynamic structure and function (Sakamoto et al. 2022; Selkoe et al. 2015). Such studies are also critical to better understand when trophic mismatches cause ecological tipping points to be crossed.

2.4 | Better Understanding SPF as Predators and Prey

SPF are planktivorous, but their diet typically varies ontogenically. Also, the spatial and temporal distribution of available prey affect the distribution and abundance of SPF. For instance, zooplankton size appears to be a primary factor influencing the gradient in SPF size across latitude (Ljungström et al. 2024) and temporally. At the same time, SPF serve as significant prey for numerous higher trophic-level predators (Engelhard et al. 2014; Surma et al. 2018), although the quantitative effects of predators on SPF populations and the adaptive abilities of predators to cope with SPF fluctuations remain poorly understood. A comprehensive understanding of the trophic ecology of SPF requires elucidating the mechanisms by which alterations in the phenology, abundance, and composition of key prey species influence SPF diet, feeding, growth, and survival (Gleiber, Hardy, Roote, et al. 2024), as well as their dynamic role as prey for predators.

Innovations in the study of SPF food-web dynamics have shed new light on environmental drivers affecting trophic interactions. Compound specific stable isotopes (Swalethorp et al. 2023), lipid composition (Bertrand et al. 2022), and food-web models (Ruzicka et al. 2024) have been recently used to compare the structure of pelagic food webs under different environmental conditions with consideration of predator–prey size relationships, and recognition of the critical, but understudied, role of larval feeding ecology (Garrido et al. 2024). Furthermore, trophic-transmitted parasites reveal long-term feeding histories of SPF and unveil undetected trophic linkages (Jacobson et al. 2024). Spatial modelling of predators can be used to understand distribution and temporal trends of SPF dynamics (Gunther et al. 2024; Gaichas et al. 2024; Wells et al. 2024). A new approach considers the behavioural or morphological traits of prey taxa, rather than just taxonomic composition, as important variables for prey selection (Gleiber, Hardy, Morganson, et al. 2024; Gleiber, Hardy, Roote, et al. 2024; Hardy et al. 2024).

Although important gaps in knowledge exist on the feeding ecology of larval stages (Boldt et al. 2022; Garrido et al. 2024), combining traditional and new techniques has refined our understanding of SPF diets, particularly for rapidly digested organisms such as gelatinous zooplankton and teleost eggs, now being detected in stomachs by DNA metabarcoding (Veríssimo et al. 2024). New studies collecting baseline information on compound-specific stable isotopic analysis allow more accurate determination of trophic position of SPF (Giménez et al. 2024). Historical hypotheses on trophic level mismatches affecting recruitment (Cushing 1990) have recently been re-evaluated with modern techniques, such as satellite data and reanalysis products (Ferreira et al. 2021) and combining fisheries-independent survey data across multiple management jurisdictions (Laurel et al. 2021; Ferreira et al. 2024). Finally, laboratory experiments, though relatively scarce during the last decade (Peck et al. 2021), offer valuable data such as prey-specific gastric evacuation rates (Fonseca et al. 2024) for modelling studies.

The trophic overlap between SPF and other planktivorous species needs to be explored, particularly how climate-driven and/or density-dependent processes impact diet overlaps. Combining different approaches in diet analyses, such as stomach content analysis, fatty acid analyses and DNA metabarcoding, should be more commonplace. Moreover, comprehensive predator diet databases need to be extended globally. Developing a global prey trait database by extending those already available in several ecosystems (e.g., NOAA Alaska Fisheries Science Center and Northeast Fisheries Science Center- NEFSC 2026, ICES; Livingston et al. 2017; Bizzarro et al. 2023) could further enhance our understanding of SPF trophic ecology (Gleiber, Hardy, Roote, et al. 2024). Comparative global studies on larval feeding ecology and the significance of SPF populations to predators, particularly place-based foragers, is needed.

