DTU Aqua
National Institute of Aquatic Resources

Emergency action for calculating stock size and refeence points in case of massive data deficiency (BREFdata)

Anders Nielsen (Ed.)

DTU Aqua Report no. 459-2024

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Preface

This report financed by the Danish EMFF program "Fiskeri, natur og miljø - Marin biodiversitet", constitutes the professional delivery of the results of the EMFF project "Emergency action for calculating stock size and reference points in case of massive data deficiency (BREFdata) with the grant no 33113-B-20-168 which, through national and international collaboration between researchers, managers and representatives of the fishery, has contributed new modelling tools for ascertaining stock assessments in a world of rapidly changing fisheries and access to monitoring and data collection, and by including ocean data and modelling has paved the way for the best use of available data when assessing fish stocks of great importance for Danish fisheries. The project leader was Anders Nielsen, and the project period was from June 2020 to March 2023.

In Danish the project title is "Hasteindsats til beregning af bestandsstørrelser og referencepunkter ved massive dataudfald" (BREFdata)".

Lyngby, June 2024

Anders Nielsen
Professor MSO

European Union
European Maritime and Fisheries Fund

HAV & FISK

Content

1. Summary

This EMFF-project “Emergency action for calculating stock size and reference points in case of massive data deficiency” has delivered the tasks specified in the project description.

This project was a timely response to the easily predictable gaps in data caused by the corona pandemic. The project has developed and implemented statistical rigorous methods for dealing with such data gaps. One consequence of gaps in the data series is that the uncertainties become larger --- even when the gaps are handled in the best way possible. The project has also developed methods to calculate reference points within the assessment model because that ensures that the (now larger) uncertainties are propagated correctly to all the results used by managers.

The SAM model, which is used for more than 30 analytical assessments in ICES, is now capable of handling data situations where individual observations are becoming more uncertain (due to partially impacted data collection) and situations where individual observations are completely missing. This works for all types of observations (even of biological parameters) and for partially observed observations it works when the larger uncertainty is a known quantity and when it is unknown and needs to be estimated by the model. The SAM model can now also estimate a range of different reference points (e.g. Fmsy, Fmax, Fspr, Fb0, Fext, and Flim) internally and these can be based on wide selection of stock-recruitment relationships (e.g. Ricker, Beverton-Holt, hockey, spline, Shepherd, power, and Hassel/Deriso). Internal estimation of these reference points ensures that they are calculated consistently with the assessment model. In combination, this gives the working groups the tools needed to correctly handle data gaps in assessment and management.

The project has thoroughly validated the implemented methods to study their performance and to strengthen confidence that they have been implemented correctly. The project has documented the developed methods in clear text, code examples, and mathematical formulas and further made them easily available in software (R package https://github.com/fishfollower/SAM) and online platform normally used to conduct such assessments (http://stockassessment.org). The project has presented these methods and helped apply them at all relevant expert and benchmark working groups.

In the initial stages of the project, it was found that data gaps were also frequently caused by other factors than a covid pandemic, so this project turned out to be even more useful and applicable than anticipated. The combination of the techniques from this project and a previous project on treating biological quantities (e.g. weights and maturities) as observations gave the added benefit of being able to predict biological quantities where they are missing. Finally, the ability to predict any observation opens a lot of possibilities of using prediction-validation or cross-validation to compare the performance of models.

2. Danish Summary

EHFF-projektet "Hasteindsats til beregning af bestandsstørrelser og referencepunkter ved massive dataudfald (BREFdata)" har udført de opgaver, der blev specificeret i projektplanen.

Projektet var et rettidigt svar på de let forudsigelige dataudfald forårsaget af coronapandemien. Projektet har udviklet og implementeret statistisk stringente metoder til håndtering af sådanne dataudfald. En konsekvens af dataudfald er, at usikkerheden bliver større - selv når udfaldene håndteres på bedst mulig vis. Projektet har også udviklet metoder til at beregne biologiske referencepunkter inden for bestandsvurderingsmodellen, da det sikrer, at de (nu større) usikkerheder bliver korrekt videreført til alle resultater, der anvendes af forvaltningsmyndighederne.

SAM-modellen, som anvendes til mere end 30 analytiske bestandsvurderinger i ICES, er nu i stand til at håndtere datasituationer, hvor enkelte observationer er mere usikre (på grund af delvist påvirket dataindsamling) og situationer, hvor enkelte observationer er helt manglende. Dette virker for alle typer af observationer (selv biologiske parametre), og for delvist observerede observationer fungerer det, når den større usikkerhed er en kendt størrelse, samt når den er ukendt og skal estimeres af modellen. SAM-modellen kan nu også estimere en række forskellige referencepunkter (f.eks. Fmsy, Fmax, Fspr, Fb0, Fext og Flim) internt, og disse kan være baseret på et bredt udvalg af bestands-rekrutterings modeller (f.eks. Ricker, Beverton-Holt, hockey stick, spline, Shepherd, power og Hassel/Deriso). Intern estimering af disse referencepunkter sikrer, at de beregnes konsistent i forhold til bestandsvurderingsmodellen. Samlet set giver dette ICES arbejdsgrupperne de værktøjer, der er nødvendige for korrekt håndtering af dataudfald ved bestandsvurdering og forvaltningsrådgivning.

Projektet har grundigt valideret de implementerede metoder for at undersøge deres virkemåde og styrke tilliden til, at de er implementeret korrekt. Projektet har dokumenteret de udviklede metoder i klartekst, kodeeksempler og matematiske formler og har desuden gjort dem let tilgængelige som software (R-pakke https://github.com/fishfollower/SAM) og på en online platform, der normalt bruges til denne type bestandsvurderinger (http://stockassessment.org). Projektet har præsenteret metoderne og hjulpet med at anvende dem i alle relevante ekspert- og benchmark-arbejdsgrupper.

I de indledende faser af projektet blev det konstateret, at dataudfald også ofte skyldtes andre faktorer end en covid-pandemi, så dette projekt viste sig at være endnu mere nyttigt og anvendeligt end forventet. Kombinationen af teknikkerne fra dette projekt og et tidligere projekt om behandling af biologiske parametre (f.eks. vægt og modenhed) som observationer gav den ekstra fordel at modellen nu kan prædikere biologiske størrelser, hvor de mangler. Endelig åbner evnen til at prædikere enhver observation mange muligheder for at bruge prædiktionsvalidering eller krydsvalidering til at sammenligne modellers ydeevne.

3. Background for the project

The project was formulated as a timely response to the foreseeable consequences of the covid-19 pandemic and BREXIT management changes on the assessment community's ability to conduct the required assessments of key stocks, and the subsequent calculation of quantities used by managers.

The covid-19 pandemic was expected to cause two things to occur that would severely impact the yearly assessment process:
a) Data sources which routinely are used in the assessment models will be missing or be incomplete. This could be the case for both data from the scientific surveys and from the fishing fleets.
b) The fishing pattern (and thereby the population development) will be different, because of lack of demand and thereby falling prices on landed fish.

It will therefore – from year 2021 – be necessary for the assessment models to be able to handle missing and incomplete data on a scale not seen before. This must be done in a statistically rigours way to limit the problem to simply having less information. Various ad hoc schemes (e.g. duplicating information from other years, or simply not using any data from 2020) will likely make the problem worse. Such approaches are problematic under normal circumstances, but even more so in 2021, because the stock development in 2020 must be expected to be different (due to b)).
The solution is to properly treat the missing observations as missing in the assessment model, which means assigning random effects and integrating over these.
Current fisheries management depends on reference points in determining the status of a stock and, in turn, the exploitation opportunities. However, reference points are estimated from data through an assessment model. Therefore, reference point estimates are inherently uncertain. Currently, this uncertainty is not accounted for in fisheries management.

Another purpose of this project is to improve the current methods for estimating reference points as well as the subsequent advice and management by quantifying and accounting for this uncertainty. The project will analyse and develop the methods and principles behind reference point estimation as well as their implementation in operational assessment models and multiannual plans through harvest control rules used, for instance, for stock rebuilding.

This project builds on recent developments from DTU Aqua. DTU Aqua developed a prototype for allowing missing observations and for estimating reference points and their uncertainty such that they are consistent with the assessment model used to evaluate the status of the stock. These approaches will form the basis of the developments in this project. This project further develops the methods to be directly applicable for management and conservation of marine living resources. Further, the new reference point method will be compared to the current method used in ICES, which does not account for estimation uncertainty. Finally, the importance of accounting for estimation uncertainty for management and conservation will be quantified and documented.

4. Development and validation of model modifications for handling lack of data in time series

All tasks in this working package have been completed without any unforeseen challenges or delays. The assessment model now has options for handling completely missing observations, observations with known or unknown larger uncertainties (e.g. resulting from incomplete survey coverage) and changing selectivity (e.g. resulting from changes in consumer preferences or changes in behaviour if the fishing fleet).

4.1 Missing data

The survey of missing data sources was carried out informally by attending the working groups (sometimes full time, and sometimes in parts) and talking stock coordinators and chairs. This was necessary, because the data issues often only became apparent during the working groups, which was also when a solution was needed. It would naturally have been preferable to have known of any data issues months in advance, but the timeline between surveys and the working groups is such that much of the data is only combined a few weeks (or sometimes only a few days) in advance of each working groups. Further, data has been collected about the commercial sampling and separated into type of sampling and reason for the sampling being impacted and split into stocks (Fig. 4.1.1). This showed that solutions to use partial data, leading to assessment input that are more uncertain in some years, is even more needed that than solutions to allow completely missing observations. It also showed that impacted sampling is caused by many more factors than just covid, which only makes the solutions developed in this project more relevant.

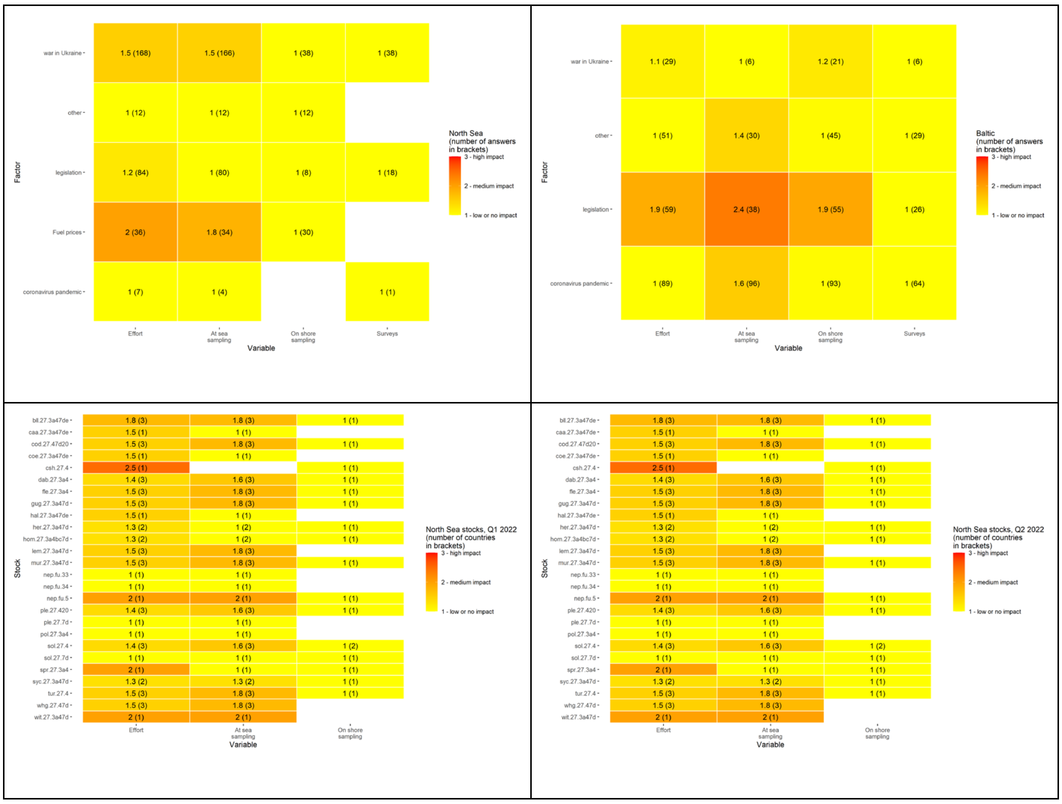

Figure 4.1.1: Survey about of impacts on different parts of the commercial sampling separated into reason for the sampling being impacted and split into stocks.

4.2 Implemented approaches

Many different model extensions were implemented to account for missing observations.

4.2.1 External estimates of increased uncertainties

The first situation to cover is if a missing data point causes partial missing (less certain) observations. This can happen because the raw observations (e.g. survey hauls) are not used directly in typical assessment models. Instead, the raw observations are modelled in a separate step, which calculates an index of stock size at the different ages. In normal/standard years the survey covers the stock area by the fishing at a specified number of stations, but in years with special challenges the survey may only be able to cover fewer stations. The separate pre-processing step may still be able to calculate a stock index (to be used by the assessment model), but the index will be more uncertain, as it is based on fewer actual data points.

It is important to account for such higher uncertainty in the stock assessment model. The higher uncertainty on an index should lead to a lower relative weighting of the affected data source in the assessment model. If we ignore the fact that a certain index has become less reliable, then the assessment model could provide a wrong estimate of stock size and stock status --- simply because it was trusting the wrong index.

The separate pre-processing step may provide estimates of uncertainty, but depending on the type of pre-processing the estimates of uncertainty may more or less detailed. At the most detailed level complete covariance matrices are available for each year (where the covariance is across age groups). At an intermediately detailed level variances, standard deviations, or CVs are available each year, but no information about correlation. At the lowest detail level only relative variance scales are available.

The assessment model has been extended to accommodate all different levels of such externally supplied uncertainty information. For each data source (e.g. a survey) it is possible to use the information simply by assigning is as an appropriator "attribute" (example below).

