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Small pelagic fish: new frontiers in science and sustainable management

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Abstract

Small pelagic fishes occupy an important trophic role in every global aquatic ecosystem, and many species are heavily exploited by fisheries, including some of the largest and most valuable capture fisheries in the world. In November 2022, a symposium on small pelagic fish titled "*Small Pelagic Fish: New Frontiers in Science and Sustainable Management*" was cohosted by PICES, ICES, and FAO in Lisbon, Portugal. This special issue contains a collection of research manuscripts that explore approaches currently being used and developed to assess and manage small pelagic fishes. In particular, this issue covers topics on novel approaches to surveying small pelagic fishes, incorporating environmental covariates into management, management strategy evaluation, and aspects of the economics of small pelagic fisheries. The conclusions highlight the importance of new approaches that seek to enhance small pelagic fish surveys and ecosystem monitoring, incorporate that ecosystem information into management strategy evaluation, and predict the potential impacts of ecosystem changes on outcomes for economies and communities that rely on sustainable populations of small pelagic fishes.

Key words: small pelagic fishes, sustainable fisheries, ecosystem based fisheries management, environmental change, management strategy evaluation, fisheries economics

Introduction

Small pelagic fishes are a critical component of ecosystems providing a forage base linking primary and secondary production in the world's oceans to upper trophic level species, including marine mammals, seabirds, and predatory fishes. Many predatory fish species are heavily exploited for human consumption and are dependent on small pelagic fishes as prey. Species of small pelagic fishes are also directly exploited by humans, through commercial, recreational, and subsistence and ceremonial harvest (e.g., Pacific herring in British Columbia, Canada). The Peruvian anchoveta (*Engraulis ringens*), a small pelagic fish caught of the west coast of South America, has been the basis of one of the largest capture fisheries in the world since its inception (Oliveros-Ramos et al. 2021), with an average annual catch of ∼5 million metric tons over the last decade (FAO 2024). On a smaller scale of catch, artisanal fisheries on small pelagic species in the African Great Lakes are regionally important, where they are estimated to decrease the vulnerability of local human populations to food and livelihood collapse (Kolding et al. 2019; Makwinja et al. 2021; Nakiyende et al. 2023).

Due to their importance for ecosystems and humans, sustainable management of small pelagic fish stocks is vital, yet these species exhibit characteristics that make them very difficult to assess. Small pelagic fishes are typically fast growing and short-lived and can experience large variations in recruitment and growth due to environmental fluctuations (McClatchie et al. 2017). These species can also be subject to extremely high natural mortality due to variable predation rates or even depensatory predation, where predation rates can be higher even at low population sizes due to the schooling behaviour of small pelagic fishes (Forrest et al. 2023). Because of their schooling and migratory behaviour, small pelagic fishes can also be difficult to survey. Two recent review papers have highlighted and summarized many of the knowledge gaps and issues with sustainable management and the biology of small pelagic fishes (Peck et al. 2021; Boldt et al. 2022). All of this work indicates that the management of small pelagic fishes needs to be robust to changes in the environment, stock productivity, abundance, and natural mortality, as well as changes in predator abundance and composition (Pikitch et al. 2012; Skern-Mauritzen et al. 2016; Siple et al. 2021).

The objective of this special issue is to build on previous work by exploring some of the current and novel approaches that are being used to assess and manage small pelagic fishes. This collection of 10 manuscripts on small pelagic fishes aims to address some of these issues. The papers arise from the *International Symposium on Small Pelagic Fish: New Frontiers in Science and Sustainable Management* cohosted by PICES, ICES, and FAO in Lisbon, Portugal in November 2022. This symposium brought together researchers from across the globe to present their work and discuss the science around small pelagic fishes. This special issue covers topics on novel approaches to surveying small pelagic fishes, incorporating environmental covariates into management, management strategy evaluation, and aspects of the economics of small pelagic fisheries. A companion issue is being published in the journal Marine Ecology Progress Series and will include research on topics related to the biology and ecology of small pelagic fishes (Peck et al. 2024).

Estimating the abundance and dynamics of small pelagic fish stocks

Directed surveys are a crucial part of monitoring and scientific assessment of small pelagic fish (Barange et al. 2009). Acoustic, egg, and larval survey programs have been conducted on a wide range of small pelagic species in many regions of the world since industrial fishing began in the 1950's (e.g., Bograd et al. 2003). While the initial surveys often focused on estimating the abundance of one or several species of small pelagic fish, the technological advances of the past decades and increased recognition of the need for robust advice to inform fisheries management on environmental drivers, including climate change, have resulted in important refinements in survey methodologies (e.g., De Robertis et al. 2019; Dorey et al. 2018). Most ongoing surveys of small pelagic fish attempt to measure additional components of the ecosystem, such as the prey field, predator abundance, and the physical environment of the survey area (Godefroid et al. 2019).