2.5 | Increase Our Fundamental Understanding of Factors and Processes Influencing Vital Rates

Intrinsic factors, such as individual-level genetics and physiology and population-level density-dependence, and extrinsic factors, such as environmental factors (both abiotic and biotic) interact to shape spatiotemporal variability in SPF vital rates such as growth, condition, and reproduction, and ultimately survival or recruitment (Peck et al. 2013). Regular decrease in fish size under climate change, in particular for SPF (Ljungström et al. 2024), underscores the urgency to explain this variability and how fish populations may adapt or acclimate to a changing environment. However, disentangling the relative contribution of genetic and plastic phenotypic responses in the face of climate change and other stressors remains challenging (Conover et al. 2009; Higgins et al. 2015). Increasing availability and length of the time-series on traits allows more robust comparisons of their variability within and across regions. Considerable knowledge can be derived from testing hypotheses at the individual to population levels using complementary approaches, such as laboratory experiments (Moyano et al. 2020; Berg et al. 2024), statistical analysis (Lindegren et al. 2020), and mechanistic models that incorporate bioenergetics (Ito et al. 2015; Huret et al. 2019; Rose et al. 2024).

Conducting controlled laboratory experiments on SPF across several life stages and/or generations is particularly challenging (Peck et al. 2021). Nevertheless, recent work has provided insights into how environmental factors, such as temperature and photoperiod, can affect growth rates or vitellogenesis (Dos Santos Schmidt et al. 2022) and have targeted species poorly studied under laboratory conditions like Peruvian anchovy (Ofelio et al. 2023). Several long-term experiments (> 3 years) have also been recently published for Atlantic herring (*Clupea harengus*). These revealed a large plasticity in Norwegian spring-spawning herring that presented similar sizes after 1 year, no matter whether they were exposed to spring (long day length) or autumn (short day length) conditions early in life (Berg et al. 2024). In a second example, herring inhabiting different salinity habitats (e.g., Baltic vs. Norwegian Sea) displayed low reproductive success at salinities other than their natal ones (Berg et al. 2019).

Revisiting data collection from field studies enables analysis of long-term trends in growth. Takahashi et al. (2024) compared growth increments and high-resolution isotopic analyses of archived otoliths of jack mackerel from the 1960s and the 2010s to demonstrate earlier spawning in the recent decade but similar growth rates as a result of winter warming. Other studies on spawning phenology have shown how maternal and environmental factors affect early growth (Berg et al. 2019). In addition to growth, significant advances have also been made on characterizing body condition based on indicators, such as morphometric proxies, lipid content or energy density. This research on SPF underscores strong seasonal differences (Gatti et al. 2018; Albo-Puigserver et al. 2020; Kenyon et al. 2022), interannual variability or trends (Véron et al. 2020; Kenyon et al. 2022), as well as regional variability (Gatti et al. 2018) in relation to environmental factors, the reproduction cycle, or density-dependent processes (Takasuka et al. 2019).

While variability in vital rates such as growth is increasingly documented and understood, growth is most often considered time-invariant in population dynamic models. In such models used in stock assessment, growth is either fixed or estimated as constant (Kuriyama et al. 2016). Although simplifications and assumptions are often needed, one can question whether these models provide reliable advice, especially for SPF whose individual growth rate (and other vital rates) fluctuate with temperature or, more generally, climate variability (Lindegren et al. 2020; Sakamoto et al. 2022) and display longer-term trends most likely associated with climate change (Canales et al. 2018; Saraux et al. 2019; Véron et al. 2020; Taboada et al. 2024). Methodologies are being developed to integrate time-varying growth based on measurements of weight-at-age (Kuriyama et al. 2016). State-space modelling approaches applied to a few gadoid stocks (Correa et al. 2023) hold promise for integrating time-varying growth (length-at-age) and should be advanced for other data-rich SPF stocks.

