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**Abstract**

Management strategy evaluation (MSE) is the state-of-the-art approach for testing and comparing management strategies in a way that accounts for multiple sources of uncertainty (e.g. monitoring, estimation, and implementation). Management strategy evaluation can help identify management strategies that are robust to uncertainty about the life history of the target species and its relationship to other species in the food web. Small pelagic fish (e.g. anchovy, herring and sardine) fulfil an important ecological role in marine food webs and present challenges to the use of MSE and other simulation-based evaluation approaches. This is due to considerable stochastic variation in their ecology and life history, which leads to substantial observation and process uncertainty. Here, we summarize the current state of MSE for small pelagic fishes worldwide. We leverage expert input from ecologists and modellers to draw attention to sources of process and observation uncertainty for small pelagic species, providing examples from geographical regions where these species are ecologically, economically and culturally important. Temporal variation in recruitment and other life-history rates, spatial structure and movement, and species interactions are key considerations for small pelagic fishes. We discuss tools for building these into the MSE process, with examples from existing fisheries. We argue that model complexity should be informed by management priorities and whether ecosystem information will be used to generate dynamics or to inform reference points. We recommend that our list of considerations be used in the initial phases of the MSE process for small pelagic fishes or to build complexity on existing single-species models.

**KEYWORDS**

closed-loop simulation, ecosystem-based fisheries management, forage fish, management procedure, population dynamics

**1 | INTRODUCTION**

Ecosystem-based fisheries management (EBFM) has been widely proposed as a way to incorporate ecological knowledge in order to conserve ecosystems, improve the resilience of fisheries, and reduce error in assessments and management actions relative to goals. One area where EBFM has gained traction is in the management of commercial fisheries for lower-trophic-level prey species, which can reduce food availability for predators. For this reason, management advice about major prey species is starting to include EBFM considerations, such as predation, climate drivers and habitat needs (see Anstead et al., 2021; Marshall et al., 2019). One set of such prey species are small pelagic fishes (hereafter referred to as SPFs). By definition, SPFs are small- to intermediate-sized pelagic species such as sardines, anchovies and herrings that are a primary food source for several marine predators (Alder et al., 2008; Butler et al., 2010; Cury et al., 2000; Furness, 2003; Overholtz et al., 2000; Szoboszlai et al., 2015). Although our focus is on fish, many of the considerations developed here also apply to invertebrate species such as squid and krill with similar ecological roles as SPFs in marine ecosystems. In addition to supporting valuable fisheries for reduction, human consumption and feed for aquaculture (Froehlich et al., 2018;

Ma et al., 2019; Metian, 2009; Tacon & Metian, 2008), SPFs serve as energy conduits in marine food webs, transferring energy from lower-trophic-level phytoplankton and zooplankton to higher-trophic-level predators (Pikitch et al., 2014), and exert top-down control on zooplankton in several ecosystems (Cury et al., 2000; Lynam et al., 2017). SPFs might therefore be one group of species for which ecosystem considerations in management are particularly important (e.g. Pikitch et al., 2014).

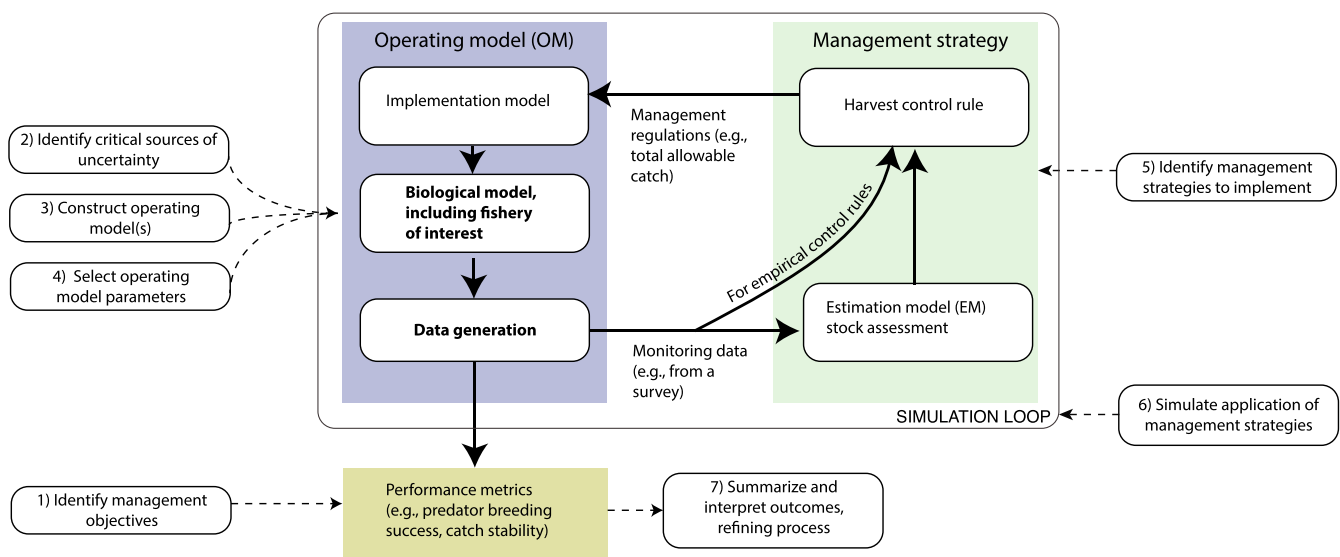
Simulation approaches provide one way to use ecosystem information to explore the robustness of management strategies (Figure 1; FAO, 2009; Möllmann et al., 2014). One such approach that has been identified as particularly useful is Management Strategy Evaluation (MSE; Perryman et al., 2021; Punt et al., 2016; Smith, 1994). Management strategy evaluation uses simulation to compare the performances of candidate management strategies in relation to a set of management objectives and priorities defined by stakeholders (Punt, Butterworth et al., 2016). Management strategy evaluation has been operationalized broadly for management, for example, regulating marine mammal harvest and bycatch (Punt & Donovan, 2007; Wade, 1998), the management of fish (De Oliveira & Butterworth, 2004; Punt & Hobday, 2009) and shark fisheries (Smith et al., 2007), management of multispecies fisheries (Fulton

et al., 2014), and for evaluating harvest rules intended to mitigate seabird bycatch (Tuck, 2011). Management strategy evaluation has also been used fairly extensively in the design of management systems for SPFs (e.g. for sardine (*Sardinops sagax*, Clupeidae) and anchovy (*Engraulis encrasicolus*, Engraulidae) in South Africa, de Moor & Butterworth, 2016; and for Atlantic menhaden (*Brevoortia tyrannus*, Clupeidae) in the USA, SEDAR, 2020).

Management strategy evaluation is particularly powerful because it can inform management advice even when most of the underlying ecological processes impacting management effectiveness are not fully understood. Even when not operationalized for management to compare alternative harvest control rules as described above, MSE can be used to examine the robustness of existing management procedures to (possibly poorly understood) sources of uncertainty (e.g. survey frequency; Punt et al., 2020), or to the use of simplified models in decision-making (e.g. Lam et al., 2019; Surma et al., 2018). Management strategy evaluation is useful in these situations because it can explicitly account for ecological process uncertainty, as well as uncertainty related to monitoring, assessments and implementation (Plagányi, 2016). Some MSEs based on multispecies or ecosystem models have had direct impacts on management; for example, Kaplan et al. (2019) and Fulton et al. (2019), who showed the value of including EBFM considerations in management strategies. Nevertheless, despite the resources available with advice for conducting MSEs (Punt, Butterworth et al., 2016; Rademeyer et al., 2007; and others), MSE has not yet been widely adopted for management at the ecosystem level. This is due to several factors. The management goals of EBFM, including balancing spatial and species tradeoffs, are often not well-articulated (Essington et al., 2016; and examples in Koehn et al., 2020). Most ecosystem models are not designed at a scale

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or level of detail to provide the degree of precision required by management, that is, they typically are not designed for tactical decision-making (see Plagányi et al., 2014) or are not focussed on a specific management question (Essington and Plagányi 2014). Here, we provide technical advice on ecosystem considerations for MSEs. SPF fisheries provide an excellent case study on the use of MSE within an EBFM context because of SPF's key role in marine ecosystems.



**FIGURE 1** Diagram of the MSE process (adapted from Punt, Butterworth et al., 2016). The parts of the process discussed in this paper are in bold. Dotted lines connect steps in the MSE development process to simulation components; solid lines indicate the flow of simulations

Simulation approaches for SPFs may require special consideration because of their unique role in marine food webs. They are known to have highly variable productivity, which, together with their short life spans, can lead to rapid and extreme fluctuations in abundance, as well as a high degree of uncertainty in their reference points related to carrying capacity (e.g. Chavez et al., 2003; Trochta et al., 2020). They also display large-scale aggregation behaviours that can lead to density-dependent catchability, sensitivity to exploitation, and localized depletion for dependent predators (Pitcher, 1995). All these characteristics must be considered in an ecosystem context, as SPFs are often key points of energy transfer in marine food webs and remain so throughout their life cycles (Cury et al., 2000). This means that predator–prey linkages and ecosystem structure are important considerations for building population models and in articulating management priorities and tradeoffs. Thus, crafting MSEs for SPFs is a particularly demanding process and will benefit from expert guidance.

An MSE approach requires users to develop a model of the system that covers the plausible range of scenarios, given the available information. Identifying situations where ecological processes could differ greatly from each other can show where more ecological information (diets, predators, etc.) may be required. A special consideration for all MSEs should be whether the level of complexity and the spatio-temporal scale of the models being used can most effectively answer the management question at hand and address the ecosystem objectives of EBFM (Plagányi et al., 2014). Finally, because of their ecological role, SPFs require a careful evaluation when it comes to management objectives and the interpretation of outputs, two other essential steps in the MSE process.

The MSE process involves the steps as outlined by Punt, Butterworth et al. (2016): (1) Identifying the management objectives and how these are represented in performance measures; (2) Identifying critical sources of uncertainty to which a management strategy must be robust; (3) Constructing one or more candidate (operating) models that represent the system to be managed, including the biology of the system, the way that data are collected from the system, and how the regulatory output from the management strategy is implemented; (4) Selecting operating model parameters and quantifying parameter uncertainty; (5) Identifying management strategies that could be implemented; (6) Simulating the application of the management strategies; and (7) Summarizing and interpreting the outcomes of these simulations, and refining the process if necessary (Figure 1).

In this study, we primarily focus on the second step of the MSE process, reviewing and summarizing critical sources of uncertainty that should be considered in the development of MSEs specifically for SPFs. We briefly review commercial SPF fisheries worldwide and use examples from several large marine ecosystems to demonstrate how important sources of uncertainty vary globally. We also discuss how, in some cases, these sources of uncertainty can be incorporated in population models that can be used in an MSE framework as an operating model (OM). This synthesis is intended to serve both directly as advice for those interested in developing MSEs for SPFs

and indirectly as a case study for how EBFM approaches might be incorporated further into an MSE framework.

## 2 | APPROACH

We invited scientific experts on SPFs from twelve countries (Canada, Chile, China, Denmark, France, Iceland, Norway, Poland, Portugal, Spain, the UK and the USA) to a workshop to discuss important sources of uncertainty about the ecology of SPFs, the data used to estimate their abundance, and how these data inform management strategies. This workshop was part of the International Council for the Exploration of the Sea North Pacific Marine Science Organization (ICES/PICES) Symposium on Drivers of Dynamics of Small Pelagic Fish Resources held in Victoria, British Columbia in March 2017. The experts comprised 28 scientists from universities and governmental research institutes with experiential knowledge of specific stocks of SPFs, their ecology and management, and quantitative tools for management. Participants were invited to answer two questions: (1) What ecological processes have been/ can be/should be considered when simulating SPF dynamics for MSE? and (2) How does the importance of these processes and our ability to incorporate them in MSEs vary among ecosystems and among species? Participants were encouraged to consider data types and data limitations, scientific capacity (e.g. whether there is a full stock assessment), ecological role, ecosystem type, predation and environmental drivers. Group members were asked to discuss knowledge from their specific locations, as well as broader patterns common to SPFs globally, and to consider monitoring, estimation and implementation uncertainty. We synthesized the results of this discussion and identified the key areas of uncertainty, for which we incorporate examples from the Humboldt Current, California Current, Gulf of Alaska, the Mediterranean Sea and a collection of Northeast Atlantic stocks that include the Baltic Sea, Bay of Biscay, Barents Sea, North Sea and Norwegian Sea (Table 1).

To assess the state of MSEs for SPFs in light of the discussion, we also reviewed existing SPF stocks worldwide and compiled an updated list of commercially fished small pelagic stocks with and without MSEs, thereby updating de Moor et al. (2011). Starting with the list of stocks included in the RAM legacy database (RAM Legacy Stock Assessment Database, 2018; Ricard et al., 2012), we added stocks from the Mediterranean and Baltic Seas, Australasia, Africa and China to extend geographical coverage and compile a full list (Table S1; Figure 2). Finally, we synthesized the outcomes to determine a set of guiding considerations for MSE of SPFs.

