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Original Article

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The ICES MSY approach to reference point estimation is not precautionary

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Abstract

In the Northeast Atlantic, the International Council for the Exploration of the Sea (ICES) provides scientific advice under the precautionary approach (PA) and maximum sustainable yield (MSY) principles. F_{MSY}, the exploitation level that achieves MSY in the long term, is derived in ICES through stochastic simulations with the software EQSIM for most of the stocks. The computed F_{MSY} is then conditioned on the PA such that fishing at F_{MSY} does not exceed a 5% probability of the spawning stock biomass falling below the limit reference point B_{lim}. We compared reference points estimated using EQSIM and a short-cut management strategy evaluation (MSE) tool (RPETool), which approximates a full-feedback control loop, and, differently from EQSIM, mimics the stock assessment advice process, including all data lags, and retains the original structure of the assessment model. Here, we showed that the simplifications of the management system and the assessment model, which are necessary for conducting simulations with EQSIM, result in the breaching of the PA for 3 of 4 recently benchmarked stocks. For the only stock for which the PA was not violated, the EQSIM estimate of F_{MSY} was still larger than the actual F_{MSY} estimated within the assessment model, and long-term yields were not maximized. Considering that EQSIM has been used since 2017 to derive reference points in ICES for more than 75% of the data-rich stocks, it is urgent that it is phased out and substituted by a more appropriate approach, like RPETool. Furthermore, the analysis highlights the asymmetry between increased risk of breaching B_{lim} when fishing at or above F_{MSY} and low risk in terms of the minimal loss in long-term yield when fishing below F_{MSY}, with <5% yield loss even if F were reduced to around 60% of F_{MSY}. Considering the wide ranges of additional uncertainties about the assessment model and the associated F_{MSY} estimate, we propose that it is time for a paradigm shift within ICES to advocate for F_{MSY} being the upper limit for advice on fishing opportunities rather than the target.

Keywords: ICES advice framework; reference points estimation; management strategy evaluation; MSY

Introduction

In 2013, the concept of maximum sustainable yield (MSY) was adopted within the European Common Fisheries Policy (CFP) (EU Regulation No. 1380/2013; the Basic Regulation, EU 2013) as the overarching management objective for the sustainable exploitation of European fisheries. Within the EU, legal obligations to implement MSY management and establish multiannual plans reflecting the specificities of different fisheries based on the best available science were set out in the reformed CFP (EU 2013). Article 2.2 of EU Regulation 1380/2013 (the Common Fisheries Policy) specifically states that '*The CFP shall apply the precautionary approach to fisheries management and shall aim to ensure that exploitation of living marine biological resources restores and maintains populations of harvested species above levels which can produce the maximum sustainable yield*'. Therefore, MSY is a target, which implies that fishing mortality should be maintained on average below and biomass above the levels that support MSY. For most Northeast Atlantic stocks, the scientific advice framework used to implement the CFP is provided by the International Council for the Exploration of the Sea (ICES; www.ices.dk). ICES defines MSY as the maximum average long-term yield that can be taken from a fish stock while maintaining its productivity (ICES 2023). The fishing mortality associated with MSY, F_{MSY}, is a key reference point in this framework. It is defined as the fishing mortality that results in MSY when the stock is in equilibrium. In addition to F_{MSY}, the framework includes several precautionary reference points: B_{lim} is the stock size below which there is a high risk of reduced productivity; F_{P05} is the fishing mortality that results in no more than 5% probability of bringing the spawning stock to below B_{lim} in the long term; MSY $B_{trigger}$ is the stock size below which advice is for a reduced fishing mortality relative to F_{MSY}, it is intended to reduce the risk of the stock size falling below B_{lim}.

In ICES, for quantitative analytical age-structured stock assessments, which cover nearly 90% of the landings in the Northeast Atlantic stocks (ICES 2021a), F_{MSY}, the exploitation level that achieves MSY, is commonly derived through stochastic forward simulations (EQSIM; Simmonds et al. 2019, https://github.com/ices-tools-prod/msy). EQSIM is a stochastic forward simulation tool (Simmonds et al. 2019) that has been widely used during benchmark processes (e.g. ICES 2024a). In the last 15 years, there were significant technical developments around simulation testing and management strategy evaluation (MSE) (ICES 2013a, Punt et al. 2016), and at the same time major work has been performed within ICES on developing the EQSIM tool to estimate MSY reference points. After limited progress towards a general approach for reference point estimation in ICES at WKMSYREF (ICES 2013b), there were significant developments when EQSIM was more widely tested during WKMSYREF2 (ICES 2014). Subsequently, a joint ICES/MYFISH (https://www.myfishproject.eu/) workshop WKMSYREF3 (ICES 2015) systematically estimated MSY reference points and F_{MSY} ranges for the North Sea and Baltic stocks to address a special request from the EU for MSY ranges. WKMSYREF4 developed the approach further and estimated MSY ranges for demersal stocks in western waters (ICES 2017). The ICES technical guidelines to estimate 'fisheries management reference points for categories 1 and 2' were published in 2017 (ICES 2017); category 1 stocks are those where a quantitative assessment exists and is assumed to provide absolute estimates of stock status, while for category 2 estimates are assumed to only provide relative estimates or trends. Since then, the ICES assessment community has used EQSIM to derive fishing mortality reference points during age-structured benchmark assessments (ICES 2019b).

EQSIM can be used to conduct closed- or open-loop simulations. Open-loop simulations involve conducting forward projections for fishing mortality levels without incorporating the feedback control loop between management advice and stock dynamics, essentially ignoring the lag between monitoring and control. In contrast, closed-loop simulations, as used in MSE, explicitly simulate the complete control cycle, including data collection, stock assessment, advice generation, and implementation with feedback between management actions and the response of the resource. The importance of closed-loop approaches for developing target, limit, and threshold reference points lies in their ability to account for assessment uncertainty, implementation delays, and management feedback that can significantly affect the probability of breaching biological limits and achieving targets. EQSIM, as used in ICES benchmarks, implements a simple forecast (open-loop simulation) for fixed levels of fishing mortality (F), incorporating limited sources of uncertainty, such as the stock and recruitment relationship and recruitment variability that propagates into future spawning stock biomass (SSB). The results are then used to estimate probability of the quantities of interest, in particular the probability that SSB is above the biomass limit B_{lim}. In addition, it provides the option of implementing the ICES MSY advice rule (ICES MSY AR) (Fig. 1) into closed-loop simulation. The emerging procedure for estimating reference points is strongly linked to the advice framework and the need to implement the ICES MSY AR (Fig. 1) to ensure that it is consistent with the ICES precautionary approach (PA). It is important to note that Fig. 1 refers to the harvest control rule (HCR) used by ICES to run simulations for the estimation of F reference points. The advice rule used by ICES to provide annual advice includes an additional provision to set F to zero if the SSB is below B_{lim} in the advice year.

Using a database of 79 category 1 stock assessments, Silvar-Viladomiu et al. (2022) showed that a total of 54 stocks have used stochastic forward simulations within EQSIM to derive F reference points for advice compared to 11 stocks that have used MSE and 6 stocks that have used other frameworks, while the remainder either did not have F reference points or these were estimated internally with the assessment model (ICES 2022a). In general, in the last 10 years, around 75% of the ICES category 1 stocks have used EQSIM for the reference point estimation in ICES. In 2025, there are 115 category 1 stock assessments in ICES (www.ices.dk).

The ICES Technical Guidelines prescribe that F_{MSY} is initially estimated as the fishing mortality that produces maximum median yield (F_{mmy}) in the stochastic forward simulations in the long term. This F_{mmy} is then conditioned on the PA such that fishing at F_{MSY} cannot exceed the precautionary fishing mortality threshold F_{P05}, which is associated with a 5% probability of the SSB falling below the limit reference point B_{lim} (defined as a deterministic spawning biomass limit below which a stock is considered to have reduced reproductive capacity; ICES 2021b). Thus, stochastic forward simulations in ICES conducted with EQSIM are conditioned to the objective to provide a solid estimation of the target operational reference point F_{MSY}. However, in practice, ICES has focused on the optimization of F_{MSY} together with an operational biomass reference point defined as a level of SSB that triggers a decline in the target fishing mortality in response to a decrease in the stock size (defined as MSY $B_{trigger}$; the biomass trigger point of the HCR, specified as change point of biomass below which fishing mortality is reduced relative to F_{MSY}; ICES 2024a). As per ICES guidelines, MSY $B_{trigger}$ is not derived from EQSIM, but it is commonly estimated as a multiplier of B_{lim}, or more rarely, as the 5^{th} percentile of B_{MSY} (ICES 2022a). It is also important to note that ICES does not routinely report the corresponding B_{MSY} defined as the average biomass around which the biomass fluctuates when fishing at F_{MSY} (Winker et al. 2025 unpublished data).