The integration of knowledge gained from controlled laboratory experiments, field process studies and spatially explicit modelling can significantly advance our mechanistic understanding of complex processes impacting SPF recruitment. Moyano et al. (2023) used such holistic approach to pinpoint the key bottom-up and top-down factors influencing mortality at each life stage of herring spawning in the western Baltic Sea. The review suggested that habitat loss, warming and predation were key during the embryonic stages, while warming and changes in the prey fields were key during the larval stages. Significant knowledge gaps on the migration paths and mixing with other stocks limited the assessment of key factors influencing juveniles and adults. Finally, changes in spawning phenology have been recorded mostly related to increased temperatures but other factors such as fish condition (e.g., prey effects, contaminants) still require further study. Overall, the review underscores the complexity of interacting, non-stationary drivers acting on that stock and provides specific recommendations for managers based on key knowledge gaps.

2.6 | Reconciling Drivers of Abundance at Decadal to Centennial Time Scales

The drivers underlying decadal-scale fluctuations in SPF have been disputed and remain incompletely understood (reviewed by Peck et al. 2021). Conceptual hypotheses on decadal fluctuations, particularly on alternating regimes of anchovies and sardines, developed using large-scale climatic and oceanographic indices and fishery records from the past several decades (Schwartzlose et al. 1999; Chavez et al. 2003) often conflict with SPF population reconstructions from sediment cores. For instance, multidecadal fluctuations in the abundance of Japanese sardine (*Sardinops melanostictus*) and anchovy (*Engraulis japonicus*) in southwest Japan during the 20th century were not observed in earlier centuries (Kuwae et al. 2017). Likewise, SPF populations in the Northern Humboldt Current reconstructed from sediment cores spanning the last 25,000 years show no evidence for alternating species regimes, with SPF abundance generally increasing with higher biological productivity and lower oxygen content in the water column (Salvatteci et al. 2019). Peruvian anchovy, one of the dominant species in the record, reached peak abundance during the current warm period, an era also characterized by high productivity and an intense oxygen minimum zone.

Earlier hypotheses have also been challenged by recent responses of SPF populations to anomalies in ocean conditions, such as the resurgence of northern anchovy (*Engraulis mordax*) and the continued collapse of Pacific sardine (*Sardinops sagax*) after a recent warm period in the California Current system (Hinchliffe et al. 2025; Koenigstein et al. 2022). Previously unconsidered environmental processes may play a role in population regulation (e.g., spatial distribution, adaptation and oxygen availability; Bertrand et al. 2004; Mhlongo et al. 2015). The increasing appreciation of non-stationarity in marine ecosystems, such as shifting relationships between abundances and physical conditions, dependent on large-scale oceanographic state or stock size, has helped ease the debate between those scientists with paleoecological and contemporary perspectives. Future research needs to combine these sources of information to better appreciate timescales of population variability in potential responses to and associated risks from future environmental change.

3 | Translating Process Knowledge to Improve Management

3.1 | Improving Survey Design and Monitoring

The life history characteristics of SPF (e.g., episodic recruitment, short life spans, schooling behaviour) offer unique challenges to the design and implementation of fisheries independent surveys (Peck et al. 2021), the backbone of modern stock assessment. Historically, this has resulted in a wider variety of survey techniques to assess or index SPF abundance relative to other taxa (Boldt et al. 2017). Surveys developed specifically for SPF, such as daily egg production methods for northern anchovy (Lasker 1985), more traditional net capture methods, and acoustic-trawl methods, are widely applied (Baker et al. 2022; De Robertis et al. 2023). However, most of these methods result in highly variable and imprecise population size and recruitment estimates.

Recent advances in data integration, modelling and technology have created new pathways for improving and enhancing surveys. For example, applying new modelling techniques to survey data can reduce uncertainty of survey biomass estimates (Oyafuso et al. 2021), stitch different surveys together (Yasumiishi et al. 2020), account for missing data (Han et al. 2023), or incorporate novel data streams, such as predator diet data (Thayne et al. 2019; Gaichas et al. 2024). In the future, technologies such as eDNA (Shelton et al. 2022; Li et al. 2022), autonomous vehicles (e.g., sail drones, De Robertis et al. 2019), or equipping existing platforms with acoustics and other sampling methods (Barbeaux et al. 2018) can increase spatial coverage, potentially in under-sampled areas and seasons. Combining new and existing data streams with artificial intelligence (AI) techniques can make processing of data more efficient. Examples of AI include the automatic determination of SPF species composition using Deep Learning applied to trawl camera images (Allken et al. 2021) or convolutional neural networks applied to acoustic signals (Yassir et al. 2023; Lekanda et al. 2024). The continued implementation of AI-based methods can increase efficiency and allow more (and more precise) data collection and processing with existing human and budget-related constraints. However, these advances depend on increased and sustained global cooperation in development and application of technology combined with robust field surveys that are routinely reviewed and updated. Adapting and implementing these future surveys will be facilitated by collaboration among environmental agencies, industry, and other stakeholders (e.g., Steins et al. 2023).