## 3 | CURRENT STATUS OF MSEs FOR SPFS

Our review of existing SPF stocks and MSEs illustrates that although there are existing MSEs for SPFs in some locations, not many are in use by management (not “operational”). For the majority of SPF stocks, the existence of a MSE is unknown or a MSE is

**TABLE 1** Important considerations for modelling small pelagic fishes (SPF) identified by regional experts of five areas (Humboldt Current, California Current, Gulf of Alaska, Northeast Atlantic and the Mediterranean Sea) and the regions for which they emerged in discussion as important considerations (in parentheses)

Theme	Must consider	Should consider	Key questions
Variation in vital rates	Temporal changes in biological parameters such as somatic growth and natural mortality (All) Environmental shifts associated with productivity regimes (Humboldt Current, GoA) Depensatory dynamics when abundance is low (CA Current)	Variation in functional responses with environmental conditions, such as bottom-up effects dominating under different environmental conditions (Humboldt Current)	Does climate impact vital rates? If so, which ones? Do multispecies interactions impact SPF vital rates and vary temporally? Are SPF vital rates density-dependent?
Spatial considerations	Fishery stock identification (Northeast Atlantic stocks, Mediterranean Sea)	Spatial variation in abundance, productivity, growth and/or natural mortality (All)	Are there spatial predator-prey interactions that are important to management objectives for the system? Does the SPF exhibit expansion-contraction effects as population size changes? Does the SPF stock span multiple jurisdictions spatially? Does productivity vary spatially?
Multispecies interactions	Predator needs and dynamics (Humboldt Current, CA Current)	Intraspecific competition, interspecific competition among forage species (Humboldt Current, CA Current, Mediterranean Sea)	Does the SPF stock interact with other SPF stocks? Are there key predators of the SPF that are an important consideration based on management objectives? Are there other key interactions impacting the stock?
Assessment error and reference points	Ability of the survey or assessment to capture dynamics (CA Current, GoA, Mediterranean Sea)	Error due to spatial structure or dynamics (All)	Are there spatial dynamics that will generate bias in reference points or biomass estimates? Is there spatial structure in the survey that may not capture spatial structure in the population?

*Note:* More detailed region-specific considerations are summarized in Siple and Koehn (2017). Northeast Atlantic stocks = Baltic Sea, Bay of Biscay, Barents Sea, North Sea, and Norwegian Sea; CA Current = California Current; GoA = Gulf of Alaska; All = CA Current, GoA, Humboldt Current, Mediterranean Sea; Northeast Atlantic stocks.

currently not built (108/153 stocks globally; Figure 2). There are 10 stocks for which MSEs for SPFs are currently in progress. These results suggest that this review may be timeous to provide guidance for developing MSEs for SPFs with the hope of subsequent operationalization. Existing MSEs, especially those that are currently operational (35/153 stocks globally; 11 of which are operational in management), provide examples to guide future development of closed-loop simulations for other SPF stocks (Table 2). [Correction added on 25 June 2021, after first online publication: Section 3 has been updated in this version]

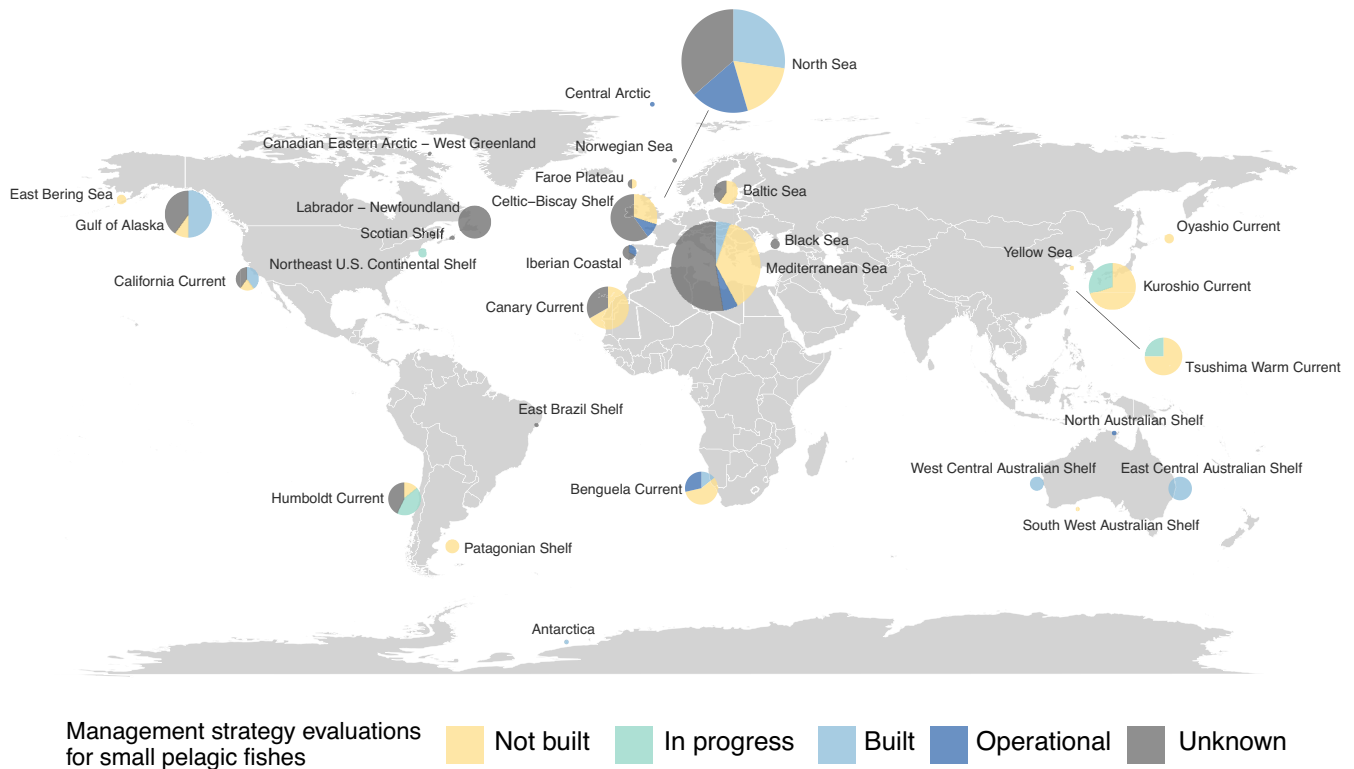
#### 4 | WHAT ECOLOGICAL PROCESSES NEED TO BE CONSIDERED WHEN SIMULATING SPF DYNAMICS FOR MSE?

Several sources of uncertainty have been identified as particularly important to consider for SPFs, given their unique ecology and management challenges. We focus on three types of

ecological uncertainties important to consider explicitly in OMs for SPFs, (Table 1; Figure 3):

1. Variation over time in vital rates, such as growth, mortality or age-at-maturity, especially as a function of predator abundance or density dependence;
2. Spatial patterns for predators and prey, including migration, multiple stocks and stock mixing, spatial differences in predator needs (e.g. for central place foragers), and spatial differences in the implementation of control rules; and
3. Species interactions among SPFs and between SPFs and their predators.

Considering important areas of uncertainty can improve MSEs in two ways: (i) by creating a more realistic set of scenarios across which to evaluate management performance by generating dynamics similar to (or plausible for) those observed in real stocks; and (ii) by adequately characterizing uncertainties for robustness tests.



**FIGURE 2** The locations of commercial fisheries for small pelagic fishes worldwide. Pie chart size indicates the number of stocks in each ecosystem; colours indicate whether a management strategy evaluation has been developed for a given stock, and if so, whether it is operational in management. Not built = An MSE has not yet been constructed for this stock; In progress = an MSE is currently being constructed, or has been constructed but has not completed the review process, or some the MSE tests certain uncertainties but does not yet cover the full range; Built = An MSE has been constructed and published; Operational = Management advice for this stock is based on MSE results; Unknown = This stock is included in the RAM legacy database or known by the authors but it is unknown whether an MSE has been built for it. Citations and details for each stock are given in Table S1 [Correction added on 25 June 2021, after first online publication: Figure 2 has been replaced in this version]

We also explore:

4. Considerations for estimating assessment errors and reference points in the estimation model (EM)

#### 4.1 | Variation in vital rates

Changes in vital rates were identified as a key consideration across all five geographical areas discussed during the workshop (Table 1), with changes in fecundity, natural mortality and age-at-maturity potentially leading to low-frequency variation in productivity, a pattern observed in many stocks, including some SPFs.

##### 4.1.1 | Recruitment

The appropriate functional form of the stock–recruit (SR) relationship is notoriously difficult to estimate, particularly for SPFs (van Deurs et al., 2020; Subbey et al., 2014), but it is important for OMs to describe past and future recruitment. The two key questions for stock–recruit relationships in SPFs are as follows: (1) Is there

a density-dependent effect, and if so, at what stock sizes? and (2) What is the magnitude and time scale of recruitment variability?

SPF dynamics are characterized by large fluctuations in population size (“boom and bust” dynamics) that arise from a high degree of recruitment variation and a short life history. These dynamics are thought to be a result of responses to environmental variability (Bartolino et al., 2014; Borja et al., 2008; Checkley et al., 2017; Lindegren et al., 2013), natural mortality (Jacobsen & Essington, 2018) or a combination of environmental variability and fishing (Essington et al., 2015; Fu et al., 2018; Lindegren et al., 2013; Pinsky & Byler, 2015). Discussions about SPF recruitment typically emphasize the effect of environmental processes on survival of early life stages (Somarakis et al., 2019; Zimmermann et al., 2019). These processes operate at low frequency, leading to regimes of high and low population productivity (Szuwalski et al., 2014; Vert-pre et al., 2013). Thus, the parameters of the stock–recruit relationship are thought to be non-stationary, and distinguishing which parameter is time-varying is difficult. Finally, because it is very difficult to distinguish whether spawning biomass is being driven by recruitment variation or vice versa for SPFs, decisions about how recruitment variation is modelled will affect interpretations about the impact of fishing (Szuwalski et al., 2019).

**TABLE 2** Examples of and guidelines for the consideration of ecological uncertainties in management strategy evaluation (MSE) for small pelagic fishes

Broader topic	Specific consideration	Example of use in an existing MSE	Example of use in an existing MSE—species or stock	Reference	Example of use (E) or technical guidance (G)
Variation in vital rates	Recruitment	Random assignment of 3 different stock–recruitment models	Northeast Atlantic mackerel	ICES (2020c)	E
	Recruitment	Use AIC-weighted average of 3 stock–recruit models (Ricker, Beverton–Holt, segmented regression), with an AR-1 correlation for error	Norwegian spring-spawning herring	ICES (2018b)	E
	Recruitment	Estimate the stock–recruit relationship differently for "boom" and "bust" years	South African sardine	de Moor et al. (2011)	E
	Recruitment	Approximate recruitment variation based on environmental drivers that occur at the same timescale	Pacific sardine in California	Hurtado-Ferro and Punt (2014)	E <sup>a</sup>
	Recruitment	Incorporate environmental drivers mechanistically	Several	Punt et al. (2014) and Haltuch, Brooks et al. (2019)	G
	Recruitment	Incorporate forecasts of environmental drivers explicitly in control rules, where appropriate	Pacific sardine in California	Tommasi et al. (2017)	E <sup>b</sup>
	Recruitment	Incorporate low-recruitment scenarios for robustness testing	South African sardine; Bay of Biscay anchovy	de Moor et al. (2017); Sánchez et al. (2019)	E
	Growth		Several	This paper	–
	Fecundity		Several	THIS paper	–
	Age-at maturity		Several	This paper	–
	Natural mortality	Include different mortality and mortality variation scenarios in robustness tests	Several	Punt, Butterworth et al. (2016), Rademeyer et al. (2007) and DFO (2019)	G
	Natural mortality	Use a multispecies model to estimate natural mortality	Several	ICES (2020a); ICES (2020b)	E
	Spatial patterns	Recruitment	Model spatial differences in carrying capacity implicitly rather than modelling recruitment differences in a spatially explicit model	Several	This paper
Migration		Where appropriate, link spatial models to oceanographic models (i.e. "end-to-end" ecosystem models)	Pacific sardine and northern anchovy	Fiechter et al. (2014)	E <sup>c</sup>
Predator needs		Explicitly model space or population structure of predators and prey using a MICE model	Pacific sardine and northern anchovy	Punt, MacCall et al. (2016)	E
Predator needs		Model spatial dynamics using a proxy that can mimic spatial patterns; use MICE model	South African sardine	de Moor et al. (2017) and Robinson et al. (2015)	E
Multiple processes simultaneously		Model structure explicitly using MICE models	Pacific sardine and northern anchovy	Punt, MacCall et al. (2016)	E
Multiple processes simultaneously		Allocate stock to different subareas, with mixing, based on parallel spatial process	South African sardine	de Moor et al. (2017)	E
Stock covering multiple jurisdictions		Include plausible ranges for historical and future catches or jurisdictions without data	Several	This paper	–

(Continues)

TABLE 2 (Continued)

Broader topic	Specific consideration	Example of use in an existing MSE	Example of use in an existing MSE—species or stock	Reference	Example of use (E) or technical guidance (G)
Multispecies interactions	Competition within forage guild	Incorporate scenarios for competition, apparent competition and different drivers where appropriate	Several	This paper	-
	Predator-prey relationship	Include different plausible values for functional response parameters if shape of relationship unknown	Several	This paper	-
	Predator-prey relationship	Use meta-analysis to parameterize functional relationships to account for uncertainty in strength or functional form of relationship	Several	This paper	-
	Accounting for predator needs	Explicitly include predators in operating model using a MICE model, if data are sufficient to fit one	Atlantic herring; Pacific sardine and northern anchovy	Deroba and Bence (2008) and Punt, MacCall et al. (2016)	E
	Accounting for predator needs	Use more complex ecosystem models to determine reference points that satisfy predator needs before testing them	Several; Atlantic menhaden	Pikitch et al. (2012), Smith et al. (2011) and SEDAR (2020)	E

Note: Not all of these examples were used explicitly in management decision-making. Cases where the specific consideration influenced the selection of a management strategy are indicated as footnotes.