MSE is a framework for testing HCRs and management objectives that account for the range of uncertainties encountered in fisheries systems (Table 1). MSE has been used widely across the globe to evaluate harvest strategies used to provide advice for diverse fisheries (Goethel et al. 2019), which include the estimation of the target operational reference point F_{MSY}. MSEs have played a key role in tuna Regional Fisheries Management Organizations such as the Indian Ocean Tuna Commission and the International Commission for the Conservation of Atlantic Tunas (Sharma et al. 2020) and South Africa (e.g. De Oliveira & Butterworth 2004) but also in ICES (ICES 2019a). MSE can be defined as a process whereby the performances of alternative harvest strategies are tested and compared using stochastic simulations of stock and fishery dynamics against a set of performance statistics developed to quantify the attainment of management objectives. Management objectives usually refer to a wide-ranging set of practices aimed at promoting sustainability in fisheries, based on ecological, social, and economic objectives (Sharma et al. 2020).

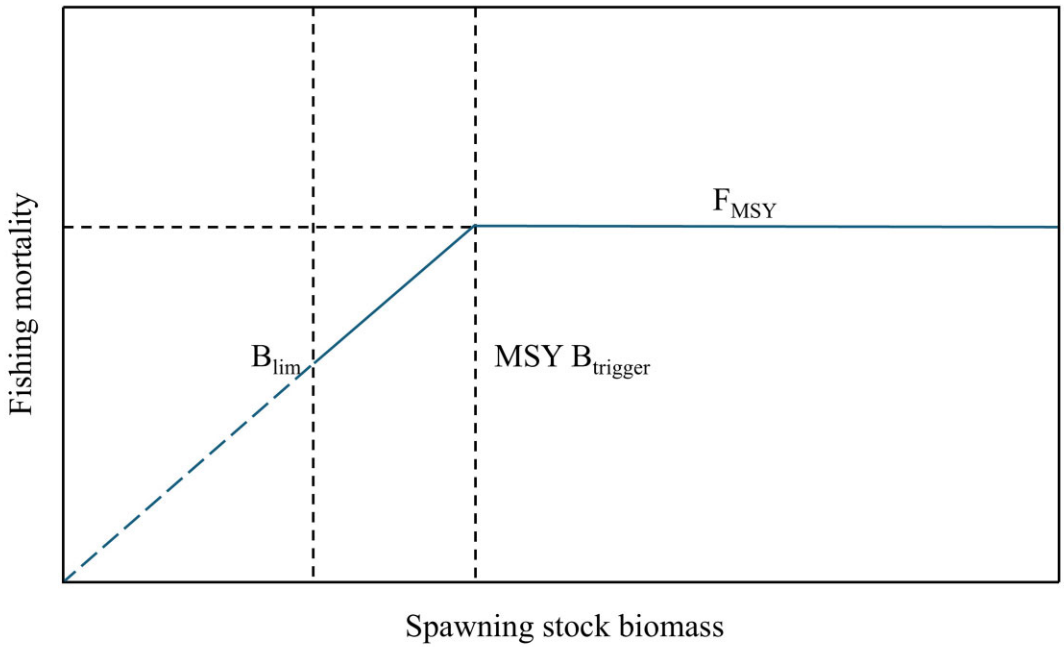

Figure 1. Schematic representation of the generic ICES MSY advice rule (ICES MSY AR) used to estimate F reference points in EQSIM simulations, for which F is decreased linearly towards the origin when the SSB is below MSY $B_{trigger}$.

Table 1. Example of the key sources of uncertainty encountered when managing fisheries.

Uncertainty type	Description
Process	Intrinsic natural variability in biological and environmental processes of the stock
Observations/data	Errors and variability in data collection
Model structure	Uncertainty about model form and assumptions
Parameters	Uncertainty in estimated model parameters
Estimation	Errors or biases due to model fits to data to estimate state variables
Implementation/management	Variability in the actual application of management measures
Outcome	Combined uncertainty in achieving management objectives
Ecosystem	Effects of ecosystem drivers and interactions on the stock

Modified from Punt et al. (2016) and ICES (2020).

Between 2013 and 2019 alone, ICES has carried out ∼30 special requests that involved MSEs, and MSEs have been implemented for 15 species comprising 24 North East Atlantic stocks, with 6 stocks being evaluated more than once (ICES 2019b). Much of the focus in ICES has been specifically on the functional form of the HCR, which determines the level of fishing mortality advice given the stock status. In fact, one of the main reasons why ICES has been requested to conduct MSEs is to establish if a given set of HCRs (i.e. a combination of limit, trigger, and targets) is consistent with the PA, intended by ICES to limit the probability of the stock falling below B_{lim} to 5%. Once the PA is fulfilled, priority is given to those HCRs that maximize yield (i.e. achieve MSY) so that both overarching principles of the CFP (PA and MSY) are satisfied at the same time. Once a set of target and operational reference points contained within a set of HCRs is agreed upon by the relevant management authorities and has been classified as precautionary by ICES, then the ICES advice will be based on those (see the 'Introduction to the ICES advice'; ICES 2023). Thus, MSEs conducted by ICES so far have aimed to provide as an overarching objective a set of 'optimal' reference points that fulfil both PA and MSY principles.

MSE is carried out as closed-loop simulation, where the stochastic population dynamics interact with a management strategy that feeds back and affects the so-called operating model (OM), therefore simulating population, fisheries, and management dynamics. A management strategy involves the entire process from data collection to management advice, including sampling and data collection schemes, an analytical or empirical assessment method, and an HCR, which is then translated via the 'implementation system' into catch advice (Punt et al. 2016). In contrast to the EQSIM stochastic forward simulations used by ICES to derive stock specific reference points during the benchmark process, the feedback control loop between management strategy and the OM(s), including the lag between the last data year and advice implementation, is a fundamental aspect of MSE. As such, MSE provides a framework to test alternative management strategies using closed-loop simulations with feedback control for many possible future outcomes before applying them in the real world.

The observation model is generally considered a key element of the management procedure, and it is typically part of the OM (Punt et al. 2016, Goethel et al. 2019). A management procedure emulates the sampling process of the observational

