DTU Aqua
National Institute of Aquatic Resources

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Alexandros Kokkalis, Tobias K. Mildenberger and Casper W. Berg

DTU Aqua Report no. 455-2024

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Preface

The work presented here was funded by the European Maritime and Fisheries Fund (EMFF) and the Danish Fisheries Agency via the project 'Robust management procedures and advice for data limited stocks (RoMA)' (Grant agreement number 33113-B-20-183). The project lasted from June 2020 to June 2023.

We would like to thank the participants of the several ICES workshops for useful feedback and discussion on various topics covered in this report, most importantly WKLIFE, WKDLSSLS and WKMSYSPICT.

DTU Aqua, Kgs Lyngby,
September 2023

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Executive summary

Background: The common fisheries policy (CFP) of the EU stipulates that the Maximum Sustainable Yield (MSY) is the best possible objective for fisheries and that scientific advice is the basis for good policy making setting fishing opportunities according to the state and productivity of all managed stocks. Nevertheless, a substantial proportion of EU's marine living resources are data-limited and still lack a quantitative assessment and, therefore, are not managed appropriately. This increases the risk of overfishing and potentially reduces long-term yield. Therefore, robust quantitative methods need to be developed and harvest control rules need to be implemented and tested that are risk-averse while ensuring high yields and that are applicable for stocks with limited data.

Aims of the project: The project has four main objectives: (i) developing guidelines and advice on good practices for data-limited assessments and, (ii) to further develop assessment methods and provide alternatives to age-based assessments, (iii) to provide new and improve existing quantitative assessments of selected fish stocks of high commercial and ecological importance, and (iv) to disseminate project results to the international scientific and management advisory community.

Results: The RoMA project further developed the surplus production model in continuous time (SPiCT) and facilitated its application for many stocks. Stochastic harvest control rules (HCRs) were introduced to account for uncertainties in maximum sustainable yield (MSY) estimates. These rules, adjusting the Total Allowable Catch (TAC) based on quantified uncertainty, demonstrated robust performance in reducing risk and yield variability across stocks. The approach was implemented in ICES guidelines and applied to multiple stocks. A software tool, SAM2SPICT, was developed that makes a surplus production model assessment for stocks with age-based assessments. This tool provides an alternative assessment for stocks managed with age-based models that can be used as replacement in case of any issues with them. The project also facilitated the assessment and provision of scientific advice for over 20 data-limited stocks, contributing to ICES benchmark and assessment working groups. The dissemination of the project was extensive with three scientific publications, presentations at scientific conferences and symposia and involvement in assessment working groups.

Conclusion: The project successfully addressed methodological gaps in stock assessment in the context of data-limited stocks. Most important contributions include, the further development and application of surplus production models, the implementation of stochastic harvest control rules, and the development of the SAM2SPiCT tool. The developments of the RoMA project were adopted in the ICES technical guidelines and were applied in the assessment of various stocks.

1. Introduction

The Common Fisheries Policy (CFP) aims at the sustainable exploitation of marine living resources considering the maximum sustainable yield (MSY) principles and the precautionary approach to fisheries management (Article 2 of Regulation No 1380/2013). However, for many fish and shellfish stocks, lack of data challenges the estimation of fisheries reference points and, thus, the quantification of stock status and hinders their sustainable exploitation. In fact, more than half (53%) of the 205 stocks within the ICES (International Council for the Exploration of the Sea) managed area lack an analytical assessment and are thus considered data-limited according to results of the EU (European Union) Tender ProByFish (Rindorf et al. 2021). A multitude of reasons lead to data-limitations. Lack of age readings is a result of difficulty to read the ages of certain species; but can also be related to lack of funding or interest for the stock. Further, absence of landing or discard information, and species misidentification leads to limited or poor available data. The assessment of data-limited stocks is often done in qualitative terms and without quantification of assessment uncertainty. Therefore, data-limited stocks are at high risk of overexploitation or collapse. To overcome such risks, scientific advice is often overly precautionary leading to reduced Total Allowable Catch (TAC).

There are many data-limited methods being developed in recent years. Such methods often rely on coarse simplifications and assumptions, such as equilibrium conditions (constant recruitment and fishing mortality), potentially impacting assessment accuracy and precision. The International Council of the Exploration of the Sea (ICES) has recently updated their stock categorisation according to data availability and assessment method and uses the following definitions (ICES, 2022a):

Category 1 – Stocks with quantitative assessments; includes stocks with full analytical assessments and forecasts that are either age-/length-structured or based on production models.

Category 2 – Stocks with analytical assessments and forecasts that are only treated qualitatively as well as stocks with surplus production models, e.g., SPiCT, JABBA, without an MSE; includes stocks with quantitative assessments and forecasts which, for a variety of reasons, are considered indicative of trends in fishing mortality, recruitment, and biomass.

Category 3 – Stocks for which survey-based assessments or exploratory assessments indicate trends; includes stocks for which survey, trends-based assessment, or other indices and life history information are available that provide reliable indications of trends in stock metrics such as total mortality, recruitment, and biomass.

Category 4 – Nephrops stocks where information on possible abundance can be inferred and stocks for which a reliable time-series of catch can be used to approximate MSY. This is where there are reasonable scientific grounds to use life-history and density information from functional units to provide advice.

Category 5 – Stocks for which either only data on landings or a short time-series of catch are available.

Category 6 – Stocks for which there are negligible landings and stocks caught in minor amounts as bycatch; includes stocks where landings are negligible in comparison to discards as well as stocks that are primarily caught as bycatch species in other targeted fisheries.

Furthermore, ICES has published technical guidelines for providing advice for stocks in categories 2 and 3 (ICES, 2022a) drafted with significant contributions by the RoMA project. They highlight the use of the stochastic production model in continuous time (SPiCT; Pedersen and Berg, 2017) that is being developed and maintained by DTU Aqua and was further developed in this project. SPiCT is a fully stochastic surplus production model that requires time series of catches and an abundance index (or time series of effort) and estimates biological reference points: maximum sustainable yield (MSY), the fishing mortality that leads to MSY (F_{MSY}) when the stock biomass has reached B_{MSY}. ICES has initiated a process of assessing all data-limited stocks, with SPiCT as the preferred method. RoMA's improved assessment methods that are used for category 2 stocks and facilitated the raising of stocks from lower categories to category 2. Additionally, RoMA provides surplus production models as alternative assessments for Category 1 stocks that use the state-space age-based model (SAM).

1.1. Project objectives

RoMA aimed at (i) providing good practice technical guidelines for surplus production models, (ii) improving assessment methods, (iii) providing state-of-the-art and robust assessments and management advice for the main data-limited stocks of high commercial and ecological importance, and (iv) disseminating and contributing to implementation of improved management procedures to and within scientific and advisory community.

1.2. Report outline

The project was structured along four work packages (WPs) and the most important outputs are summarised in the following sections:

WP1: Evaluation of stock assessment methods

The main tasks of the first work package included the compilation of available stock assessment methods along with classification according to data requirements and model performance (Section 2.1); since this has been accomplished by several recent peer-reviewed publications that were published just prior or during RoMA (Cope et al. 2023; Dowling et al. 2019, 2023; Goethel et al. 2023), the presentation is not very thorough and is mostly to illustrate available method categories. Main contribution of RoMA was the review paper on good practice using surplus production models (Kokkalis et al., 2024). An outline of that review paper is in Section 2.2. Finally, we identified gaps in existing data-limited stock assessment methods (Section 2.3), which were the basis for further developments in stock assessment methods in WP2.