<sup>a</sup>Recruitment assumptions were key because the harvest control rule includes sea surface temperature, which is (with noise) a driver of the stock-recruitment function.

<sup>b</sup>Temperature impacted the harvest guideline being tested in the simulation. This simulation was a research exercise, so no harvest guideline was formally adopted based on these results.

<sup>c</sup>Movement and migration rates informed by the environment were shown to influence availability to the fleet.

Thus, recruitment variation is an important consideration both in how reality is represented in the OM and in how the results of the MSE are interpreted.

Methods for modelling recruitment for SPFs include using multiple stock-recruitment functions (as in the MSE for Northeast Atlantic mackerel [*Scomber scombrus*, Scombridae]; ICES, 2019c), estimating stock-recruit parameters for boom and bust years separately and conservatively projecting using only the “bust” year parameters in projections (de Moor et al., 2011) or including periodic “boom” years too, and approximating recruitment variation based on environmental drivers that occur at the same time scale (e.g. Hurtado-Ferro & Punt, 2014). One could also estimate different stock-recruit functional forms for alternative OMs, particularly when, given the high recruitment variability, no single functional form fits the historical data best. For cases where environmental variation is thought to drive recruitment variation, Haltuch, Brooks et al. (2019) provide several suggestions for how environmental drivers can be incorporated into MSEs. We direct readers to De Oliveira and Butterworth (2005) and De Oliveira et al. (2005) for warnings about using environmental indices as predictors of recruitment success, and Punt et al. (2014) for suggestions about incorporating environmental uncertainty in simulation approaches. Explicit integration of environmental drivers can also allow an assessment of the robustness of management strategies to hypothesized directional changes in recruitment in response to climate change (e.g. Haltuch et al., 2019).

#### 4.1.2 | Other vital rates

Other vital rates can also vary over time in SPF stocks. Existing MSE advice includes robustness trials to variation in natural mortality (Punt, Butterworth et al., 2016; Rademeyer et al., 2007), which is particularly important for SPFs given their role as prey. We discuss natural mortality below under “Multispecies interactions” and discuss the other vital rates here.

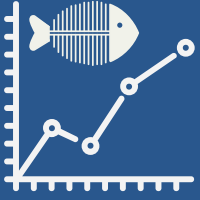
Time-varying vital rates may be particularly important for SPFs because of the sensitivity of their dynamics to interacting effects of predation and fishing mortality. Growth, fecundity and age-at-maturity can vary temporally for SPFs (Hunter et al., 2019; van der Lingen et al., 2006; SEDAR, 2020; Silva et al., 2006; Smoliński, 2019). Disease outbreaks, parasites and environmental conditions such as hypoxia also vary over time (de Moor et al., 2017) and can affect life history. OMs should be able to reproduce historically observed variations in abundance in order to produce realistic future projections, and time-varying parameters may be required to achieve this. Changes in predator needs can lead to temporal changes in natural mortality (see “*Multispecies interactions*” section). Though estimates of these time-varying parameters are not always readily available, processes that are plausible a priori but lack data or conclusive evidence should not necessarily be excluded from investigations. In cases where environmental drivers might affect both recruitment and another vital rate such as growth, we recommend that modellers conduct analyses to identify correlations between



# TAILORING MANAGEMENT STRATEGY EVALUATION TO SMALL PELAGIC FISHES

How to build realistic operating and estimation models

IMPORTANT CONSIDERATIONS FOR SMALL PELAGICS



**TIME-VARYING PRODUCTIVITY AND OTHER LIFE HISTORY PARAMETERS**

Make sure that operating models can recreate amplifications in abundance. Consider that changes in natural mortality may occur with changes in predator abundance

## THINK ABOUT SPACE IN OPERATING MODELS AND ESTIMATION MODELS

Small pelagic fish density, predator density, and catches vary spatially. Consider aggregation behavior in both estimation and operating models



## CONSIDER SPECIES INTERACTIONS



Predation, competition, and different responses to environmental drivers will all influence small pelagic abundance, responses to management, and trade-offs

## THINK CAREFULLY ABOUT MODELING ASSESSMENT ERROR

Simulated data should reflect that observed in reality. If the management strategy is assessment-based, test the performance of simplified assessment methods (i.e., "shortcut methods") using complex operating models



## MAKE TRADEOFFS EXPLICIT



Explicitly considering tradeoffs is a main component of ecosystem-based fisheries management. Make sure that tradeoffs among objectives can be clearly communicated from the simulation results

## 4.2 | Spatial considerations

Spatio-temporal dynamics are an essential component of how SPFs behave and how predators and fisheries exploit them. Spatial issues include hyperstability, migration, stock mixing, spatial differences in predator needs, particularly for central place foragers susceptible to localized depletion, and spatial differences in the implementation of harvest control rules, such as when multiple countries share the same resource. How these are represented in the OM will depend on the research question and the performance objectives for the stock. Stock identification (the identification of biologically distinct stocks for the purposes of management) and the spatial mixing between these management units are an issue for several stocks, including: Pacific herring (*Clupea pallasii*, Clupeidae) in the Gulf of Alaska whose growth and fecundity vary spatially; Northeast Atlantic sprat (*Sprattus sprattus*, Clupeidae) (Hunter et al., 2019; McKeown et al., 2020; Quintela et al., 2020); anchovy and sardine in the Mediterranean Sea (Fiorentino et al., 2014); two stocks of Atlantic herring (*Clupea harengus*, Clupeidae), namely, western Baltic spring-spawning herring and central Baltic herring (ICES, 2018a); and South African sardine (de Moor et al., 2017; Weston et al., 2015).

Many SPFs undergo range contractions when abundance is lower (i.e. the "basin model" of MacCall, 1990), which can affect productivity if it results in depensatory dynamics (Holling, 1959; Liermann & Hilborn, 2001; Swain & Benoit, 2015; Walters & Kitchell, 2011). Conversely, range collapses might be explained using information about biomass, changes in recruitment or spatial vulnerability to disease (e.g. MacCall, 1990). These behaviours can also affect the precision and accuracy of abundance indices when range expansions in high-abundance years result in surveys missing a proportion of the stock (Barange et al., 2009; Hilborn & Walters, 1992; MacCall et al., 2016). For example, in the California Current, where sardine habitat appears to extend northward at high population sizes and under specific oceanographic conditions, the extent of the spring acoustic survey for sardine depends on an environmentally based estimate of spawning habitat extent to ensure that all potential spawning habitat is sampled (Zwolinski et al., 2011). While expansion-contraction effects can be modelled empirically, there is seldom a mechanistic way to model them.

Recruitment can also vary spatially, and the limitations of recruitment by habitat may drive dynamics. For example, optimal spawning habitat for Pacific sardine is associated with specific oceanographic conditions (Nieto et al., 2014; Reiss et al., 2008; Weber & McClatchie, 2010; Zwolinski et al., 2011). Recruitment can be spatially correlated because of sensitivity to local environmental conditions (e.g. in north Atlantic and northeast Pacific herring stocks; Zheng, 1996). Stocks can also be expected to be less productive at their margin of distribution if they follow the basin model (MacCall, 1990; Saraux et al., 2014). Alternatively, the underlying stock-recruit relationship might change with local depletion because density-dependent effects occur at small spatial scales (e.g. Casini et al., 2011). An OM may need to consider local dynamics if

FIGURE 3 Infographic summarizing the main recommendations

biological parameters and so they can be included in the OM. Punt et al. (2014) offer further guidance for using MSE to evaluate the impact of environmental variation on management performance when environmental drivers influence changes in abundance or parameter values.

they lead to emergent patterns at the stock scale (MacCall et al., 2019; Punt, MacCall et al., 2016). This is possible with some ecosystem models that have small-scale dynamics and have been used for MSE (e.g. Fulton et al., 2011). As the stock–recruit relationship varies spatially, so will carrying capacity, which might be easier to model implicitly using depensatory stock–recruitment relationships instead of explicitly with a spatial model (Liermann & Hilborn, 2011). Spatial models linked to oceanographic models (i.e. “end-to-end” ecosystem models) can generate spatio-temporal dynamics in recruitment, but conditioning these such models is so resource-intensive that applying them at a resolution relevant to management is often not an option.

Interactions between predators and SPFs are also inherently spatial, and predator populations may not have access to the entire region of SPF distribution. Spatial models can capture some of the dynamics and behaviour of predators that forage from a fixed location like a breeding colony (e.g. Barrett et al., 2006). Some spatial structure can be captured using Models of Intermediate Complexity (MICE; Plagányi et al., 2014) with limited spatial structure (e.g. Punt, MacCall et al., 2016; Robinson et al., 2015). Alternatively, spatial structure could be approximated by modelling an (annually varying) proportion of the population to be within the foraging area and thus subject to the predation of a predator. Short time steps (e.g. monthly or quarterly) may be required to effectively model individual prey movement.

If fishing pressure differs throughout a SPF's distribution range, the MSE may require spatial structuring in the OM to adequately account for these differences. The effect of fishing activities on the dynamics and movement of SPFs should be considered in spatial models (Sydeman, Thompson et al., 2017; Okamoto et al., 2020). Plausible spatial distributions of fishing activity can be generated using random utility models of fisher behaviour and port-level landings (e.g. Rose et al., 2015). While explicit modelling of areas is preferable where data permit, in some cases, selectivity can be used as a proxy for area (the “areas as fleets” approach; Cope & Punt, 2011; though some simulation studies now indicate that this approach is sub-optimal). For example, spatially disaggregated fishing effort may be adequately reflected by age-disaggregated selectivity if the SPFs move through different areas as they grow (e.g. South African anchovy de Moor & Butterworth, 2016). SPFs often occupy an area that spans the jurisdictions of multiple countries. For example, Pacific sardine are fished across Canada, the USA and Mexico (Punt, MacCall et al., 2016). The South Peru–North Chile anchovy stock is managed independently between Peru and Chile, with different assessments (Canales et al., 2020). In cases where the stock is not managed cooperatively across its range, management outcomes for the whole stock will depend on the combined effects of each country's management plan. While the benefits of cooperative management across the stock's range have been documented for some taxa (e.g. Pacific hake [*Merluccius productus*, Merlucciidae; Hamel et al., 2015], SPFs are often large stocks, the majority of which are fished by more than one country (139 of 224 stocks, based on FAO wild capture production from 2019). Additionally, the need to work

cooperatively in a short timeframe is unique to SPFs, given that acquiring data can sometimes take longer than the time for which the fish is available to the fishery (for example, recruitment fisheries for age-0 individuals). In cases where data are not available for all jurisdictions, simulations can include alternative plausible ranges for historical and future catches for countries for which dynamic management strategies are not available, such that fishery impacts on the entire stock can be modelled. Attempting to model dynamics across jurisdictions can identify data gaps where more information should be gathered (Fulton et al., 2011).

The choice of spatio-temporal dynamics in the OM depends on the research question, the scale of the dynamics, the resolution of the data, and the objectives of the strategic management decision being investigated. For example, the OM could explicitly include space or stock structure if users want to evaluate management strategy performance with respect to benefits to central place foragers such as seabirds (e.g. sardine and anchovy in the California Current, Punt, MacCall et al., 2016; South African sardine, de Moor et al., 2017). Alternatively, if users want to evaluate performance with respect to spatially-dependent harvest rates or implementation error (e.g. overshooting quotas), such as when multiple countries with different management structures harvest the same straddling stock, the OM could (minimally) be structured to represent the stock distributed by country. Spatial differences in recruitment, natural mortality, growth and fleet dynamics may necessitate a spatially explicit model. Choosing the appropriate spatial scale to represent is a central challenge, as misspecification can lead to incorrect representation of recruitment and of the management values that are used to estimate reference points (Kapur et al., n.d.). Other considerations include conceptual decisions about the hypotheses being tested and tactical decisions about how mortality and recruitment occur over space (Punt, 2019).

Not all spatial dynamics can or should be included in an MSE. One example of this is the case of sardine in South Africa, where the harvest control rule implemented after MSE testing provides total sardine quotas (spatially disaggregated by west/south coast in some years). In addition to this harvest control rule, an island closure experiment has restricted purse seine fishing around some key African penguin breeding islands (e.g. Ross-Gillespie & Butterworth, 2020; Sherley, 2020). In this case, the relatively small spatial scale of the 20-km radius around the penguin breeding islands was not explicitly modelled in the MSE but under EBFM, the impact of fishing on penguins is still being evaluated (de Moor, 2018). Spatial issues are likely to become even more urgent in the future, as climate change continues to influence the movement and distribution of SPFs. Management strategy evaluations that allow decision-makers to balance tradeoffs for multiple jurisdictions will be useful.

### 4.3 | Multispecies interactions

SPFs are characterized by their role as prey for a diverse assemblage of predators, including predatory fish, marine mammals and seabirds (Engelhard et al., 2014; Pikitch et al., 2014; Smith et al., 2011). The

availability of alternative prey for predators is a key consideration, but there is considerable uncertainty surrounding interactions between prey species and how these impact predators.

Properly characterizing the ecological relationships among multiple SPF stocks and how predators might respond to fluctuations in their prey is an important step in generating realistic dynamics for each species and determining the outcomes for fisheries that harvest them and predators that may depend on more than one species. Negative correlations between species abundance can be evidence of competition, apparent competition or opposite drivers. Thus, if there is little information or conflicting information about intraguild relationships, OMs with multiple forage species may need to include a range of possible options. For example, sardine–anchovy relationships can appear to be positive (McClatchie, 2012) or negative (Chavez et al., 2003), and different biological and non-biological processes can be invoked to explain the same observations (Hosack et al., 2013; Siple et al., 2020). Competitive relationships between SPFs can also change over the life cycle of a species, as in the Norwegian Sea where Atlantic mackerel feed on herring larvae (Allan et al., 2021; Skaret et al., 2015), while the adults of both species compete for planktonic prey on their feeding grounds (Nikolioudakis et al., 2019). There are several possible scenarios for intraguild relationships in fisheries where SPFs are part of a multispecies fishery. Considering different interactions between exploited SPF stocks could help to capture dynamics associated with competition or apparent competition due to food availability.