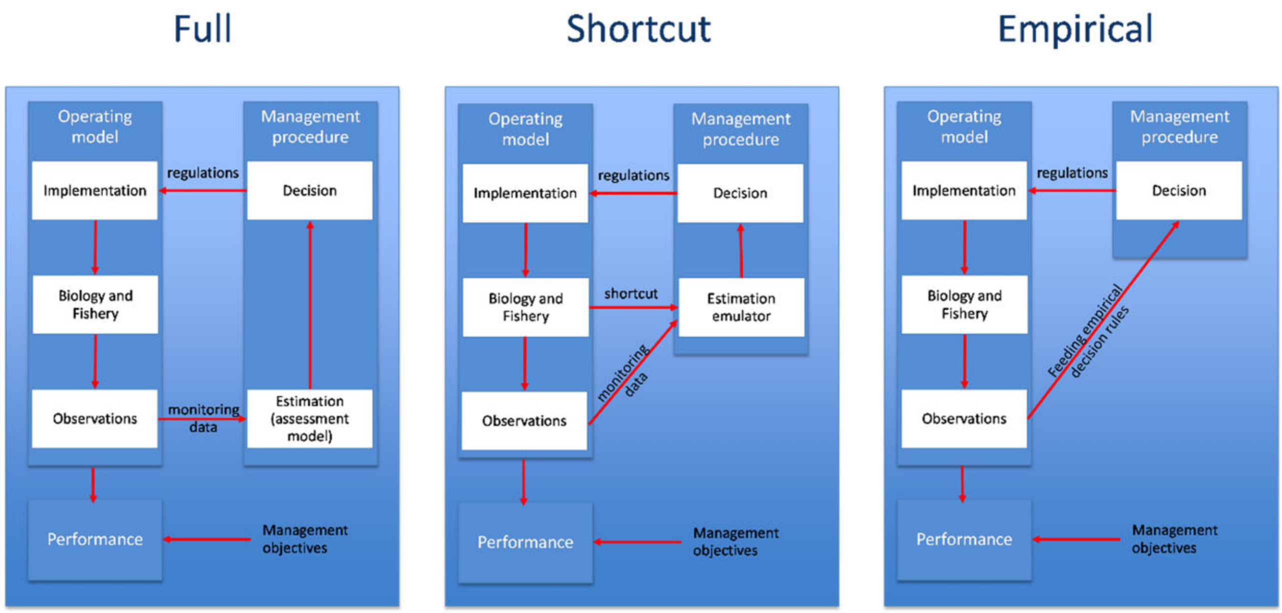

Figure 2. Schematic illustrating the difference between the full and shortcut approaches for Management Strategy Evaluation (MSE). Management procedure can be based on either model or empirical based rules. Empirical approaches use observations directly in the advice rule, rather than model based estimates. The main difference between the full and shortcut approaches is that the shortcut replaces the estimation model with an emulator, where typically fishing mortality or biomass is taken directly from the Operating Model (OM) but modified with noise and bias before being used in the Harvest Control Rule (HCR). Originally modified from Punt et al. (2016) and reproduced from ICES (2020) with the permission of ICES.

data and involves updating the observation model that can take on forms ranging from a simple empirical rule (e.g. trend in the index) to full integrated assessment model, such as Stock Synthesis (SS3; Methot and Wetzel 2013). Thus, a management procedure has the same components as a management strategy. The distinction is that each component of a management procedure is formally specified, and the combination of monitoring data, analysis method, HCR, and management measure has been simulation tested to demonstrate adequately robust performance in the face of plausible uncertainties about stock and fishery dynamics (see https://tuna-org.org/Documents/MSEGlossary_tRFMO_MSEWG2018.pdf for a useful glossary).

Although a full feedback MSE is typically designed to simulate the complete observation and model processes (Butterworth and Punt 1999), for pragmatic reasons scientists have adopted the short-cut MSE to apply in situations where the assessment advice process involves a full annual update of complex assessment models (Fig. 2). This reduces the computational burden at the cost of realism. In ICES, this has been often the case where the focus was on testing the performance of alternative HCRs for providing annual total allowable catch (TAC) advice. Here, we used the definition of a short-cut MSE as described in ICES (2020).

In contrast to a full MSE, the short-cut MSE mimics an annual update of the benchmark assessment model by passing a metric (SSB) from the OM the 'true' age-structured dynamics to the HCR with a lognormal error added to represent that expected in the stock assessment. In the model used here, a similar error is added to the implementation system, which calculates the catch that will lead to the fishing mortality level (F) set by the HCR. The HCRs are implemented using a simulated feedback control loop between the implementation system and the OM, where the implementation system translates the emulated assessment outcome via the HCR and short-term forecasts into the TAC advice. The feedback control loop between the implementation system and the OM allows accounting for the lag between the last year of data used in the assessment and the implementation year of catch advice. The implementation system of the HCR assumes that advice is given for year y + 1 based on an assessment completed in year y, which is fitted to data up until the last data year y − 1. Therefore, implementation of the derived catch advice through HCR requires projection of the stock dynamics by way of a short-term forecast. To do this, numbers-at-age are projected through the year of assessment. For some ICES stocks, data can be available up to year y, e.g. if there is an in-year index. This was not the case for stocks used here but, if necessary, the short-cut MSE can be easily adapted. Future recruitment, selectivity, natural mortality, weight at age, and maturity at age are generally set as the mean of the last three to five years of the assessment time series. A projection based on a fixed fishing mortality-at-age to the last year (y − 1) in the assessment is then made through to the implementation year (y + 1). In a full MSE, it is typical to include uncertainty for additional metrics and to consider any relevant correlation structures between OMs metrics and their uncertainty. On the other hand, the limitations of the short-cut MSE are that it cannot fully account for uncertainties resulting from imperfect sampling of the full age-structure (e.g. poorly sampled recruits), observation error, and uncertainty derived from refitting the stock assessment model. In the short-cut MSE, uncertainty on SSB and F as derived from the assessment model is included, albeit in a simplified manner that differs from refitting the stock assessment model, while uncertainty in recruitment is derived from resampling from the stock and recruitment function estimated by the assessment model. It is important to note that the specific cases of the short-cut MSE presented here have a rather simplified structure, and there is only one OM per stock. However, structural uncertainty, as another major source of uncertainty, can be integrated in the short-cut MSE, and several OMs can be used and ensembled, implementation error and retrospective bias can be included (even if not used in this analysis). On the other hand, the short-cut MSE is straight-forward to implement and reduces complexity and computation time when the focus is predominantly optimizing HCRs for setting quotas on the premise that a benchmark assessment forms the basis for the advice as it is the case in ICES, and that potential error and bias in the assessment model is correctly captured.

Here, we used recent results of an ICES benchmark workshop (WKBSS3; ICES 2025) to compare the target operational reference point F_{MSY} derived from EQSIM and the same target operational reference point F_{MSY} derived using the short-cut MSE. Strictly following ICES guidelines for the estimation of reference points (ICES 2021b), we first estimated B_{lim} and MSY $B_{trigger}$, then, using EQSIM, we estimated F_{P05} and F_{MSY}, ensuring that F_{MSY} does not exceed the precautionary reference point F_{P05}. Subsequently, we used the same B_{lim} and MSY $B_{trigger}$ values in the short-cut MSE, along with the estimated value of F_{MSY}, which was considered as the upper bound for the range of F values to be tested in the short-cut MSE. Our results showed that EQSIM reference points are not precautionary, which is likely caused by not accounting for the feedback control between the assessment advice and management implementation, which is lacking in EQSIM, and the oversimplification of the assessment model, which is necessary for EQSIM to be used.

Methods

Stock assessment models

In 2025, a Benchmark workshop on application of SS3 on selected stocks (WKBSS3; ICES 2025) was held at ICES. Four stocks were assessed: white anglerfish (*Lophius piscatorius;* mon.27.8c9a) in divisions 8.c and 9.a, Cantabrian Sea and Atlantic Iberian waters; black-bellied anglerfish (*Lophius budegassa;* ank.27.8c9a) in divisions 8.c and 9.a, Cantabrian Sea, Atlantic Iberian waters; pollack (*Pollachius pollachius;* pol.27.67) in subareas 6–7, Celtic Seas and the English Channel; blackspot seabream (*Pagellus bogaraveo;* sbr.27.9) in subarea 9, Atlantic Iberian waters. The stocks pertain to three ICES Assessment Working Groups (Working Group for the Bay of Biscay and Iberian Waters Ecoregion—WGBIE; Working Group for the Celtic Seas Ecoregion—WGCSE and Working Group on Biology and Assessment of Deep-sea Fisheries Resources—WGDEEP) and were selected based on ICES criteria (ICES 2025) and the availability of appropriate data and resources.

The structure of the stock assessment model used here was the same as agreed at WKBSS3. White anglerfish was assessed using a multi-fleet, seasonal, sex-structured SS3 model. Black-bellied anglerfish was assessed using a multi-fleet, seasonal, sex-structured SS3 model. Pollack was assessed by a multi-fleet, annual, sex-aggregated SS3 model. Blackspot seabream was assessed by a multi-fleet, annual, and protandrous hermaphroditic species SS3 model. For more details, the reader can consult model descriptions in the WKBSS3 report (ICES 2025).