WP2: Improving stock assessment methods

The second WP had two main aims, first to further develop SPiCT based on the input from WP1. The new developments are made available as open-source software in the `spict` R package. The main development was about stochastic Harvest Control Rules (Section 3.1 and Mildenberger et al 2022). Other developments of spict are summarised in Section 3.2. And second, to streamline the use of SPiCT as alternative assessment method for age-based assessments (Section 3.3).

WP3: Providing stock specific management advice

The ICES process to implement SPiCT for a large number of data-limited stocks was facilitated by the RoMA project in a series of Benchmark meetings. A description of stock specific management advice and application of the new versions of spict in WP2 is show in Section 4.

WP4: Stakeholder involvement and dissemination

The final WP, dealt with the important aspect of disseminating the results of the project in various international forums, several with stakeholder participation (Section 5).

2. Evaluation of stock assessment methods (WP1)

2.1. Stock assessment methods

Stock assessment methods are categorised according to input data; this is not an exhaustive list. The categorisation is based on two ICES reports: (i) the "Report on the classification of stock assessment methods" (ICES, 2012) and the WKLIFE-IV report (ICES, 2014b). The order corresponds available data, in increasing order in terms of data demands:

Catch only methods: minimal data requirements, consisting only of time-series of annual catch. The population dynamics are ignored and priors of life-history parameters and depletion levels are required. Examples: Depletion-Corrected Average Catch (DCAC, MacCall; 2009) and the Catch-MSY method (Martell and Froese, 2013). Such methods can be very problematic as they are bad classifiers of stock status and should not be used for fisheries management; additionally, if catch only methods would be used to manage a stock the information content of the catch information would be degraded (Free et al. 2020).

Production models: additional to the catch time-series, these methods require one or more time-series of abundance index. The total exploited biomass of population is characterised by its carrying capacity and its intrinsic growth. Examples: the Schaefer model (Schaefer, 1954), the Pella-Tomlinson model (Pella and Tomlison, 1969) and the Stochastic surplus Production model in Continuous Time (SPiCT, Pedersen and Berg, 2017).

Delay-difference models: models that include population structure, but instead of dealing with the population structure at each age/size class, the dynamics are simplified by making assumptions about mortality and growth at each life-stage. Example: Meyer-Millar model (Meyer and Millar, 1999).

Size-based methods: this is a broad category of methods that relies on the size composition of the catch or surveys. This category includes methods that estimate the total mortality, e.g., length converted catch curves (Wetherall et al., 1987) or the Beverton-Holt method (Beverton and Holt, 1957). Further, statistical catch-at-size methods, e.g., MULTIFAN-CL (Fournier et al., 1998) or the updated versions of ELEFAN in TropFishR (Mildenberger et al. 2017).

Virtual Population Analysis (VPA): methods that require yearly catch-at-age, weight-at-age and one or more age-specific biomass index as a tuning series. Limitation of such methods is that input data are assumed to be observed without error. These methods estimate time series of fishing mortality and biomass. Examples: XSA (Shepherd, 1999), ADAPT (Gavaris, 1988).

Statistical catch-at-age models: methods that have similar data requirements as VPA. This category includes many data-intensive methods. Example: State-space Assessment Model (SAM, Nielsen and Berg, 2014), which is used as the main age-based assessment model in ICES.

Integrated analysis: methods that use all available information, so they can accommodate data-limited cases – usually simulating an age-based population parameterised informed by available data and additional assumptions. Example: Stock Synthesis (Methot and Wetzel, 2013).

2.2. Good practice for surplus production models (SPMs)

Surplus production models play an important role for the assessment of data-limited and data-moderate fish stocks as they only require information about the commercial catches and an abundance index. Nevertheless, the adoption, application, and utilization of these models differ among regions and case studies. Establishing good practice guidelines can standardize modelling processes, guide the acceptance or rejection of assessments, and help derive management recommendations from accepted assessments. Therefore, we developed detailed guidelines for the use of surplus production models to estimate fisheries management advice. These guidelines are based on the results of multiple assessment, benchmark, and methods working groups and are supported by a simulation study that evaluated the performance of an age-based operating model and the surplus production model SPiCT across more than 50 scenarios, considering various assumptions related to data quantity, quality, and model priors. Among others, the simulations confirmed that SPiCT can well approximate the age-based population dynamics, but that the accuracy and precision of estimated reference points and stock status is a function of simulated uncertainty (Fig. 1). The guidelines are summarised in a scientific article (Kokkalis et al., 2024). The article delves into prevailing practices concerning the use of surplus production models and advocates for good practice guidelines specifically tailored for their application in stock assessment and outlines distinct good practice guidelines for two frequently utilized state-space SPMs: SPiCT and JABBA. The article also discusses limitations and potential directions for advancing SPMs in the future.

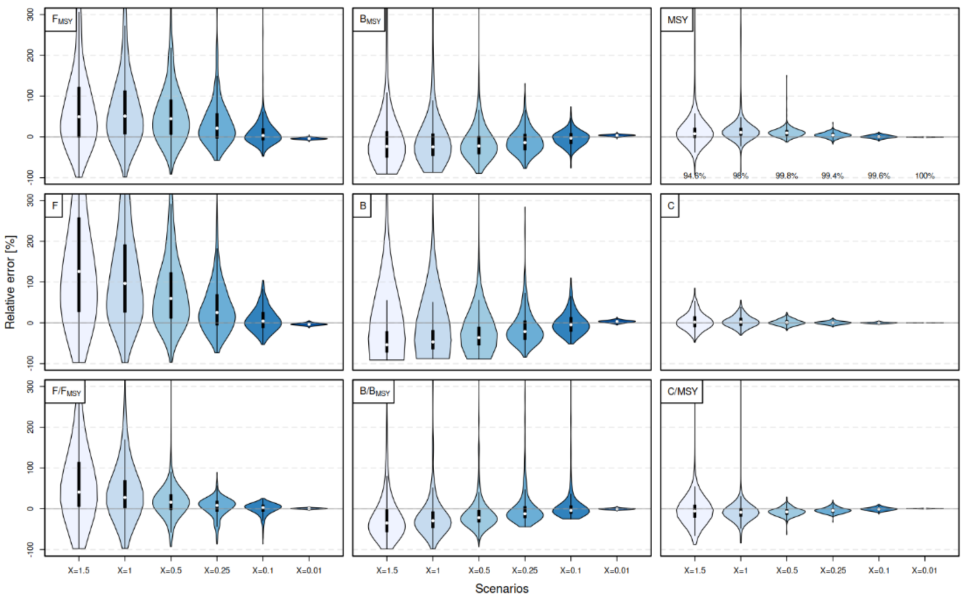

Figure 1. Relative error in reference points and absolute and relative states simulated with an age-based operating model and estimated with a surplus production model for varying process and observation uncertainty levels expressed as a factor of the default levels (x axis).

2.3. Identifying methodological gaps and areas for improvement

In the final stakeholder workshop for the precursor project ManDaLiS, findings and future perspectives were discussed. It was concluded that future method developments are needed for robust management procedures and advice. Highlighted improvements include the need to increase the model stability of SPiCT when input time series have different lengths, the potential of using neglected information in the assessment (e.g. discard information, effort data, or the non-exploitable part of the abundance index), the need to assess the implications of prior distributions on the accuracy of reference points and stock status, as well as the potential of using SPiCT for an alternative assessment to an age-based assessment (e.g. SAM assessment) to identify model problems. Ideally, data-limited management procedures are robust to high observation uncertainty, show low interannual variability in yield, have a low probability of stock collapse due to overfishing, and can identify assessment limitations. Further, it can uncover additional sources of information that would be needed to increase the accuracy and precision of the assessment.