Predator–prey relationships—particularly functional responses and predation rates—may be one of the most important ecosystem processes driving the dynamics of SPFs. If possible, empirical data on functional response relationships (the shape of the relationships between predator demographic rate and prey abundance) should be used to parameterize predator responses (Koehn et al., 2021). These data may be available from meta-analyses, for example, seabird functional responses to changes in forage fish abundance (Cury et al., 2011) or from case studies of individual populations (e.g. Robinson et al., 2015; Suryan et al., 2006). Alternatively, statistical relationships representing the presence and strength of pairwise species interactions, including competition, can be estimated directly from time-series data using multivariate autoregressive models (Ives et al., 2003; Lindegren et al., 2009). However, even in data-rich cases, the shape of predator functional responses or estimated interaction terms are subject to uncertainty (Sherley et al., 2015; Sydeman, Piatt et al., 2017). Hence, alternative OMs might include different shape parameter values for the functional response.

Realized prey is a function of preferred prey, spatial overlap and the availability of other prey items (Blanchard et al., 2014). If predators eat non-preferred prey when it is abundant but a more preferred prey if available, a single-predator, single-prey model would be unable to sufficiently capture the plausible range of predation rates experienced by the prey (e.g. Pinnegar et al., 2003; Plagányi et al., 2014). Care should also be taken as

to the importance of the focal SPF in the ecosystem. While one or two species of SPF are the key forage species in some ecosystems (i.e. “wasp-waisted” ecosystems; Cury et al., 2000) SPFs can be part of a diverse forage category, in which case models with predators must be flexible enough to characterize the dynamics of other forage species and the potential for key predators to prey-switch (e.g. with sardine and anchovy in the California Current; Koehn et al., 2016). Ecosystem models with the appropriate degree of structure can be helpful in distinguishing whether a given species is a “key” component or not (Plagányi & Essington, 2014). Incorrect assumptions about functional responses could lead to over- or under-estimation of the impacts of SPF fisheries on predators (Plagányi & Butterworth, 2005). Therefore, it is important to consider uncertainty in the strength and shape of predator–prey functional responses when assembling the reference set of OMs and robustness tests. The effects of a disturbance or a large increase in predator abundance may not propagate through the food web in a manner that is consistent across ecosystems, and the observed strength of trophic cascades depends on the response of the particular SPF to changes in food availability, as well as density dependence (Heath et al., 2014). These processes can be represented in OMs implicitly in the form of time-varying natural mortality and uncertainty in stock–recruit relationships, respectively.

The number of species, sites or ecosystem components included in the OM is important decisions to consider for SPFs because they are never at the top of the food chain; thus, there is no natural limit on model complexity. Accounting for additional non-predator–prey food web relationships may result in more realistic OMs than single-species models, although sometimes it suffices to model ecosystem components such as predation with a realistic range of natural mortalities (Deroba et al., 2018) or allow the OM to explicitly account for predator needs (Fulton et al., 2014; Pikitch et al., 2012). Theoretically, including more species increases the likelihood that the OM better represents the real world, provided the ecological processes are well understood, but the increased number of parameters required for a more complex OM involves evaluating an ever-larger set of robustness trials, which can quickly become prohibitive when parameters are unknown and cannot be estimated reliably. This may be the case when there are one or more forage species without stock assessments. In some cases, other analyses can be used to quantify the benefits of including additional ecological information to models (e.g. economic analyses; Essington et al., 2018) and to optimize the degree of model complexity (Collie et al., 2016), given the model error, that is, the uncertainty in the input variables propagating to the model output (Saltelli, 2019).

When OMs include predators as drivers of prey abundance, it is important for OMs to generate plausible levels of variability in predator and prey abundances if the objectives of management are based on desired levels of predator reproduction or abundance. The latter has been the primary way that multispecies interactions have been considered in MSEs for SPFs so far. For example, the MSE for Atlantic herring in the USA evaluated control rules based on the

needs of seabirds and piscivorous fish (Deroba et al., 2018; Feeney et al., 2018) and represents one case where an MSE approach has been used explicitly to support EBFM (Townsend et al., 2019). The MSE for California Current sardine and anchovy included performance metrics related to the abundance of predators (sea lions and brown pelicans) and the probability that those predators fell below abundance thresholds (Punt, MacCall et al., 2016). Penguin feeding has also been included in the MSE for South African sardine, where performance metrics included the projected impact of alternative sardine management strategies on penguin dynamics based on the estimated relationship with sardine abundance (de Moor, 2018; Robinson et al., 2015).

Generating realistic amounts of variation in natural mortality in single-species models for SPFs may be difficult for some stocks. Proxies such as predator abundance may be used to bracket a realistic range of values and develop plausible scenarios for low-frequency variability in natural mortality. For example, in the Barents Sea, cod abundance is used to simulate capelin mortality, and in the North Sea, a multispecies assessment model is used to calculate natural mortality for several species (ICES, 2020a,b). Hazen et al. (2019) review the ways that predator diet, movement, life history, reproduction and demography can be used to make inferences about unobserved ecosystem components including the abundance of SPFs (fish and invertebrates) and provide guidance for how to employ them to detect changes at different timescales. It is important to ensure that predator abundance proxies for natural mortality are linked to the life-history parameter that is most likely to be actually involved in the relationship. For instance, changing predator abundance may be more appropriate to link to depensatory recruitment than natural mortality if predators select younger prey.

The complexity of the OM should be informed by the research question and management priorities and how ecosystem information is to be used, that is, to generate dynamics or to inform ecosystem reference points. Complex ecosystem models are useful for making strategic management decisions but are generally not recommended for use as operating models in an MSE (Punt, Butterworth et al., 2016; Sainsbury et al., 2000). They can, however, be used to determine reference points or harvest rates that might satisfy predator needs (Pikitch et al., 2012; Smith et al., 2011), before those reference points are evaluated in a single-species MSE. MICE models are more practical for making tactical, practical and quantitative management decisions. For example, Smith et al. (2015) used a small pelagics-specific variant of an Atlantis ecosystem model (Atlantis-SPF) to evaluate reference points for the Commonwealth Small Pelagic Fishery; for northern British Columbia herring. Surma et al. (2018) applied an ecosystem model to ascertain ecological outcomes for harvest control rules, while socio-economic impacts were assessed by industry and community members for their societal desirability (Lam et al., 2019). Pikitch et al. (2012) added variability to Ecosim food web models to test a broad range of harvest control rules. On the other hand, MICE models can address both tactical and strategic

questions, because they can be conditioned on data, provide estimates of current abundance and exploitation while retaining important ecological interactions. Predator effects on prey can be modelled explicitly when data are available to condition a MICE model (e.g. the NWACS-MICE model built for Atlantic menhaden; SEDAR, 2020). These simpler models can be beneficial to use as OMs, as they illustrate how a management strategy performs in complex situations without the uncertainty and computational burden associated with more complex ecosystem models.

#### 4.4 | Considerations for modelling assessment error and reference points in the estimation model (EM)

The OM should generate pseudo-data about the biological system that match what would be available in reality. In practice, these data would either be used directly in a harvest control rule (empirical management strategies; for example advice for North sea horse mackerel is based on changes in survey indices; ICES, 2019a, b, c), as input to an assessment when the harvest control rule depends on assessment model outputs (model-based Management Strategies), or both, when the control rule depends on both data and results from an assessment. For model-based management strategies, the Estimation Model (EM) should either be the existing or proposed assessment method to be used to manage the stock in question; or generate uncertainty similar to the existing or proposed assessment method.

The inclusion of spatially explicit and/or time-varying components in the OM will assist the evaluation of the performance of a management strategy for spatially structured SPFs relative to its objectives. In particular, performance metrics using reference points may require spatially explicit or time-varying reference points (RPs). RPs are benchmarks to which stock level and fishing intensity are compared for management purposes (e.g.  $B_{MSY}$ ). RPs for determining stock status should be chosen appropriately given the "boom and bust" dynamics exhibited by many SPF populations. Some harvest control rules are linked to RPs. In some cases, externally estimated RPs (i.e. not estimated within an assessment) are used in management and can easily be input as time-invariant values in the MSE. In other instances, harvest control rules depend on annually estimated reference points output from the latest assessment (the EM) and time-varying changes to the RPs calculated by the EM should be considered. Where spatially explicit advice is to be provided, the EM would need to estimate spatially explicit reference points or spatially explicit relative stock status to inform the harvest control rule. This would ensure that performance of dynamic or spatially explicit management strategies is evaluated given realistic errors in the estimation of stock status and reference points.

EMs that include other ecosystem components are rare, but in some cases, they may help to meet new EBFM-related challenges. Tommasi et al. (2017) found through an MSE process that harvest

guidelines explicitly incorporating sea surface temperature predictions as a driver of future SPF productivity increased biomass and yield and reduced the probability of biomass or yield falling below accepted thresholds when combined with harvest restrictions at low biomass. Environmental conditions are used in some harvest guidelines to ensure catch quotas are responsive to recruitment variation (e.g. in Pacific sardine; Kuriyama et al., 2020) and have been proposed in others as a way to avoid bias in biomass estimates (Peruvian anchoveta; IMARPE, 2019). Predator data collection could improve the characterization of uncertainty in EMs of SPFs and could allow predator abundance (Hollowed et al., 2000) or predator diet composition (Velarde et al., 2015; Zador & Yasumiishi, 2018) to be used as an indicator of prey abundance and distribution within management strategies. Predator diets may also be used as an indicator for SPF community composition (Elliott et al., 2015; Sydeman, Thompson et al., 2017). However, approaches that use ecosystem information in EMs for SPFs are rare and the OM would need to be constructed to generate data that reflects the uncertainty associated with using such information for management purposes (De Oliveira et al., 2005).

## 5 | SUMMARY AND RECOMMENDATIONS

A key step in the development of any MSE is identifying uncertainties that are likely to be consequential. Sources of uncertainty are plentiful and input from experts is crucial for capturing the full range of scenarios that should be explored and identifying areas of focus (Punt, Butterworth et al., 2016). The process of identifying major sources of ecological uncertainty will require input from experts with knowledge of the ecosystem, the fishery and the quantitative models used for decision-making. Knowing these sources of uncertainty can help analysts interpret MSE results across ecosystems, even if data are insufficient to confirm whether certain plausible hypotheses can be supported. They can also identify “blind spots” where uncertainties are not known but could be impactful. Our study is intended to serve as a guide for those interested in applying MSE to a stock of SPF by providing concrete suggestions to incorporate more ecological processes into MSEs. Here, we share the results of a broader discussion among experts from several systems to demonstrate how uncertainties could be incorporated in models used for MSE.

Ecosystem processes arise at nearly every stage in the MSE process. In the construction of an OM, ecological information can be used in two primary ways: (1) to identify important sources of process and observation uncertainty, which management strategies should ideally be robust to and (2) to ensure the OM produces realistic population dynamics, such that the data generated from the OM are indistinguishable from the actual data, including some of the biases and known issues with the actual data. Our list of considerations (Table 1; Figure 3) should facilitate future modelling in support of management goals, particularly for those who are undertaking an MSE focussed on SPFs. It can be used to

build model complexity, then identify robustness tests where, for example, parts of that model complexity are uncertain. For SPFs, identifying management objectives (step 1 of the MSE process); and interpreting results and communicating tradeoffs to stakeholders (step 7) often involve the consideration of EBFM priorities and ecological processes. The SPF-specific challenges of identifying EBFM priorities are documented in several case studies (Drew et al., 2021; Koehn et al., 2020).

A key decision in the design of any MSE is the choice of which tool(s) are appropriate in scope and scale for the research question; this manuscript will aid scientists in making such decisions. The models typically used to evaluate ecosystem outcomes for fisheries management have not been used extensively in simulation frameworks such as MSE because of the computational burden of running many simulations with complex ecosystem models such as Atlantis. However, some processes can be represented using modifications to a single-species model or MICE model. Accounting for some ecosystem processes will also be key to developing new ways to explicitly address tradeoffs (e.g. between the harvest of predators and prey; Koehn et al., 2017), a consideration inherent to EBFM (Link, 2010). We advise analysts constructing an OM to build in complexity in a way that is informed by the management priorities and whether the ecosystem information is being used to generate realistic dynamics, inform ecosystem reference points, or both.

Not all of the elements discussed here are necessary to include directly in an MSE for SPFs. Including too many sources of uncertainty is likely to lead to results that are difficult to interpret, and considering implausible sources of uncertainty could lead to the selection of an incorrect management strategy (Punt, Butterworth et al., 2016). Furthermore, there are costs to collecting ecosystem information (e.g. Essington et al., 2018) and incorporating it in an MSE. When information is not available about a specific interaction or ecosystem, we recommend meta-analysis as a tool for identifying a realistic range of values and robustness testing, especially if analysts are familiar with the studies therein. Finally, we encourage researchers carrying out MSEs for SPFs to clearly identify which hypotheses can be investigated given the available data. Making sure the OM can be conditioned on available data will build credibility during a management focussed MSE process and allow for the use of the MSE to support tactical decision-making and management. Although it is not straightforward to account for substantial missing data in an MSE, MSE can be tailored to address certain data limitation issues. However, MSE should not be limited to hypotheses that are supported by the data. For example, while depensation is often not supported by data (because of insufficient contrast), it should be considered for inclusion in the set of hypotheses on which the MSE is based unless it can be excluded given the likely substantial impact of depensation of the performance of candidate management strategies.