3.2 | New Data Sources and Management Strategies

There is a long history and ongoing effort to develop and refine harvest control rules to manage SPF stocks. Such rules typically involve identifying maximum permissible fishing mortality rates, which are scaled down as biomass falls below precautionary reference points (Kvamsdal et al. 2016; Siple, Essington, and Plagányi 2021; Wildermuth et al. 2024; Schiano et al. 2024). In addition to output controls, such as catch limits, there is renewed interest in input controls for SPF management, including spatial and seasonal closures (e.g., for Portuguese Iberian waters, US East Coast and Gulf of Mexico, and Peru), size limits (e.g., for Portuguese Iberian waters and Mexico's NW Coast), and limited entry (e.g., South Africa, Portuguese Iberian waters, the US West Coast, and Mexico's NW Coast) (Oliveros-Ramos et al. 2021 and example applications in Quezada-Escalona et al. 2025). Notably, some of these regulations respond to variability, such as spatial shifts and recruitment pulses of small fish. This near real-time management may offer robust solutions for sustainable, ecosystem-based management of SPF but require rapid ‘in-season’ surveys. Walker et al. (2023) demonstrated that timely survey estimates of stock biomass, combined with a simple constant fishing mortality rate, performed better than empirical trend-based rules in terms of managing exploitation rates of the data-limited European sprat (*Sprattus sprattus*) stock. In a second example, for the last decade, Peruvian anchoveta industrial fisheries have temporary in-season closures in response to an increased (> 10%) percentage of juveniles in landings, related to changes in distribution overlap between juveniles and adults (Arias Schreiber 2012; Oliveros-Ramos et al. 2021). In a third example, the value of a “fast-reactive” approach was summarized for Bay of Biscay anchovy by Uriarte et al. (2023). In this system, after a fishery collapse, decades of fishery management experience, and engagement with stakeholders, monitoring was expanded to include juvenile as well as adult anchovy, and the lags between monitoring and management actions were reduced to just 1–2 months. Subsequently, total allowable catches (TACs) were set immediately after accurate information was available regarding the abundance of new recruits, which form a large part of harvested biomass for this short-lived and dynamic species. Notably, Uriarte et al. (2023) demonstrated that the fast-reactive approach provides enough information gain to be “win-win”, allowing higher mean annual catches while also reducing biological risk.

Nevertheless, for many SPF stocks, there remains a lag of 1+ years between observations and management actions. Examples of operational management approaches tuned to the boom-and-bust dynamics of SPF stocks include sets of decision rules based on fisheries-dependent and -independent indicators for sardine and anchovy in South African (de Moor et al. 2011). Due to the high variability in SPF abundance and uncertainty in SPF stock assessments, threshold rules have generally performed well. These rules establish a minimum biomass reference point, below which fishing is halted, in addition to a fishing mortality rate that increases (up to a maximum target level) as biomass reaches a threshold (or trigger) reference point. Threshold rules can safeguard minimal biomass levels, and prevent excessive levels of fishing (Siple, Koehn, et al. 2021). Wildermuth et al. (2024) showed via a