Furthermore, feedback from assessors, working group chairs and participants in methodological ICES working groups was taken into account. Most importantly, WKMSYSPiCT suggested a list of important further developments for SPiCT, and WKLIFE and WKDLSSLS had Terms of Reference regarding further development and testing of SPiCT. This valuable feedback was the basis for further developing the SPiCT R package and drafting technical guidelines and good practice for surplus production models.

3. Improving stock assessment methods (WP2)

3.1. Stochastic harvest control rules

The concept of maximum sustainable yield (MSY) plays an important role in the CFP and suggests that a theoretical high yield can be obtained over a long period. However, estimated MSY reference points as well as the size of the stock and fishing pressure relative to them are typically characterised by substantial uncertainty, particularly, in data-limited stock assessments (Fig. 1). Considering the precautionary approach to fisheries management, we developed stochastic harvest control rules (HCRs) that account for this uncertainty by adjusting the recommended Total Allowable Catch (TAC) as a function of the quantified uncertainty. In other words, the recommended TAC is defined as the fractile of the predicted catch distribution. We tested a wide range of these stochastic HCRs (varying fractiles and considering other distributions in addition to the predicted catch distribution) and alternative HCRs with precautionary measures such as biomass limit and threshold reference points within a management strategy evaluation framework. The stochastic HCRs showed a robust performance leading to high long-term yield and low risk of low stock biomass (Fig. 2).

This risk-yield trade-off is not proportional and to some degree, risk can be reduced without or only with a minor loss in yield. The absolute levels of reduced risk and forgone yield depend on the chosen fractile of the catch distribution. While the choice of the acceptable risk and thus the fractile should be taken based on stock-specific management strategy evaluation and under consideration of the manager’s willingness to take risks, we recommended the default 0.35 fractile of the predicted catch distribution rather than the median which does not take any uncertainty into account.

In summary, employing stochastic harvest control rules are a promising precautionary strategy which effectively incorporate and propagate uncertainty into management advice. They consistently reduce risk and yield variability across stocks and various levels of scientific uncertainty. Notably, they prove highly effective for shorter-lived species, likely due to their population dynamics' fluctuations. These dynamics challenge the traditional MSY concept, especially in defining target reference points. For shorter-lived species, a fishing mortality lower than F_{MSY} over a broad biomass range could be crucial for precautionary fisheries management. Additionally, stochastic harvest control rules consider F_{MSY} as a target only when uncertainty is near zero, emphasizing it as a limit reference point. Consequently, these buffers incentivize minimizing observation uncertainty and therefore incentivising enhancing data-sampling programs.

All new management functionality of the `spict` R package was improved, and the stochastic harvest control rules were implemented in a generic way that allows application of different stochastic HCRs (spict v. 1.3.0, https://github.com/DTUAqua/spict/releases/tag/v1.3.0).

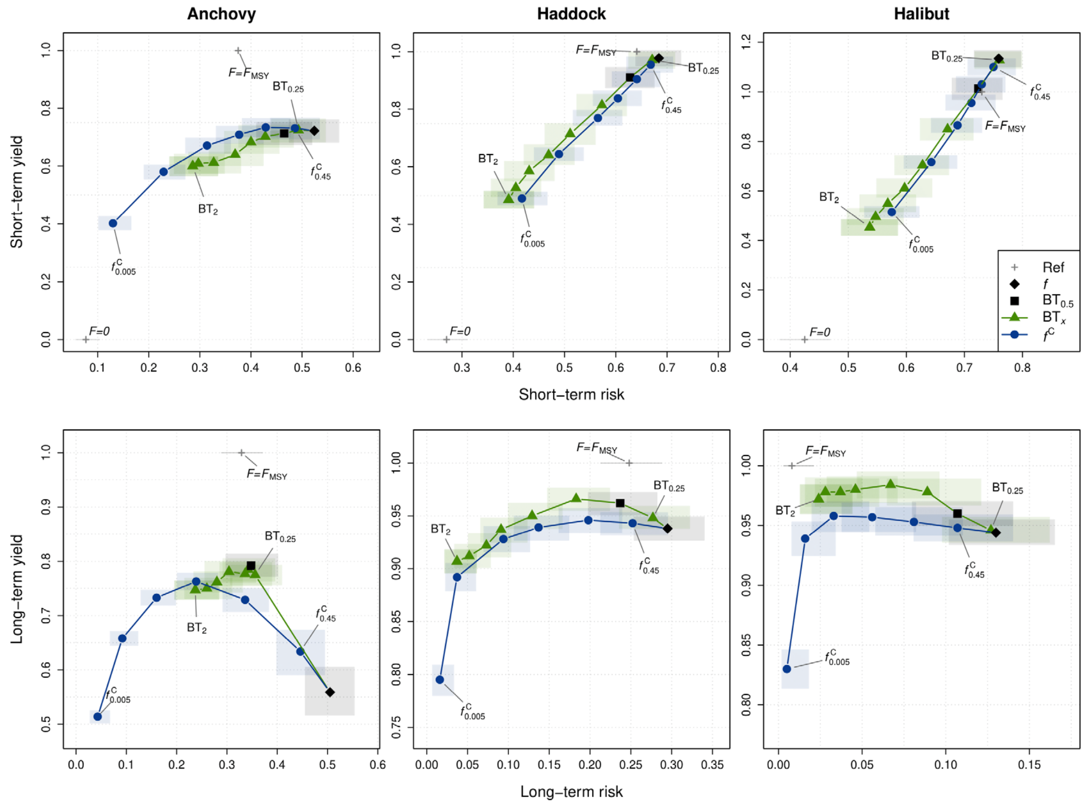

Figure 2. Short- and long-term yield vs short- and long-term risk in the upper and lower row, respectively. The blue points and line describe the yield-risk trade-off of the stochastic harvest control rules with decreasing fractile of the predicted catch distribution starting from the black diamond that corresponds to fishing at FMSY.

The results were presented and discussed in multiple ICES workshops (WKLIFE X, WKLIFE XI) and published as a scientific article (Mildenberger et al., 2022). The stochastic HCRs are now implemented in the official ICES guidelines for fisheries management advice based on surplus production models (Category 2 in the list above; ICES, 2022a). The rule has been applied for multiple stocks during the last years, such as Norway lobster, pollack and brill (Table 1). Section 4 contains more details about the implementation of these rules.

3.2. Further development of spict

Apart for the new management functionality of the `spict` presented above. Several further developments were identified in WP1 and were implemented over the course of RoMA.

Retrospective analysis - Mohn's rho

It is crucial that an assessment is robust and is able to reliably estimate stock status. Retrospective analysis compares the assessment of consecutive model fits where subsequent years of data are removed. Mohn's rho is a way of quantifying mean bias, and ICES follows guidelines lined out by Hurtado-Ferro et al. (2015) where acceptable mean bias is between 0.15 - 0.2. New retrospective plots were implemented in `spict` along with calculation of Mohn's rho were added in `spict` version 1.3.0 (Fig. 3).