Other sources of uncertainty are not discussed at length here but merit further investigation and methodological development. Climate change will lead to ecological changes at several scales,

the emergent patterns of which will likely drive SPF populations in ways that are difficult to predict. Future studies may need to consider dynamic interactions between the processes discussed here. We have not considered the societal uncertainties that can arise from the diverse sources of knowledge and values of fishery stakeholders and citizens (Lam et al., 2019). These societal uncertainties can influence the identification of management objectives, performance measures and management strategies considered in participatory MSE processes (Fulton et al., 2014). They also can affect the implementation of and compliance with management strategies recommended from MSEs, adding another layer of complexity and uncertainty to be considered in MSE best practices (Punt, Butterworth et al., 2016).

This review demonstrates the remarkable diversity of systems and management needs for SPFs globally. SPFs present unique challenges to management, but some of these can be addressed if management strategies are evaluated subject to an appropriate and defensible set of uncertainties. Future evaluations of management strategies for SPFs would benefit from a consideration of their unique ecological properties, as suggested throughout this study. Discussion among experts in the ecosystem of interest is also crucial for identifying sources of uncertainty for the simulation process. SPFs represent a case study for how information from these discussions can be leveraged in an MSE framework, which is key for producing robust management decisions that can be used for EBFM.

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## CONFLICT OF INTEREST

The authors have no conflicts of interest to report.

## DATA AVAILABILITY STATEMENT

This manuscript contains data aggregated from other studies; the compiled information is provided in Table S1. The code used to produce Figure 2 is available at <https://github.com/mcsiple/ff-pices>.

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## REFERENCES

- Alder, J., Campbell, B., Karpouzi, V., Kaschner, K., & Pauly, D. (2008). Forage Fish: From Ecosystems to Markets. *Annual Review of Environment and Resources*, 33(1), 153–166. <https://doi.org/10.1146/annurev.enviro.33.020807.143204>
- Allan, B. J. M., Ray, J. L., Tiedemann, M., Komyakova, V., Vikebø, F., Skaar, K. S., Stiasny, M. H., Folkvord, A., Nash, R. D. M., Stenevik, E. K., & Kjesbu, O. S. (2021). Quantitative molecular detection of larval Atlantic herring (*Clupea harengus*) in stomach contents of Atlantic mackerel (*Scomber scombrus*) marks regions of predation pressure. *Scientific Reports*, 11, 5095. <https://doi.org/10.1038/s41598-021-84545-7>
- Anstead, K. A., Drew, K., Chagaris, D., Schueller, A. M., McNamee, J. E., Buchheister, A., Nesslage, G., Uphoff, J. H., Wilberg, M. J., Sharov, A., Dean, M. J., Brust, J., Celestino, M., Madsen, S., Murray, S., Appelman, M., Ballenger, J. C., Brito, J., Cosby, E., ... Townsend, H. (2021). The path to an ecosystem approach for forage fish management: A case study of Atlantic menhaden. *Frontiers in Marine Science*, 8. <https://doi.org/10.3389/fmars.2021.607657>
- Barange, M., Coetzee, J., Takasuka, A., Hill, K., Gutierrez, M., Oozeki, Y., van der Lingen, C., & Agostini, V. (2009). Habitat expansion and contraction in anchovy and sardine populations. *Progress in Oceanography*, 83(1), 251–260. <https://doi.org/10.1016/j.pocean.2009.07.027>
- Barrett, R. T., Chapdelaine, G., Anker-Nilssen, T., Mosbech, A., Montevecchi, W. A., Reid, J. B., & Veit, R. R. (2006). Seabird

- numbers and prey consumption in the North Atlantic. *ICES Journal of Marine Science*, 63(6), 1145–1158. <https://doi.org/10.1016/j.icesjms.2006.04.004>
- Bartolino, V., Margonski, P., Lindegren, M., Linderholm, H. W., Cardinale, M., Rayner, D., Wennhage, H., & Casini, M. (2014). Forecasting fish stock dynamics under climate change: Baltic herring (*Clupea harengus*) as a case study. *Fisheries Oceanography*, 23(3), 258–269. <https://doi.org/10.1111/fog.12060>
- Blanchard, J. L., Andersen, K. H., Scott, F., Hintzen, N. T., Piet, G., & Jennings, S. (2014). Evaluating targets and trade-offs among fisheries and conservation objectives using a multispecies size spectrum model. *Journal of Applied Ecology*, 51(3), 612–622. <https://doi.org/10.1111/1365-2664.12238>
- Borja, A., Fontán, A., Sáenz, J., & Valencia, V. (2008). Climate, oceanography, and recruitment: The case of the Bay of Biscay anchovy (*Engraulis encrasicolus*). *Fisheries Oceanography*, 17, 477–493.
- Butler, C. M., Rudershausen, P. J., & Buckel, J. A. (2010). Feeding ecology of Atlantic bluefin tuna (*Thunnus thynnus*) in North Carolina: Diet, daily ration, and consumption of Atlantic menhaden (*Brevoortia tyrannus*). *Fishery Bulletin*, 108, 56–69.
- Canales, T. M., Lima, M., Wiff, R., Contreras-Reyes, J. E., Cifuentes, U., & Montero, J. (2020). Endogenous, Climate, and Fishing Influences on the Population Dynamics of Small Pelagic Fish in the Southern Humboldt Current Ecosystem. *Frontiers in Marine Science*, 7. <https://doi.org/10.3389/fmars.2020.00082>
- Casini, M., Kornilovs, G., Cardinale, M., Möllmann, C., Grygiel, W., Jonsson, P., Raid, T., Flinkman, J., & Feldman, V. (2011). Spatial and temporal density dependence regulates the condition of central Baltic Sea clupeids: Compelling evidence using an extensive international acoustic survey. *Population Ecology*, 53(4), 511–523. <https://doi.org/10.1007/s10144-011-0269-2>
- Chavez, F. P., Ryan, J., Lluch-Cota, S. E., & Miguel Niquen, C. (2003). From anchovies to sardines and back: Multidecadal change in the Pacific Ocean. *Science*, 299(5604), 217–221. <https://doi.org/10.1126/science.1075880>
- Checkley, D. M., Asch, R. G., & Rykaczewski, R. R. (2017). Climate, anchovy, and sardine. *Annual Review of Marine Science*, 9(1), 469–493. <https://doi.org/10.1146/annurev-marine-122414-033819>
- Collie, J. S., Botsford, L. W., Hastings, A., Kaplan, I. C., Largier, J. L., Livingston, P. A., Plagányi, É., Rose, K. A., Wells, B. K., & Werner, F. E. (2016). Ecosystem models for fisheries management: Finding the sweet spot. *Fish and Fisheries*, 17(1), 101–125. <https://doi.org/10.1111/faf.12093>
- Cope, J. M., & Punt, A. E. (2011). Reconciling stock assessment and management scales under conditions of spatially varying catch histories. *Fisheries Research*, 107(1), 22–38. <https://doi.org/10.1016/j.fishres.2010.10.002>
- Cury, P., Bakun, A., Crawford, R. J. M., Jarre, A., Quinones, R. A., Shannon, L. J., & Verheye, H. M. (2000). Small pelagics in upwelling systems: Patterns of interaction and structural changes in "wasp-waist" ecosystems. *Ices Journal of Marine Science*, 57(3), 603–618. <https://doi.org/10.1006/jmsc.2000.0712>
- Cury, P. M., Boyd, I. L., Bonhommeau, S., Anker-Nilssen, T., Crawford, R. J. M., Furness, R. W., Mills, J. A., Murphy, E. J., Osterblom, H., Paleczny, M., Piatt, J. F., Roux, J.-P., Shannon, L., & Sydeman, W. J. (2011). Global seabird response to forage fish depletion—one-third for the birds. *Science*, 334(6063), 1703–1706. <https://doi.org/10.1126/science.1212928>
- de Moor, C. L. (2018). *The 2018 Operational Management Procedure for the South African sardine and anchovy resources. (Branch Fisheries Document FISHERIES/2018/DEC/SWG-PEL/37)*. Department of Agriculture, Forestry and Fisheries.
- de Moor, C. L., & Butterworth, D. (2016). Chapter 11: Incorporating technological interactions in a joint Management Procedure for South African sardine and anchovy. In C. T. T. Edwards, & D. J. Dankel (Eds.), *Management Science in Fisheries: An Introduction to simulation-based methods* (pp. 205–231).
- de Moor, C. L., Butterworth, D. S., & De Oliveira, J. A. A. (2011). Is the management procedure approach equipped to handle short-lived pelagic species with their boom and bust dynamics? The case of the South African fishery for sardine and anchovy. *ICES Journal of Marine Science: Journal Du Conseil*, 68(10), 2075–2085. <https://doi.org/10.1093/icesjms/fsr165>
- de Moor, C. L., Butterworth, D. S., & van der Lingen, C. D. (2017). The quantitative use of parasite data in multistock modelling of South African sardine (*Sardinops sagax*). *Canadian Journal of Fisheries and Aquatic Sciences*, 74(11), 1895–1903. <https://doi.org/10.1139/cjfas-2016-0280>
- De Oliveira, J. A., & Butterworth, D. S. (2004). Developing and refining a joint management procedure for the multispecies South African pelagic fishery. *ICES Journal of Marine Science*, 61(8), 1432–1442. <https://doi.org/10.1016/j.icesjms.2004.09.001>
- De Oliveira, J. A. A., & Butterworth, D. S. (2005). Limits to the use of environmental indices to reduce risk and/or increase yield in the South African anchovy fishery. *African Journal of Marine Science*, 27(1), 191–203. <https://doi.org/10.2989/18142320509504078>
- De Oliveira, J. A. A., Uriarte, A., & Roel, B. A. (2005). Potential improvements in the management of Bay of Biscay anchovy by incorporating environmental indices as recruitment predictors. *Fisheries Research*, 75(1–3), 2–14. <https://doi.org/10.1016/j.fishres.2005.05.005>
- Deroba, J. J., & Bence, J. R. (2008). A review of harvest policies: Understanding relative performance of control rules. *Fisheries Research*, 94(3), 210–223. <https://doi.org/10.1016/j.fishres.2008.01.003>
- Deroba, J. J., Gaichas, S. K., Lee, M.-Y., Feeney, R. G., Boelke, D. V., & Irwin, B. J. (2018). The dream and the reality: Meeting decision-making time frames while incorporating ecosystem and economic models into management strategy evaluation. *Canadian Journal of Fisheries and Aquatic Sciences*, 76, 1112–1133. <https://doi.org/10.1139/cjfas-2018-0128>
- Deurs, M., Brooks, M. E., Lindegren, M., Henriksen, O., & Rindorf, A. (2020). Biomass limit reference points are sensitive to estimation method, time-series length and stock development. *Fish and Fisheries*, 22(1), 18–30. <https://doi.org/10.1111/faf.12503>
- DFO (2019). *Evaluation of management procedures for Pacific Herring (Clupea pallasii) in the Strait of Georgia and the West Coast of Vancouver Island management areas of British Columbia (No. 001. Canadian Science Advisory Secretariat Science Response)*. DFO.
- Drew, K., Cieri, M., Schueller, A. M., Buchheister, A., Chagaris, D., Nesslage, G., McNamee, J. E., & Uphoff, J. H. J. (2021). Balancing Model Complexity, Data Requirements, and Management Objectives in Developing Ecological Reference Points for Atlantic Menhaden. *Frontiers in Marine Science*, 8. <https://doi.org/10.3389/fmars.2021.608059>
- Elliott, M. L., Bradley, R. W., Robinette, D. P., & Jahncke, J. (2015). Changes in forage fish community indicated by the diet of the Brandt's cormorant (*Phalacrocorax penicillatus*) in the central California Current. *Journal of Marine Systems*, 146, 50–58. <https://doi.org/10.1016/j.jmarsys.2014.07.015>
- Engelhard, G. H., Peck, M. A., Rindorf, A., Smout, S., van Deurs, M., Raab, K., Andersen, K. H., Garthe, S., Lauerburg, R. A. M., Scott, F., Brunel, T., Aarts, G., van Kooten, T., & Dickey-Collas, M. (2014). Forage fish, their fisheries, and their predators: Who drives whom? *Ices Journal of Marine Science*, 71(1), 90–104. <https://doi.org/10.1093/icesjms/fst087>
- Essington, T., Levin, P., Anderson, L., Bundy, A., Carothers, C., Coleman, F. C., Gerber, L., Grabowski, J. H., Houde, E. D., Jensen, O., Möllmann, C., Rose, K. A., Sanchirico, J. N., & Smith, T. (2016). *Building Effective Fishery Ecosystem Plans*. <https://pew.org/2e4kq6V>
- Essington, T. E., Moriarty, P. E., Froehlich, H. E., Hodgson, E. E., Koehn, L. E., Oken, K. L., Siple, M. C., & Stawitz, C. C. (2015). Fishing