For instance can data on relative weight be included in SAM. This is done by assigning a weight attribute to the corresponding survey or catch data before it is passed to setup.sam.data(). The weight attribute "W" must have the same dimensions as the corresponding observation matrix, and provide the relative log-scale precision (1/variance) of each observation. The correlation structures can be estimated internally in SAM using the configuration "keyCorObs" simultaneously as external weights are utilized. The following example illustrates key lines where we include data on observation weight from a fleet:

```
#Attach the precision to the survey data
attributes(surveys$`surveyName`)$weight <- W
#Set up data, the external variances are now included
dat <- setup.sam.data(surveys=surveys,...)
```

No other part of the assessment model needs updating. The supplied weights are carried through all the analyzes, and if a for a year the weight is e.g. 1/10, then it corresponds to the model assigning 10 times less weight to the corresponding observation. In addition to plain weights, a matrix of variances, a list of covariance matrices, or a list of correlation matrices can be supplied. These quantities are supplied in a similar way.

The model extension has been documented, with detailed description and coding examples, along with the other configuration options at the site http://www.stockassessment.org but can also be found here: http://www.nielsensweb.org/configurations.html (near the bottom of the page).

4.2.2 Increased uncertainties, but no external estimates

A separate model stock assessment model extension has been implemented to cover the case where we have reason to believe that in some years (e.g. due to lower coverage) the produced indices of stock size (at age) is more uncertain than in standard years, but the data pre-processing gives no quantitative measure of how much the uncertainty has increased. In this case the assessment model can now be configured to estimate variance scaling parameters, which allows the model to treat those observations as less certain.

The new configuration is designed to be as flexible as possible, which unfortunately makes it a bit cumbersome to set up. For each observation, where a variance scaling should be estimated, a line must be specified stating the fleet number, the year, the age, and the parameter coupling. The parameter coupling allows the estimated variance scaling parameters to be shared across observations (by using the same index). The code example below shows such a configuration, where index of all ages (1-5) of the second fleet are believed to be more uncertain in the years 2021 and 2022. The variance scaling parameter is assumed top be the same across the ages, but allowed to be separate in each year.

```
$keyXtraSd
 # An integer matrix with 4 columns ( fleet year age coupling ),
 # which allows additional uncertainty to be
 # estimated for the specified observations
 2 2021 1 0
 2 2021 2 0
 2 2021 3 0
 2 2021 4 0
 2 2021 5 0
 2 2022 1 1
 2 2022 2 1
 2 2022 3 1
 2 2022 4 1
 2 2022 5 1
```

4.2.3 Flexible selection pattern

A related model feature, that deserves mentioning here, is the flexible selection pattern, which is a fairly unique feature in the stock assessment model SAM. This feature was not developed specifically to deal with covid-19 issues of missing data and changed fishing, but is very helpful here also. Most commonly applied assessment models will assume that the relative selection of the fishing of the different age groups is constant in time (or in blocks of time). This makes sense when thinking about the mechanics of the fishing gear in isolation, but the fishing fleet can target e.g. different areas and thereby change the selection towards younger or older fish. In the time of covid-19 many restaurants were closed and the demand for certain fish species/sizes changed. This could imply that the selectivity of the fleet changed and hence that the model should allow for that.

4.2.4 When observations are completely missing

In cases where observations are completely missing (e.g. catches-at-age for an entire year, a survey was not conducted for a year or two, or conducted in a way such that the expert group would not allow its use), then it is not possible to solve the problem by allocating or estimating more uncertainty. Consider the case where all information about catch is missing for all age classes for an entire year. Notice that it is the information about the catch that is missing, which is not the same as saying that zero catch was taken. The catch that was taken (quantity unknown to us) still would affect the stock.

The correct way to handle missing information, which may affect the estimates we are interested in (e.g. stock size and fishing pressure) and which may affect the expectation w.r.t. other observed quantities (e.g. surveys), is to account for all possible outcomes of the missing information. In a discrete case this corresponds to summing over all possibilities (weighted with their probabilities) and in the continuous case it similarly corresponds to integrating out all the unobserved quantities.

Integrating out multiple missing observations could potentially be a computational challenging task. However, consistent with the approach used to integrate latent processes in the assessment model itself the Laplace approximation can be used to approximate the required integral (Kristensen et al. 2015). This approach is now implemented to handle missing observations.

To make the approach to handle missing values most useful and user friendly it works in exactly the same way for all data types in the assessment model. Whenever an observation is missing the code for missing 'NA' (not assigned) is put in the data set where the observation should have been. This is all the user has to do. The assessment model will then --- internally --- replace the missing code with a latent variable and use the Laplace approximation to integrate it out. The added uncertainty originating from the missing observation(s) will automatically be propagated to all estimated quantities of interest (e.g. estimates of spawning stock biomass and fishing pressure). Further the added uncertainties will automatically propagate to all derived model validation measures e.g. Mohn’s rho (Brevik et al. 2023).

4.2.5 When biological observations are missing

A recent project concerned with obtaining better predictions in the forecast period of the biological parameters (maturity, mortality, stock weight, and catch weights) can be combined with --- and further utilize --- this way of integrating out missing observations. Prior to the biological parameter project the biological input were not considered to be observations (subject to observation noise), but merely as covariates assumed known. This was unrealistic and the biological parameter project shifted them to be observations which gave a lot of benefits (20% better predictions of SSB and more realistic propagation of uncertainties). This project further allows integrating out missing observations, which allows the added uncertainty from missing biological parameters to be realistically represented in the estimates of interest.

4.2.6 Further useful in model validation

An additional benefit of using the Laplace approximation to integrate out the missing observations is actually a side effect of the way the integration is performed. The Laplace approximation works by approximating the distribution with a normal distribution around the optimal point, which means that part of the algorithm is to find the optimal point. This optimal point can at the same time be used as a prediction of the missing observation. Having the ability to predict missing observations is the key to a number of useful model validation and model comparison techniques. One such technique is cross-validation, where models (or configurations within same model) are compared by leaving out observations and comparing how precisely they are predicted.

4.3 Validation of the implemented approaches

The approaches implemented are all rigorous common-sense statistical methods, but it is still important to validate them in settings mimicking the actual applications. The scale of variation, signal to noise ratio, and the amount of data available can affect how well these methods perform. Furthermore, the actual implementation (code written) could be flawed, so validation is important to strengthen confidence in its correctness. Hundreds of cases and simulations were constructed and verified, but here only a few examples will be demonstrated. As the basis for these comparisons, we pick the assessment of Northeast Arctic Saithe and then try to modify the observations in different ways to match the different problems that could occur.

4.3.1 Accounting for increased uncertainty

There are two main ways to account for increased uncertainty: 1) When a quantitative measure of the increased uncertainty is (assumed) known from external sources and 2) when it is believed that the data is less certain in some specific years, but it is not externally quantified.

To mimic the situation where observations are more uncertain in some years we took the original data set from the saithe assessment and simulated new observations with a ten times higher variance (ca. 3 times higher standard deviation). The observations were simulated on log-scale and for the last three years of the assessment (2018, 2019, and 2020) and in a three-year period in the middle (1990, 1991, and 1992).

If we use the unchanged model, which still assumes unchanged observation uncertainty in all years, it changes the estimates (e.g. of SSB and Fbar) in the years where the observations are more uncertain, but also in the neighboring years (Fig. 4.3.1). In this simulation the estimated SSB became much higher in the final years and Fbar became lower. This happens because the model wrongly assuming same variance in all years will follow the highly uncertain (unreliable) observations more than it should (Fig. 4.3.1).

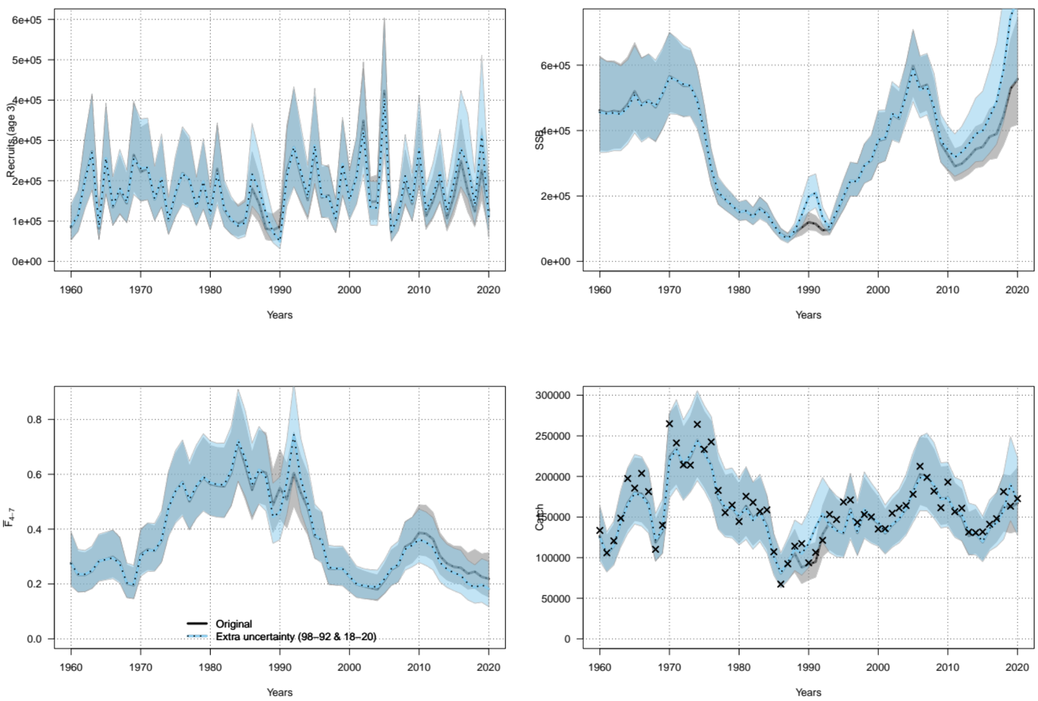

Figure 4.3.1: Original estimates based on the original data set (solid black line and gray confidence area). Estimates from same model, but with simulated uncertain observations in the years 1990-1992 and 2018-2020 (black/blue dashed line and blue confidence area).

If quantitative estimates of the observation variances are available (from the pre-processing step), then the extension to the model allows us to use those estimates. If we use the same data as above (and as in Fig. 4.3.1) and use the correct variance weighting of setting the relative weight of the simulated uncertain observations to 1/10, then the model is able to recover the true estimates much more closely (Fig. 4.3.2). The estimates are still more uncertain, which is to be expected, but the estimates are not dragged in some random direction (Fig. 4.3.2). This is because the model has now been informed that those observations are more uncertain.

When the quantitative estimates of the observation variances are unavailable, but it is still believed that the uncertainty in certain years are greater than in standard years, then the model is now able to estimate additional variances. If we use the same data as above (and as in Fig. 4.3.1) and let the model estimate the additional variance (one per fleet) in the specified years, then the model is able to recover the true estimates as closely as when the known variance scaling was given (Fig. 4.3.3 and 4.3.2). The estimates are still more uncertain, which is to be expected, but the estimates are not dragged in some random direction. The model is able to estimate the additional variance.

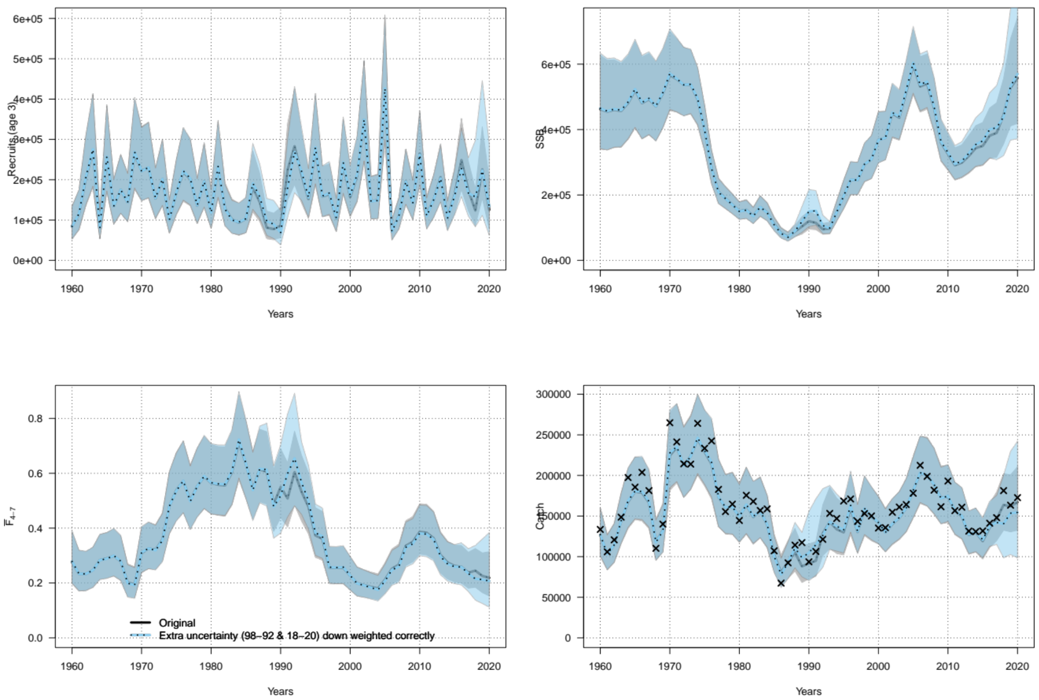

Figure 4.3.2: Original estimates based on the original data set (solid black line and gray confidence area). Estimates from model with simulated uncertain observations in the years 1990-1992 and 2018-2020, and where the correct variance weighting is assumed known from external sources (black/blue dashed line and blue confidence area).