SS3 model input and outputs were successively used to condition an age-structured OM to be used for the estimation of the reference points using the Fisheries Library in R (FLR, Kell et al. 2007, https://flrproject.org/). FLR is an open-source software framework developed in the R language for quantitative fisheries science and provides a set of methods and data structures for simulation modelling, including the conditioning of OMs on outputs from stock assessments. It enables the integration of uncertainty, implementation of management procedures, and calculation of reference points, for conducting MSE (Kell et al. 2024a, Kell and Sharma 2025).

Estimation of reference points

EQSIM general settings used for all analysed stocks

For all stocks, the original SS3 model has been simplified for sex, seasons and fleets, and was then saved as a stock object using FLR. This is strictly necessary, as EQSIM cannot run with a more complex structure. The employed OMs contain more dimensions than those the EQSIM code can handle, for two sexes or multiple seasons. Thus, the stocks were simplified by (i) adding catch numbers along seasons and sexes, (ii) setting abundances as those of both sexes at the first season, (iii) averaging weights-at-age in the catch, weighted by numbers in each sex and season, setting weights-at-age in the stock to be those in the spawning season, averaged across both sexes, and (iv) recomputing the fishing mortalities from the aggregated abundances and catches.

For each stock analysed here, we first ran EQSIM, which was set following the ICES guidelines for the estimation of the reference points (ICES 2021b). EQSIM provides ICES MSY reference points based on the equilibrium distribution of stochastic projections. Productivity parameters (i.e. year vectors for natural mortality, weights-at-age, maturity-at-age, and selectivity) are resampled at random from the last years of the assessment. Recruitments are resampled from their predictive distribution, which is based on parametric models fitted to the full time-series provided. Uncertainty in the stock–recruitment relationship (SRR) can be considered by applying model averaging using smooth AIC weights (Buckland et al. 1997) although for all stocks used here the SRR is the same estimated by the SS3 model. For the assessment error in the advisory year (F_{cv}) and the autocorrelation in the assessment error for F among the advisory years (F_{phi}), ICES default values (i.e. 0.212 and 0.423) were used (ICES 2015) for all stocks. The stock-recruitment relationship used in EQSIM was a Beverton and Holt that was specified identical to the one estimated by the SS3 model and agreed at the benchmark (ICES 2025). Simulations were run for 200 years with the last 50 years retained to compute equilibrium values from. Autocorrelation of recruitment was used in EQSIM simulations for all stocks. The biomass reference points B_{lim} and MSY $B_{trigger}$ (biomass trigger point of the HCR, specified as change point of biomass below which fishing mortality is reduced relative to F_{MSY}; ICES 2023) were set following ICES current guidelines (ICES 2021b). The key quantity of interest, F_{MSY}, was calculated along with the probability of SSB falling below B_{lim}, which is used by ICES to evaluate if the set of reference points is consistent with the ICES precautionary and MSY frameworks (ICES 2023). The F_{MSY} value derived from EQSIM was computed as the fishing mortality that corresponds to the peak of the median landings yield curve derived from stochastic forward projections. Within the ICES advice framework, F_{MSY} requires meeting the condition that $F_{MSY} < F_{P05}$ in accordance with the ICES PA.

EQSIM stock specific settings

In Table 2, we present the key parameters B_{lim} and MSY $B_{trigger}$ used for each stock in the EQSIM simulations. For additional details about the EQSIM code used, the reader should consult specific stock section in the WKBSS3 report (ICES 2025) and https://github.com/akatan999/MSErefpts/tree/main/MSE.

Short-cut MSE

For all stocks, the original SS3 model has been simplified for seasons and fleets but retaining the two-sex structure for black-bellied and white anglerfish and the original protandrous hermaphroditism structure for blackspot seabream when translated into FLR to be used for short-cut MSE. For pollack, the model structure is the same as used in EQSIM as the original model was already a sex-aggregated model. It is important to note that the short-cut MSE can be run with additional complexities (see the 'Introduction and discussion' section) but here we used the sex-structure as an example of complexities that EQSIM is not able to handle and to evaluate how this would affect the estimation of F_{MSY} within the context of the PA principles. Also, having one stock for which the structure is the same as in EQSIM provides additional contrast for evaluating the effect of the full-feedback control loop when comparing EQSIM and the short-cut MSE.

A feedback loop simulation tool for reference points estimation (a short-cut MSE hereafter defined as RPETool; Reference Point Estimation Tool) was developed in line with WKREFNEW (ICES 2024a) recommendations. The RPETool was implemented using the tools available from several FLR packages (https://flrproject.org/), particularly the mse package version 2.2.3.9354, and the code is available under https://github.com/akatan999/MSErefpts/. When running RPETool, B_{lim} and MSY $B_{trigger}$ were set equal to those used for EQSIM simulations for each stock (see previous section for stock specific details).

Successively, the EQSIM derived F_{MSY} was compared to alternative levels of fishing mortality using RPETool. A very similar implementation framework has been already used for deriving reference points for Central Baltic herring (ICES 2023) and Northern shrimp (ICES 2022b). As noted above, RPETool has the clear advantage compared to an open loop simulation used in EQSIM because it emulates an annual update of the benchmark assessment model by passing outcomes (SSB and F) from the 'true' age-structured dynamics from the OM with assessment error (approximated by the coefficient of variation of the SSB estimated in the last year of the assessment) to the HCR and catch implementation system by way of short-term forecasts. The feedback control loop between the implementation system and the OM allows accounting for the lag between the last of year data used in the assessment and the implementation year of the catch advice. Moreover, it provides the ability to retain the dynamics of a sex-structured stock of the original assessment models when present as in the stocks analysed here. The simulations used 1000 iterations and an MSE horizon covering at least 3 generations time for all stocks. Several scenarios with fractions of the value of F_{MSY} estimated by the SS3 benchmark model ranging from 1.0 to 0.4 were tested, as well as a scenario with the F target set to F_{MSY} estimated by EQSIM with MSY $B_{trigger}$ (defined as Fmsy.eq.Btri in Tables S1–S4) and a scenario where the F target is the deterministic F_{MSY} of the SS3 benchmark model without MSY $B_{trigger}$ (defined as Fmsy.OM in Tables S1–S4). All scenarios tested used the generic ICES MSY AR, with exception of Fmsy.OM. The different scenarios were compared using a set of performance statistics, including the probability of SSB falling below B_{lim} and the long-term catches expressed as relative to MSY, which are used by ICES as overarching criteria for selecting reference points (see further details in the 'Introduction' section). A comparison of the key differences between EQSIM and the MSE short-cut used here is presented in Table 3.

Performance statistics

The performance of the different candidates HCR was evaluated through six main metrics: depletion risk ($P3(B < B_{lim})$), the proportion of simulation replicates for which the stock falls below the biomass limit reference point B_{lim}), catch (relative to MSY; Catch/MSY), stock size (SSB relative to B_{MSY}; B/B_{MSY}), F(relative to F_{MSY}; F/F_{MSY}), the probability that SSB is larger than 80% of B_{MSY} ($B > 80B_{MSY}$), and median annual variation in catches (AAV). These metrics were calculated for the long term (the last 25 years of the projections with 1000 iterations). These metrics allowed a summary of the management performance of the candidates HCR, including both biological (stock size, depletion risk, harvest rate) and economic (catch) quantities. MSY, F_{MSY}, and B_{MSY} refer to the SS3 benchmark model estimates.

Results

EQSIM and RPETool

The summary of the results of the EQSIM and RPETool simulations used to determine F_{MSY} for each of the stocks assessed during WKBSS3 (ICES 2025) and used in this analysis is presented in Table 4 along with the deterministic value of F_{MSY} estimated by the SS3 benchmark model. The values of the performance statistics are reported in Figs. 3–6 and Tables S1–S4. For additional details about the EQSIM and RPETool results and the code used, the reader should consult specific stock section in the WKBSS3 report (ICES 2025), https://github.com/akatan999/MSErefpts/tree/main/EQSIM and https://github.com/akatan999/MSErefpts/tree/main/MSE.