- amplifies forage fish population collapses. *Proceedings of the National Academy of Sciences*, 112(21), 6648–6652. <https://doi.org/10.1073/pnas.1422020112>
- Essington, T. E., Sanchirico, J. N., & Baskett, M. L. (2018). Economic value of ecological information in ecosystem-based natural resource management depends on exploitation history. *Proceedings of the National Academy of Sciences*, 115(7), 1658–1663. <https://doi.org/10.1073/pnas.1716858115>
- Essington, T. E., & Plagányi, E. E. (2014). Pitfalls and guidelines for “recycling” models for ecosystem-based fisheries management: Evaluating model suitability for forage fish fisheries. *Ices Journal of Marine Science*, 71(1), 118–127. <https://doi.org/10.1093/icesjms/fst047>
- FAO. (2009). *Report of the Workshop on toolbox for applying the ecosystem approach to fisheries, Rome, 26–29 February 2008*. FAO. <http://www.fao.org/3/i0946e/i0946e00.htm>
- Feeney, R. G., Boelke, D. V., Deroba, J. J., Gaichas, S. K., Irwin, B. J., & Lee, M.-Y. (2018). Integrating Management Strategy Evaluation into fisheries management: Advancing best practices for stakeholder inclusion based on an MSE for Northeast U.S. Atlantic herring. *Canadian Journal of Fisheries and Aquatic Sciences*, 76, 1103–1111. <https://doi.org/10.1139/cjfas-2018-0125>
- Fiechter, J., Rose, K. A., Curchitser, E. N., & Hedstrom, K. S. (2014). The role of environmental controls in determining sardine and anchovy population cycles in the California Current: Analysis of an end-to-end model. *Progress in Oceanography*, 138, 381–398. <https://doi.org/10.1016/j.pocean.2014.11.013>
- Fiorentino, F., Massuti, E., Tinti, F., Somarakis, S., Garofalo, T., Russo, T., Facchini, M. T., Carbonara, P., Kapiris, M., Tugores, P., Cannas, R., Tsigenopoulos, C., Patti, B., Colloca, F., Sbrana, M., Mifsud, R., Valavanis, V., & Spedicato, M. T. (2014). *Stock units: Identification of distinct biological units (stock units) for different fish and shellfish species and among different GFCM-GSA*. (pp. 460). STOCKMED Deliverable 03: FINAL REPORT. STOCKMED. Rome, Italy: General Fisheries Commission for the Mediterranean (GFCM-FAO).
- Froehlich, H. E., Jacobsen, N. S., Essington, T. E., Clavelle, T., & Halpern, B. S. (2018). Avoiding the ecological limits of forage fish for fed aquaculture. *Nature Sustainability*, 1(6), 298–303. <https://doi.org/10.1038/s41893-018-0077-1>
- Fu, C., Travers-Trolet, M., Velez, L., Grüss, A., Bundy, A., Shannon, L. J., Fulton, E. A., Akoglu, E., Houle, J. E., Coll, M., Verley, P., Heymans, J. J., John, E., & Shin, Y.-J. (2018). Risky business: The combined effects of fishing and changes in primary productivity on fish communities. *Ecological Modelling*, 368, 265–276. <https://doi.org/10.1016/j.ecolmodel.2017.12.003>
- Fulton, E. A., Link, J. S., Kaplan, I. C., Savina-Rolland, M., Johnson, P., Ainsworth, C., Horne, P., Gorton, R., Gamble, R. J., Smith, A. D. M., & Smith, D. C. (2011). Lessons in modelling and management of marine ecosystems: The Atlantis experience. *Fish and Fisheries*, 12, 171–188. <https://doi.org/10.1111/j.1467-2979.2011.00412.x>
- Fulton, E. A., Punt, A. E., Dichmont, C. M., Harvey, C. J., & Gorton, R. (2019). Ecosystems say good management pays off. *Fish and Fisheries*, 20(1), 66–96. <https://doi.org/10.1111/faf.12324>
- Fulton, E. A., Smith, A. D. M., Smith, D. C., & Johnson, P. (2014). An Integrated Approach Is Needed for Ecosystem Based Fisheries Management: Insights from Ecosystem-Level Management Strategy Evaluation. *PLoS One*, 9(1), e84242. <https://doi.org/10.1371/journal.pone.0084242>
- Furness, R. W. (2003). Impacts of fisheries on seabird communities. *Scientia Marina*, 67(S2), 33–45. <https://doi.org/10.3989/scimar.2003.67s233>
- Haltuch, M. A., A'amar, Z. T., Bond, N. A., & Valero, J. L. (2019). Assessing the effects of climate change on US West Coast sablefish productivity and on the performance of alternative management strategies. *ICES Journal of Marine Science*, 76(6), 1524–1542. <https://doi.org/10.1093/icesjms/fsz029>
- Haltuch, M. A., Brooks, E. N., Brodziak, J., Devine, J. A., Johnson, K. F., Klibansky, N., Nash, R., Payne, M. R., Shertzer, K. W., Subbey, S., & Wells, B. K. (2019). Unraveling the recruitment problem: A review of environmentally-informed forecasting and management strategy evaluation. *Fisheries Research*, 217, 198–216. <https://doi.org/10.1016/j.fishres.2018.12.016>
- Hamel, O. S., Ressler, P. H., Thomas, R. E., Waldeck, D. A., Hicks, A. C., Holmes, J. A., & Fleischer, G. W. (2015). Biology, fisheries, assessment and management of Pacific hake (*Merluccius productus*). In H. Arancibia (Ed.), *Hakes: Biology and Exploitation* (pp. 234–262). John Wiley & Sons Ltd.
- Hazen, E. L., Abrahms, B., Brodie, S., Carroll, G., Jacox, M. G., Savoca, M. S., Scales, K. L., Sydeman, W. J., & Bograd, S. J. (2019). Marine top predators as climate and ecosystem sentinels. *Frontiers in Ecology and the Environment*, 17(10), 565–574. <https://doi.org/10.1002/fee.2125>
- Heath, M. R., Speirs, D. C., & Steele, J. H. (2014). Understanding patterns and processes in models of trophic cascades. *Ecology Letters*, 17(1), 101–114. <https://doi.org/10.1111/ele.12200>
- Hilborn, R., & Walters, C. (1992). *Quantitative fisheries stock assessment: Choice, dynamics and uncertainty* (Vol. 2). Retrieved from <http://link.springer.com/article/10.1007/BF00042883>
- Holling, C. S. (1959). The Components of Predation as Revealed by a Study of Small-Mammal Predation of the European Pine Sawfly. *The Canadian Entomologist*, 91(5), 293–320. <https://doi.org/10.4039/Ent91293-5>
- Hollowed, A. B., Ianelli, J. N., & Livingston, P. A. (2000). Including predation mortality in stock assessments: A case study for Gulf of Alaska walleye pollock. *ICES Journal of Marine Science*, 57(2), 279–293. <https://doi.org/10.1006/jmsc.1999.0637>
- Hosack, G. R., Trenkel, V. M., & Dambacher, J. M. (2013). The relative importance of environmental stochasticity, interspecific interactions, and observation error: Insights from sardine and anchovy landings. *Journal of Marine Systems*, 125, 77–89. <https://doi.org/10.1016/j.jmarsys.2012.09.003>
- Hunter, A., Speirs, D. C., & Heath, M. R. (2019). Population density and temperature correlate with long-term trends in somatic growth rates and maturation schedules of herring and sprat. *PLoS One*, 14(3), e0212176. <https://doi.org/10.1371/journal.pone.0212176>
- Hurtado-Ferro, F., & Punt, A. E. (2014). *Revised analyses related to Pacific Sardine harvest parameters*. Pacific Fishery Management Council.
- ICES. (2018a). *Report of the workshop on mixing of western and central Baltic herring stocks (WKMixHER)* (ICES CM 2018/ACOM:63; p. 39). ICES.
- ICES. (2018b). *Report of the Workshop on the determination of reference points for Norwegian Spring Spawning Herring (WKNSSHREF)*, 10–11 April 2018. ICES Headquarters. ICES CM 2018/ACOM:45, 83 pp.
- ICES (2019a). *Report of the Working Group on Widely Distributed Stocks (WGWIDE)*. <https://doi.org/10.17895/ICES.PUB.5574>
- ICES (2019b). *Workshop on the Iberian Sardine Management and Recovery Plan (WKSARMP)* (1:18; ICES Scientific Reports, 125 pp.). ICES.
- ICES (2019c). *Workshop on North Sea stocks management strategy evaluation (WKNSMSE)*. ICES Scientific Reports. 1:12. 378 pp. <https://doi.org/10.17895/ices.pub.5090>
- ICES (2020a). *2020 Report Working Group on the Assessment of Demersal Stocks in the North Sea and Skagerrak*. ICES. <https://doi.org/10.17895/ICES.PUB.6092>
- ICES (2020b). *Arctic Fisheries Working Group 2020 Report*. ICES. <https://doi.org/10.17895/ICES.PUB.6050>
- ICES (2020c). *Workshop on Management Strategy Evaluation of Mackerel (WKMSEMAC)*. *ICES Scientific Reports*, 2(74), 175. <https://doi.org/10.17895/ices.pub.7445>
- IMARPE (2019). *Protocolo: Elaboración de la Tabla de Decisión para la determinación del Límite Máximo de Captura Total Permisible por temporada de pesca en la pesquería del Stock Norte-Centro de la anchoveta peruana (v4.1-set2019)*. Instituto del Mar del Perú.