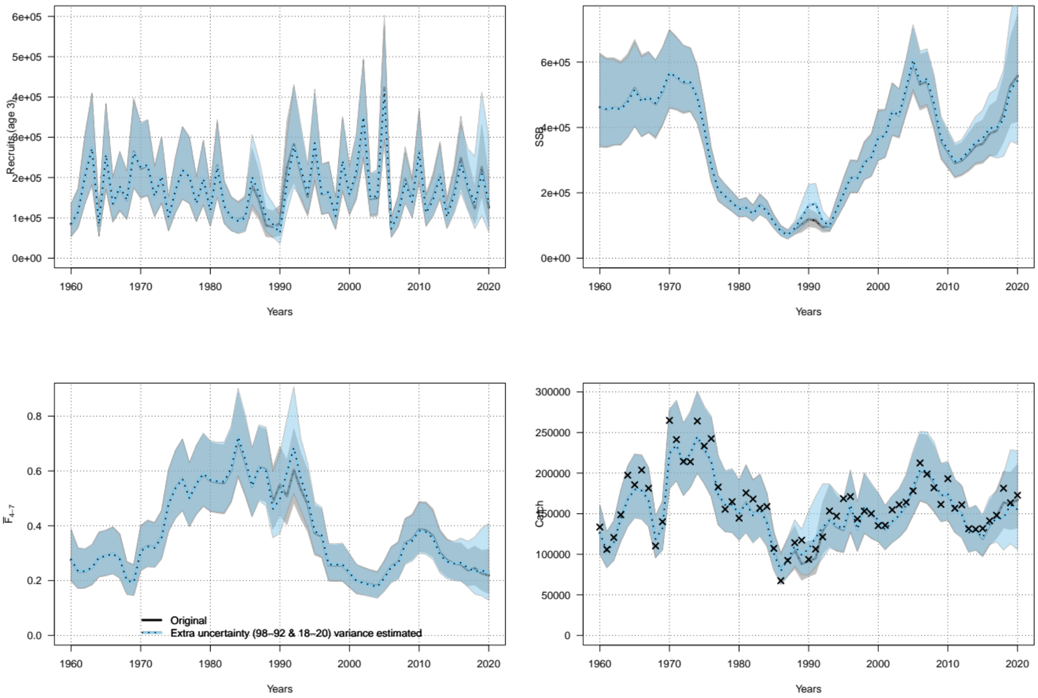

Figure 4.3.3: Original estimates based on the original data set (solid black line and gray confidence area). Estimates from model with simulated uncertain observations in the years 1990-1992 and 2018-2020, and where the increased variance weighting is not known, but estimated within the model (black/blue dashed line and blue confidence area).

4.3.2 Flexible selection pattern

Validating that the model is actually able to follow changing selection pattern, is done in a bit of an indirect way. A scenario is constructed where two fleets are fishing on the stock. The selection pattern is relatively constant within each fleet, but the overall selection pattern is changing dramatically. The overall selection pattern is changing because the two fleets have the opposite selection pattern and because the catches are shifting from being dominated by one fleet in the beginning of the time period to being dominated by the other fleet at the end of the time period (Fig. 4.3.4). The overall selection pattern was estimated in two ways via a multi-fleet taking this specific scenario into account and via the standard single fleet model. The results showed that the single fleet model was able to recover the changing selection pattern and hence validated the flexible selection pattern implemented in the model. More details about the multi-fleet model and this validation can be found in (Nielsen et al. 2021).

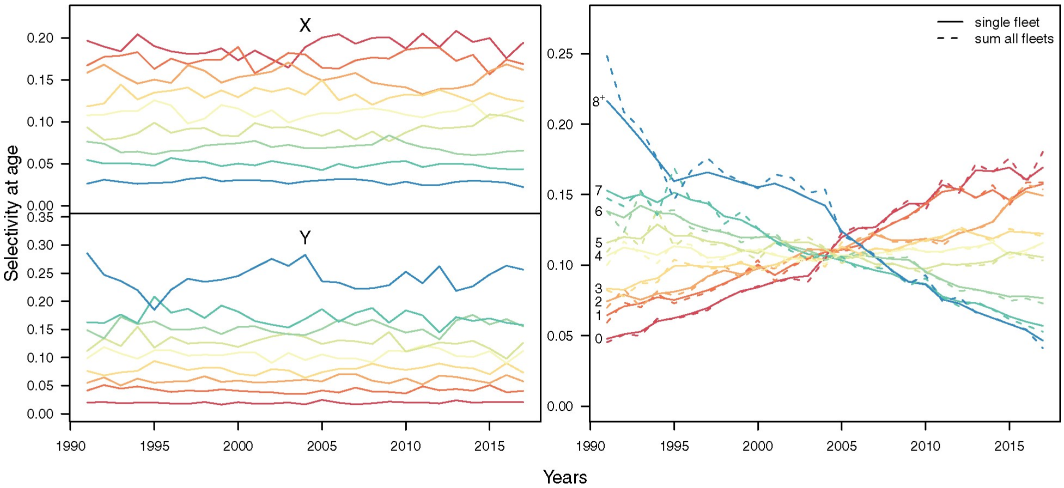

Figure 4.3.4: Compared estimates of selectivity from a single- and multi-fleet model in a simulated scenario where two fleets (X and Y) have very different, but fairly time-invariant selectivity, but the overall selectivity changes due to a change in the relative catch from the two fleets.

4.3.3 When observations are completely missing

Real assessments were used to validate the implemented solution for completely missing observations (Northeast Arctic Saithe shown here). Observations were left out by replacing them with "NA"s (code for not assigned), and the assessment results were compared to the results when all observations were included. Completely leaving out some observations will --- and should logically --- lead to larger uncertainties on the estimated quantities of importance. The validation is to see if the estimates are still realistic (given the reduced information) and if the estimates from using all data are within the confidence intervals produced with missing observations. Removing all observations from years 1990-1992 and 2018-2020 from the assessment of Northeast Arctic Saithe resulted in an assessment that was working and gave the same overall trends as the assessment using all data (Fig. 4.3.5). The reduced data resulted in lower estimates of SSB and higher estimates of average F the last years, but still within the confidence intervals of the assessment using the full data set. The reduced data resulted in the wider confidence intervals which covered the estimates from the model using all observations.

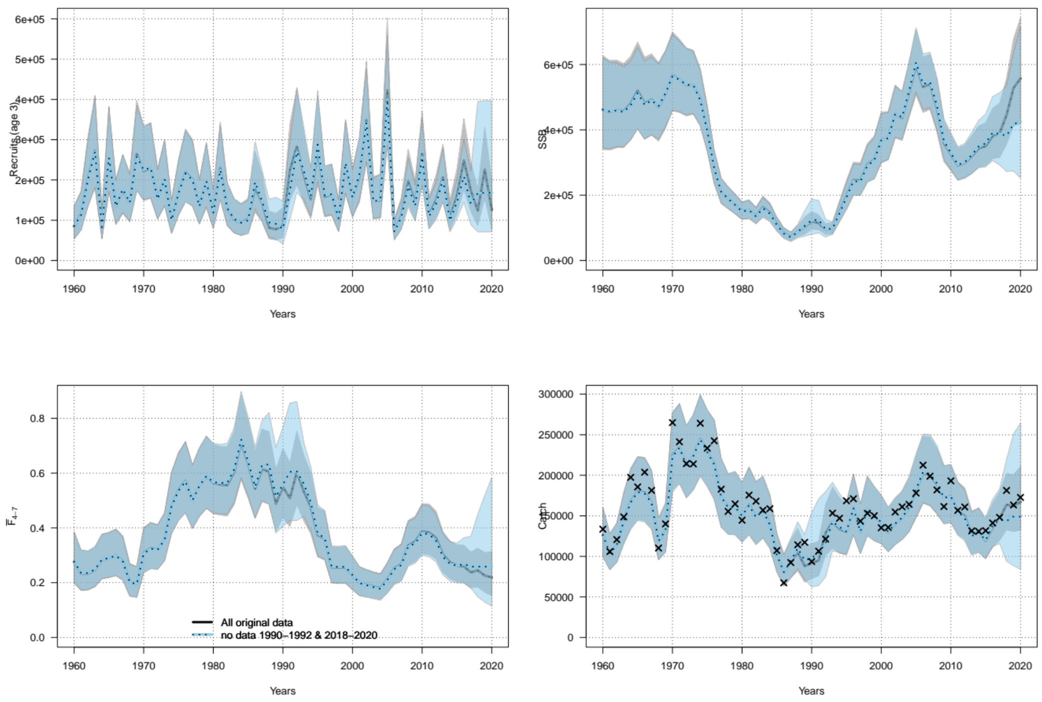

Figure 4.3.5: Original estimates based on the full data set (solid black line and gray confidence area). Estimates from model where all observations were omitted in years 1990-1992 and 2018-2020 (black/blue dashed line and blue confidence area).

4.4 References

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5. Achieving model consistency when estimating reference points

5.1 Background

Reference points are central to catch advice in fisheries management. Within the common fisheries policy, management aims to exploit marine living resources at the level that maximises equilibrium yield, FMSY. This reference point is determined by the population dynamics of the exploited stock, which must be estimated from available data sources. Therefore, it can only be known with uncertainty.

Within the ICES framework, assessment model estimates are used to derive reference points, such as FMSY, through post hoc methods. For data rich stocks, the spawning stock biomass (SSB) and recruitment estimates from the assessment model are used to provide the basis of the stock recruitment relationship that is then used in stock projections to estimate maximum sustainable yield (MSY) reference points. Uncertainty in the stock-recruitment relationship is simulated through resampling on the SSB and recruitment estimates. This first step ignores therefore the uncertainty in the SSB and recruitment estimates themselves and assumes that the SSB estimates are known without error. This uncertainty will depend on the available data and will increase for years with reduced sampling efforts as was seen during the pandemic. Thereafter, the stock is projected to the equilibrium using the resulting stock-recruitment relationship and MSY reference points are derived. This second step therefore ignores the variability in biological processes that were estimated within the assessment model and could have been projected forward. Further, a different stock-recruitment relationship is often used in the assessment model and the reference point estimation. This two-steps-method inherently ignores assessment model errors, and little is currently known on how this could affect reference point estimates and subsequent advice.

Current fisheries advice commonly uses harvest control rules in multiannual plans to inform managers about fishing opportunities on fish stocks, and these harvest control rules are shaped given reference point values. While multiannual plans are invaluable for sustainable management, the negative consequences of ignoring reference point uncertainty may accumulate for each year in the multiannual plan. Using an over-estimated reference point in a harvest control rule can lead to over-exploitation of the stock. Therefore, using such a reference point estimate, without accounting for the uncertainty, in, for instance, a rebuilding plan may make it impossible to rebuild the stock to a sustainable level. On the other hand, using an under-estimated reference point can lead to under-exploiting the stock with great economic and social consequences.

The work package included four milestones:

1. Implement reference point estimation in the SAM model
2. Quantify potential bias from post hoc estimation of reference points
3. Quantify the influence of uncertainty in reference point estimates on harvest control rules for precautionary management

4. Make the reference point implementation available to stock assessors for use in benchmarks via the stock assessment package and the transparent online portal stockassessment.org

The results are described below.

5.2 Implementation of reference points in the SAM model

Reference points can be derived from the population dynamics estimated within the SAM model. However, reference points are typically the result of an optimization (e.g., maximizing yield), which is technically a challenge for the estimation framework of the SAM model. At the start of the project, the estimation framework, TMB, did not allow optimizations with dynamic stopping criteria. Therefore, the initial implementation of reference point estimation in the SAM model used the theoretical framework described in Albertsen and Trijoulet (2020). In this framework, the optimization criterion is added to the likelihood function. In turn, the reference point can be estimated, and uncertainty can be calculated through a combination of the implicit function theorem and the delta method.

As part of this project, TMB was extended to include a newton optimizer with adaptive convergence criterion. Therefore, the reference point estimation in the SAM model could be fully implemented within the model code. Both reference points and stock-recruitment functions are implemented as specializations of abstract classes to provide a general framework for easily implementing additional options. In the current SAM model, 30 recruitment functions were implemented. The functions include both compensatory and depensatory relations and covers functional, time-series, and semi-parametric functions. Furthermore, nine types of reference points were implemented. Several of the reference points allow user determined configurations.

Name	*Type*	*Parameters*
ICES forecast type	Independent of SSB	0
No recruitment	Independent of SSB	0
Log-scale random walk	Independent of SSB	0
Ricker	Compensatory	2
Beverton-Holt	Compensatory	2
Periodical constant mean	Independent of SSB	Determined by configuration
Logistic hockey stick	Compensatory	3
Hockey stick	Compensatory	2
Log-scale AR(1)	Independent of SSB	2
Smooth hockey stick	Compensatory	3
Power function (power < 1)	Compensatory	2
Power function (power > 1)	Depensatory	2
Shepherd	Compensatory	3
Hassel/Deriso	Compensatory	3
Saila-Lorda	Compensatory/Depensatory	3
Sigmoidal Beverton-Holt	Compensatory/Depensatory	3
CMP Spline	Compensatory	Determined by configuration

Smooth spline	Compensatory/Depensatory	Determined by configuration
Unrestricted spline	Compensatory/Depensatory	Determined by configuration
Convex-compensatory spline	Compensatory	Determined by configuration
Type B depensatory Ricker	Depensatory	3
Type B depensatory Beverton-Holt	Depensatory	3
Type B depensatory hockey stick	Depensatory	3
Type B depensatory smooth hockey stick	Depensatory	4
Type B depensatory power function (power < 1)	Depensatory	3
Type B depensatory Shepherd	Depensatory	4
Type B depensatory Hassel/Deriso	Depensatory	4
Type B depensatory CMP spline	Depensatory	Determined by configuration
Type B depensatory convex-compensatory spline	Depensatory	Determined by configuration
Type C depensatory Ricker	Depensatory	4
Type C depensatory Beverton-Holt	Depensatory	4
Type C depensatory CMP spline	Depensatory	Determined by configuration
Type C depensatory convex-compensatory spline	Depensatory	Determined by configuration

Reference point	*Description*
MSY	F that maximizes equilibrium yield
MSY range	F that gives x% of maximum equilibrium yield
Max	F that maximizes yield per recruit
Fraction dYPR	F such that the derivative of the yield per recruit curve is a user determined fraction of the derivative for F = 0
Fraction SPR	F such that the number of spawners per recruit is a user determined fraction of the number of spawners per recruit for F = 0
Fraction B0	F such that the equilibrium biomass is a user determined fraction of the equilibrium biomass for F = 0
Crash	F such that the slope of the replacement line is equal to the slope of the recruitment function when SSB goes to 0.
Ext	F such that equilibrium biomass is 1
Lim	F such that equilibrium biomass is the breakpoint of the stock-recruitment relationship (only applicable to hockey stick models)

The user interface is a single function called ‘deterministicReferencepoints’, available in the ‘stockassessment’ R package. The function is called with a fitted assessment model object. Further, the reference points to be calculated are requested with the ‘referencepoints’ argument. For example, if ‘fit’ is a fitted assessment of Greenland offshore cod assuming a Ricker stock-recruitment relationship (see the figure below), MSY, 95% MSY range, and 20% of B_0 reference points are requested with

```
refpt <- deterministicReferencepoints(fit,
           referencepoints = c("MSY","0.95MSYRange", "0.2B0"))
```