Management Strategy Evaluation (MSE) that, given frequent monitoring and yearly assessments, dynamic threshold or 'hockey stick' rules that adjusted reference points to stock productivity performed well in terms of SPF stock biomass, catch, and catch variability if reference points were conservative enough. Such MSE requires an operating model or simulated 'real world', which captures realistic environmentally-driven fluctuations in SPF recruitment. One solution, used for an MSE of the Iberian sardine stock, was to estimate time-varying stock-recruit relationships (ICES 2023) which are then included in the operating model within simulation testing of harvest control rules. Recent work by Wildermuth et al. (2024) illustrates different solutions, including linking simulated recruitment to environmental indices (e.g., Pacific Decadal Oscillation), and also driving simulated recruitment with output from the DynaMICE ecosystem model of Koenigstein et al. (2022). Timely indicators of ecosystem condition (e.g., plankton abundance) could also be used to adjust SPF fishing rates, as has been proposed by Howell et al. (2021) as an 'F_ECO' approach.

Recent examples highlight how harvest control rules and management actions need to be tailored to local market and fishing industry conditions, and that they can include ecosystem considerations as well as economic impacts. For example, Uriarte et al. (2023) tested biomass-based catch bounded harvest control rules, which included minimum catch levels (before closure), representing minimum economically viable catches. Uriarte et al. (2023) also considered maximum caps on total catch, based on estimates of regional market absorption capacity in the Bay of Biscay, and a desire to minimize landings gluts that depress prices. Similarly, the MSE of Wildermuth et al. (2024) evaluated harvest rules that included caps on maximum catch values during 'bonanza' years. These factors related to markets and price are highly specific to each region and fishery, but may be more important than fine-tuning details of harvest rules. Harvest control rules increasingly account for the role of SPF as forage, such as work by Schiano et al. (2024) that considered the consumption of menhaden (*Brevoortia tyrannus*) by striped bass (*Morone saxatilis*), and appropriate harvest rates for these interconnected species. An area that requires more work is research on the extent to which management actions are robust to climate-driven shifts in the productivity, size composition, and distribution of SPF stocks (e.g., Wildermuth et al. 2024; Quezada-Escalona et al. 2025) and to bolster the ability of managers to foresee distribution shifts, in particular transboundary shifts that affect stock availability and fishing portfolios of fleets and nations.

3.3 | Revealing the Adaptive Capacity of Fish, Fleets and Human Communities

Adaptive capacity of socio-ecological systems to climate change, particularly in terms of their governance or socio-economic attributes, is understudied (Mason et al. 2022), as are potential strategies that can enable coastal communities to better cope with projected changes in the availability of species they depend on for sustenance and economic well-being (Eurich et al. 2024). The "boom and bust" dynamic of SPF populations and fisheries has provided ample opportunity to highlight adaptations taken by fishing communities and downstream sectors to changes in access to resources in response to fishery closures, shifting species distributions (van der Lingen 2021; Powell et al. 2022; Quezada-Escalona et al. 2025), and other market shocks, such as COVID (Makwinja et al. 2021; Quezada et al. 2023; Vasquez Caballero et al. 2023; Beckensteiner et al. 2024). The Peruvian fishing fleet targeting anchoveta has been actively cooperating with managers to implement in-season fisheries closures based on demographic changes in the stock, a practice that decreases the vulnerability of stock collapse. This type of responsiveness to impacts of short-term climate variability and/or longer-term climate change is rare. Ortega-Cisneros et al. (2021) highlighted the lack of climate adaptation plans of South African fisheries management and stress the need for climate-ready plans to decrease the vulnerability of the sector.