- Ives, A. R., Dennis, B., Cottingham, K. L., & Carpenter, S. R. (2003). Estimating community stability and ecological interactions from time series data. *Ecological Monographs*, 73(2), 301–330.
- Jacobsen, N. S., & Essington, T. E. (2018). Natural mortality augments population fluctuations of forage fish. *Fish and Fisheries*, 19(5), 791–797. <https://doi.org/10.1111/faf.12290>
- Kaplan, I. C., Francis, T. B., Punt, A. E., Koehn, L. E., Curchitser, E., Hurtado-Ferro, F., Johnson, K. F., Luch-Cota, S. E., Sydeman, W. J., Essington, T. E., Taylor, N., Holsman, K., MacCall, A. D., & Levin, P. S. (2019). A multi-model approach to understanding the role of Pacific sardine in the California Current food web. *Marine Ecology Progress Series*, 617–618, 307–321. <https://doi.org/10.3354/meps12504>
- Kapur, M., Siple, M. C., Olmos, M., Privitera-Johnson, K., Adams, G., Best, J., Method, R. D. (n.d.). Equilibrium calculations for the next generation of spatial assessment models: Technical & practical considerations. *Submitted to Fisheries Research*.
- Koehn, L. E., Essington, T. E., Levin, P. S., Marshall, K. N., Anderson, L. G., Bundy, A., Carothers, C., Coleman, F., Grabowski, J. H., Houde, E., Jensen, O. P., Möllmann, C., & Smith, A. D. M. (2020). Case studies demonstrate capacity for a structured planning process for ecosystem-based fisheries management. *Canadian Journal of Fisheries and Aquatic Sciences*, 77(7), 1256–1274. <https://doi.org/10.1139/cjfas-2019-0202>
- Koehn, L. E., Essington, T. E., Marshall, K. N., Kaplan, I. C., Sydeman, W. J., Szoboszlai, A. I., & Thayer, J. A. (2016). Developing a high taxonomic resolution food web model to assess the functional role of forage fish in the California Current ecosystem. *Ecological Modelling*, 335, 87–100. <https://doi.org/10.1016/j.ecolmodel.2016.05.010>
- Koehn, L. E., Essington, T. E., Marshall, K. N., Sydeman, W. J., Szoboszlai, A. I., & Thayer, J. A. (2017). Trade-offs between forage fish fisheries and their predators in the California Current. *ICES Journal of Marine Science*, 74(9), 2448–2458. <https://doi.org/10.1093/icesjms/fsx072>
- Koehn, L. E., Siple, M. C., & Essington, T. E. (2021). A structured seabird population model reveals how alternative forage fish control rules benefit seabirds and fisheries. *Accepted at Ecological Applications*.
- Kuriyama, P. T., Zwolinski, J. P., Hill, K. T., & Crone, P. R. (2020). *Assessment of the Pacific sardine resource in 2020 for U.S. management in 2020–2021*. <https://www.pcouncil.org/coastal-pelagic-species/stock-assesment-and-fishery-evaluation-safe-documents/>
- Lam, M. E., Pitcher, T. J., Surma, S., Scott, J., Kaiser, M., White, A. S. J., Pakhomov, E. A., & Ward, L. M. (2019). Value- and ecosystem-based management approach: The Pacific herring fishery conflict. *Marine Ecology Progress Series*, 617–618, 341–364. <https://doi.org/10.3354/meps12972>
- Liermann, M., & Hilborn, R. (2001). Depensation: Evidence, models and implications. *Fish and Fisheries*, 2(1), 33–58. <https://doi.org/10.1046/j.1467-2979.2001.00029.x>
- Liermann, M., & Hilborn, R. (2011). Depensation in fish stocks: A hierarchical Bayesian meta-analysis. *Canadian Journal of Fisheries and Aquatic Sciences*, 54(9), 1976–1984. <https://doi.org/10.1139/f97-105>
- Lindgren, M., Checkley, D. M. Jr, Rouyer, T., MacCall, A. D., & Stenseth, N. C. (2013). Climate, fishing, and fluctuations of sardine and anchovy in the California Current. *Proceedings of the National Academy of Sciences of the United States of America*, 110, 13672–13677. <https://doi.org/10.1073/pnas.1305733110>
- Lindgren, M., Möllmann, C., Nielsen, A., & Stenseth, N. C. (2009). Preventing the collapse of the Baltic cod stock through an ecosystem-based management approach. *Proceedings of the National Academy of Sciences*, 106(34), 14722–14727.
- Link, J. (2010). *Ecosystem-Based Fisheries Management: Confronting Tradeoffs* (1st edn). Cambridge University Press.
- Lynam, C. P., Llope, M., Möllmann, C., Helaouët, P., Bayliss-Brown, G. A., & Stenseth, N. C. (2017). Interaction between top-down and bottom-up control in marine food webs. *Proceedings of the National Academy of Sciences of the United States of America*, 114, 1952–1957. <https://doi.org/10.1073/pnas.1621037114>
- Ma, S., Cheng, J., Li, J., Liu, Y., Wan, R., & Tian, Y. (2019). Interannual to decadal variability in the catches of small pelagic fishes from China Seas and its responses to climatic regime shifts. *Deep Sea Research Part II: Topical Studies in Oceanography*, 159, 112–129. <https://doi.org/10.1016/j.dsr2.2018.10.005>
- MacCall, A. D. (1990). *Dynamic Geography of Marine Fish Populations: Books in Recruitment Fishery Oceanography*. University of Washington Press.
- MacCall, A. D., Francis, T. B., Punt, A. E., Siple, M. C., Armitage, D. R., Cleary, J. S., Dressell, S. C., Jones, R. R., Kitka, H., Lee, L. C., Levin, P. S., Mclsaac, J., Okamoto, D. K., Poe, M., Reifenstuhl, S., Schmidt, J. O., Shelton, A. O., Silver, J. J., Thornton, T. F., ... Woodruff, J. (2019). A heuristic model of socially learned migration behaviour exhibits distinctive spatial and reproductive dynamics. *ICES Journal of Marine Science*, 76(2), 598–608. <https://doi.org/10.1093/icesjms/fsy091>
- MacCall, A. D., Sydeman, W. J., Davison, P. C., & Thayer, J. A. (2016). Recent collapse of northern anchovy biomass off California. *Fisheries Research*, 175, 87–94. <https://doi.org/10.1016/j.fishres.2015.11.013>
- Marshall, K. N., Koehn, L. E., Levin, P. S., Essington, T. E., & Jensen, O. P. (2019). Inclusion of ecosystem information in US fish stock assessments suggests progress toward ecosystem-based fisheries management. *ICES Journal of Marine Science*, 76(1), 1–9. <https://doi.org/10.1093/icesjms/fsy152>
- McClatchie, S. (2012). Sardine biomass is poorly correlated with the Pacific Decadal Oscillation off California. *Geophysical Research Letters*, 39(13), L13703. <https://doi.org/10.1029/2012GL052140>
- McKeown, N. J., Carpi, P., Silva, J. F., Healey, A. J. E., Shaw, P. W., & van der Kooij, J. (2020). Genetic population structure and tools for the management of European sprat (*Sprattus sprattus*). *ICES Journal of Marine Science*, 77(6), 2134–2143. <https://doi.org/10.1093/icesjms/fsaa113>
- Metian, A. G. J. T. M. (2009). Fishing for Feed or Fishing for Food: Increasing Global Competition for Small Pelagic Forage Fish. *AMBIO: A Journal of the Human Environment*, 38(6), 294–302. <https://doi.org/10.1579/08-A-574.1>
- Möllmann, C., Lindgren, M., Blenckner, T., Bergström, L., Casini, M., Diekmann, R., Flinkman, J., Müller-Karulis, B., Neuenfeldt, S., Schmidt, J. O., Tomczak, M., Voss, R., & Gårdmark, A. (2014). Implementing ecosystem-based fisheries management: From single-species to integrated ecosystem assessment and advice for Baltic Sea fish stocks. *ICES Journal of Marine Science*, 71(5), 1187–1197. <https://doi.org/10.1093/icesjms/fst123>
- Nieto, K., McClatchie, S., Weber, E. D., & Lennert-Cody, C. E. (2014). Effect of mesoscale eddies and streamers on sardine spawning habitat and recruitment success off Southern and central California. *Journal of Geophysical Research: Oceans*, 119(9), 6330–6339. <https://doi.org/10.1002/2014JC010251>
- Nikolioudakis, N., Skaug, H. J., Olafsdottir, A. H., Jansen, T., Jacobsen, J. A., & Enberg, K. (2019). Drivers of the summer-distribution of Northeast Atlantic mackerel (*Scomber scombrus*) in the Nordic Seas from 2011 to 2017; a Bayesian hierarchical modelling approach. *ICES Journal of Marine Science*, 76(2), 530–548. <https://doi.org/10.1093/icesjms/fsy085>
- Okamoto Daniel K., Poe Melissa R., Francis Tessa B., Punt André E., Levin Phillip S., Shelton Andrew O., Armitage Derek R., Cleary Jaclyn S., Dressell Sherri C., Jones Russ, Kitka Harvey, Lee Lynn C., MacCall Alec D., Mclsaac Jim A., Reifenstuhl Steve, Silver Jennifer J., Schmidt Jörn O., Thornton Thomas F., Voss Rüdiger, ... Woodruff John (2020). Attending to spatial social-ecological sensitivities to improve trade-off analysis in natural resource management. *Fish and Fisheries*, 21, (1), 1–12. <http://dx.doi.org/10.1111/faf.12409>
- Overholtz, W. J., Link, J. S., & Suslowicz, L. E. (2000). Consumption of important pelagic fish and squid by predatory fish in the northeastern

- USA shelf ecosystem with some fishery comparisons. *ICES Journal of Marine Science*, 57(4), 1147–1159. <https://doi.org/10.1006/jmsc.2000.0802>
- Perryman, H. A., Hansen, C., Howell, D., & Olsen, E. (2021). A Review of Applications Evaluating Fisheries Management Scenarios through Marine Ecosystem Models. *Reviews in Fisheries Science & Aquaculture*, 1–36. <https://doi.org/10.1080/23308249.2021.1884642>
- Pikitch, E., Boersma, P. D., Boyd, I. L., Conover, D. O., Cury, P., Essington, T. E., Heppell, S. S., Houde, E. D., Mangel, M., Pauly, D., Plagányi, E. E., Sainsbury, K. J., & Steneck, R. S. (2012). *Little Fish, Big Impact: Managing a crucial link in ocean food webs* (108 p). Lenfest Ocean Program.
- Pikitch, E. K., Rountos, K. J., Essington, T. E., Santora, C., Pauly, D., Watson, R., Sumaila, U. R., Boersma, P. D., Boyd, I. L., Conover, D. O., Cury, P., Heppell, S. S., Houde, E. D., Mangel, M., Plagányi, É., Sainsbury, K., Steneck, R. S., Geers, T. M., Gownaris, N., & Munch, S. B. (2014). The global contribution of forage fish to marine fisheries and ecosystems. *Fish and Fisheries*, 15(1), 43–64. <https://doi.org/10.1111/faf.12004>
- Pinnegar, J. K., Trenkel, V. M., Tidd, A. N., Dawson, W. A., & Buit, M. H. D. (2003). Does diet in Celtic Sea fishes reflect prey availability? *Journal of Fish Biology*, 63(s1), 197–212. <https://doi.org/10.1111/j.1095-8649.2003.00204.x>
- Pinsky, M. L., & Byler, D. (2015). Fishing, fast growth and climate variability increase the risk of collapse. *Proceedings of the Royal Society B: Biological Sciences*, 282(1813), 20151053. <https://doi.org/10.1098/rspb.2015.1053>
- Pitcher, T. J. (1995). The impact of pelagic fish behaviour on fisheries. *Scientia Marina*, 59(3–4), 295–306.
- Plagányi, É. E. (2016). Using simulation evaluation to account for ecosystem considerations in fisheries management. In C. T. T. Edwards, & D. J. Dankel (Eds.), *Management Science in Fisheries: An introduction to simulation-based methods*. (298–318). Routledge.
- Plagányi, E. E., & Butterworth, D. S. (2005). Indirect fishery interactions. In J. E. Reynolds, W. F. Perrin, R. R. Reeves, & S. Montgomery (Eds.), *Looking to the Horizon: Future Directions in Marine Mammal Research* (pp. 19–45). John Hopkins University Press.
- Plagányi, É. E., & Essington, T. E. (2014). When the SURFs up, forage fish are key. *Fisheries Research*, 159, 68–74. <https://doi.org/10.1016/j.fishres.2014.05.011>
- Plagányi, É. E., Punt, A. E., Hillary, R., Morello, E. B., Thébaud, O., Hutton, T., Pillans, R. D., Thorson, J. T., Fulton, E. A., Smith, A. D. M., Smith, F., Bayliss, P., Haywood, M., Lyne, V., & Rothlisberg, P. C. (2014). Multispecies fisheries management and conservation: Tactical applications using models of intermediate complexity. *Fish and Fisheries*, 15(1), 1–22. <https://doi.org/10.1111/j.1467-2979.2012.00488.x>
- Punt, A. E. (2019). Spatial stock assessment methods: A viewpoint on current issues and assumptions. *Fisheries Research*, 213, 132–143. <https://doi.org/10.1016/j.fishres.2019.01.014>
- Punt, A. E., A'mar, T., Bond, N. A., Butterworth, D. S., de Moor, C. L., De Oliveira, J. A. A., Haltuch, M. A., Hollowed, A. B., & Szuwalski, C. (2014). Fisheries management under climate and environmental uncertainty: Control rules and performance simulation. *ICES Journal of Marine Science*, 71(8), 2208–2220. <https://doi.org/10.1093/icesjms/fst057>
- Punt, A. E., Butterworth, D. S., de Moor, C. L., De Oliveira, J. A. A., & Haddon, M. (2016). Management strategy evaluation: Best practices. *Fish and Fisheries*, 17(2), 303–334. <https://doi.org/10.1111/faf.12104>
- Punt, A. E., & Donovan, G. (2007). Developing management procedures that are robust to uncertainty: Lessons from the International Whaling Commission. *ICES Journal of Marine Science*, 64, 603–612. <https://doi.org/10.1093/icesjms/fsm035>
- Punt, A. E., & Hobday, D. (2009). Management strategy evaluation for rock lobster, *Jasus edwardsii*, off Victoria, Australia: Accounting for uncertainty in stock structure. *New Zealand Journal of Marine and Freshwater Research*, 43(1), 485–509. <https://doi.org/10.1080/00288330909510017>
- Punt, A. E., MacCall, A. D., Essington, T. E., Francis, T. B., Hurtado-Ferro, F., Johnson, K. F., Kaplan, I. C., Koehn, L. E., Levin, P. S., & Sydeman, W. J. (2016). Exploring the implications of the harvest control rule for Pacific sardine, accounting for predator dynamics: A MICE model. *Ecological Modelling*, 337, 79–95. <https://doi.org/10.1016/j.ecolmodel.2016.06.004>
- Punt, A. E., Siple, M. C., Francis, T. B., Hammond, P. S., Heinemann, D., Long, K., Moore, J. E., Sepulveda, M., Reeves, R. R., Sigurðsson, G. M., Vikingsson, G., Wade, P. R., Williams, R., & Zerbini, A. N. (2020). Robustness of potential biological removal to monitoring, environmental, and management uncertainties. *ICES Journal of Marine Science*, 77(7–8), 2491–2507. <https://doi.org/10.1093/icesjms/fsaa096>
- Quintela, M., Kvamme, C., Bekkevold, D., Nash, R. D. M., Jansson, E., Sørvik, A. G., Taggart, J. B., Skaala, Ø., Dahle, G., & Glover, K. A. (2020). Genetic analysis redraws the management boundaries for the European sprat. *Evolutionary Applications*, 13(8), 1906–1922. <https://doi.org/10.1111/eva.12942>
- Rademeyer, R. A., Plagányi, É. E., & Butterworth, D. S. (2007). Tips and tricks in designing management procedures. *ICES Journal of Marine Science*, 64(4), 618–625. <https://doi.org/10.1093/icesjms/fsm050>
- RAM Legacy Stock Assessment Database. (2018). *RAM Legacy Stock Assessment Database v4.44*. Zenodo. <https://doi.org/10.5281/zenodo.2542919>
- Reiss, C. S., Checkley, D. M., & Bograd, S. J. (2008). Remotely sensed spawning habitat of Pacific sardine (*Sardinops sagax*) and Northern anchovy (*Engraulis mordax*) within the California Current. *Fisheries Oceanography*, 17(2), 126–136. <https://doi.org/10.1111/j.1365-2419.2008.00469.x>
- Ricard, D., Minto, C., Jensen, O. P., & Baum, J. K. (2012). Examining the knowledge base and status of commercially exploited marine species with the RAM Legacy Stock Assessment Database: The RAM Legacy Stock Assessment Database. *Fish and Fisheries*, 13(4), 380–398. <https://doi.org/10.1111/j.1467-2979.2011.00435.x>
- Robinson, W. M. L., Butterworth, D. S., & Plagányi, É. E. (2015). Quantifying the projected impact of the South African sardine fishery on the Robben Island penguin colony. *ICES Journal of Marine Science*, 72(6), 1822–1833. <https://doi.org/10.1093/icesjms/fsv035>
- Rose, K. A., Fiechter, J., Curchitser, E. N., Hedstrom, K., Bernal, M., Creekmore, S., Haynie, A., Ito, S.-I., Lluch-Cota, S., Megrey, B. A., Edwards, C. A., Checkley, D., Koslow, T., McClatchie, S., Werner, F., MacCall, A., & Agostini, V. (2015). Demonstration of a fully-coupled end-to-end model for small pelagic fish using sardine and anchovy in the California Current. *Progress in Oceanography*, 138, 348–380. <https://doi.org/10.1016/j.pocean.2015.01.012>
- Ross-Gillespie, A., & Butterworth, D. S. (2020). *Updated implementation of the Algorithm recommended by the Panel for the 2016 International Stock Assessment Workshop for assessing whether or not to continue with the penguin island closure experiment*. (Branch Fisheries Document FISHERIES/2020/JAN/SWG-PEL/09). Department of the Environment, Forestry and Fisheries.
- Sainsbury, K. J., Punt, A. E., & Smith, A. D. M. (2000). Design of operational management strategies for achieving fishery ecosystem objectives. *ICES Journal of Marine Science*, 57(3), 731–741. <https://doi.org/10.1006/jmsc.2000.0737>
- Saltelli, A. (2019). A short comment on statistical versus mathematical modelling. *Nature Communications*, 10, 3870. <https://doi.org/10.1038/s41467-019-11865-8>
- Sánchez, S., Ibaibarriaga, L., Uriarte, A., Prellezo, R., Andres, M., Abaunza, P., Jardim, E., Lehuta, S., Pawlowski, L., & Roel, B. (2019). Challenges of management strategy evaluation for small pelagic fish: The Bay of Biscay anchovy case study. *Marine Ecology Progress Series*, 617, 245–263. <https://doi.org/10.3354/meps12602>