When printing the result, a table with estimated fishing mortality rates, equilibrium biomass, and equilibrium yield corresponding to the reference points are returned:

```
> refpt

Fishing mortality rate Estimate    Low   High
  MSY                    1.0795 0.3948 2.9518
  0.95MSYRange (Lower)   0.6398 0.2544 1.6090
  0.95MSYRange (Upper)   1.7261 0.5322 5.5990
  0.2B0                  1.7968 0.6767 4.7708

Equilibrium Biomass       Estimate        Low       High
  MSY                    7014.6055  4418.1468 11136.9525
  0.95MSYRange (Lower)  9634.8308  6036.6871 15377.6339
  0.95MSYRange (Upper)  4963.7180  3150.0478  7821.6262
  0.2B0                  4805.9507  3282.2214  7037.0520

Equilibrium Yield         Estimate        Low       High
  MSY                    6843.4961  3899.9587 12008.7011
  0.95MSYRange (Lower)  6501.3212  3704.9607 11408.2659
  0.95MSYRange (Upper)  6501.3213  3704.9608 11408.2660
  0.2B0                  6439.7774  3539.2733 11717.3016
```

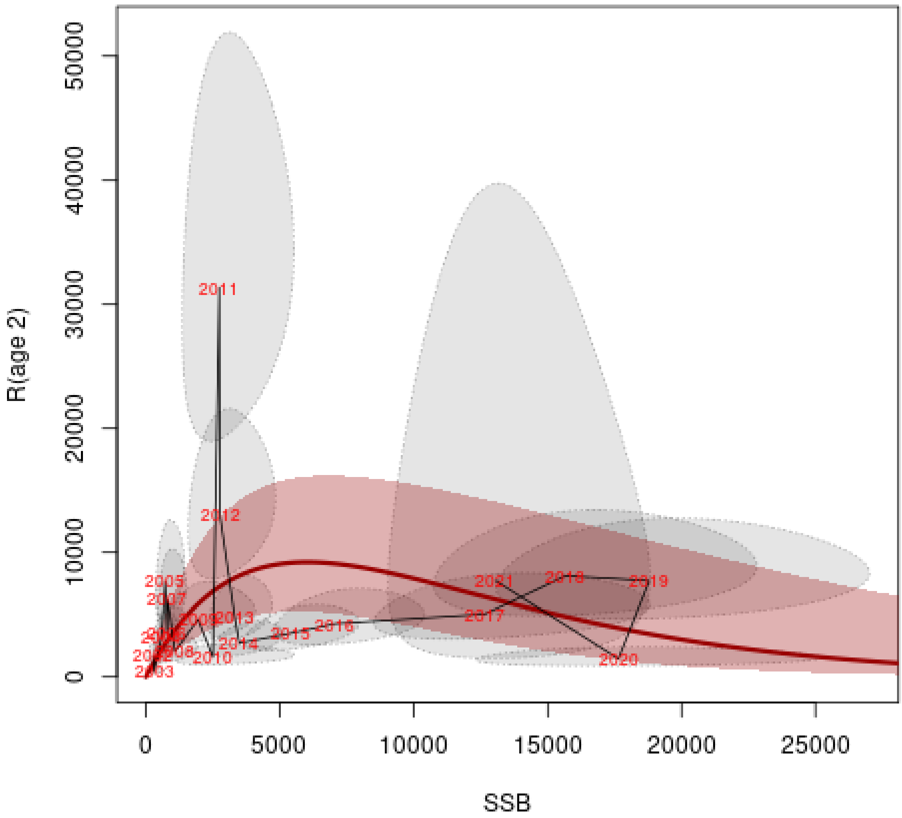
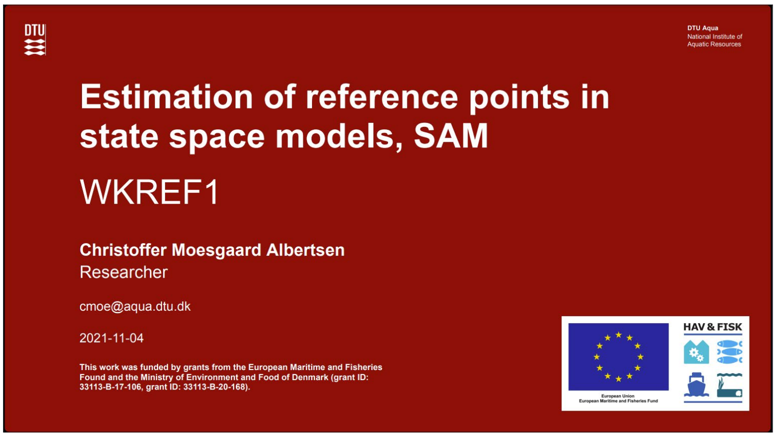


Figure 5.2.1: Estimated recruitments (p5% with uncertainty areas) and the estimated stock-recruitment relationship (red).

The novel framework for reference point estimation ensures transparency and consistency in assumptions between the assessment and subsequent reference points. This is essential to ensure an optimal management of marine living resources. The implementation was presented at the ICES workshop “Workshop on ICES reference points (WKREF1)” in November 2021.



5.3 Quantifying potential bias from post hoc estimation of reference points

The MSY reference points internal estimation implemented in the first milestone was compared to the post hoc method the most used in ICES (EqSim model), for 11 stocks, via a simulation study where the true reference points are known. This work has been published in Trijoulet et al. (2022) and the main conclusions are detailed below.

The study compared bias and variance in estimated reference points for 3 methods: SAM internal estimation (PR method), EqSim using the SAM fit with stock-recruitment relationship (EqS method), EqSim using a SAM fit assuming random walk in recruitment (EqSrw method). The MSY reference points are estimated when both the stock-recruitment relationship is known and unknown. Stock-recruitment model selection and coverage probability were also considered as diagnostics. The Figure below summarises the methods used in the study.

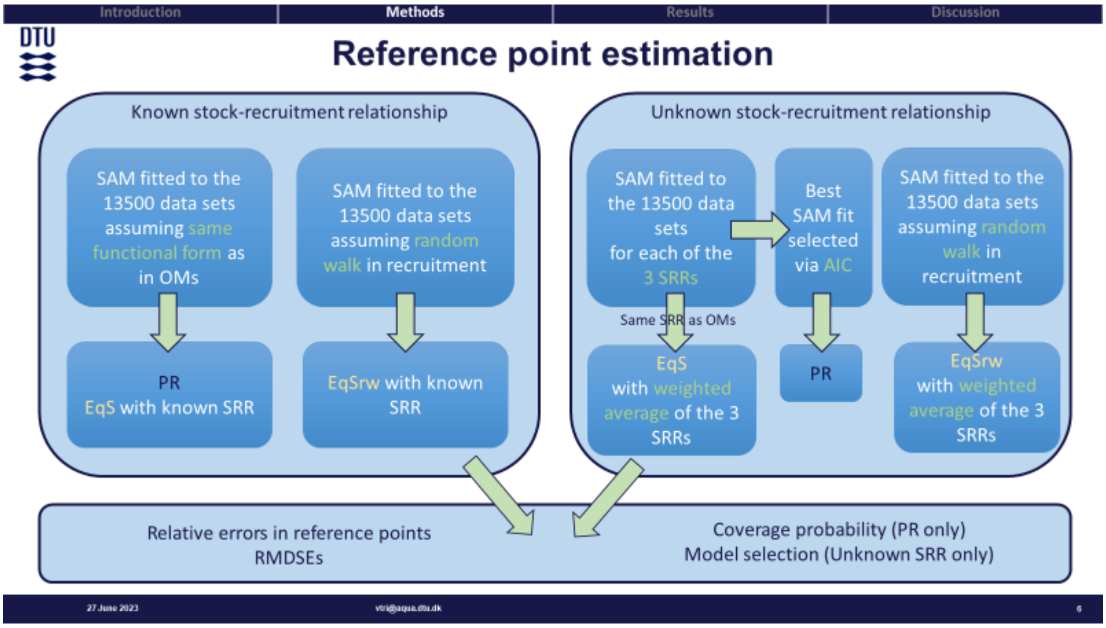


Figure 5.3.1: Summary of the methods used in the study.

The study shows that, overall, the internal estimation of reference points does better than EqSim in estimating the true reference points, in terms of both bias and variance. For instance, the Table below shows that the bias (estimated as the absolute median relative error) is lowest for the PR method, then EqS, then EqSrw, no matter the knowledge of the stock-recruitment relationship and the reference point considered.

Table 5.3.1: Mean across stocks of absolute median relative errors in MSY reference points.

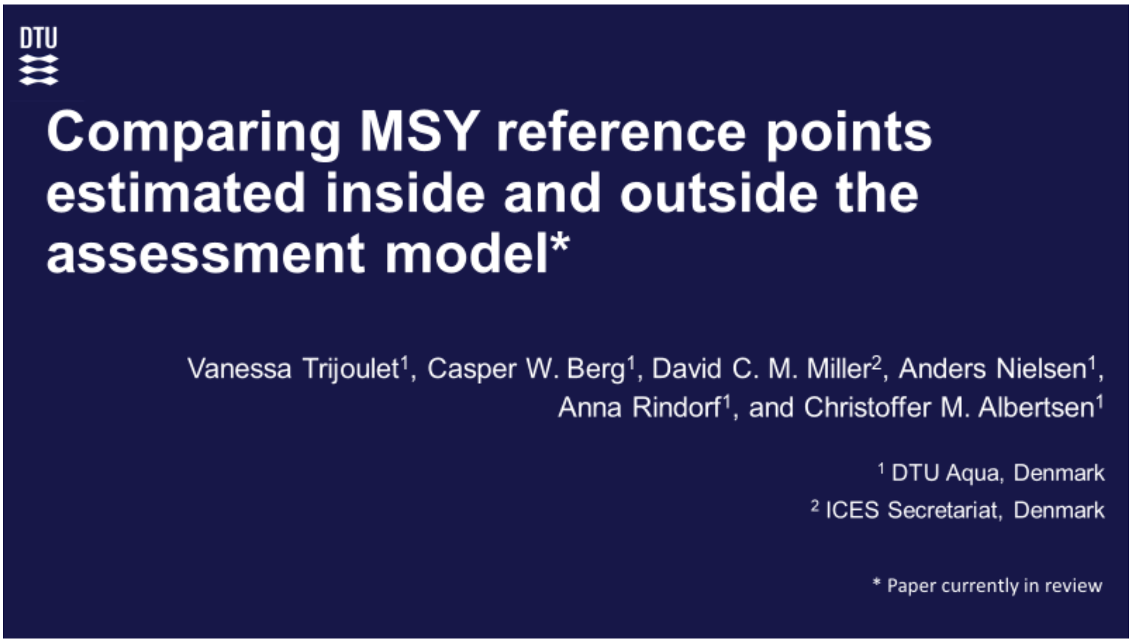
		PR			EqS			EqSrw		
SRR assumption	SRR	F_{MSY}	B_{MSY}	MSY	F_{MSY}	B_{MSY}	MSY	F_{MSY}	B_{MSY}	MSY
Known	Ricker	0.09	0.14	0.14	0.06	0.14	0.16	0.2	0.18	0.16
	Beverton-Holt	0.08	0.2	0.13	0.16	0.25	0.14	0.17	0.24	0.13
	Smooth hockey-stick	0.05	0.04	0.01	0.15	0.14	0.04	0.11	0.18	0.05
	Mean all SRR	0.07	0.13	0.09	0.12	0.18	0.11	0.16	0.2	0.11
Unknown	Ricker	0.12	0.18	0.12	0.08	0.16	0.16	0.14	0.15	0.17
	Beverton-Holt	0.12	0.25	0.14	0.2	0.32	0.18	0.28	0.36	0.19
	Smooth hockey-stick	0.07	0.08	0.03	0.16	0.16	0.03	0.17	0.19	0.05
	Mean all SRR	0.1	0.17	0.1	0.15	0.21	0.12	0.2	0.23	0.14

Stock-recruitment model selection varies across stocks and stock-recruitment relationship but is overall best for the PR method. Using a weighted average of stock-recruitment relationships in EqSim helps reducing the bias when the stock-recruitment relationship is wrongly selected.

The internal estimation of reference points in SAM allows to obtain confidence intervals around the MSY reference points, contrarily to EqSim, and coverage probability, i.e., the true reference point is within the confidence interval of the estimated reference point, is good.

The study also shows that the extra arguments in EqSim that allow for consideration of uncertainty in inputs via re-sampling can create bias in the MSY reference points.

This study was presented at the Workshop on ICES reference points (WKREF1) in November 2021 (see first and last slides below).



5.4 Quantifying the influence of uncertainty in reference point estimates on harvest control rules

Harvest control rules are a central component of fisheries management. While the common fisheries policy requires fishing at F_{MSY}, it is recognized that the fishing pressure should be reduced for stocks at low biomass. Within the ICES framework, fishing pressure is advised to correspond to F_{MSY} when biomass is no less than the 5% quantile of the distribution of equilibrium SSB when fishing at F_{MSY} (MSY $B_{trigger}$). Below this level, fishing pressure is reduced linearly to zero. If SSB gets below B_{lim}, fishing is advised to stop unless B_{lim} can be reached within a short time frame.

To allow users to forecast with the ICES advice rule, or other harvest control rules, a general six parameter harvest control function was implemented. The variety of shapes available are show in the figure below. To use the harvest control rule in a forecast, the user must specify the target F (FMSY in the ICES framework) and the SSB that triggers the control rule (MSY $B_{trigger}$ in the ICES framework). Further, the user can specify an SSB where the control rule is capped, such that the output F is constant below that value. Finally, the user can specify a different point of origin which F is reduced to below the trigger value.