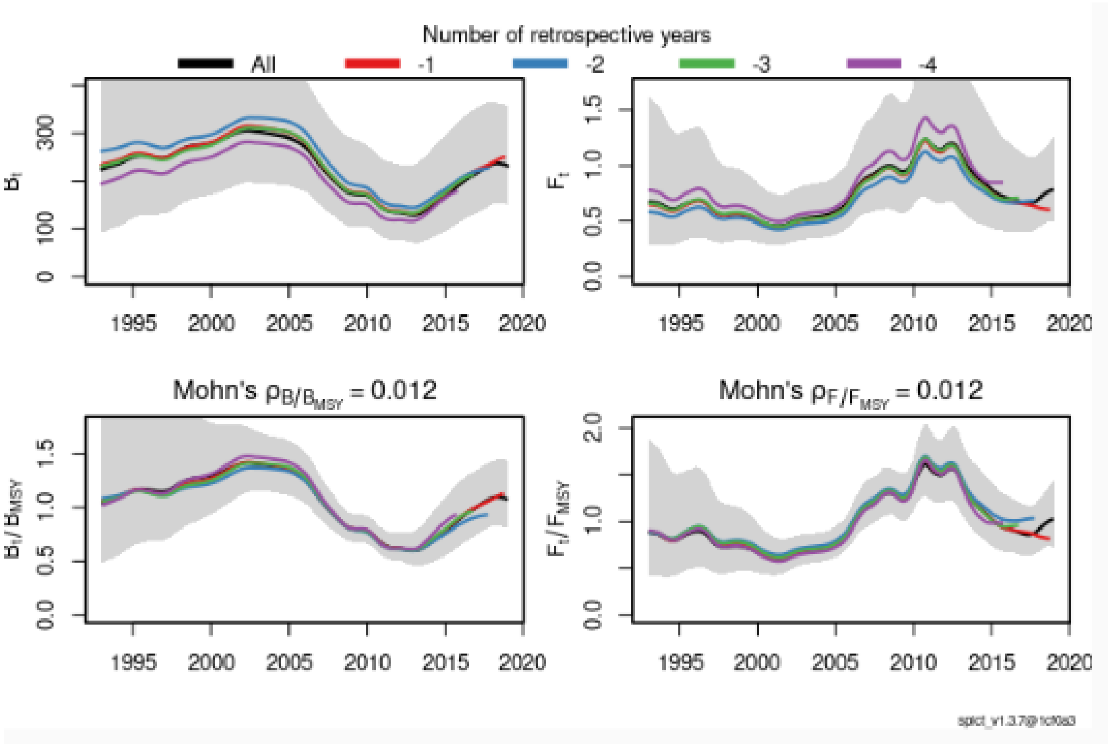

Figure 3. Example of retrospective analysis in `spict`. Mohn's rho for the relative fishing mortality and relative biomass are shown above the plots.

Hindcast analysis

Similar to retrospective analysis, in hindcast analysis the assessment is redone by removing data and refitting the model, but in this case only index data are removed. The Mean Absolute Scale Error (MASE) quantifies how well the model is able to estimate the index. Values above one can indicate issues with the assessment. The hindcast is implemented in `spict` in version 1.3.7 (Fig. 4).

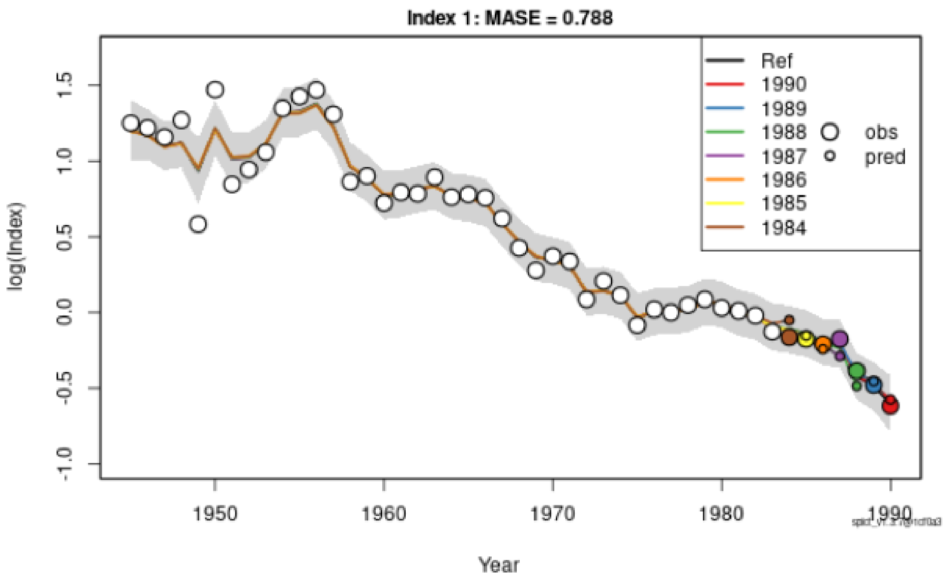

Figure 4. Example of hindcast analysis in `spict`. MASE is shown above the plot.

Process residuals

SPiCT has two processes, fishing mortality and exploitable biomass. In `spict` v. 1.3.8, process residual calculation was implemented along with statistical tests to check for bias, normality and autocorrelation (Fig. 5).

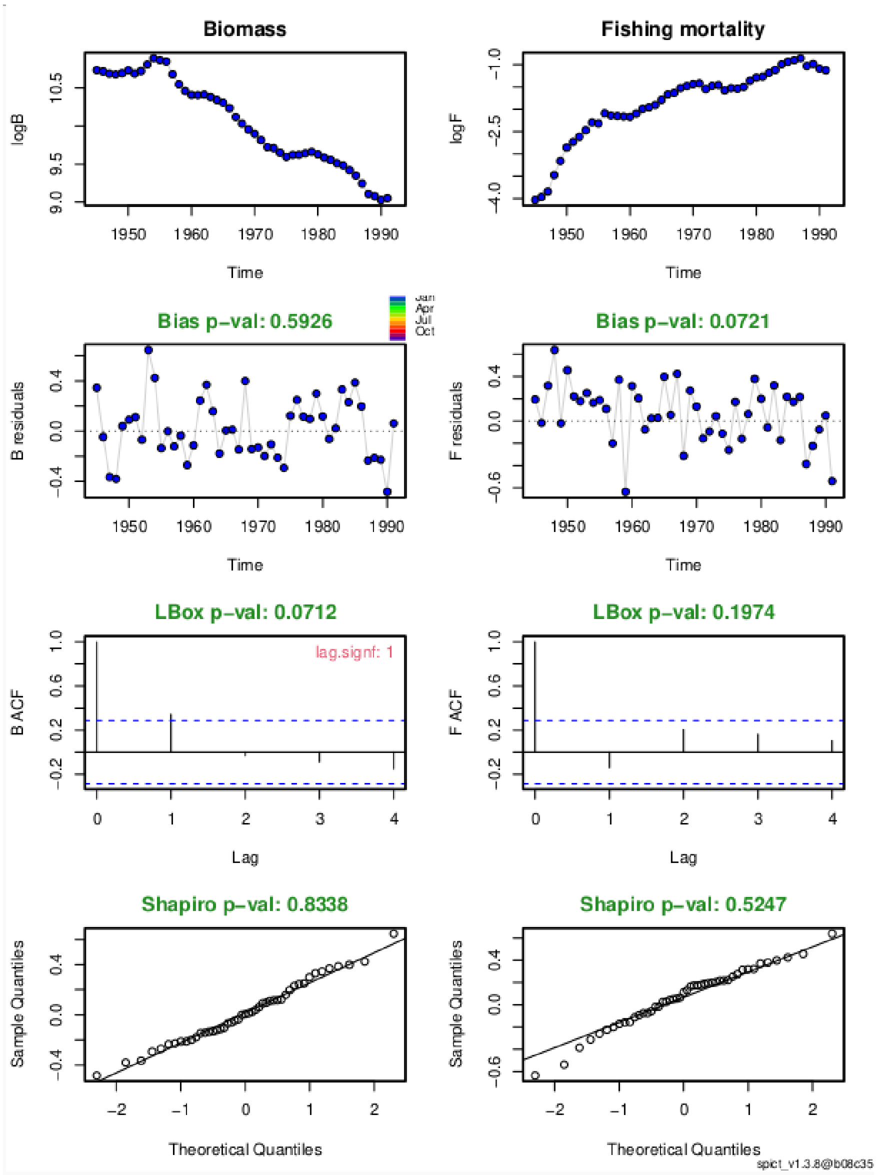

Figure 5. Diagnostic plots for process residuals for biomass (right column) and fishing mortality (left column). The plots show the processes in log scale (top row), the process residuals with a test for bias (second row), the autocorrelation test with a Ljung-Box test (third row) and a QQ-plot with a test for normality (bottom row).