- Saraux, C., Fromentin, J.-M., Bigot, J.-L., Bourdeix, J.-H., Morfin, M., Roos, D., Beveren, E. V., & Bez, N. (2014). Spatial Structure and Distribution of Small Pelagic Fish in the Northwestern Mediterranean Sea. *PLoS One*, 9(11), e111211. <https://doi.org/10.1371/journal.pone.0111211>
- SEDAR. (2020). *SEDAR 69 - Atlantic Menhaden Benchmark Stock Assessment Report*. SEDAR. Retrieved from [https://www.asmfc.org/uploads/file/5e4c3a4bAtlMenhadenSingleSpeciesAssmt\\_PeerReviewReports.pdf](https://www.asmfc.org/uploads/file/5e4c3a4bAtlMenhadenSingleSpeciesAssmt_PeerReviewReports.pdf)
- Sherley, R. B. (2020). *Revising the key results in MARAM/IWS/2019/PENG/P4 in light of the 2019 Panel recommendations (Branch Fisheries Document FISHERIES/2020/JUL/SWG-PEL/53REV)*. Department of the Environment, Forestry and Fisheries.
- Sherley, R. B., Winker, H., Altwegg, R., van der Lingen, C. D., Votier, S. C., & Crawford, R. J. M. (2015). Bottom-up effects of a no-take zone on endangered penguin demographics. *Biology Letters*, 11(7), 20150237. <https://doi.org/10.1098/rsbl.2015.0237>
- Silva, A., Santos, M. B., Caneco, B., Pestana, G., Porteiro, C., Carrera, P., & Stratoudakis, Y. (2006). Temporal and geographic variability of sardine maturity at length in the northeastern Atlantic and the western Mediterranean. *ICES Journal of Marine Science*, 63(4), 663–676. <https://doi.org/10.1016/j.icesjms.2006.01.005>
- Siple, M. C., Essington, T. E., Barnett, L. A. K., & Scheuerell, M. D. (2020). Limited evidence for sardine and anchovy asynchrony: Re-examining an old story. *Proceedings of the Royal Society B: Biological Sciences*, 287(1922), 20192781. <https://doi.org/10.1098/rspb.2019.2781>
- Siple, M. C., & Koehn, L. E. (2017). SPF Workshop on "Simulation approaches of forage fish populations for management strategy evaluations". *PICES Press*, 25(2), 24–26.
- Skaret, G., Bachiller, E., Langøy, H., & Stenevik, E. K. (2015). Mackerel predation on herring larvae during summer feeding in the Norwegian Sea. *ICES Journal of Marine Science*, 72(8), 2313–2321. <https://doi.org/10.1093/icesjms/fsv087>
- Smith, A. D. M. (1994). Management strategy evaluation – the light on the hill. In D. A. Hancock (Ed.), *Population dynamics for fisheries management*. Australian Society for Fish Biology.
- Smith, A. D. M., Brown, C. J., Bulman, C. M., Fulton, E. A., Johnson, P., Kaplan, I. C., Lozano-Montes, H., Mackinson, S., Marzloff, M., Shannon, L. J., Shin, Y.-J., & Tam, J. (2011). Impacts of fishing low-trophic level species on marine ecosystems. *Science*, 333(6046), 1147–1150. <https://doi.org/10.1126/science.1209395>
- Smith, A. D. M., Fulton, E. J., Hobday, A. J., Smith, D. C., & Shoulder, P. (2007). Scientific tools to support the practical implementation of ecosystem-based fisheries management. *ICES Journal of Marine Science*, 64(4), 633–639. <https://doi.org/10.1093/icesjms/fsm041>
- Smith, A., Hurtado, F., Klaer, N., & Fulton, E. (2015) *Review and update of harvest strategy settings for the Commonwealth Small Pelagic Fishery Single species and ecosystem considerations*. Retrieved September 3, 2020, from Undefined website: <http://paper/Review-and-update-of-harvest-strategy-settings-for-Smith-Hurtado/6ad8cfc7b8a3edfd7ebf6367cfd3fc059af13c0>
- Smoliński, S. (2019). Sclerochronological approach for the identification of herring growth drivers in the Baltic Sea. *Ecological Indicators*, 101, 420–431. <https://doi.org/10.1016/j.ecolind.2019.01.050>
- Somarakis, S., Tsoukali, S., Giannoulaki, M., Schismenou, E., & Nikoloudakis, N. (2019). Spawning stock, egg production and larval survival in relation to small pelagic fish recruitment. *Marine Ecology Progress Series*, 617–618, 113–136. <https://doi.org/10.3354/meps12642>
- Subbey, S., Devine, J. A., Schaarschmidt, U., & Nash, R. D. M. (2014). Modelling and forecasting stock–recruitment: Current and future perspectives. *ICES Journal of Marine Science*, 71(8), 2307–2322. <https://doi.org/10.1093/icesjms/fsu148>
- Surma, S., Pitcher, T. J., Kumar, R., Varkey, D., Pakhomov, E. A., & Lam, M. E. (2018). Herring supports Northeast Pacific predators and fisheries: Insights from ecosystem modelling and management strategy evaluation. *PLoS One*, 13(7), e0196307. <https://doi.org/10.1371/journal.pone.0196307>
- Suryan, R. M., Irons, D. B., Brown, E. D., Jodice, P. G. R., & Roby, D. D. (2006). Site-specific effects on productivity of an upper trophic-level marine predator: Bottom-up, top-down, and mismatch effects on reproduction in a colonial seabird. *Progress in Oceanography*, 68(2–4), 303–328. <https://doi.org/10.1016/j.pocean.2006.02.006>
- Swain, D. P., & Benoît, H. P. (2015). Extreme increases in natural mortality prevent recovery of collapsed fish populations in a Northwest Atlantic ecosystem. *Marine Ecology Progress Series*, 519, 165–182. <https://doi.org/10.3354/meps11012>
- Sydeman, W. J., Piatt, J. F., Thompson, S. A., García-Reyes, M., Hatch, S. A., Arimitsu, M. L., Slater, L., Williams, J. C., Rojek, N. A., Zador, S. G., & Renner, H. M. (2017). Puffins reveal contrasting relationships between forage fish and ocean climate in the North Pacific. *Fisheries Oceanography*, 26(4), 379–395. <https://doi.org/10.1111/fog.12204>
- Sydeman, W. J., Thompson, S. A., Anker-Nilssen, T., Arimitsu, M., Bennison, A., Bertrand, S., Boersch-Supan, P., Boyd, C., Bransome, N. C., Crawford, R. J. M., Daunt, F., Furness, R. W., Gianuca, D., Gladics, A., Koehn, L., Lang, J. W., Logerwell, E., Morris, T. L., Phillips, E. M., ... Zador, S. (2017). Best practices for assessing forage fish fisheries-seabird resource competition. *Fisheries Research*, 194, 209–221. <https://doi.org/10.1016/j.fishres.2017.05.018>
- Szoboszlai, A. I., Thayer, J. A., Wood, S. A., Sydeman, W. J., & Koehn, L. E. (2015). Forage species in predator diets: Synthesis of data from the California Current. *Ecological Informatics*, 29, 45–56. <https://doi.org/10.1016/j.ecoinf.2015.07.003>
- Szuwalski, C. S., Britten, G. L., Licandeo, R., Amoroso, R. O., Hilborn, R., & Walters, C. (2019). Global forage fish recruitment dynamics: A comparison of methods, time-variation, and reverse causality. *Fisheries Research*, 214, 56–64. <https://doi.org/10.1016/j.fishres.2019.01.007>
- Szuwalski, C. S., Vert-Pre, K. A., Punt, A. E., Branch, T. A., & Hilborn, R. (2014). Examining common assumptions about recruitment: A meta-analysis of recruitment dynamics for worldwide marine fisheries. *Fish and Fisheries*, 16(4), 633–648. <https://doi.org/10.1111/faf.12083>
- Tacon, A. G. J., & Metian, M. (2008). Global overview on the use of fish meal and fish oil in industrially compounded aquafeeds: Trends and future prospects. *Aquaculture*, 285(1–4), 146–158. <https://doi.org/10.1016/j.aquaculture.2008.08.015>
- Tommasi, D., Stock, C. A., Pegion, K., Vecchi, G. A., Methot, R. D., Alexander, M. A., & Checkley, D. M. (2017). Improved management of small pelagic fisheries through seasonal climate prediction. *Ecological Applications*, 27(2), 378–388. <https://doi.org/10.1002/eap.1458>
- Townsend, H., Harvey, C. J., deReynier, Y., Davis, D., Zador, S. G., Gaichas, S., Weijerman, M., Hazen, E. L., & Kaplan, I. C. (2019). Progress on Implementing Ecosystem-Based Fisheries Management in the United States Through the Use of Ecosystem Models and Analysis. *Frontiers in Marine Science*, 6. <https://doi.org/10.3389/fmars.2019.00641>
- Trochta, J. T., Branch, T. A., Shelton, A. O., & Hay, D. E. (2020). The highs and lows of herring: A meta-analysis of patterns and factors in herring collapse and recovery. *Fish and Fisheries*, 21(3), 639–662. <https://doi.org/10.1111/faf.12452>
- Tuck, G. N. (2011). Are bycatch rates sufficient as the principal fishery performance measure and method of assessment for seabirds?: SEABIRD BYCATCH RATES. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 21(5), 412–422. <https://doi.org/10.1002/aqc.1201>
- van der Lingen, C., Fréon, P., Fairweather, T., & van der Westhuizen, J. (2006). Density-dependent changes in reproductive parameters and condition of southern Benguela sardine *Sardinops sagax*. *African Journal of Marine Science*, 28(3–4), 625–636. <https://doi.org/10.2989/18142320609504212>
- Velarde, E., Ezcurra, E., & Anderson, D. W. (2015). Seabird diet predicts following-season commercial catch of Gulf of California Pacific

- Sardine and Northern Anchovy. *Journal of Marine Systems*, 146, 82–88. <https://doi.org/10.1016/j.jmarsys.2014.08.014>
- Vert-pre, K. A., Amoroso, R. O., Jensen, O. P., & Hilborn, R. (2013). Frequency and intensity of productivity regime shifts in marine fish stocks. *Proceedings of the National Academy of Sciences*, 110(5), 1779–1784. <https://doi.org/10.1073/pnas.1214879110>
- Wade, P. R. (1998). Calculating Limits to the Allowable Human-Caused Mortality of Cetaceans and Pinnipeds. *Marine Mammal Science*, 14(1), 1–37. <https://doi.org/10.1111/j.1748-7692.1998.tb00688.x>
- Walters, C., & Kitchell, J. F. (2011). Cultivation/depensation effects on juvenile survival and recruitment: Implications for the theory of fishing. *Canadian Journal of Fisheries and Aquatic Sciences*, 58(1), 39–50. <https://doi.org/10.1139/f00-160>
- Walters, C., Pauly, D., & Christensen, V. (1999). Ecospace: Prediction of Mesoscale Spatial Patterns in Trophic Relationships of Exploited Ecosystems, with Emphasis on the Impacts of Marine Protected Areas. *Ecosystems*, 2(6), 539–554. <https://doi.org/10.1007/s100219900101>
- Weber, E. D., & McClatchie, S. (2010). Predictive models of northern anchovy *Engraulis mordax* and Pacific sardine *Sardinops sagax* spawning habitat in the California Current. *Marine Ecology Progress Series*, 406, 251–263. <https://doi.org/10.3354/meps08544>
- Weston, L. F., Reed, C. C., Hendricks, M., Winker, H., & van der Lingen, C. D. (2015). Stock discrimination of South African sardine (*Sardinops sagax*) using a digenean parasite biological tag. *Fisheries Research*, 164, 120–129. <https://doi.org/10.1016/j.fishres.2014.11.002>
- Zador, S., & Yasumiishi, E. (2018). *Ecosystem Status Report 2018 Gulf of Alaska* (p. 194). North Pacific Management Council.
- Zheng, J. (1996). Herring stock-recruitment relationships and recruitment patterns in the North Atlantic and Northeast Pacific oceans. *Fisheries Research*, 26(3), 257–277. [https://doi.org/10.1016/0165-7836\(95\)00435-1](https://doi.org/10.1016/0165-7836(95)00435-1)
- Zimmermann, F., Claireaux, M., & Enberg, K. (2019). Common trends in recruitment dynamics of north-east Atlantic fish stocks and their links to environment, ecology and management. *Fish and Fisheries*, 20(3), 518–536. <https://doi.org/10.1111/faf.12360>
- Zwolinski, J. P., Emmett, R. L., & Demer, D. A. (2011). Predicting habitat to optimize sampling of Pacific sardine (*Sardinops sagax*). *ICES Journal of Marine Science*, 68(5), 867–879. <https://doi.org/10.1093/icesjms/fsr038>

## SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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