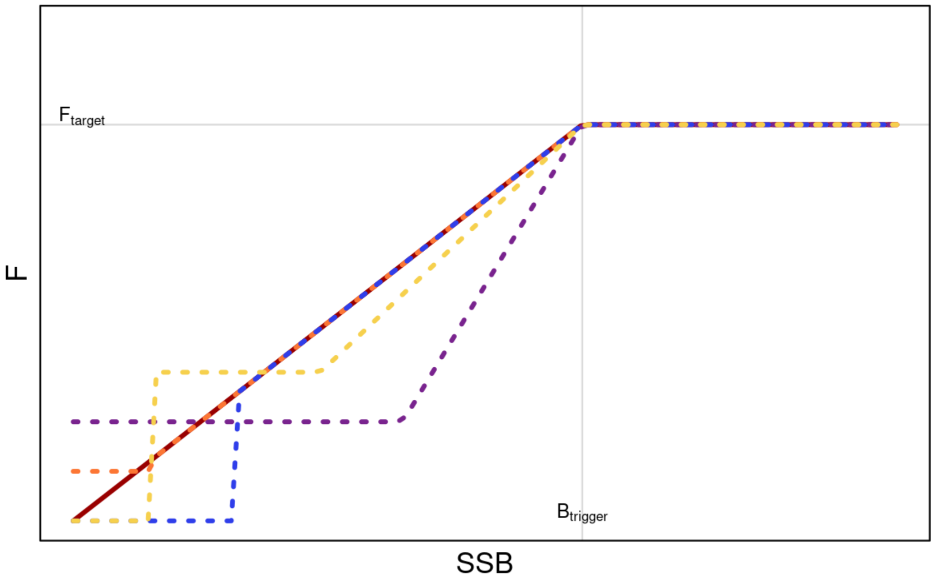


Figure 5.4.1: Harvest control rules

5.4.1 Case study

To evaluate the influence of reference point estimation uncertainty on fisheries management, a simulation study was conducted. Using Greenland offshore cod as a model stock, a short-cut management strategy evaluation (MSE) was implemented. In the MSE, different strategies for mitigating uncertainty were evaluated and compared to using estimated F_{MSY} directly.

5.4.2 Method

To inform the operating model, Greenland offshore cod was used as a case study for the MSE. Parameters for the operating model were obtained by estimating a SAM model with Ricker recruitment to the data (available from stockassessment.org with stock name WKGREENCOD_GRO). In turn, the operating model as used to simulate historical data.

Based on the historical data, the estimation model was fitted to the simulated historical data and reference points were estimated. This step ensured that estimation uncertainty was reflected in the reference points used in the harvest control rule. The estimation model had the same configuration as the operating model.

Starting from the last year of the assessment, a harvest control rule was used to set the future catch opportunities in a short-cut MSE. For each year in the MSE, the control rule set F for the next year based on SSB in the present year. In turn, the operating model is used to simulate an additional year of abundance and fishing pressure. With a short-cut MSE, additional data is not simulated as the estimation is not refitted within the loop. After 50 simulated years, results were collected and compared between scenarios.

In the short-cut MSE, five mitigation options were considered. First, the target F was set to the estimated F_{MSY}. In the four other cases, the target F was set to the 10, 20, 30, and 40% quantiles of the asymptotic normal estimator of F_{MSY}, respectively. Thereby, larger uncertainty in the estimated F_{MSY} lead to lower target F. Note that the base case corresponds to the 50% quantile. The approach was similar to the one proposed by Mildenberger et al. (2021) for surplus production models. Further, a base case was included where the advice was set to F_{MSY} without using a harvest control rule. Finally, the results were compared to a management strategy constantly fishing at the "true" F_{MSY}, which is known from the operating model. In all cases, the biomass trigger for harvest control rules was set to the estimated B_{MSY}.

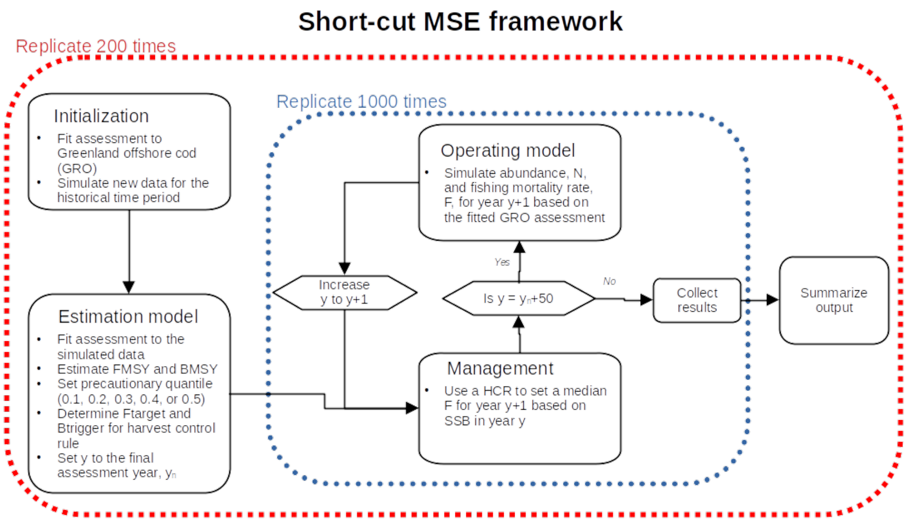


Figure 5.4.2: Short-cut MSE diagram.

5.4.3 Results

A total of 200 simulated data series were constructed. For each of the simulated historical data sets, 1000 trajectories were simulated 50 years forward for each management strategy, and median yield, SSB, and F were calculated for the final year. The final year was assumed to represent the equilibrium. Further, the risk of being below 20% of B_0 was calculated in the final year. The distributions for the 89 simulations are plotted below. Each point represents a simulation, and the full lines show a convex hull around the points.

Table 5.4.1: Risk, yiels and spawning stock biomass summaries

	Risk			***Yield***			***Spawning stock biomass***		
	Average	**Min.**	**Max.**	**Average**	**Min.**	**Max.**	**Average**	**Min.**	**Max.**
FMSY	0.298	0.218	0.418	7506.5	6882.6	8129.6	8290.0	5995.0	10925.7
Q50	0.221	0.162	0.320	7644.8	6943.5	8616.4	9865.0	7891.2	12384.4
Q40	0.206	0.154	0.280	7605.8	6744.6	8457.8	10488.0	8428.3	12844.5
Q30	0.189	0.128	0.267	7597.1	6721.8	8376.9	11227.0	8838.3	14932.8
Q20	0.174	0.117	0.244	7545.0	6640.6	8308.8	12171.6	9525.0	15468.0
Q10	0.158	0.119	0.192	7439.2	6539.1	8354.4	13614.2	11212.1	17064.2
True FMSY	0.278			7615.2			8552.1		
True FMSY w HCR	0.219			7745.9			10042.7		

When perfect knowledge of the system was available, which can only be the case in a simulation study, the risk of getting below 20% of B_0 in the final year was 27.8% when fishing at a constant rate of F_{MSY}. The risk was reduced to 21.9% by using the harvest control rule. Median yield in the final year was slightly higher, 7746t compared to 7615t when using the harvest control rule. Further, median SSB was substantially higher in the final year, 10043t compared to 8552t.

In the scenarios without perfect knowledge of the system, population dynamics were inferred from data and reference points were estimated. In turn, this perceived knowledge of the system was used for management. In the management using a constant fishing rate at an estimated FMSY, the risk of being below 20% of B0 in the final year was increased to an average of 30%, ranging from 22% to 42% in the individual trajectories. On average, yield was only reduced by 3% compared to the perfect knowledge scenario with harvest control rule. However, in individual trajectories, yield ranged from a reduction of 11% to an increase of 5%.

In the mitigation scenarios, risk was reduced in all four cases. In the case where target F was set to the 10% quantile of the F_{MSY} estimator, the average risk was reduced to 15.8%, ranging from 11.9% to 19.2% in individual trajectories. Consequently, SSB was increased in all trajectories compared to the perfect knowledge scenario. However, the average yield was only reduced by 4%. In individual trajectories, yield ranged from a reduction of 16% to an increase of 8%.

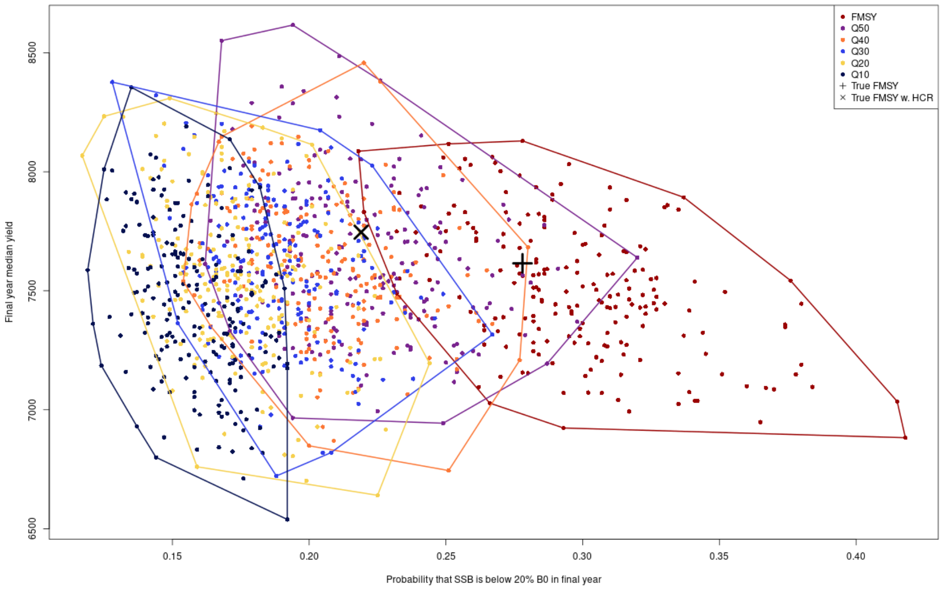


Figure 5.4.3: Simulated distribution of final year's yield and probability of SSB below 20% for the six scenarios.

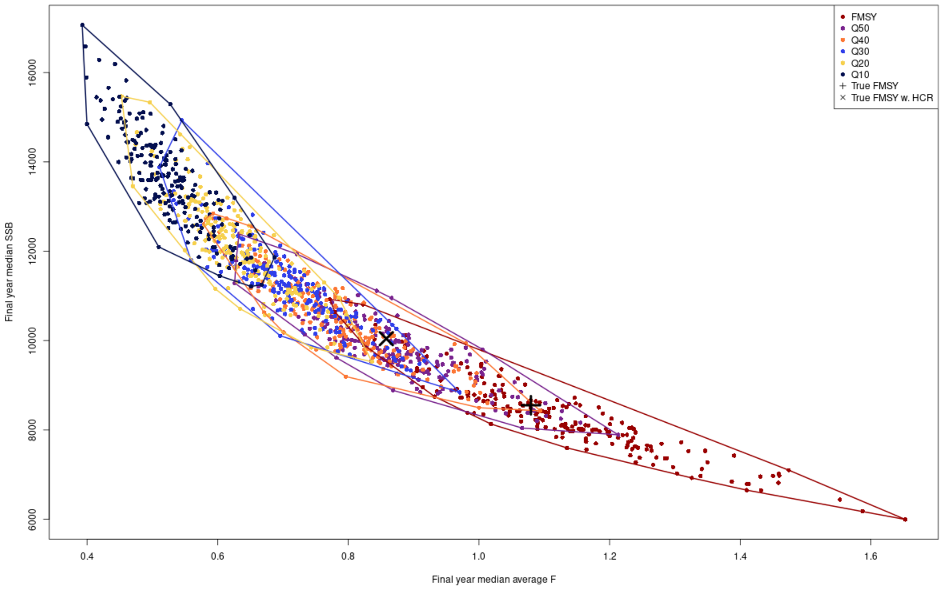


Figure 5.4.4: Simulated distribution of final year's median Fbar and median SSB for the six scenatios.

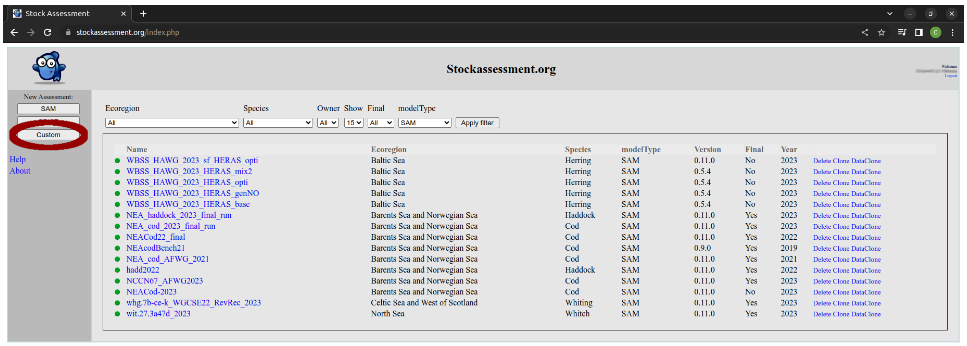
5.4.4 Conclusion

Within the ICES framework, the FMSY reference point is central to advice on fishing opportunities and subsequent management of marine living resources. However, reference points are estimated from data with an inherent stochasticity. Therefore, they can only be known with uncertainty. In the ICES framework, this uncertainty is not accounted for.

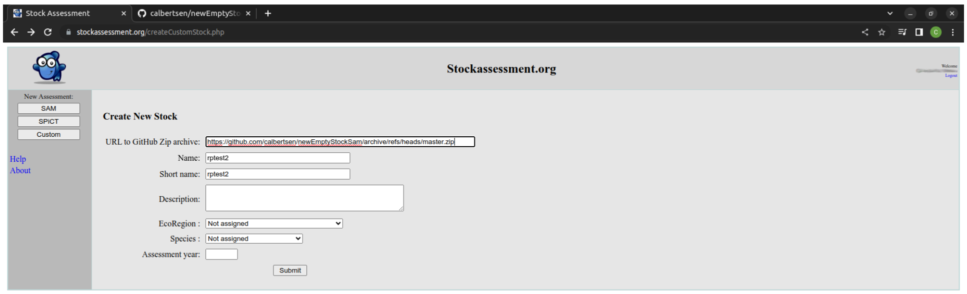
Using a short-cut MSE, with Greenland offshore cod as a model stock, we showed that this uncertainty directly influences the risk of over-exploitation. In the least precautionary management strategy, the average risk of bringing the stock below 20% of B0 was 30%. However, using mitigation strategies, reducing the target F based on the uncertainty of the estimated FMSY, the risk could be substantially reduced with a limited impact on yield. With the most precautionary management strategy, the risk was almost halved to 16%, while average yield was only reduced by 0.9% compared to the least precautionary strategy.