Except for black-bellied anglerfish, the F_{MSY} estimated by EQSIM with the generic ICES MSY AR as being consistent with the ICES PA and MSY frameworks was very similar to deterministic F_{MSY} estimated by the SS3 benchmark model (Table 4). However, the RPETool results indicate that, for the scenario estimated by EQSIM, the probability of SSB $< B_{lim}$ is larger than 5%. Thus, the F_{MSY} estimated by EQSIM is not precautionary *sensu* ICES, instead, based on the RPETool simulations, the F_{MSY} being consistent with the ICES PA and MSY frameworks is lower than F_{MSY} estimated by EQSIM. The only exception is blackspot seabream, for which RPETool results indicate that the F estimated by EQSIM with the generic ICES MSY AR is consistent with the ICES PA and MSY frameworks as the probability of SSB $< B_{lim}$ is smaller than 5% (Table S4). Thus, the F_{MSY} estimated by EQSIM is precautionary *sensu* ICES for this stock. However, it is larger than F_{MSY} estimated by the assessment model (Table 4) although it generates marginally larger long-term catches at equilibrium than F_{MSY} estimated by SS3 (Fig. 6 and Table S4). Therefore, F_{MSY} estimated by EQSIM for Blackspot seabream is also not in accordance with the ICES MSY approach.

Table 2. Definition of B_{lim} and MSY $B_{trigger}$ for each stock. B_0 is the unfished spawning biomass that is given by the product of virgin recruitment R_0 (implicit to the SRR) and the unfished spawning biomass-per-recruit (SPR_0) being a function of weight-at-age, maturity-at-age and natural mortality.

Stock	B_{lim} rationale	MSY $B_{trigger}$	Source
White anglerfish	10% B_0 (2936 t)	B_{pa} (4373 t)	ICES (2024a)
Black-bellied anglerfish	Lowest SSB with median R (788 t)	B_{pa} (1095 t)	ICES (2021b), (2024a)
Pollack	SSB in 2020 (14 298 t)	B_{pa} (19 869 t)	ICES 2021, (2024a)
Blackspot seabream	15% B_0 (412 t)	B_{pa} (690 t)	ICES (2024a)

B_{pa} is defined as a precautionary safety margin incorporating the uncertainty stock estimates designed to have a low probability of the SSB to be below B_{lim}. When the SSB is estimated to be above B_{pa}, the probability of impaired recruitment is expected to be low (ICES 2021b). For all stocks, B_{pa} was calculated according to ICES guidelines (ICES 2023) as $B_{lim} * \exp(1.645 * sigmaB)$ where *sigmaB* is the coefficient of variation of the SSB in the last year of the assessment. Source indicates the guidelines from which the rationale to set B_{lim} and MSY $B_{trigger}$ has been taken.

Table 3. Differences between EQSIM and MSE in treatment of uncertainty.

Feature	EQSIM	Management strategy evaluation
Objectives	Derives reference points (e.g. F_{MSY}) under a set of model assumptions, primarily to provide tactical advice, i.e. on setting quotas.	Evaluates management strategies against broad objectives, explicitly incorporating feedback loops to ensure robust performance despite uncertainty.
Sources of uncertainty considered	Focuses mainly on parameter uncertainty and process error for a single (or a limited number) of scenarios, usually related to recruitment and biological parameters. Consideration of structural uncertainty is limited.	Includes parameter, process, model (structural), and implementation uncertainty. Multiple alternative OM scenarios are usually considered to ensure robustness is tested under many possible 'realities'.
Implementation of uncertainty	Adds stochasticity (e.g. recruitment residuals) to projections, but typically runs projections without feedback, i.e. using a fixed stock assessment and harvest rule.	Simulates the full cycle: stock, monitoring, assessment, management response (advice rule), and implementation.
Feedback mechanism	One-way: projects forward based on initial conditions, using pre-defined advice rule. There is no simulated response to observed outcomes, i.e. there is no management feedback.	Full feedback: management advice depends on the estimated stock status, which is affected by assessment, estimation, and measurement error, as well as past management actions.
Uncertainty analysis	Narrow: as usually only a 'best assessment' scenario with sensitivity runs is considered. Despite these reference points use tails of probability distributions.	Broader: multiple OMs, scenarios, and management procedures are compared to formally test robustness.
Use in ICES advice	Used for precautionary and MSY reference points estimation but may underestimate risk or be non-precautionary when uncertainties are high or models are mis-specified.	Used to evaluate management plans and advice rules, providing more realistic risk estimates and precautionary validation under high uncertainty.

Table 4. Results of the EQSIM and RPETool simulations.

Stock	EQSIM F_{MSY}	SS F_{MSY}	RPETool $_{MSY}$
White anglerfish	0.198	0.194	0.179
Black-bellied anglerfish	0.530	0.473	0.367
Pollack	0.337	0.349	0.288
Blackspot seabream	0.110	0.099	0.099

Both EQSIM and RPETool are run with the generic ICES MSY AR, while the deterministic value of F_{MSY} from the SS3 benchmark model is not estimated using the generic ICES MSY AR.

Overall, the results of the simulations showed that F_{MSY} estimated by EQSIM with the ICES MSY AR was not consistent with the ICES PA and MSY frameworks when tested using RPETool and therefore should be rejected (see Figs. 3–6 and Tables S1–S4). Also, the simulations showed that for all stocks the F used to provide advice can be reduced to around 60% of the EQSIM F_{MSY}, with a long-term loss in yields around 5% but with a substantial gain in SSB. Specifically, reducing F down to 0.118, 0.260, 0.214, and 0.056 will result in a loss of only 5%, 5%, 4%, and 5% of the long-term catches with almost 77%, 80%, 20%, and 50% more SSB than at F_{MSY} for white anglerfish, black-bellied anglerfish, pollack, and blackspot seabream, respectively (Figs. 3–6 and Tables S1–S4).

Discussion

ICES' definition of F_{MSY} is that of an operational control point used in the advice rule, i.e. it is a target, rather than being derived as the fishing mortality that at equilibrium would result in a biomass of B_{MSY}. First, the fishing mortality that corresponds to the peak of the median landings yield curve is derived from stochastic forward projections. Then, in accordance with ICES PA, F_{MSY} must also meet the condition that it is less than F_{P05}, and thus the fishing mortality that results in no more than 5% probability of bringing the spawning stock below B_{lim} in the long term (ICES 2023). During the last two decades, most of the stocks in ICES have used the software EQSIM to derive fishing mortality reference points for providing catch advice. For practical reasons, due to the large number of stocks, ICES has rarely used MSE to derive reference points for use in the advice rule and opted for a less demanding approach to estimate reference points: EQSIM. Unlike in an MSE, EQSIM does not emulate an annual update of the benchmark assessment model and advice process as it omits the process of conducting short-term forecasts and ignores the lag between assessment data and the implementation year (Punt et al. 2016, ICES 2020).

To conduct simulations with EQSIM, the stock assessment is simplified and reduced to an annual single fleet, and single sex model based on the stock assessment model, which can be