3.3. Production models as alternatives to age-based assessments

From time-to-time age-based stock assessment models are rejected by ICES expert groups or the advice committee (ACOM), because they do not pass all model validation criteria such as lack of retrospective patterns. A retrospective pattern is when a model systematically diverges from past estimates from previous years stock assessment with the same model and is a sign of model misspecification. In such cases, production models can be used as fall-back option.

Examples of this are the two cod stocks in the Baltic Sea (eastern and western). Both stocks were previously running a state-space age-based assessment model (SAM), but these were rejected for various reasons including retrospective patterns. The EMFAF project “ManDaLis” contributed to further development of the production model SPiCT, such that it could be applied to Eastern Baltic cod and account for time-variant productivity, and this model is still being run as a simple alternative to the more complex assessment model used now (Stock Synthesis 3). During this project, a software tool was developed that allows for quick and straightforward application of the SPiCT model to an age-structured data set in the SAM data format, the so-called SAM2SPiCT tool. When the Western Baltic cod stock assessment model was rejected at the 2022 assessment meeting, this tool was used to quickly convert the existing age-disaggregated data in numbers to exploitable stock biomass, run a SPiCT assessment, and compare the results (Fig. 6). The comparison showed similar trends of relative biomass and fishing mortality, but the reference points could not be estimated with acceptable precision, so the stock was downgraded to a category three assessment (an assessment without reference points, that only uses biomass trends).

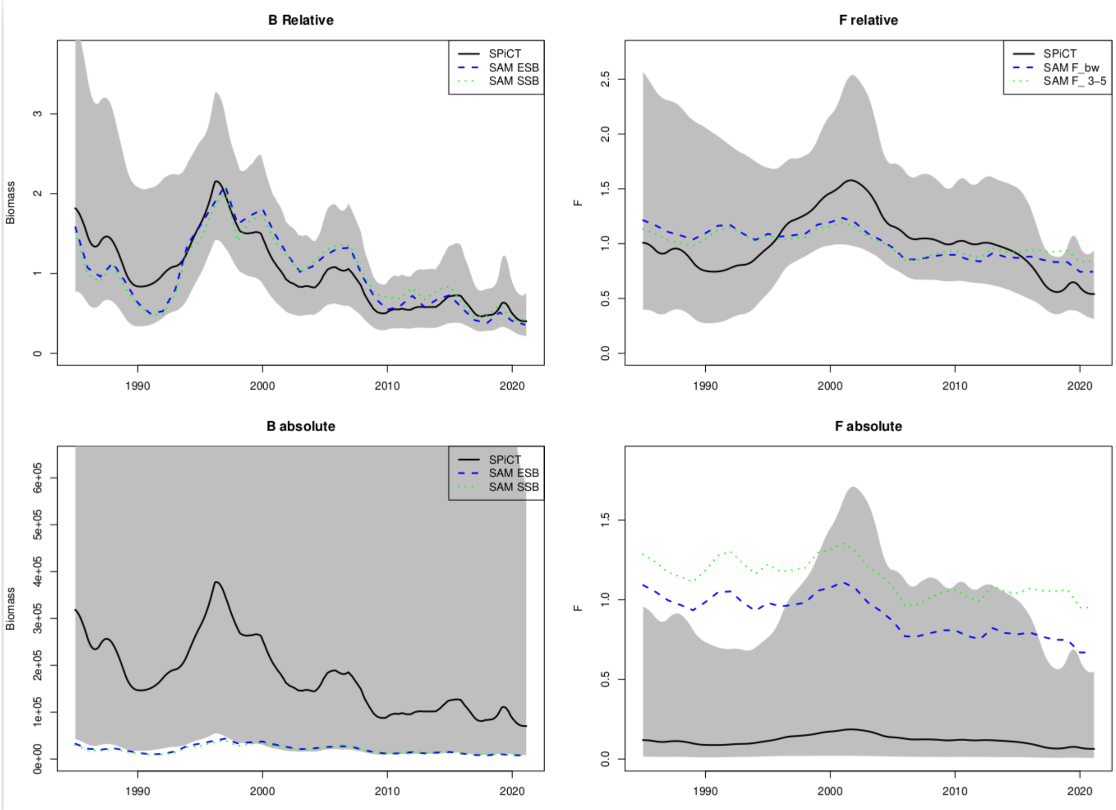

Figure 6. Western Baltic cod assessment comparison, SAM is the blue dashed line and SPiCT is shown with black solid lines. Grey area represents 95% confidence interval from SPiCT. While there is agreement in the development in relative biomass and fishing mortality (top row), the absolute estimates (bottom row) are from SPiCT are very uncertain for this stock.

It is important to note that SPiCT only estimates the exploitable stock biomass (ESB), i.e., the part of the population that is vulnerable to commercial fishing, which typically excludes the juveniles. This contrasts with SAM, where all or nearly all age groups are included in the state vector. The following section explains how data and model output are transformed from age based multivariate to univariate time series to facilitate comparison in the SAM2SPiCT software.

An index of exploitable biomass can be calculated from SAM data as follows. For each age group, the selectivity ratio between commercial and survey data at age is approximated by the average ratio of biomass-at-age in the commercial catches and the corresponding biomass-at-age in the surveys. The selectivity ratio at age is then multiplied with survey biomass-at-age for each year and summed over age groups to give the exploitable biomass index.

Weight-at-age in the surveys (needed to calculate biomass at age from numbers at age) are typically not known from SAM data since only the numbers-at-age and the time of the survey are used. Only mean weight-at-age in the catches and in the stock are needed in SAM, where the latter is usually assumed to be around January 1st where SSB is calculated. For some stocks mean weight at age in the stock are taken to be the same as in the catches (often due to the larger available sample sizes from the catches), although often they are obtained from a spring survey. Thus, we have used the convention that if the mean relative discrepancy between stock and catch mean weights is less than 5%, stock mean weights are assumed to apply to 1st of July rather than January (assuming that the fishing effort is evenly distributed over the year). If the mean relative discrepancy is larger than 5%, then stock mean weights are assumed to come from the earliest of the surveys available. Given that we know the time when stock mean weights at age are collected, we can interpolate stock mean weights at other times of the year using a generalized additive model.