Five key messages have been identified to advance SPF fishery adaptive capacity and social science. First, heterogeneity in industry responses to changes in SPF needs to be recognized in assessments of resilience to future variability in SPF dynamics (Quezada et al. 2023). Second, key challenges include defining fisheries and community attributes that can enhance flexibility of fleets (e.g., to diversify or shift fishing grounds), management (e.g., equitable solutions to high variability and shifts in shared stocks, spatial closures and shifting transboundary stocks), and markets (e.g., changes in prices associated with fish size or quality) (Quezada-Escalona et al. 2025). Third, critical information can be gained from dialogue with diverse stakeholder groups to understand changes in the profitability of fishing fleets, alternative governance, and fishing strategies to increase sustainability and resilience of stocks and livelihoods (e.g., Ramos et al. 2022; Bagsit et al. 2023). Fourth, in many locations, there are serious issues with equity in the provisioning of SPF for protein and nutrient security of local communities. These equity issues are amplified by the balance between SPF use by local industry and exporting (Nash et al. 2022). These issues can be exacerbated when fishing busts in some regions create a need for imports to maintain processing plants active (Beckensteiner et al. 2024) and are complicated with the need to balance direct use of SPF for human use with conserving forage for predators including other fish stocks (Cury et al. 2011; Free et al. 2021). Finally, diversification can enhance industries' resilience to rapid changes in SPF abundance (van der Lingen 2021; Quezada et al. 2023). The potential expansion of fleets to exploit macrozooplankton and mesopelagic fishes (e.g., myctophids), particularly during periods of SPF population collapse or fishing moratoria, spurs the need to expand our science and research on SPF to include these groups with emerging fisheries.

4 | Harnessing Mechanistic Modelling Tools

Ecological modelling tools have rapidly advanced and are now addressing several of the ongoing challenges related to better understanding the ecological responses of SPF to environmental drivers and to improving SPF surveys and fisheries management. For example, bioenergetics modelling can examine how energy from ingested food is used for fuel, growth, somatic maintenance, and/or reproduction, and can explore how different SPF populations may respond to environmental change. In one example, simulations by Menu et al. (2023) highlighted the importance of not only prey quantity but also prey quality in observed differences in latitudinal variation in growth and body size for European anchovy and European sardine (*Sardina pilchardus*), and suggested reductions in prey quality were a likely factor for the decrease in the size of these stocks in the last two decades. Thus, this modelling highlights that work on the impact of prey quality on vital rates is an important avenue of future research (Peck et al. 2021) and that prey quality should be better represented within bioenergetics models.

Coupled biogeochemical, fish bioenergetics, and individual-based models (IBMs) may provide insights into populations with inadequate survey data (Huret et al. 2019; Akimova et al. 2023). This type of coupled modelling has been applied to link changes in SPF phenology to seasonal foraging demands of predators of SPF to assess the optimal timing of seasonal fishery closures and fisheries-independent surveys for stock assessment (Huret et al. 2018; Olmos et al. 2023). Ecological simulation approaches, particularly those based on bioenergetics (Rose et al. 2024), permit researchers to better explore the ecosystem responses under climate conditions and population states that are beyond the ranges of those observed in the recent past, assess tipping points or threshold responses. Individual-based models, coupled end-to-end models, and process-based (multi-species) population models for SPF have been used to investigate those topics, integrating quantitative data of multiple types (i.e., oceanography, biogeochemistry and plankton, physiology of SPF and piscivorous predators) (Fiechter et al. 2021; Koenigstein et al. 2022; Rovellini et al. 2024; Liu et al. 2025).

Ecosystem models should be used more often to inform SPF management advice. Simulation testing via MSE has identified harvest rules that are generally robust despite 1+ year lags between surveys and management action. The outputs of food web models have informed ecosystem-based advice for harvests of SPF that take into account not just target stock abundance, but also prey or predator abundance and trophodynamic impacts (Surma et al. 2018; ICES 2023; Schiano et al. 2024). Ecosystem modelling and MSE can and should also be used to test spatial management, recruitment forecasts, and real-time responses. These models also reflect the life history realities of these species and the goal of preserving the forage role of SPF when setting total allowable catches. Simulation testing should continue to assess strategies in surveying SPF to evaluate future data combinations, technologies, or methodologies. Ecosystem model simulations can be used to inform on how monitoring programs might need to be adjusted or expanded to capture relevant population dynamics or to better understand how environmental factors such as climate change impact populations (Skogen et al. 2024).