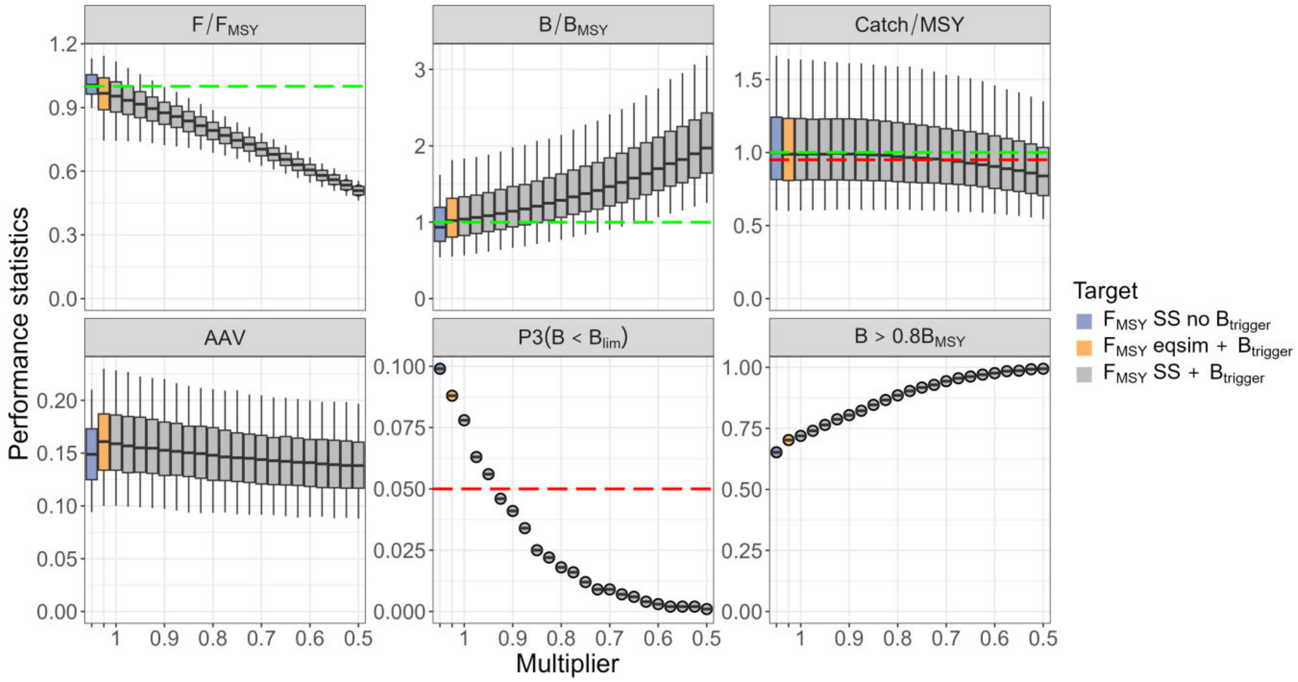

Figure 3. Results of the RPETool simulations for white anglerfish. Several scenarios (Candidates HCRs) with fractions of F_{MSY} estimated by the SS3 benchmark model ranging from 1.0 to 0.5 with MSY $B_{trigger}$ for all stocks (except for blackspot seabream, for which 1–0.4 F_{MSY} was used) were tested, as well as a scenario with the F target set to F_{MSY} estimated by EQSIM with MSY $B_{trigger}$ (defined as Fmsy.eq.Btri in Tables S1–S4) and a scenario where the F target is the deterministic F_{MSY} of the SS3 benchmark model without MSY $B_{trigger}$ (defined as Fmsy.OM in Tables S1–S4). All scenarios tested used the generic ICES MSY AR with the same MSY $B_{trigger}$ estimated following ICES guidelines, with exception of Fmsy.OM, where MSY $B_{trigger}$ was not used. F/F_{MSY} is the median ratio at the equilibrium between the realized F and F_{MSY}, B/B_{MSY} is the median ratio at the equilibrium between the SSB and B_{MSY}, Catch/MSY is the long-term catch expressed relative to MSY, AAV is the interannual variation of the advised catches, $P3(B < B_{lim})$ is the probability of the SSB to fall below B_{lim}, and $P(B > 0.8\ B_{MSY})$ is the probability of the SSB to be above 80% of B_{MSY} at the equilibrium. The red line in the Catch/MSY is the 95% MSY, while the green line is MSY.

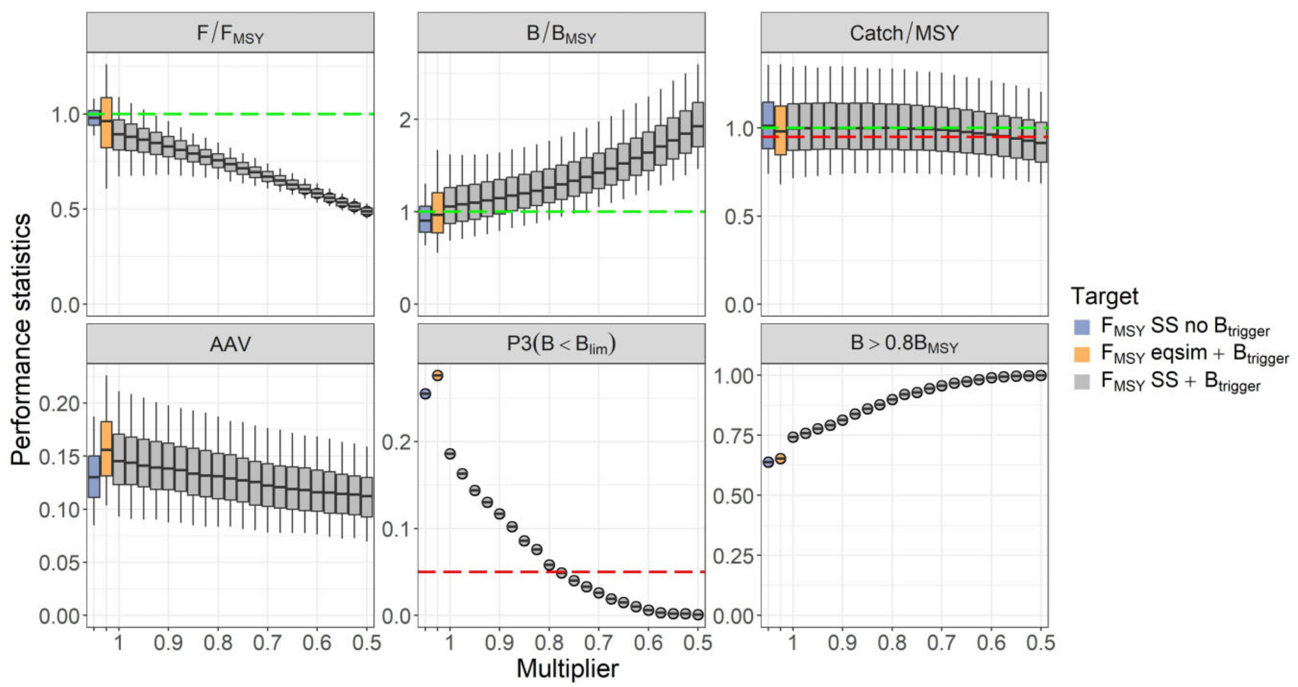

Figure 4. Results of the RPETool simulations for black-bellied anglerfish. See Fig. 3 for caption details.

more complex (ICES 2025). We showed that the simplifications of the management and resource, which are necessary for conducting simulations with EQSIM, result in the breaching of the PA for 3 of 4 recently benchmarked stocks. The probability of the stock falling below B_{lim} for 3 of the 4 stocks analysed here was much lower when derived with EQSIM com-

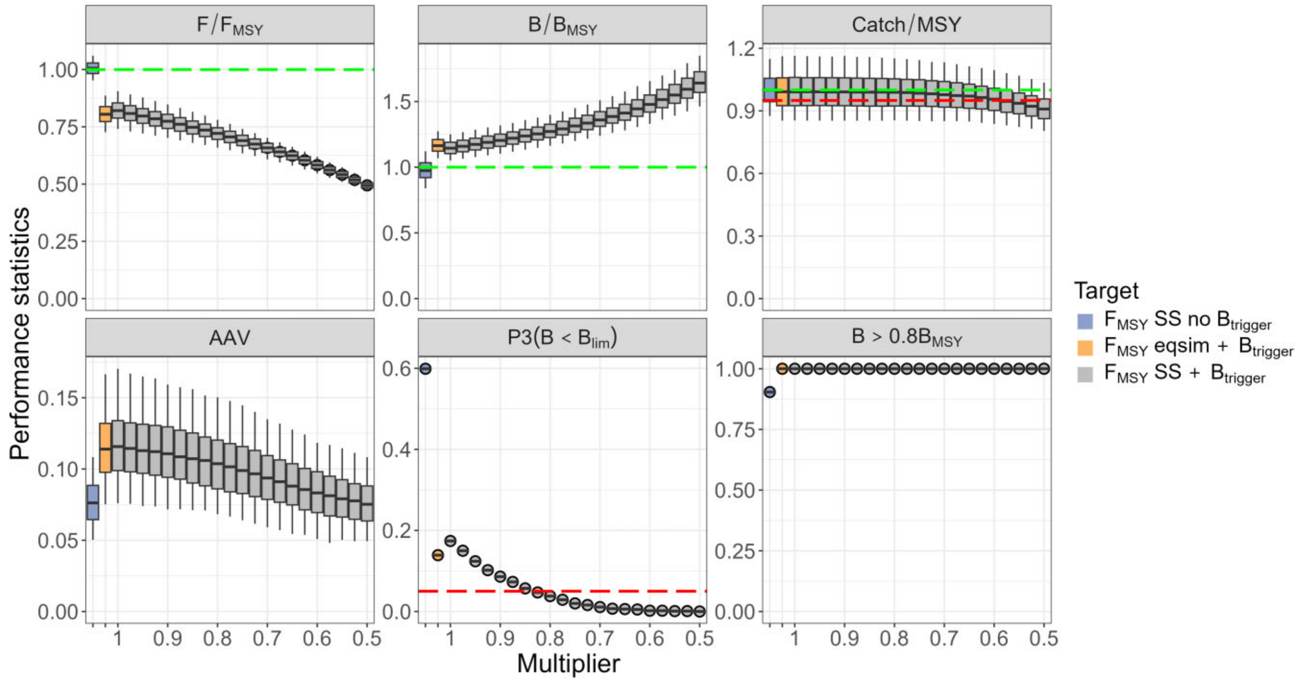

Figure 5. Results of the RPETool simulations for pollack. See Fig. 3 for caption details.