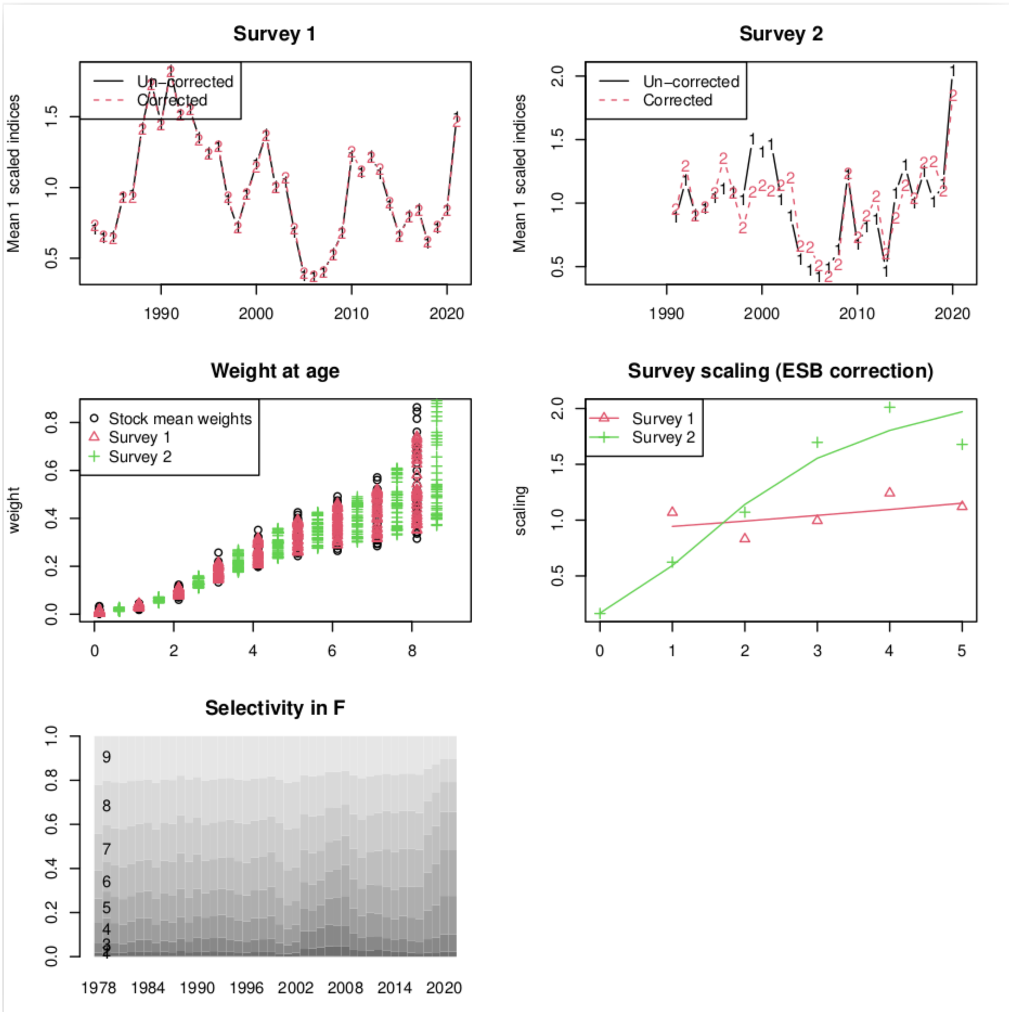

Figure 7. Example of output from the conversion of age-based survey indices from SAM to exploitable stock biomass indices in SAM2SPiCT. The example is using data from the North East Artic cod assessment. In this case only "Survey 2" needs some correction (top row). The interpolation of weight-at-age is shown in the middle-left plot, and the selectivity ratios are shown in the middle right plot.

Exploitable stock biomass also needs to be calculated from the SAM fit in order to do the comparison. This is calculated by multiplying biomass-at-age with the selectivity-at-age from SAM. The average fishing mortality in SAM is usually calculated by taking averages over a selected number of the most common age groups, but for this comparison we use a weighted average of fishing mortality-at-age, with weights being the average caught biomass by age (Fig. 7).

The modelling of exploitable stock biomass (ESB) rather than total stock biomass (TSB) or spawning stock biomass (SSB), was found to be important for several of the stocks tested. The model using SSB did not converge, so no fit is shown for this. Note that the model using ESB fits the observed surplus production much better than the other two models (Fig. 8).

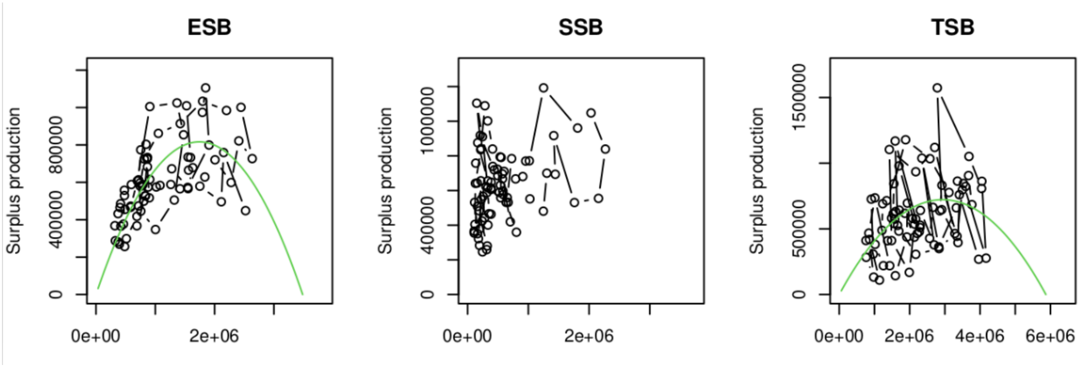

Figure 8. Production curves for North East Arctic cod using different definitions of biomass (from left: exploitable stock biomass, spawning stock biomass, and total stock biomass).

The SAM2SPiCT package made it possible to test SPiCT on a large number of existing SAM assessments. This helped to identify several small possible improvements of the SPiCT software (Fig. 9). One problem was that SPiCT has a harder time to estimate past biomass levels for periods when there is only catch data available but no survey data. A promising solution was implemented, which uses an initial spin-up of the model. Rather than assuming that the initial biomass can be virtually anything, the spin-up implies that the initial state has a prior distribution (e.g., the biomass cannot be well above the carrying capacity of the stock). This option resulted in better agreement with the SAM assessments in several cases. The spin-up option is available in spict version 1.3.8.

Another result obtained by comparing SAM and SPiCT assessments using the SAM2SPiCT package was that the agreement in estimates of absolute biomass often can be improved by imposing an appropriate prior distribution on the parameter in SPiCT, that governs population doubling time at small biomasses, the so-called intrinsic growth rate ‘r’. Such priors can easily be obtained from published meta-studies, e.g., the FishLife package (Thorson, 2017) or the FishBase website (www.fishbase.se). This result was utilized at the WKBMSYSPICT, WKBMSYSPICT2, and WKELASMO working groups, which used such r-priors with success.

The SAM2SPiCT software package was not completely finalized at the time this report was written. The source code can be obtained by contacting Casper W. Berg (cbe@aqua.dtu.dk). Once finalized the package will be published as open-source software.

