WORKSHOP ON NORTH SEA STOCKS MANAGEMENT STRATEGY EVALUATION (WKNSMSE)

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Contents

i Executive summary

WKNSMSE (Workshop on North Sea stocks Management Strategy Evaluation) took place over two physical meetings (19-21 November 2018 and 26-28 February 2019, but at ICES HQ, Copenhagen) and several WebEx meetings, was chaired by José De Oliveira (UK) and included 30 participants from Denmark, Germany, Netherlands, Norway, Sweden, UK and the European Commission, and two reviewers from South African and New Zealand. The purpose of this work was to evaluate long-term management strategies for jointly-managed stocks in the North Sea (cod, haddock, whiting, saithe and autumn-spawning herring) between the European Union and Norway, following a request from EU-Norway. The first physical meeting provided an ICES interpretation of the EU-Norway request, agreed the specifications of the MSE, decided on the tools and approaches to use, and developed a work plan, while the second meeting (and subsequent follow-up WebEx meetings) discussed results, developed conclusions, ensured the minimum requirements for conducting MSEs (developed by WKGMSE2) were met, and finalised the report. ICES were tasked to find "optimal" combinations of harvest control rule parameters (F_{target} and $B_{trigger}$) for management strategies with or without stability mechanisms (TAC constraints and banking and borrowing scenarios). "Optimal" combinations were defined as those combinations of F_{target} and $B_{trigger}$ that simultaneously maximised long-term yield while being precautionary (long-term risk3≤5%). The request also asked for sensitivity tests once the management strategies were "optimised". The approach adopted for all stocks was to include the assessment and forecast in a full-feedback MSE simulation, and to condition the baseline operating model on the benchmarked ICES assessment. The one exception was haddock, where it was not possible to include TSA in the full-feedback simulation because it was too slow to converge and requires manual intervention; SAM was used instead as a reasonable approximation. The approach also considered alternative operating models to capture a broader range of uncertainties. Full-feedback simulations were computationally challenging and required the use of parallelisation and high-performance computing; it also meant that the time-frame for the work was extremely tight, and in some cases, analyses were restricted. Nonetheless, the work was completed for all stocks, and "optimal" combinations for most management strategies were found. There were some notable issues that arose through this suite of MSEs, including that some management strategies that were precautionary in the long-term could have unsavoury and avoidable features in the short term (depending on the management strategy), and that reference points estimated by EqSim were, in many cases, no longer found to be precautionary in the MSE.

ii Expert group information

Expert group name	Workshop on North Sea Stocks Management Strategy Evaluation (WKNSMSE)
Expert group cycle	NA
Year cycle started	2018
Reporting year in cycle	1/1
Chair	José De Oliveira, UK
Meeting venue and dates	WKNSMSE 1: 19-21 November 2018, Copenhagen, Denmark (20 participants)
	WKNSMSE 2: 26-28 February 2019, Copenhagen, Denmark (28 participants)

1 Terms of Reference

WKNSMSE- Workshop on North Sea Stocks Management Strategy Evaluation

2018/2/ACOM61 A **Workshop on North Sea Stocks Management Strategy Evaluation**, chaired by José De Oliveira, United Kingdom and reviewed by (Carryn de Moor), and (Matthew Dunn), will meet at ICES HQ, Copenhagen

19–21 November 2018 to:

1. Provide an ICES interpretation of the EU-Norway Special request to evaluate management strategies for key North Sea roundfish stocks (cod, haddock, saithe, whiting, autumn-spawning herring); this interpretation should make clear what will be evaluated in computer code (including the stability scenarios).
2. Agree on the specifications of the MSE; this should include the operating models to be used, performance statistics to be presented, and criteria to be used to draw conclusions on the performance of the various management strategies.
3. Decide on the tools to be used for each stock.
4. Develop a work plan leading up to the final meeting in 2019. This should include strategic WebEx meetings to check progress on the work.

26–28 February 2019 to:

1. Analyse the results of the MSE for all stocks, and develop conclusions in relation to ICES guidelines on whether the management strategies are precautionary or not.
2. Ensure that the minimum requirements for conducting MSE, as developed by WKGMSE2, are met for the MSEs presented
3. Produce a report describing the management strategies evaluated, the specifications of the MSE, results and conclusions for each stock.