5.5 Making the implementations available on stockassessment.org

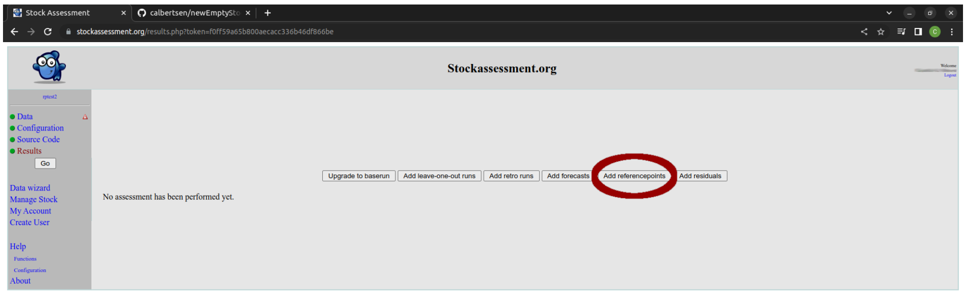
To maximize the applicability of the novel reference point estimation framework, templates have been created to be used from the assessment portal stockassessment.org. To utilize the estimation framework from the web interface, the user must simply add a “Custom” assessment from the menu to the left.



In the “Create New Stock” dialog appearing, the user inputs the link to the template (https://github.com/calbertsen/newEmptyStockSam/archive/refs/heads/master.zip) and fills out the remaining form. When the stock is created, a recent version of the ‘stockassessment’ package should be requested in the configuration to ensure full compatibility.



The template adds an “Add reference points” button to the results site. When pushed, reference points are calculated, and figures and tables are added to the results.



Figures and tables are customizable from the Source Code panel. Below, an estimated yield per recruit curve and a reference point table with equilibrium biomass are shown for illustration.

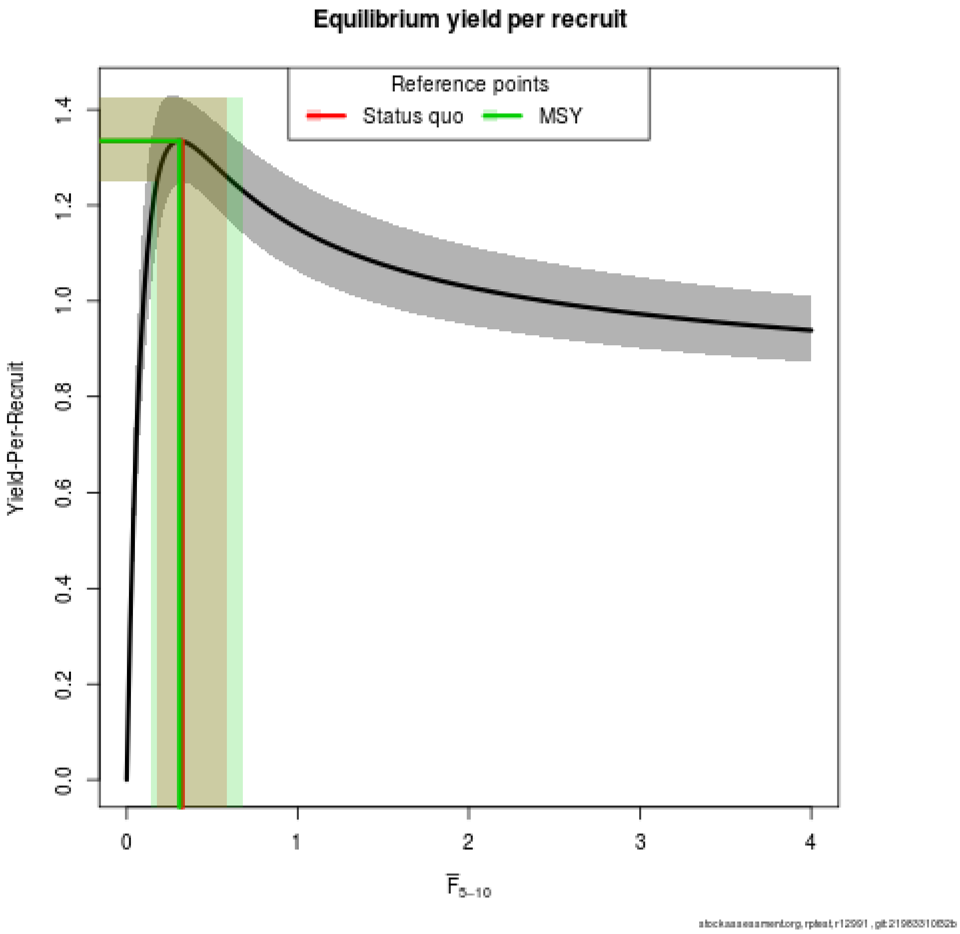


Figure 5.5.1: Example yield-per-recruit plot from stockassessment.org

Table 5.5.1: Example table of reference points from stockassessment.org

Reference point table 4. Biomass.

Reference point	Estimate	Low	High
Status quo	1526110.570	676387.490	3443312.458
Zero catch	12109322.463	10203633.690	14370928.530
MSY	1643806.153	562420.477	4804410.182
Max	1643553.592	562341.840	4803605.595
0.1	3328634.968	1446398.566	7660274.985
Crash			
Ext			
35%	4236618.029	2066343.062	8686327.383
lim			

5.6 References

Albertsen, C. M. and Trijoulet, V. (2020) Model-based estimates of reference points in an age-based state-space stock assessment model. Fisheries Research, 230, 105618. doi: 10.1016/j.fishres.2020.105618

Mildenberger, T. K., Berg, C. W., Kokkalis, A., Hordyk, A. R., Wetzel, C., Jacobsen, N. S., Punt, A. E., & Nielsen, J. R. (2022). Implementing the precautionary approach into fisheries management: Biomass reference points and uncertainty buffers. *Fish and Fisheries*, 23, 73– 92. https://doi.org/10.1111/faf.12599

Trijoulet, V., Berg, C.W., Miller, D.C.M., Nielsen, A., Rindorf, A. and Albertsen, C.M. (2022) Turning reference points inside out: comparing MSY reference points estimated inside and outside the assessment model. ICES Journal of Marine Science, Volume 79, Issue 4, May 2022, 1232–1244. doi: 10.1093/icesjms/fsac047

6. Model Implementation and statistical support at ICES Expert Groups, Benchmarks and IBPs

6.1 Goals

This work package was planned to ensure statistical support for the ICES working groups in dealing with the unusual data situations caused by the covid-19 pandemic and issues related to reference point uncertainty in general.

Three main cases were included WKNSCS (North Sea and Celtic Sea stocks) Benchmark 2022, WKBCOD (Benchmark Workshop for Northern Shelf cod stocks) in 2023, and the Benchmark on Sandeel (Ammodytes spp.) in 2022 (WKSandeel).

6.2 BREFdata support for the WKNSCS (North Sea and Celtic Sea stocks) Benchmark Workshop in 2022-23

The participation in this benchmark workshop provided an excellent opportunity to showcase the SAM model developed for handling missing data.

Short summary

The WKNSCS (North Sea and Celtic Sea stocks) Benchmark Workshop in 2022-23 aimed to evaluate data and models for fish stocks in the North Sea and Celtic Sea regions and explore models capable of handling missing data. The workshop report discusses various modelling approaches and emphasizes the importance of standardized data reporting and adaptive management strategies. The SAM model was successfully applied to assess North Sea Haddock, North Sea Plaice, and Celtic Sea Plaice stocks, providing reliable estimates and predictions. However, the SAM model was not used for Herring stocks North and West of Scotland and Ireland, likely due to limitations in data on population structure and thus uncertainties associated with stock dynamics. Future research on the genetic structure of these stocks will help develop more appropriate assessment methods.

Introduction

The WKNSCS (North Sea and Celtic Sea stocks) Benchmark Workshop, held in 2022, aimed to assess fish stocks in the North Sea and Celtic Sea regions and provide recommendations for their sustainable management. One key aspect of the workshop was the evaluation of fish stock assessment models capable of handling missing data, which is crucial for obtaining reliable estimates and predictions, especially in situations such as the covid-19 outbreak. The workshop report, published as ICES Scientific Reports (volume 4, issue 85), offers valuable insights into the use of these models and provides recommendations for improved data collection and management practices.

Handling Missing Data in Fish Stock Assessments

The workshop participants explored various approaches to address the issue of missing data in fish stock assessments. Missing data can arise due to factors such as incomplete or inconsistent catch or survey information, limited sampling, or data gaps. These gaps significantly affect the accuracy and precision of stock assessments and subsequent management decisions. To overcome these challenges, innovative methodologies and modelling frameworks were investigated during the workshop, aiming to effectively incorporate available information, account for uncertainties associated with missing data, and provide reliable stock status and reference points.

Modelling Approaches and Recommendations

The workshop report extensively discusses the different modelling approaches considered, including statistical models such as state-space models, Bayesian hierarchical models, and integrated stock assessment models. These models integrate available data sources, such as catch, survey, and biological information, while accounting for missing or incomplete data. By combining multiple data sources and considering uncertainty, these models offer more robust and reliable estimates of stock abundance, recruitment, and fishing mortality. The report also emphasizes the importance of standardized data reporting, increased cooperation among stakeholders, and the development of adaptive management strategies to address uncertainties arising from missing data.

SAM Model Application for North Sea Haddock, North Sea Plaice, and Celtic Sea Plaice

During the WKNSCS benchmark workshop, the SAM (Stock Assessment Model) was applied to assess the North Sea Haddock, North Sea Plaice, and Celtic Sea Plaice stocks. The SAM model, with its ability to handle missing data, proved useful in providing reliable estimates and predictions for these stocks despite the presence of data gaps. By incorporating catch, survey, and biological information, the SAM model generated comprehensive assessments of stock abundance, recruitment, and fishing mortality rates, enabling informed management recommendations.

Exclusion of SAM Model for Herring Stocks

In contrast, the SAM model was not applied to the assessment of Herring stocks in the North and West of Scotland and the Northwest of Ireland and West of Scotland. The workshop report likely provides arguments and justifications for this exclusion. Reasons may include limitations in available data, high levels of uncertainty associated with stock dynamics, or specific characteristics of the Herring populations in these regions. Different fish stocks possess unique ecological traits and complexities, and as such, stock assessment models may not be universally applicable across all species and regions.

Conclusion

The WKNSCS benchmark workshop report underscores the significance of fish stock assessment models capable of handling missing data in the North Sea and Celtic Sea regions. The SAM model demonstrated its utility in providing reliable estimates for North Sea Haddock, North Sea Plaice, and Celtic Sea Plaice stocks. However, the decision not to apply the SAM model for Herring stocks in the North and West of Scotland and the Northwest of Ireland and West of Scotland suggests compelling arguments justifying alternative approaches or models better suited to these specific stocks. Future insights into the genetic structure of these stocks will provide a more detailed understanding of the failure of SAM in the specific cases of herring, ensuring appropriate methods are employed considering specific data availability, uncertainties, and population dynamics characteristics.

6.3 BREFdata support for the WKBCOD (Benchmark Workshop for Northern Shelf cod stocks) in 2023

Short summary

The BREFdata project provided support for the WKBCOD (Benchmark Workshop for Northern Shelf cod stocks) in 2023. The preliminary report highlights the comparison between a single stock SAM (Stock Assessment Model) and a multi-stock SAM for the combined cod stocks of the Northern shelf area. The single stock SAM showed consistent results but had issues with residual diagnostics and retrospective pattern. Therefore, the multi-stock SAM, specifically the three-stock model, was considered more suitable, offering improved diagnostics and a more accurate representation of the biological reality. The report also discusses recommendations from the workshop, including incorporating industry data, increasing transparency, and applying gained experience to other species. Other topics covered include the use of commercial indices, genetic data analysis, and sensitivity runs to explore different factors affecting the assessment.BREFdata support for the WKBCOD (Benchmark Workshop for Northern Shelf cod stocks) in 2023.

Workshop Background

With support from the BREFdata project, a multi-stock SAM was developed and compared to the performance of a single stock SAM for the combined cod stocks of the Northern shelf area. In summary, the single SAM runs for the combined northern shelf cod stock exhibited consistent results but had problematic residual diagnostics and a borderline acceptable retrospective pattern. As a result, the multi-stock SAM configuration, particularly the three-stock model, was determined to be more suitable, providing better model diagnostics and a more accurate representation of the biological reality. The benchmark report has not yet been finalised.
The preliminary report of the Benchmark Workshop for Northern Shelf cod stocks (WKBCOD) includes information on the discussions and outcomes related to the estimation of biological reference points using the multi-stock SAM (Stock Assessment Model) for the benchmark of Northern Shelf cod stocks. Below is a summary of the key points.

Aim

The workshop (WKBCOD) aimed to identify evidence needs for the management of cod fisheries in the northern shelf seas, share assessment plans, and incorporate additional knowledge into the advisory process. The challenges identified included the Landing Obligation, use of advice by managers, lack of agreement on stock status, and inclusion of fishery information.

Recommendations from WKRRCOD

The workshop (WKRRCOD) made six recommendations to address the identified challenges, including the incorporation of industry data in the benchmark and assessment process, increasing transparency of the benchmark process, using knowledge from industry for assessment improvements, involving managers in the advice process, and applying the experience gained to other species.

Use of Commercial Indices

The suggestion to use commercial indices of stock abundance, specifically estimates of commercial landings per unit effort (LPUE) of potentially spawning cod, was presented at the data evaluation workshop. LPUE was intended for potential use in the stock assessment of cod in the Greater North Sea and West of Scotland.
Decision on Commercial Biomass Index: During the data evaluation workshop, it was decided not to include the commercial biomass index as input for the assessment at that point. The reasons included the lack of consideration for zero catches and the limited coverage of the Danish trawler fleet. However, it was acknowledged that commercial CPUE (catch per unit effort) could be beneficial as an index for older and mature fish.