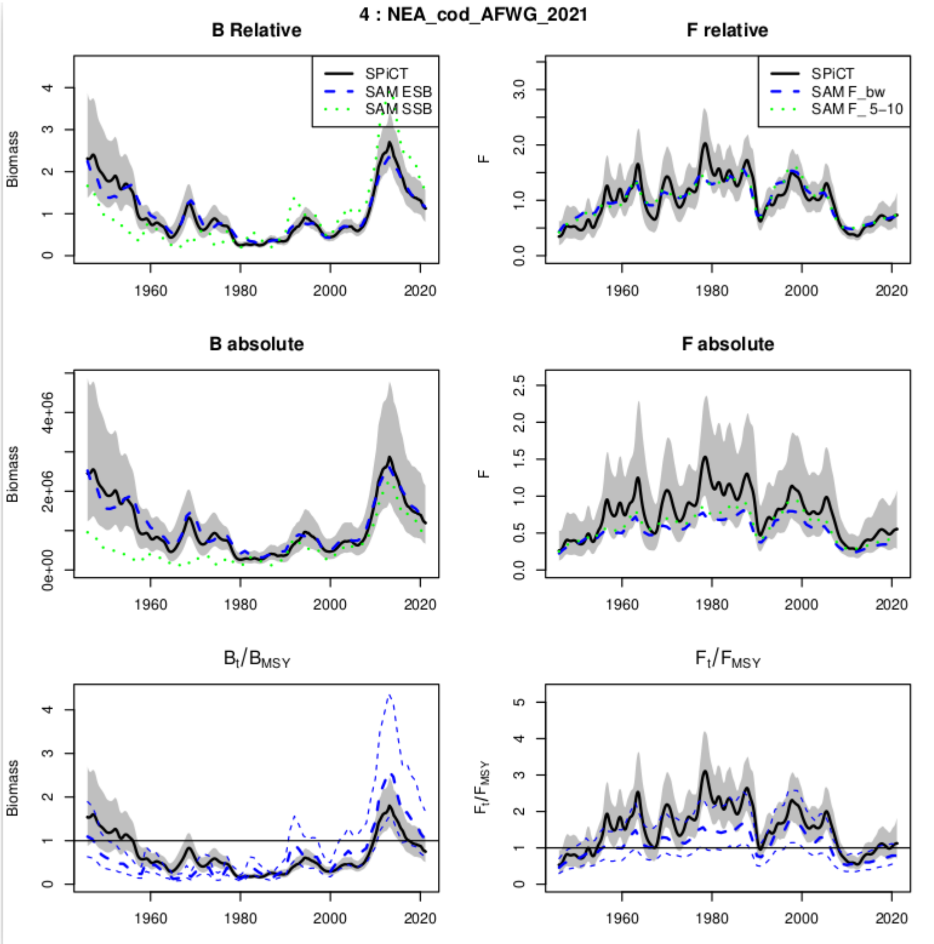

Figure 9. North East Artic cod assessment comparison. SAM is the blue dashed line and SPiCT is shown with black solid lines. Grey area represents 95% confidence interval from SPiCT.

4. Providing stock specific management advice (WP3)

Stock-specific management advice for more than 20 data-limited stocks was provided and facilitated within the frame of RoMA (Table 1). The assessment of 11 of these stocks were accepted and fisheries management advice according to the stochastic harvest control rule (Section 3) provided. Two ICES benchmark workshops for the assessment of data-limited stocks by means of surplus production models were held: WKMSYSPICT (ICES 2021) and WKBMSYSPICT2 (ICES, 2023c). Data-limited assessment methods also played a major role in the benchmark workshop for the assessment of elasmobranchs (WKELASMO; ICES, 2022b). In addition, we assisted and reviewed multiple stock coordinators and assessors with their data-limited stock assessments. These workshops and additional assessments are summarised below.

Table 1. Summary of the 23 data-limited stocks for which stock-specific assessments were conducted, reviewed, and benchmarked during RoMA.

Species	Area	Assessment	Advice	Workshop
Megrim	Division 6b	Accepted	SPiCT	WKBMSYSPiCT
Black-bellied anglerfish	Divisions 8c and 9a	Accepted	SPiCT	WKBMSYSPiCT
Norway lobster	Functional Unit 25	Accepted	SPiCT	WKBMSYSPiCT
Norway lobster	Functional Unit 26-27	Accepted	SPiCT	WKBMSYSPiCT
Norway lobster	Functional Unit 28-29	Rejected	Based on category 3	WKBMSYSPiCT
Norway lobster	Functional Unit 31	Accepted	SPiCT	WKBMSYSPiCT
Tusk	Subareas 1-2	Rejected	Based on category 3	WKBMSYSPiCT
Tusk	Subareas 4 and 7-9 and divisions 3a, 5b, 6a, and 12b	Rejected	Based on category 3	WKBMSYSPiCT
Porbeagle	Northeast Atlantic	Accepted	SPiCT	WKELASMO
Thornback ray	Divisions 8abd	Accepted	Bayesian state-space surplus production model	WKELASMO
Thornback ray	Division 8c	Rejected	Based on category 3	WKELASMO
Undulate ray	Divisions 7d-e	Accepted	SPiCT	WKELASMO
Cuckoo ray	Divisions 6,7,8abd	Accepted	SPiCT	WKELASMO
Brill	Subarea 4 and divisions 3a and 7d-e	Accepted	SPiCT	WKBMSYSPiCT2
Striped red mullet	Subarea 4 and divisions 3a and 7d	Rejected	Based on category 3	WKBMSYSPiCT2
Plaice	Divisions 7f and 7g	Not presented	Not evaluated	WKBMSYSPiCT2
Pollack	Subareas 6-7	Accepted	SPiCT	WKBMSYSPiCT2
Pollack	Subarea 8 and division 9a	Rejected	Based on category 3	WKBMSYSPiCT2

Species	Area	Assessment	Advice	Workshop
Thornback ray	Division 8c	Accepted	SPiCT	WKBMSYSPiCT2
Boarfish	Subareas 6-7	Rejected	Based on category 3	WKBMSYSPiCT2
Whiting	Subarea 8 and division 9a	Not presented	Based on category 3	WKBMSYSPiCT2
Whiting	Division 3a	Not presented	Not evaluated	WKBMSYSPiCT2
Plaice	Subarea 8 and division 9a	Rejected	Not evaluated	WKBMSYSPiCT2

WKMSYSPICT

The Benchmark Workshop on MSY advice using SPiCT focused on assessing stocks in category 3, a first for ICES (ICES, 2021). The workshop included learning sessions for model developers and assessors before the data evaluation meeting. Thirteen stocks were chosen from four ICES Assessment Working Groups based on data availability and network capacity, covering demersal fish and Nephrops Functional Units (Table 1). SPiCT was successfully used for assessments of certain stocks, indicating potential for upgrading their category. However, for some Tusk stocks and Norway lobster Functional Units, distinguishing stock status was challenging due to data limitations. Pollock in specific areas did not yield successful model configurations. The workshop highlighted recommendations on using historical catches, standardizing CPUE, and improving SPiCT model diagnostics.

WKELASMO

The WKELASMO workshop assessed and forecasted four elasmobranch stocks (ICES, 2022b): Porbeagle in the Northeast Atlantic, thornback ray in the Bay of Biscay, undulate ray in the Channel, and cuckoo ray in western waters (Table 1). Porbeagle in the Northeast Atlantic: The workshop utilized SPiCT assessment based on historical landings and indices, placing the stock in category 2. The stock's harvest is primarily below F_{MSY}, with biomass below MSY $B_{trigger}$. Thornback ray in the Bay of Biscay: Stock boundaries in Subarea 8 suggested two stocks. The workshop accepted a Bayesian state-space biomass model for 8.abd, categorizing it as category 2 due to exploitation close to F_{MSY}. However, high uncertainty kept 8.c in category 3 with empirical methods used for advice. Undulate ray in the English Channel: SPiCT assessment, using removals since 2005 and survey indices, categorized the stock as category 2, revealing it to be harvested well below F_{MSY} with biomass above B_{MSY}. Cuckoo ray in western waters: Stock identity investigations did not justify splitting. SPiCT assessment with combined abundance indices and landings since 2005 led to category 2. The stock is harvested below F_{MSY}, with biomass above B_{MSY}, attributed to its non-target status and high growth rate.