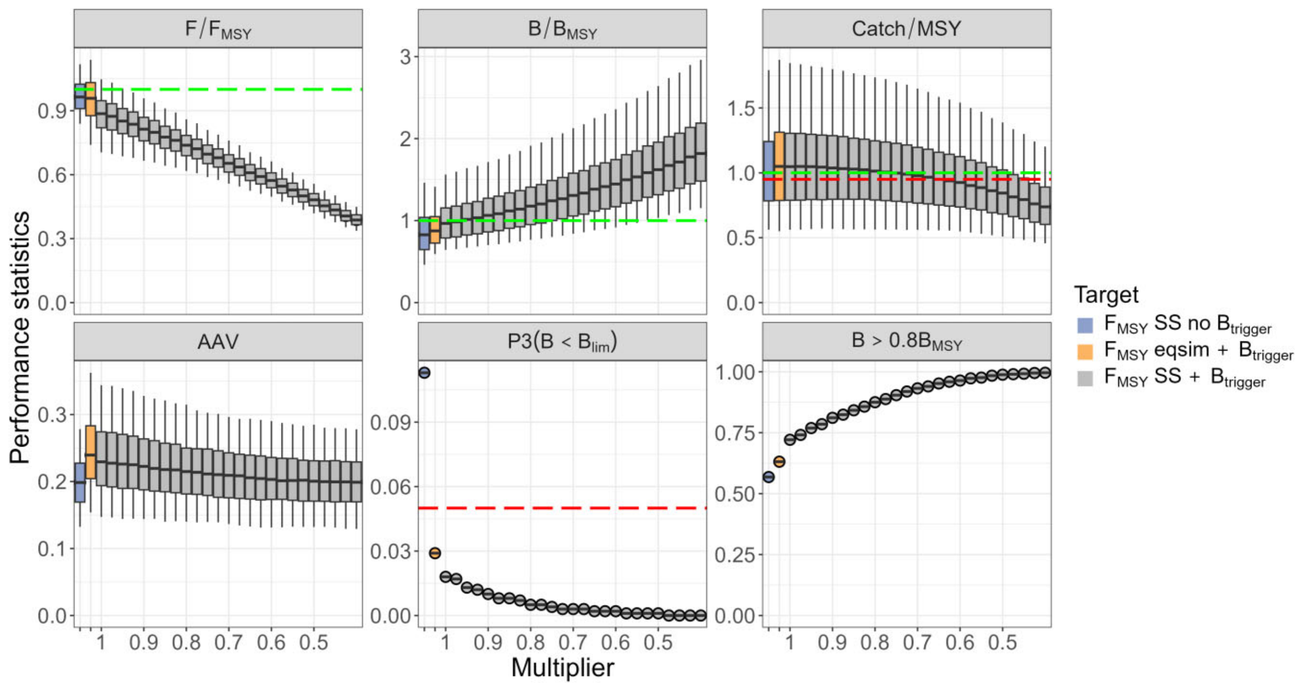

Figure 6. Results of the RPETool simulations for blackspot seabream. See Fig. 3 for caption details.

pared to the estimate from a short-cut MSE (RPETool) for the same level of fishing mortality. In other words, both methods scan over a series of F values to find the one that fulfils the ICES criteria, which are (i) PA and (ii) maximizing yields, and the F value that achieves 95% of the MSY. Using these criteria, EQSIM selected an F value that resulted in a probability larger than 5% of the SSB falling below B_{lim} when tested with RPETool, and F needed to be reduced in RPETool to find a value of F that fulfils the ICES PA criteria. This pattern was consistent across species. Moreover, having a stock (i.e. pollack) with the same structure for EQSIM and RPETool, and three stocks for which sex dimorphism was retained in the RPETool but not in EQSIM, demonstrated that the different results are likely caused by both the simplifications of the management system and the assessment model. Moreover, for the blackspot seabream, the EQSIM estimate of F_{MSY} was larger than F_{MSY} estimated by the SS3 model used in the benchmark. Although the F_{MSY} estimated by EQSIM was precautionary when tested using RPETool, it resulted in reduced yield in the long term, which is not in accordance with the ICES

MSY framework (ICES 2023). It is also important to note that using the ICES MSY advice rule (see Fig. 1) when running EQSIM would result in an even more optimistic F_{MSY} estimate. Therefore, EQSIM F_{MSY} is not consistent with the ICES PA and MSY frameworks for all stocks analysed here. This possibility has already been identified by ICES by highlighting that the F_{MSY} estimated by EQSIM might not be precautionary (e.g. see whiting and herring examples in the WKNSMSE report; ICES 2019b), although in these cases, the time series of data used in EQSIM compared to the MSE may have differed.

Another interesting result was the low ratios of F to F_{MSY} needed to attain 95% of the deterministic MSY, which has been recently proposed by ICES as long-term target instead of MSY (ICES 2024a). For all stocks, F could be reduced to around 60% of F_{MSY} (and less for blackspot seabream) with a long-term yield loss around 5% but with a substantial gain in the size of the stock in terms of SSB. Considering the wide ranges of additional uncertainties about the assessment model, which are often associated with a positively biased F_{MSY} estimate (Kell et al. 2024b), F_{MSY} should be rather considered the upper limit for advice on fishing opportunities than the target as it is currently used by ICES. This is because the F associated with 95% of MSY on the upper part of the range (defined by ICES as F_{MSY} upper and currently used to provide advice for several stocks; ICES 2023) was found to be not necessarily precautionary for small and medium sized teleosts (Rindorf et al. 2017) and requires to be tested for precautionary considerations. On the other hand, it is important to note that there are short-term losses associated with drastically reducing the F used for advice, but those can be alleviated through Management Plans, where F is progressively reduced towards the new target. Furthermore, simulations showed that reducing F is negatively correlated with AAV, which would provide improved stability from year-to-year in the fishery. The asymmetric impact on risk when fishing below or above F_{MSY} is well established in the literature (Beverton 1998, Mace 2001, Hilborn 2010, Hordyk et al. 2019). Restrepo et al. (1998) showed that fishing at just 75% of F_{MSY} would still yield on average more than 95% of MSY based on deterministic age-structured models that were parameterized with 600 combinations of variations of life history parameters. In practice, losses in long-term catches are very small when F is significantly lower than F_{MSY} as also shown by Mace (1994). Thus, fishing down SSB with the intent of achieving MSY might be associated with far greater risks than keeping biomass at relatively high levels through a lower F target. This will not jeopardize long-term catches as shown here and will be *de facto* compatible with the Ecosystem Approach to Fisheries Management (EU-COM 2008, 2017) and in line with current legislation (EU Regulation No 1380/2013; the Basic Regulation; EU 2013) given the large, often unaccounted uncertainty we have in any assessment model. Thus, a lower F target not only will sustain larger catches and lower fishing costs associated with higher catch-per-unit-effort, but it can also help maintain and restore ecosystem functioning and increase the resilience of the marine ecosystems to the future changes. Larger biomass can also play a pivotal role in the Ecosystem Approach to Fisheries Management since stock resilience to anthropogenic effects as for example climate change, and the role that species play in ecosystem dynamics, are directly linked to their abundance and age structure (Mildenberger et al. 2022, Griffiths et al. 2023, Eurich et al. 2024).