In addition, there have been advances in our ability to model survey data (Thorsen 2019; Anderson et al. 2024) to produce more precise and less biased abundance estimates, and to use ecosystem models to reduce the uncertainty by testing survey designs (Holmin et al. 2020). These methods have improved our ability to utilize imperfect data (e.g., surveys with missing stations or years), combine and compare data across surveys, gear types and regions (O'Leary et al. 2022), and standardize commercial catch data to produce indices of catch-per-unit-of-effort (Hsu et al. 2021).

Two of the manuscripts in this special collection focus on utilizing novel data or methods from unconventional sources to develop estimates of abundance for small pelagic fishes. Gaichas et al. (2024) used the stomach contents of 22 piscivorous fish species to examine the distribution and index the aggregate abundance of 21 small pelagic fish species. These studies incorporated spatial–temporal modelling methods to produce the abundance index. Arguably one of the most useful features of this effort was the ability to derive indices of small pelagic fish species that are not commonly encountered in surveys, but are important components of predatory fish diets. A second manuscript on novel survey methodologies incorporated modelling to more fully utilize daily egg production method (DEPM) data to estimate the spawning biomass of small pelagic fishes (Citores et al. 2024). To overcome spurious egg mortality estimates in the application of DEPM, Citores et al. (2024) applied a coherent Bayesian approach including priors on egg mortality. They also modelled egg densities by age, by including either spatial random effects, smoothing functions (GAM), or kriging-like models (geostatistics). When applied to Bay of Biscay anchovy, this approach resulted in better fits to data than non-spatial models, and greater precision of both daily egg production and mortality estimates, generating additional insights into the spatial variability of egg production and leading to better estimates of spawning biomass.

Management strategy evaluation, the environment, and ecosystem based fisheries management

Over the last two decades, the quest for harvest and management strategies that are robust to ecosystem changes has become a major area of research (Goethel et al. 2019; Collie et al. 2021; Silvar-Viladomiu et al. 2022). Management strategy evaluation (MSE) can also be used to examine alternative assumptions about the structure of small pelagic fish populations and their dynamics, such as using models that explicitly incorporate processes like density dependence into the operating models (OM).

Productivity of pelagic fish stocks is known to change as a result of changes in environmental drivers (Szwalski and Hilborn 2015; Szwalski et al. 2019). In some cases, the relationship between environmental conditioning and stock productivity changes over time or when longer series of observations become available (e.g., Pacific sardine; Zwolinski and Demer 2019; Muhling et al. 2020). In these cases, alternative harvest control rules (HCRs) should be tested for their relative performance across a range of putative population OMs (Punt et al. 2014, 2016). Wildermuth et al. (2024) conducted an MSE to assess the current and alternative Pacific sardine HCRs across future climate- or non-climate-driven recruitment scenarios. Their results indicated that HCRs with dynamic unfished biomass (B_0) reduced the frequency of closures as compared to HCRs with equilibrium B_0 while allowing relatively high biomass and catches across all recruitment scenarios. This aligns with former studies suggesting that using reference points with respect to a dynamic B_0 may improve fishery performance under time-varying productivity (Berger 2019; Bessell-Browne et al. 2022). However, as management performance varied more among recruitment scenarios than among HCRs, they also pointed out that achieving a better understanding and modelling drivers of the climate-conditioning of recruitment may be of greater relevance than refining HCR functional forms.

In a laboratory experiment performed on Baltic herring (*Clupea harengus membras*) eggs, Makinen et al. (2024) found that elevated temperature impacted reproductive success in this important species. The study found mixed effects of warming, including faster development and better hatching success but also occurrences of malformed larvae and a smaller size at hatch at higher temperatures. In addition, the thyroid hormone levels of the maternal parent played a key role in mediating these processes. This laboratory study has implications for future survival and recruitment of Baltic herring under warming conditions. Integrating these results into simulation testing through MSE would be one way to test future approaches to assessing the effect of warming temperatures on fisheries.

Predation is a critical process determining the population sizes of small pelagic fish. Including representative measures of predation impacts on the small pelagic fish population dynamics in simulations can improve the ability to develop HCRs that are robust to changes in ecosystem structure, the environment, and fishing pressure. The study by Moosa and Butterworth (2024) showed that including all sources of predation, not just the major species, is important for obtaining accurate results when modelling historical abundance trends. Other studies examined multiple, ecologically interdependent, fished species. For example, Schiano et al. (2024) use a detailed striped bass–Atlantic menhaden predator–prey system model, along the East Coast of the U.S., to test the performance of different HCRs to achieve current management targets. They explored a range of HCRs for the two species independently and with some dependence between them. Although none of the HCRs tested met all ecosystem management objectives for striped bass and Atlantic menhaden, these and other authors have concluded that, despite the difficulties of simultaneously achieving management objectives for multiple species, there is still value in this approach (Schiano et al. 2024; Kaplan et al. 2021; Pérez-Rodríguez et al. 2022). These studies highlight the need for sufficient basic biological knowledge of both predators and prey to inform ecosystem models in support of MSE strategies.