Stock Summaries

The report provides summaries of the North Sea cod and West of Scotland cod stocks. The North Sea cod assessment was improved in 2021 by revising survey indices, biological data, and the SAM assessment model configuration. An ad hoc adjustment was made to account for migration to the West of Scotland area. The West of Scotland cod assessment faced challenges related to stock structure, uncertain commercial catch data, limited continuous survey indices, and the impact of seal predation.

Multistock SAM

The SAM model has been extended to fit multiple cod assessments concurrently. It allows fitting independent or correlated abundance processes for assessments. The model can incorporate genotype data and estimate stock or catch compositions. The data call for WKCOD 2023 requested national landings data disaggregated by year, quarter, cod area, and ICES rectangle to consider a sub-stock approach.
Genetic Data: Genetic data analysis was conducted to investigate mixing of cod populations in the North Sea, with a focus on juveniles. The analysis identified mixing of Viking and Dogger juveniles within the North Sea, indicating a dominance of Viking juveniles in the Skagerrak. Further development using full genome sequencing is underway to improve genetic marker tools for stock assessments.

Single stock SAM

For comparison a series of single stock SAM assessment runs were performed.
The results of the single SAM runs using the combined northern shelf cod data were consistent, but they presented some issues. The residual diagnostic was problematic, and the retrospective pattern was borderline acceptable at best. As a result, it was determined that the multi-stock SAM configuration, specifically the three-stock model, was more suitable for supporting the intended management options. The three-stock model had better diagnostic performance, provided a more accurate representation of the biological reality, and yielded results comparable to the total estimates obtained from the multi-stock SAM model.

Data

The selected reference model for the combined stock incorporated various data sets, including catch-at-age observations, quarter 1 and quarter 3&4 index-at-age data, and a recruitment index. These observations were assumed to be independent and normally distributed at the logarithmic scale. The model also accounted for fishing mortalities, stock sizes, natural mortalities, and catchability parameters. The fishing mortalities and stock sizes were considered unobserved random variables. The model employed a state-space framework, with the fishing mortalities following a multivariate random walk and the stock sizes following specific processes. The model parameters were estimated via maximum likelihood, and the random effects were integrated out using the Laplace approximation.

Results

The reference model produced results consistent with the total estimates from the multi-stock SAM model, with some minor differences. The retrospective pattern for spawning stock biomass (SSB) exhibited a Mohn's rho of 22%, surpassing the 20% threshold defined in ICES guidelines. However, this retrospective pattern was deemed acceptable because it was predominantly influenced by a single assessment point (the one ending in 2017), and the three most recent peels showed no issues.
On the other hand, the residual pattern for the reference model, which represented one-observation-ahead predictions, was problematic. It displayed a clear pattern of negative residuals for the two or three oldest age groups in the last 10-15 years, both in catches and quarter 1 survey indices. This residual pattern posed a significant challenge for the combined assessment, as no modifications to the configuration options could resolve this issue effectively.

Sensitivity

Sensitivity runs were conducted to explore the impact of various factors such as excluding the recruitment index, altering the plus group definition, using shorter time series, and adjusting configuration options. The sensitivity runs consistently produced similar estimates for recruitment, SSB, fishing mortality, and catch. The inclusion or exclusion of the recruitment index and the choice between 6+ or 7+ as the plus group had noticeable effects on the results. However, using a shorter time series from 1983 yielded nearly identical estimates.
Regarding the missing maturity-at-age observations before 1983, two approaches were compared: using the age-specific average over all observed years and smoothing the maturity internally in SAM. These alternatives resulted in visually different SSB estimates before 1983 but did not significantly affect other aspects of the model. Another configuration option that led to visually distinct estimates was introducing correlation in the two age-specific survey indices, which resulted in higher estimated fishing mortality and lower SSB in the years 2005-2015.

Despite the various sensitivity runs and standard configuration options, no improvements were observed in the residual or retrospective pattern. Additional experiments were conducted to identify potential causes for these issues, such as excluding specific years of data or modifying the assumed natural mortality. While changing the natural mortality values for ages 4-7+ between 2005 and 2022 improved both the residuals and retrospective pattern, and excluding catches in 2017-2018 improved the retrospective pattern, neither of these scenarios were considered realistic options.

Conclusion

In summary, the single SAM runs for the combined northern shelf cod stock exhibited consistent results but had problematic residual diagnostics and a borderline acceptable retrospective pattern. As a result, the multi-stock SAM configuration, particularly the three-stock model, was determined to be more suitable, providing better model diagnostics and a more accurate representation of the biological reality.

6.4 BREFdata support for the Benchmark Workshop on Sandeel (Ammodytes spp.) in 2022-23 (WKSandeel)

6.4.1 Short summary

The draft report of the Benchmark Workshop on Sandeel (Ammodytes spp.) in 2022 provides important insights into how oceanographic data support the understanding of larval drift and population structure in North Sea lesser sandeel. The report includes sections on larval drift modelling and genetic structure analysis, with additional information expected from otolith micro-chemistry patterns. The findings suggest heterogeneous spawning activity and potential connectivity issues between different areas, indicating a need for revising management areas. The report also discusses a tag-and-recapture study, highlighting migration patterns and recapture rates of adult sandeel. Proposed area divisions that better represent population structure are suggested, and the report emphasizes the need for considering biological factors and model consistency in sandeel stock assessment and management.

6.4.2 Input to the sandeel benchmark

The draft report of the Benchmark Workshop on Sandeel (Ammodytes spp.) in 2022 provides important insights into how oceanographic data inform data and models of larval drift and population structure in North Sea lesser sandeel. The report presently includes two main sections on this topic: Larval drift modelling and Genetic structure analysis, however analyses of otolith micro-chemistry patterns are further expected to cast light on drift and migration processes.
Two other studies also informed the benchmark on population structure and migration that is important when deciding on the resulting sandeel assessment areas which most likely will be the basis for fisheries management advice.

The sandeel benchmark process was not finalised ultimo 2022 as anticipated, but the support for the sandeel benchmark from BREFdata continued until the finalisation of the project. However no final conclusions from the work supporting WKSANDEEL2022 can be drawn at this stage.

6.4.3 Larval drift modelling

The study conducted larval sampling and larval drift modelling to understand the distribution and movement patterns of sandeel larvae in the North Sea. The research was conducted between 2015 and 2020 and revealed heterogeneous distribution of spawning activity across the North Sea. Spawning hotspots were identified on Dogger Bank, Horns Reef, and along the Norwegian trench between 4 and 10 degrees east. However, very few larvae were captured to the west of 1 degree east, and there was a noticeable gap in spawning activity in the central North Sea. The authors recommend considering these results as indications that Dogger Bank is separated from other areas in terms of connectivity and that the current divide between management areas should be reconsidered. They suggest combining these findings with tagging studies, genetics, and otolith chemistry to develop recommendations for revised stock units and management areas. By integrating all three sources of data, it may be possible to infer homing behavior to spawning locations.

The larval sampling was conducted using a specialized net called the MIKey M net, which allowed for the collection of small, recently hatched sandeel larvae. The samples were obtained during coordinated surveys in the North Sea, and the abundance of larvae was estimated by calculating the volume of filtered water. The study covered sandeel habitats in Denmark, Germany, Norway, the Netherlands, and France. Larvae were sorted, counted, and measured, and their sizes were used in larval drift simulations. The drift simulations accounted for factors such as larval size, time of capture, and temperature-dependent hatching times. The model results indicated settlement hotspots and connectivity patterns, suggesting that most larvae hatched on Dogger Bank either stayed there or drifted eastward to settle east of Dogger. Larvae found near Horns Reef drifted northward to settle between Horns Reef and the Norwegian trench, while larvae along the Norwegian trench often drifted away from sandeel habitats. The model also confirmed that the distribution of sampled larvae reflected major spawning hotspots (see figure 5 from draft report of WKSandeel_2022).

Spatial distribution of larvae was further analysed using generalized additive models (GAMs), which allowed for the estimation of fish abundances while accounting for various factors such as spatial position, depth, and time of day. The GAMs provided predictions of fish abundances in space and time and showed differences in larvae distribution between years. Including larvae length in the model had a minor impact on the results.

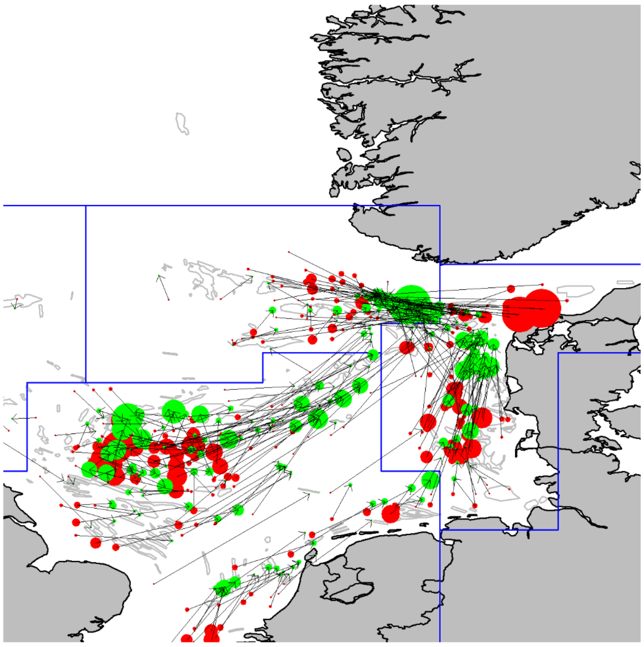


Figure 6.4.1: Results from forward drift simulation. Red bubbles represent start position and green bubbles settlement position (centroid of probability ellipse; note that the probability ellipse only include those larvae ending up close enough to sandeel habitat). Bubble size represents the number of larvae in the haul. All pairs of green and red bubble are connected by an arrow.

6.4.4 Genetic structure analysis

The genetic analysis aimed to investigate the demographics and migration behaviors of North Sea lesser sandeel. Previous studies had identified limited genetic differences among samples from different sandeel areas (SA1r, 2r, 3r, and 4r), indicating potential stock connectivity issues. The current study used Single Nucleotide Polymorphism (SNP) markers to analyze samples collected during Danish and Scottish dredge surveys in 2019-2020. Larval samples were also included to compare gene frequencies in different age groups. The preliminary results showed the presence of three genotypes (haplotypes) in the analysed samples. Frequencies of these genotypes were estimated based on spawning areas, banks, sampling years, and age classes. The results provided insights into genetic differentiation and patterns of genetic variation across different locations and age classes of sandeel populations.

In conclusion, the draft report provides valuable information on larval drift patterns and population structure in sandeel species. The findings suggest heterogeneous distribution of spawning activity, potential connectivity issues between different areas, and the need for revising management areas based on.

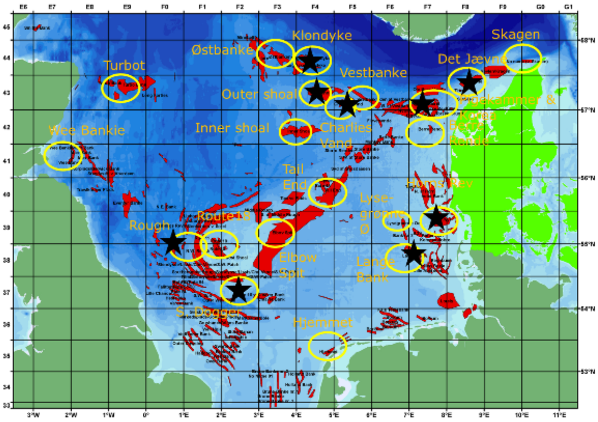


Figure 6.4.2: North Sea lesser sandeel banks (red), and collection locations for dredge survey (yellow circles) and MIK larvae (black stars) samples analysed with 96 SMP markers.

6.4.5 Tag- and recapture

The tag-recapture study on sandeel in the North Sea from 2020-2022 aimed to investigate the migration patterns and recapture rates of adult sandeel. The study was conducted by Mosegaard H. and Olesen H.J., with additional data contributors Dolby J., Pedersen E.M., Egekvist J., DPPO, DFPO, MID. The main conclusions of the study are described below.

Batches with a mean size less than 12 cm showed no recaptures, indicating that the results should be considered indications of adult sandeel migrations.

Six sub-areas were defined in the study: SA4, SA1-west, SA1-DK.EEZ (Tailend), SA2-S.of.56N (Horns rev), SA2.N.of.56N (Fisher banks etc.), and SA3E-EU.EEZ. Norwegian catches in SA3r were not expected to have recaptures.

Most recaptured sandeels were found within the same sub-area as their release. However, between 12% and 25% of recaptured sandeels were caught outside their sub-area of release.

Batches released at Horns rev showed a higher degree of recaptures in other sub-areas compared to batches released in other sub-areas. SA3-EU.EEZ and SA2-North appeared to act as sinks for migration of larger sandeels, while SA2-Horns acted as a source.

The study suggests that the mid and northern part of SA2r should not be considered as separate assessment areas.

The material and methods section provides details on the tagging process. Sandeels were tagged with Passive Integrated Transponders (PIT) tags, and catch and handling processes were optimized to maximize survival during tagging and release. Over 15,000 sandeels were tagged and released at their sand bank habitats in different areas of the North Sea over a three-year period.

The recapture process involved scanner systems mounted on the tubes of major pumping stations that received landings for Danish fishmeal factories. Efficiency was estimated to be over 98% recovery of tagged sandeels passing a scanner, and more than 80% of all sandeel landings were scanned. The recapture data, along with logbook information and fleet effort distribution, were used to estimate the most probable catch locations.

The report also describes the land-based setup of the scanner systems, the testing of scanner efficiency, and the process of backtracking catch locations from fishing trips using time stamps and AIS data. Tagging cruises were conducted using modified mussel dredges and commercial sandeel trawls.

The results section presents the findings of the tag-recapture study in 2021, including the number of recaptures, the relationship between catches and recaptures, and the patterns observed in different sub-areas. Maps and figures illustrate the distribution of the fishery and the unique combinations of release and catch positions (see figure 10 from draft report of WKSandeel_2022).

Finally, the discussion section highlights the significance of recaptures from batches with a mean length greater than 12 cm, the influence of fishery coverage and effort on recaptures, and the need for further analysis on age-specific recapture rates.
The report references the relevant studies on otolith microchemistry, which provide insights into the natal origin and dispersal of sandeel populations in specific regions of the North Sea.