Although ICES is generally open to accept evaluations using the short-cut MSE, there is also the notion to consider that the short-cut MSE is inferior compared to the full MSE. In this context, it is generally argued that full MSEs are needed to estimate the optimal set of reference points to be used in the HCRs and/or evaluate additional management measures proposed by managers and included in the HCRs. The main arguments listed by the proponents of the full MSE philosophy are (i) running an assessment model within the simulation loop is needed to account for retrospective pattern in the assessment; (ii) only the full MSE approach is able to represent uncertainty adequately; (iii) MSE is able to account for additional more complex management measures requested by the managers and included in the HCRs as for example banking and borrowing of catches between years and/or limitation on the inter-annual change in TAC. On the other hand, the newly developed tool RPETool can integrate several key sources of uncertainty (Punt et al. 2016), including retrospective pattern, implementation error (see ICES 2022b), structural uncertainty (using an ensemble of OMs, see Jardim et al. 2021 and ICES 2024b for a practical application), and can evaluate additional measures as for example banking and borrowing or implementation error beside the estimation of the reference points. Also, the RPETool can retain the key structure (e.g. two sex and/or hermaphroditic structure but also others can be added) of complex integrated models as SS3. Nevertheless, MSE with feedback and an embedded assessment model (i.e. full MSE) remains the gold standard for testing fisheries management procedures, as it explicitly simulates the entire management process, including data collection, assessment, and decision-making, under a range of uncertainties. However, this approach is computationally intensive and time-consuming, often requiring substantial resources and extended timelines that can be challenging for stock assessment working groups to accommodate. The shortcut MSE approach, by contrast, assumes that retrospective-based error patterns from existing assessments adequately represent future assessment behaviour. This introduces some circularity, as both the OM and the emulator are conditioned on the same assessment, which may under-represent the potential for bias and risks arising from model misspecification. However, shortcut MSEs can be implemented relatively quickly and efficiently, making them valuable for screening of management strategies and for situations where time and resources are limited. As such it is well suited for benchmarks where standard ICES reference points are estimated but where for pragmatic reasons a full MSE cannot be conducted. Hybrid workflows, i.e. using shortcut MSEs for rapid preliminary evaluation and then validating promising options with a set of full MSEs will offer a practical compromise, balancing the need for scientific rigour with the operational realities of providing timely fisheries management advice. Most importantly, the consequence of maintaining the current EQSIM approach is providing reference points and thus advice that is not precautionary *sensu* ICES. Although discussion is ongoing within ICES about the process to phase out EQSIM, and how to recalculate current reference points for all stocks, newly estimated reference points are still provided using EQSIM. Along with most of the currently used reference points within ICES, which are estimated with EQSIM, those are currently used to provide advice by ICES that is likely to be not precautionary. In summary, the benefits of the new approach (RPETool) is that it provides a flexible tool that mimic closely the management system, can integrate multiple sources of uncertainty, is able to closely maintain the original structure of the assessment and, can provide a robust estimation of the level of F fulfilling the criteria of the ICES MSY framework within the time constraints of the ICES benchmark system. Finally, although the new approach RPETool is tailored to the ICES system, the recommendation to use a feedback-loop simulation when estimating reference points during benchmarks is also applicable outside ICES. Thus, we first propose that it is time for paradigm shift within ICES and advocate that EQSIM is phased out. In this context, we recommend using a new approach like RPETool in future benchmarks but also to recalculate with RPETool current F reference points for all stocks that have used EQSIM to avoid providing advice that is not in accordance with the ICES MSY framework. Finally, we also recommend that F_{MSY} is replaced by a lower level of F advice which will have minimal losses in long term yields (if any) with large gains in resilience through larger biomass and higher proportion of older fish in the population and an increased stability of the catches.

Conclusions

EQSIM systematically underestimated the probability of falling below B_{lim}. This was because derivation of reference points using open-loop simulation ignores several sources of uncertainty, particularly those arising from assessment model error and the absence of feedback control mechanisms. The superiority of closed-loop (i.e. MSE) over open-loop simulation has been well-established (e.g. Butterworth and Punt 1999, Punt et al. 2016). MSE explicitly incorporates the feedback loops between stock dynamics, observation processes, assessment methods, and management implementation that are fundamental to real-world fisheries systems (Goethel et al. 2019). The absence of these feedback mechanisms in EQSIM is an oversimplification that compromises the precautionary nature of derived reference points. This is a reason why Regional Fisheries Management Organizations are increasingly adopting MSE frameworks for management (Sharma et al. 2020).

The asymmetric nature of risks associated with F_{MSY} has been recognized for decades. Restrepo et al. (1998) demonstrated that fishing at 75% of F_{MSY} yields more than 95% of MSY while substantially reducing the risk of stock collapse. This asymmetry impacts the practice of treating F_{MSY} as a target rather than an upper limit. The yield curve around MSY is typically flat-topped, so that large reductions in fishing mortality result in minimal yield losses while providing major conservation benefits (Hilborn 2010, Hordyk et al. 2019). This is particularly pronounced when uncertainty in F_{MSY} estimation is explicitly considered, supporting arguments for precautionary reference points (FAO 1996).

In addition, the current focus on single-species MSY fails to account for ecosystem-level considerations (Mace 2001, Pikitch et al. 2004, Link 2010). For example, larger, older fish play disproportionate roles in population resilience and ecosystem function (Griffiths et al. 2023), while higher stock biomass provides greater buffer capacity against environmental perturbations (Eurich et al. 2024). The transition from open to closed-loop reference point estimation faces practical challenges. The computational intensity of full MSE approaches has led to the development of 'short-cut' MSE methods that retain key feedback mechanisms while reducing computational burden. While these approaches represent a compromise, they provide substantially more realistic representation of management systems than current open-loop approaches.

The challenges identified in ICES reference point estimation are not unique to the Northeast Atlantic. Similar concerns have been raised regarding US stock assessment practices under the Magnuson-Stevens Act (Gabriel and Mace 1999, Punt et al. 2016), while other regions have successfully implemented more robust approaches. For example, in Australia the scientific advice framework mandates MSE testing of all HCR (Fulton et al. 2019). Rather than treating F_{MSY} as a target to be achieved, it should be considered as an upper limit with fishing mortality targets set lower to account for the multiple sources of uncertainty inherent in stock assessment and management. This aligns with 'pretty good yield' approaches (Hilborn 2010) and precautionary implementation of MSY (Mildenberger et al. 2022). Such approaches recognize that optimization is neither achievable nor desirable given assessment uncertainty, and that robust performance under a range of scenarios is preferable to optimal performance under a single assumed scenario, either based on model ensembles (Jardim et al. 2021) or MSE with OMs conditioned on appropriate hypotheses (Kell et al. 2024b) that explicitly account for the key uncertainties inherent in fisheries systems.

Conflict of interest

None declared.

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Author contributions

Henning Winker (Conceptualization [lead], Methodology [lead], Writing – review & editing [lead]), Massimiliano Cardinale (Conceptualization [lead], Methodology [lead], Writing – review & editing [lead]), Paz Sampedro (Formal analysis [equal], Writing – review & editing [equal]), Hans Gerritsen (Formal analysis [equal], Writing – review & editing [equal]), Juan Gil Herrera (Formal analysis [equal], Writing – review & editing [equal]), Laurence Kell (Conceptualization [supporting], Methodology [supporting], Writing – review & editing [equal]), Iago Mosqueira (Conceptualization [lead], Methodology [lead], Writing – review & editing [equal]), Teresa Moura (Formal analysis [equal], Writing – review & editing [equal]), Ines Farias (Formal analysis [equal], Writing – review & editing [equal]), and Paola Castellano (Formal analysis [equal], Writing – review & editing [equal])

Supplementary material

Supplementary data is available at *ICES Journal of Marine Science* online.

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Data availability

The original dataset of stock assessment inputs and outputs is available via ICES as part of the WKBSS3 benchmark group. R code to reproduce the analysis is freely available via GitHub (https://github.com/akatan999/MSErefpts/).

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