Ecosystems are complex, so including mortality impacts from only major predators does not always tell a complete story or allow HCRs to be developed for effectively managing both predator and prey if both are heavily exploited (Schiano et al. 2024). The biology of small pelagic fishes can also be hard-wired for optimum success through adaptation to local conditions (Makinen et al. 2024). In these cases, MSE can be used to guide further development and enhancement of data streams and studies of ecosystem impacts (Kell et al. 2024). Kell et al. (2024) demonstrated a method for integrating information from multiple sources for a data-poor small pelagic stock into a framework addressing both fishery and ecological objectives. Information from ecosystem modelling and life history theory informed an operating model, and simple indicators and management procedures were tested for robustness across a range of common small pelagic population scenarios including highly variable natural mortality and recruitment. This evaluation is important, as it can be used to direct resource allocation to identify and prioritize key improvements in the knowledge of fish stocks, such as the role and impact of predation on mortality (Kell et al. 2024; Moosa and Butterworth 2024; Schiano et al. 2024).

Incomplete knowledge on interactions among species and the environment that affect the dynamics of small pelagic fishes should not prevent the inclusion of ecosystem considerations in small pelagic fish population management. De Moor (2024) reviewed approaches that included ecosystem considerations in MSEs of small pelagic fish. They reviewed examples that ranged from the inclusion of a complete ecosystem model in the operating model of an MSE that defined the interdependence of several prey and predators to simpler cases where the effects or dependency of predators on their prey serves to define management objectives and performance indicators (e.g., defining minimum biomass threshold levels of prey species). Simpler cases, such as just changing fishing targets for ecosystem considerations (Chagaris et al. 2020; Bentley et al. 2021), are also included in the review. Overall, the paper shows that different approaches can be applied to achieve Ecosystem Based Fishery Management, and that it is not necessary to wait until a full ecosystem model is developed to pursue this approach.

Implications for the economics of fisheries targeting small pelagic fishes

Given their tendency for large fluctuations in abundance and distribution in response to environmental variability, harvest, and predation pressure, small pelagic fish species can be vulnerable to boom and bust cycles. Because they also play such a critical role in ecosystems, it is important to have tools that allow managers to evaluate tradeoffs between large-scale, directed catches of small pelagic fishes, small pelagic fishes' role as a forage base in pelagic ecosystems, and harvest opportunities and benefits to coastal communities as a source of livelihood and nutrition. Changes in distribution and abundance can result in changes in fisheries behaviour (Quezada et al. 2024). However, it is often difficult to predict how these changes will play out in small-scale fisheries. The example study by Quezada et al. (2024) shows that the ability of fishers to access other sectors, such as invertebrate fisheries like Dungeness crab and squid, can result in unpredictable impacts on fisher behaviour and coastal community resilience. This is in contrast to small pelagic fisheries that focus on one or a few species, where a downturn in that species has a larger impact on the economics of the fishery (Beckensteiner et al. 2024), with the possibilities of fishers losing their role in the market. Thus, it is important to consider the ability of fisheries to adopt alternative targets to be able to adapt to climate change and implement effective alternative harvest strategies (Wildermuth et al. 2024).

Future directions

A few key themes for future research emerged from the *International Symposium on Small Pelagic Fish: New Frontiers in Science for Sustainable Management* held in November 2022. In general, these themes for future directions in research included:

- Using commercial fishing vessels and data on large scales to assess the abundance of small pelagic fishes;
- Extending the use of fish surveys as platforms for monitoring ecosystem structure and function;
- Further implementation of Ecosystem Based Fisheries Management for small pelagic fishes;
- Incorporating predator–prey dynamics into assessment models and MSE;
- Explicit inclusion of climate change into MSE simulations;

- Developing dynamic HCRs robust to changes in stock productivity; and
- Developing advanced technologies, tools, and techniques in sampling, analyzing, and modelling to sustainably manage small pelagic fishes.

The collection of papers in this issue address many of these themes and suggest potential ways forward for others.

Conclusions

Both the symposium and the papers in this issue highlight the fact that integrated surveys of small pelagic fish and their physical and biological environment are necessary to monitor, assess, and manage ecosystems. Fast-growing areas of research include advanced survey technologies, exploring unconventional data sets, and new modelling methods that enable the use of imperfect data and data from multiple sources, as well as spatio-temporal dynamics of small pelagic fish.

The use of simulation modelling in MSEs to test alternative HCRs that include ecosystem considerations (e.g., climate, predation, interspecies dependencies) is another area of productive and fast-moving research. Using MSE, there is potential to include end-to-end studies that can both incorporate the biology of the species, as well as changes in the environment, interactions with other species, and harvest and economic considerations to provide a full and coherent picture of the types of management actions that can be successful under future climate change.

Using simulation modelling in MSE is helpful in that it identifies knowledge gaps, such as the need for basic biological research on small pelagic fish (e.g., predator–prey interactions, habitat, effects of pressures), but these knowledge gaps should not prevent the inclusion of ecosystem considerations in the management of small pelagic fish populations. Iterative advances by including new information as it becomes available will provide additional tools that can allow managers to evaluate tradeoffs between fisheries, ecosystems, and benefits to coastal communities.

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Competing interests

The authors declare there are no competing interests.

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