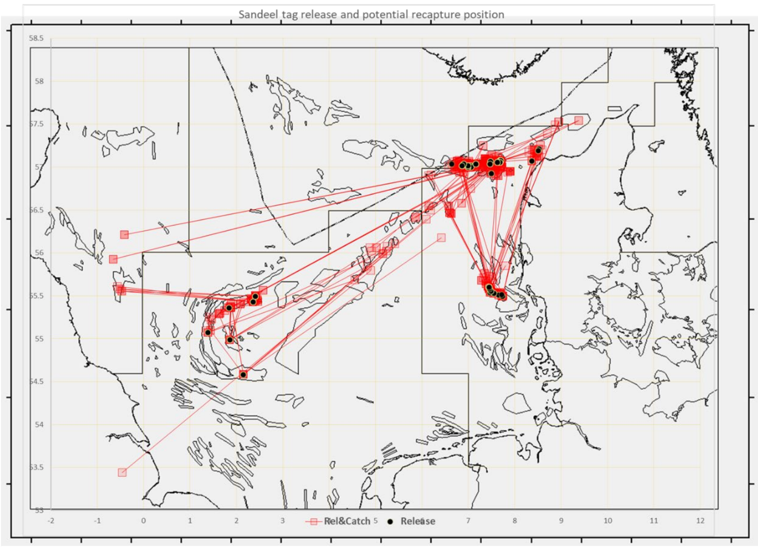


Figure: 6.4.3: Release positions (black dots) with recaptured sandeels and potential catch locations on fishing trips with identified recaptures (red squares), red lines connect every registered tag from a release position with all potential fishing locations.

6.4.6 Demographic differences

The sandeel benchmark draft report consists of several sections that provide insights into the sandeel stock assessment and management. One section focuses on demographic differences and suggests potential improvements in the sandeel area divisions.
According to the Swap-analysis conducted by Casper Berg, swapping squares between certain areas would enhance the overall Age-Length key consistency. This analysis utilized sandeel dredge survey data age samples and evaluated the consistency of an age-length key model using AIC. The results indicate that specific swaps between areas could improve the model's performance.

6.4.7 Proposed area divisions that would represent population structure

Based on the presented results the stock delineation and assessment unit scenarios were discussed. The Data Evaluation Meeting for WKSAND 2022 proposed two alternative area divisions, WKSAND 2022a and WKSAND 2022b, in addition to the current stock areas. These proposals aimed to address evidence of multiple populations within the sandeel stock and revisited the boundaries between certain areas. The meeting participants emphasized the need to evaluate these alternative divisions through the stock assessment model during the benchmark.

Moreover, the report highlights the boundary between the Norwegian EEZ and the EU Zone and its lack of biological support for any stock unit. Several studies and preliminary results from ongoing projects suggest that the border between these zones intersects an area that acts as a sink, receiving larvae and adults from adjacent sandeel banks and management areas. The evidence indicates mixing from multiple sources and questions the self-sustaining larval production in this area. Therefore, the report concludes that the current boundary does not make biological sense.

Overall, these sections provide valuable insights into demographic differences and stock area divisions, emphasizing the importance of considering biological factors and model consistency in sandeel stock assessment and management.

7. Using links between biology and oceanography to fill gaps

7.1 Background for a developing technology of integrated assessments

Oceanographic and environmental data are of paramount importance in predicting fish population development and filling data gaps for fish stock assessment. These data provide valuable insights into the factors that influence fish populations, allowing for more accurate predictions regarding their abundance, distribution, and recruitment. The integration of such data is crucial for effective fisheries management and conservation efforts.

Several studies have highlighted the significance of oceanographic and environmental data in understanding fish population dynamics.
The population dynamics and stock assessment of sandeel (Ammodytes marinus) in the North Sea can be informed by a wealth of oceanographic information and data. Several studies, including Henriksen et al. (2021), Wright et al. (2019), Lindegren et al. (2018), and Worsøe Clausen et al. (2018), have investigated the influence of oceanographic factors on sandeel recruitment, survival, productivity, and potential fisheries yield. These studies provide valuable insights into the interactions between sandeel populations and the marine environment, highlighting the importance of considering oceanographic variables in stock assessment and management strategies.

For instance, Henriksen et al. (2021a) utilized commercial catch data to reveal the behavioral responses of sandeel to ocean warming, demonstrating how changes in temperature can impact the distribution and abundance of sandeel populations. Additionally, Henriksen et al. (2021b) and Henriksen et al. (2018) investigated the effects of temperature and body size on sandeel recruitment and survival. They found that higher temperatures and larger body sizes positively influenced recruitment and survival rates. These findings emphasize the significance of temperature as a key driver of sandeel population dynamics and highlight the potential consequences of climate change on their abundance and distribution. Pécuchet et al. (2015) conducted a comparative study of North Sea and Baltic Sea fish stocks, including sandeel, to assess the impacts of the local environment on recruitment. The study highlights the importance of considering specific environmental conditions in different regions and their effects on sandeel recruitment patterns.

A study by Lindegren et al. (2022) presents a spatial statistical approach to identify population structuring in European sprat. The researchers employed oceanographic tools, including sea surface temperature and salinity data, to investigate the spatial distribution and connectivity of sprat populations in the Baltic Sea. The study revealed distinct population structuring and highlighted the importance of environmental factors in shaping the genetic differentiation and migration patterns of sprat.
On the North Atlantic scale, Payne et al. (2022) presented skilful decadal-scale predictions of fish habitat and distribution shifts with examples for Atlantic mackerel, blue

whiting and tuna, underscoring the significance of predictive models that incorporate environmental data. The North Atlantic system appears to have a very high predictability compared to the North Sea.

When it comes to integration of oceanographic and environmental data with data and models for fish stock assessment, Thorson (2019) provided guidance on the application of the Vector Autoregressive Spatio-Temporal (VAST) package in stock, ecosystem, habitat, and climate assessments. This guidance enhances the precision and workflow of spatiotemporal analysis of compositional data, contributing to improved stock assessments (Thorson & Haltuch, 2019). Thorson and Kristensen (2016) proposed a generic method for bias correction in statistical models using random effects, offering examples of its application in spatial and population dynamics contexts.
This approach has been utilised by Coro et al. (2022) that demonstrates the options of integrating spatiotemporal and environmental modelling to address data gaps in trawl surveys for fish stock assessment. By incorporating environmental variables, the study fills missing data, improves estimates of fish stock abundance and distribution, and enhances the precision of assessments. This approach could provide more comprehensive and reliable information for decision-making and sustainable fisheries management.

To conclude, the review of these studies and additional relevant literature highlights the critical role of oceanographic and environmental data in predicting fish population development and potential for filling data gaps for fish stock assessment. By integrating these data, researchers can gain a comprehensive understanding of the factors that influence fish populations, leading to more effective fisheries management and conservation strategies. It should however be born in mind that the selection of oceanographic and environmental will be case specific regarding which population, what vital rates, migration pattern or abundance parameters that needs to be predicted.

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7.2 Stock assessment with environmental and oceanographic timeseries

Using links between biology and oceanography to fill gaps in the time series can be done utilize the same techniques as used to correctly handling of missing observations (in chapter 1 of this rapport). At the most fundamental level some observable environmental quantities (e.g. sea surface temperature or chlorophyll level) may be helpful in predicting abundance, yearly recruitment, or level of fishing, because they co-vary (positively or negatively). If a model is constructed where the environmental quantities are included alongside other more standard observations (e.g. catches and survey indices), then if one of them are missing, then the model can predict the missing observation. The ability to predict missing observations require that the model has been setup to properly handle missing observations, as this project has done for the state-space assessment SAM.

At the technical level there is no difference between predicting a missing catch at age A in year Y from all other observations in the assessment (including catch at age A-1 in year Y-1) and predicting catch in year Y from observed sea surface temperature and chlorophyll level in year Y. The accuracy of the prediction will naturally on the observation uncertainty and on the strength of the correlation. An example showing this principle is the recent extension of the SAM model to link between stocks (Albertsen et al. 2018), where missing observations from one stock can be predicted by observations from stocks which are somehow connected. A recent state-space assessment model, which is based on the same principles as SAM (Stock & Miller 2012) has included the feature to include environmental observations, which then is used to predict recruitment and survival.

The same principle may also be applied with indices beyond linked stocks and environmental correlates, e.g., price and expenses.

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7.3 Oceanographic Information and Data for Sandeel Population Dynamics and Stock Assessment in the North Sea

In a series of bio-physical life cycle modelling developments the spatial population dynamics of a sedentary species with pelagic larval stages have been investigated. Insights into sandeel larval transport patterns and the influence of hydrodynamics was first provided by Christensen et al. (2007) and Christensen et al. (2008). These studies employed individual-based hydrodynamic models to track the movement of sandeel larvae in the North Sea, shedding light on the factors influencing larval dispersal and connectivity. Further Christensen et al. (2009) conducted spatially resolved fish population analyses to inform the design of marine protected areas (MPAs) for sandeel. The study emphasizes the importance of considering the influence of neighbouring habitats and the spatial distribution of sandeel populations when designing effective MPAs. Christensen et al. (2013) worked toward an integrated forecasting system for fisheries on habitat-bound stocks, which has implications for sandeel management. The study emphasizes the importance of considering habitat suitability and environmental conditions when developing forecasting tools for sandeel populations. The approach was further refined in Christensen et al. (2018) where a generic framework for individual-based modelling and physical-biological interactions was presented, offering a valuable tool for studying the influence of oceanographic variables on sandeel populations. This framework allows for the integration of physical and biological processes, facilitating a comprehensive understanding of the dynamics between the marine environment and sandeel populations.

The most recent development (Christensen et al. unpublished) which is the basis for modelling input to the sandeel benchmark in 2022-23 describes a generic novel model framework for coupled physical, demographic and genetic simulation applied to support biological parameterisation for sandeel within current stock assessment units in North Sea. The authors demonstrate the potential for generalizing the framework to other sedentary species occupying a habitat network with suitable reparameterization. The framework aims to support biological parameterization and provides insights into genetic variability. The authors also discuss the simulation period, the simplicity of the demographic model, the representation of larval mortality, and the potential extension of the framework to encompass post-settlement migration. They highlight the use of loci ensemble simulations to test statistical significance and the assumption of a spatially uniform correction factor for effective population size. The manuscript emphasizes the generality, transparency, and future research directions of the framework, including the exploration of inverse genetic modelling and the understanding of connectivity asymmetry in ecosystem management.

In a forward-backwards connectivity simulation the influence of hydrographical model on drift pattern and estimated importance of spawning aggregations is demonstrated in figure 4.3.1.

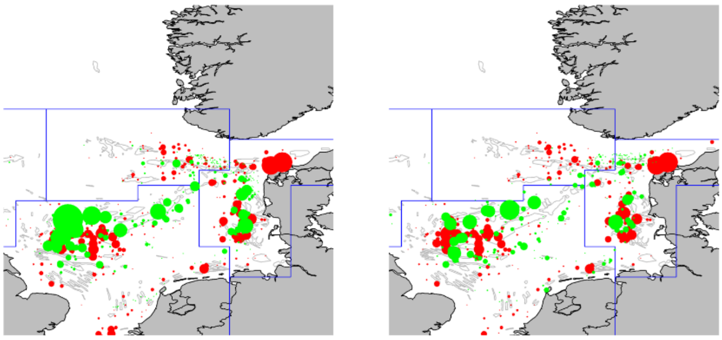

Figure 7.3.1. Comparison of simulated drift pattern (ending as metamorphosed sandeel, green dots) and estimates importance of spawning aggreations (red dots). Left is modelled with data from NWSHELF and right is modelled with data from GLOBAL.

When applying hydrographical models for bio-physical processes it is generally recommended to apply ensemble modelling (Christensen et al. 2018).

Referencer

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8. Project coordination, dissemination of results and provision of national advice

The Emergency action for calculating stock size and reference points in case of massive data deficiency has been presented to both fisheries stakeholders and the scientific community.

Network discussions with the fishing industry (supported by a work package in the EMFF project "Dansk Fisker-Forsker Netværk 3. fase" Journal nr. 33112-P-19-063) have been useful for identifying changes in fishing pattern and effort as well as the underlying socio-economic mechanisms which directly influence catch composition and quantities. The approach was also discussed during contact meetings between the fishing sector and DTU Aqua. Danish Fishers PO (DFPO) and Danish Pelagic PO (DPPO) have provided a list of causes for changes in fishing pattern and utilisation of Danish quotas[1] based on an earlier ministry report (http://d3jo9v3q67jiro.cloudfront.net/2016/06/05073228/kvoteudnyttelse.pdf) where a number of direct causes for changes in landings can be extracted.

The work package has led the coordination of effort in the different advisory and scientific fora of ICES. The results have been disseminated and applied in connection with ICES' advisory work. Work related to improving biological advice for a number of fish stocks was presented and discussed in ICES benchmark workshops and working groups, e.g. WKSandeel_2022 Benchmark Workshop on Sandeel (Ammodytes spp.) in 2022-23, WKNSCS (North Sea and Celtic Sea stocks) Benchmark Workshop in 2022-23, WKBCOD (Benchmark Workshop for Northern Shelf cod stocks) in 2023, and WGNSSK.

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[1] Liste over mulige årsager til ændring i fangst og landing:
• 'Vind og vejr'
• 'Manglende tæthed i bestandene'
• 'Andre naturlige udsving i fiskebestandene'
• 'Muligheden for at fange visse arter frem for andre'
• 'Prisen på brændstof og andre variable omkostninger'
• 'Manglende fangstkapacitet i fiskeflåden'
• 'For lille fangstkapacitet blandt ejerne af industrifiskekvoter'
• 'Prisen på at leje fangstrettighederne til især industrifisk men også andre arter'
• 'Vilkårene for at leje fangstrettigheder til industrifisk'.
• 'Et uigennemskueligt marked for køb, salg og bytte af kvoter'
• 'Manglende vilje til at udleje industrifiskekvoter til interesserede fiskere'
• 'Fiskemelsfabrikkernes begrænsede kapacitet ved spidsbelastning'
• 'En for lav afregningspris på industrifisk eller anden lavt prissat fisk'
• 'Afregningsprisernes volatilitet'
• 'Krav til redskaber og redskabsvalg'
• 'Bifangstkvoter på især sild'
• 'Andre regler'

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