WKBMSYSPICT2

The second ICES Benchmark Workshop on using SPiCT to determine MSY advice for specific stocks (WKBMSYSPiCT2) represents ICES' second attempt to offer MSY advice for stocks previously classified as category 3 (ICES, 2023c). This workshop included model learning sessions involving developers and assessors before the data evaluation meeting. Ten stocks, including nine demersal fish stocks and one elasmobranch, from five ICES Assessment Working Groups were chosen based on data availability and network capacity (Table 1). Successful SPiCT assessments were conducted for two demersal stocks: Brill in Subarea 4 and divisions 3.a and

7.d–e, Pollack in Subareas 6–7, and one elasmobranch, Thornback ray in Division 8.c. However, Plaice in Divisions 7.f and 7.g and Whiting in Division 3.a were not presented by the stock assessor during the benchmark. For Whiting in Subarea 8 and Division 9.a, only input data for category 3 methods were evaluated. WKBMSYSPiCT2 suggested that the current category of these stocks could be upgraded as the methodology proved suitable for determining stock status and short-term catch forecasts. Different model configurations were tested for the remaining stocks, but the available data did not allow for distinguishing between varying plausible stock statuses or the proposed model configurations did not pass diagnostic tests. The thorough examination of input data and model setups in the workshop resulted in several recommendations concerning the standardization of commercial CPUE, encompassing spatial, target, and technological creep effects, as well as SPiCT model settings.

Other assessments
The assessment of the Norway lobster stocks (Table 1) was updated and published in a scientific article (Herraiz et al., 2023). These assessments provided the first MSY based reference points and associated stock status for these stocks. The results indicated low biomass for most stocks and identified long-term temporal and spatial changes in the population dynamic of Norway lobster in the Northwest Iberian coast.

A SPiCT assessment of Greenland halibut in NAFO areas 0+1 was presented to the NAFO Scientific council meeting in 2023 with contributions from project participants (Nogueira et al. 2023).

A presentation about good practice using Surplus production model in Continuous Time (SPiCT), technical guidelines applying it, and new developments were presented to the ICES assessment working groups WGCRAB and WGSCALLOP. Additionally, questions were answered about usage and assumptions of SPiCT and feedback was given on preliminary assessments of different stocks using SPiCT in these groups.

5. Dissemination of results and future perspectives

The RoMA dissemination did not only include the good practices guidelines (Chapter 2), the model and harvest control rule development (Chapters 3 & 4), and the provision of stock-specific assessments and management advice (Chapter 5), but also the presentation and discussion of model developments, performance, and implementation in the ICES workshops for data-limited stock assessment methods:

- The Tenth Workshop on the Development of Quantitative Assessment Methodologies based on Life-history traits, exploitation characteristics, and other relevant parameters for data-limited stocks (WKLIFE X) developed and evaluated 'fractile rules' that account for uncertainty and allow to consider any percentile and demonstrated that 'fractile rules' are more effective and precautionary than the median rule (50th percentile) and the '2-over-3' rule. For assessments using the stochastic surplus production model in continuous time (SPiCT). WKLIFE X also revised technical guidance on methods and advice rules for stocks in Category 3 (ICES, 2020).
- The Eleventh Workshop on the Development of Quantitative Assessment Methodologies based on Life-history traits, exploitation characteristics, and other relevant parameters for data-limited stocks (WKLIFE XI) presented detailed responses to collated comments from the ICES' community on the empirical harvest control rules for Category 3 data-limited stocks and surplus production models for Category 2 stocks; together with further guidance (ICES, 2023b).

Furthermore, the results of work performed within the frame of RoMA was published in three scientific articles:

- Mildenberger, T.K., Berg, C.W., Kokkalis, A., Hordyk, A.R., Wetzel, C., Jacobsen, N.S., Punt, A.E. and Nielsen, J.R., 2022. Implementing the precautionary approach into fisheries management: Biomass reference points and uncertainty buffers. Fish and Fisheries, 23(1), pp.73-92. https://doi.org/10.1111/faf.12599
- González Herraiz, I., Vila, Y., Cardinale, M., Berg, C.W., Winker, H., Azevedo, M., Mildenberger, T.K., Kokkalis, A., Vázquez Vilamea, A.A., Morlán, R. and Somavilla, R., 2023. First Maximum Sustainable Yield advice for the Nephrops norvegicus stocks of the Northwest Iberian coast using stochastic Surplus Production model in Continuous Time (SPiCT). Frontiers in Marine Science, 10, 1062078. https://doi.org/10.3389/fmars.2023.1062078
- Kokkalis, A., Berg, C. W., Kapur, M., Winker, H., Jacobsen, N. S., Taylor, M. H., Ichinokawa, M., Miyagawa, M., Medeiros-Leal, W., Nielsen, J. R., Mildenberger, T. K. 2024. Good practices for surplus production models. Fisheries Research, 275, p.107010. https://doi.org/10.1016/j.fishres.2024.107010

RoMA results were also presented at following international conferences and symposia:

- Mildenberger, T. K., Kokkalis A, Berg CW, Nielsen JR. 2021. Time-variant productivity in biomass dynamic models on seasonal and long-term scales. Recorded virtual presentation. ICES Annual Science Conference online.

- Sparholt, H., and Mildenberger, T. K. 2021. Management Strategy Evaluation (MSE) with a Biomass Dynamic Model as operating model. Recorded virtual presentation. ICES Annual Science Conference online.
- Berg, C. W. Process and observation errors - can SPiCT be used? A scientific symposium organised by the “MSE project” group – 23 November 2022.

Future perspectives

Data-limited conditions remain a challenging and prevalent topic within European and Danish fisheries management. More than half of the stocks for which ICES provides fisheries management advice for are considered data-limited (ICES, 2023b). While some stocks might only support negligible commercial catches, they might support recreational fisheries, have an important ecological role, or might restrict other commercially important stocks as bycatch species (“choke species”). Thus, the evaluation of data-limited methods and their further development will remain an important endeavour in the future. A roadmap outlining future data-limited research, assessment and management advice within ICES was developed during WKLIFE XI (ICES, 2023b). Among others, this roadmap includes important considerations regarding future development of data-limited stock assessment frameworks such as the further development of length-based assessment models and empirical harvest control rules. Regarding surplus production models, the roadmap includes following points (ICES, 2023b):

- The default priors of SPiCT might in some cases not be sufficient or adequate. Specific guidelines on model fitting and validation and priors are required. This includes generic priors reflecting likely doubling times or process noise levels for taxonomic groups as well as guidance on how to derive priors from case-specific data or analyses.
- Develop SPiCT further by, for example,
    - Implementing the option for multiple fleets.
    - Implementing a stage-based version that models the unexploitable stock biomass.
- Diagnostics, in particular reflecting prediction skill, are essential for model validation. Additional prediction skill metrics, such as ROC (receiver operating characteristic) curves or leave-one-out method, should be included in the diagnostics toolbox of SPiCT.
- Evaluate the performance of surplus production models under the assumption of strong recruitment pulses or non-stationary processes (e.g., gradual environmental changes and shocks).
- Evaluate the methods for accepting, rejecting, weighting of individual models in an ensemble, e.g., SPiCT models with different prior assumptions.
- Develop a data-poor harvest control rule management advice on production models that is not based on reference points, but rather on stabilising the biomass or a biomass level from a reference period.
- Consider including catch constraints to reduce inter-annual variability.

Future work should also be allocated to further development of the sam2spict software and surplus production-based management strategy evaluation frameworks.

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