Future work should compare estimates of spatial (distribution) or temporal (survival, growth) dynamics derived from different models, such as statistical (e.g., SDMs), Lagrangian advection/dispersal (e.g., IBMs), trait-based (e.g., size-spectrum), and full ecosystem (e.g., trophodynamic) or end-to-end models, as well as ensemble approaches (e.g., FishMIP, Blanchard et al. 2024) for the same species in the same region. This will help define structural uncertainty, rank among the processes operating at different biological, spatial and temporal scales, and either provide new insights into SPF dynamics or reveal gaps in process knowledge (Peck et al. 2021; Tittensor et al. 2021; Rovellini et al. 2024).

5 | Explore the Equitable Harvesting of SPF

Research is needed to understand how to cope with uncertainty and difficulty in the equitable harvesting of SPF with further global warming and other anthropogenic impacts. Identifying precautionary ways forward while reaching consensus on management actions and achieving conservation and equity objectives will be crucial. To achieve these goals, the best possible ecology and social science should be integrated for holistic analyses of both small-scale and industrialized SPF fisheries (e.g., taking ecosystem-based and food-systems approaches, e.g., Pikitch et al. 2014; Wessels et al. 2023). To this end, we propose the following five priority areas of SPF research, summarized by our impression of the ease of implementing them in the short- and long-term.

In the short-term (1–5 years), (1) model-based investigations of the robustness of assessment models and management advice to bias and uncertainty in survey observations and ecological processes can improve fishery resilience as marine economies and ecosystems change due to global drivers. The tools and expertise already exist for management strategy evaluations and simulation studies that test the performance of management procedures to a variety of uncertainties (process, observation, implementation, structural, etc.), which can be brought to bear for the most pressing marine resource management questions (e.g., de Moor et al. 2011; Wildermuth et al. 2024). Additionally, (2) investigations of bottom-up forcing of SPF dynamics through lower trophic drivers (i.e., planktonic prey interactions) can make use of extensive long-term datasets and physiology experiments. For several decades the sciences of fisheries oceanography, physiology, and population dynamics have existed in relative isolation from each other. These fields are overdue for an interdisciplinary integration of these datasets and knowledgebases to connect understanding of biogeochemical processes to the crucial forage communities that support the rest of the vertebrate food web. A focused integration of phyto/zooplankton-SPF community dynamics can further be supported by innovative technologies as they develop in the longer term (e.g., eDNA, fatty acid tracer analyses, autonomous observation platforms, etc.).

From a long-term perspective (5+ years), (3) efforts must be redoubled to increase the coverage and resolution of socioeconomic and natural history datasets to improve mechanistic understanding of the roles SPF play in socioecological systems and achieve closure of their life history. Annual time series of spawning biomass and revenue are not enough to understand these highly dynamic species. Long-term datasets must be established at relevant (finer) scales to understand ontogenetic changes and drivers of SPF cohorts and the effects of their availability to fishing communities in time and space on intra-annual scales. Finally—and most importantly – (4) responsive, effective management frameworks must be established to quickly and nimbly observe, assess, and respond to changes in SPF dynamics to ensure equitable and sustainable harvests. Again, due to the short, highly dynamic life cycles of SPF, traditional data collection and management structures with their built-in time lags may not be as effective for managing these populations as they have been for longer-lived, slower growing stocks. Innovative efforts to establish in-season surveys (e.g., South Africa, Spain) or near-real-time stock sorting (e.g., Gulf of California, Mexico), for example, have shown early promise in shortening the time between monitoring and decision-making. For stocks or jurisdictions that cannot implement additional monitoring schemes, opportunities in model-based forecasts of stock dynamics or availability based on global or regional ocean modelling are increasingly available (e.g., the Changing Ecosystems and Fisheries Initiative (CEFI) in the USA). Although these management tools may already exist, we recognize that it takes time to affect change in any management institution to ensure understanding and trust among community members and interest groups.

Key to these efforts is the need for more "well-worked" case studies from different communities at different scales around the world. In each case, research must advance social-ecological analyses (i.e., economic models with more realistic biology, ecological models with more realistic economics) to provide the best possible science-based advice needed to critically evaluate management objectives and actions for SPF in the context of social-ecological systems.

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Data Availability Statement

The authors have nothing to report.

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