WKNSMSE will report by 15th March 2019 for the attention of ACOM.

2 Introduction

This workshop was initiated following a request from EU-Norway to evaluate long-term management strategies for joint stocks (North Sea cod, haddock, whiting, saithe and autumn-spawning herring) between the European Union and Norway (Annex 2). Two meetings were held, the first (19-21 November 2018) was to provide an ICES interpretation of the request, agree the specifications of the Management Strategy Evaluation (MSE), decide on the tools to use, and derive a work plan. The second meeting (26-28 February 2019) was to analyse the result of the MSE for all stocks, develop conclusions, ensure the minimum requirements for conducting an MSE were met, and finalise this report. The agendas for the two meetings are provided in Annex 4, and participants listed in Annex 1. In between these two meetings, a series of three WebEx meetings were held (11 December 2018, 21 January 2019 and 12 February 2019) to report on progress, help familiarise the reviewers with the work and incorporate any feedback. In addition to this, a workshop was held at the JRC in Ispra during the week of the 21st January 2019 to support implementation of the a4a framework for MSEs for those needing such support. A number of follow-up WebEx meetings were held (two each for herring and the remainder) following the second physical meeting in order to finalise work.

2.1 Management strategies

Management strategies comprise the harvest control rule (HCR) in combination with the stability mechanism (TAC constraints and banking and borrowing scheme). The HCRs associated with the long-term management strategies are illustrated in Figure 2.1 (for cod, haddock, whiting and saithe) and Figure 2.2 (for autumn-spawning herring) without the stability mechanisms as defined in the request (TAC constraints and banking and borrowing; Annex 2). F_{target} and $B_{trigger}$ are control parameters in the HCRs, and the request asks for the combination of these control parameters to be found that simultaneously maximises long-term yield and meets the precautionary criterion (risk3≤5%[1]; Annex 2). We have termed this process (maximising long-term yield while ensuring the precautionary criterion is met) "optimising" the management strategy. The B_{lim} used in the HCRs are the currently-accepted B_{lim} for the stocks, resulting from the most recent benchmark assessment (and shown in the most recent advice sheet; for saithe the most recent estimate follows an inter-benchmark held January/February 2019). These are listed in Table 2.1.

Table 2.1. B_{lim} values used as part of the HCR in each of the management strategies evaluated.

Stock	B_{lim}
Cod	107 000 t
haddock	94 000 t
whiting	119 970 t
saithe	107 297 t
autumn-spawning herring	800 000 t

[1] risk3 is defined as the maximum of the annual P(SSB<B_{lim}) over a pre-defined period.

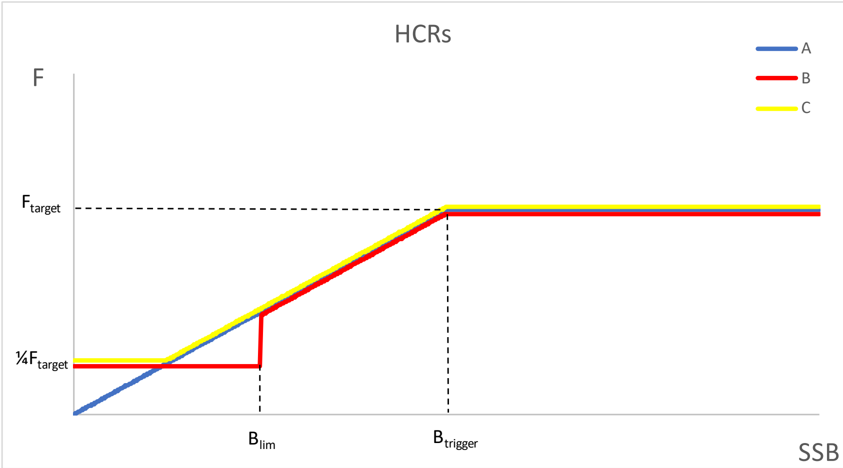


Figure 2.1. Harvest Control Rules A, B and C for cod, haddock, whiting and saithe. The bottom left corner of the plot is the origin (F=0 and SSB=0).

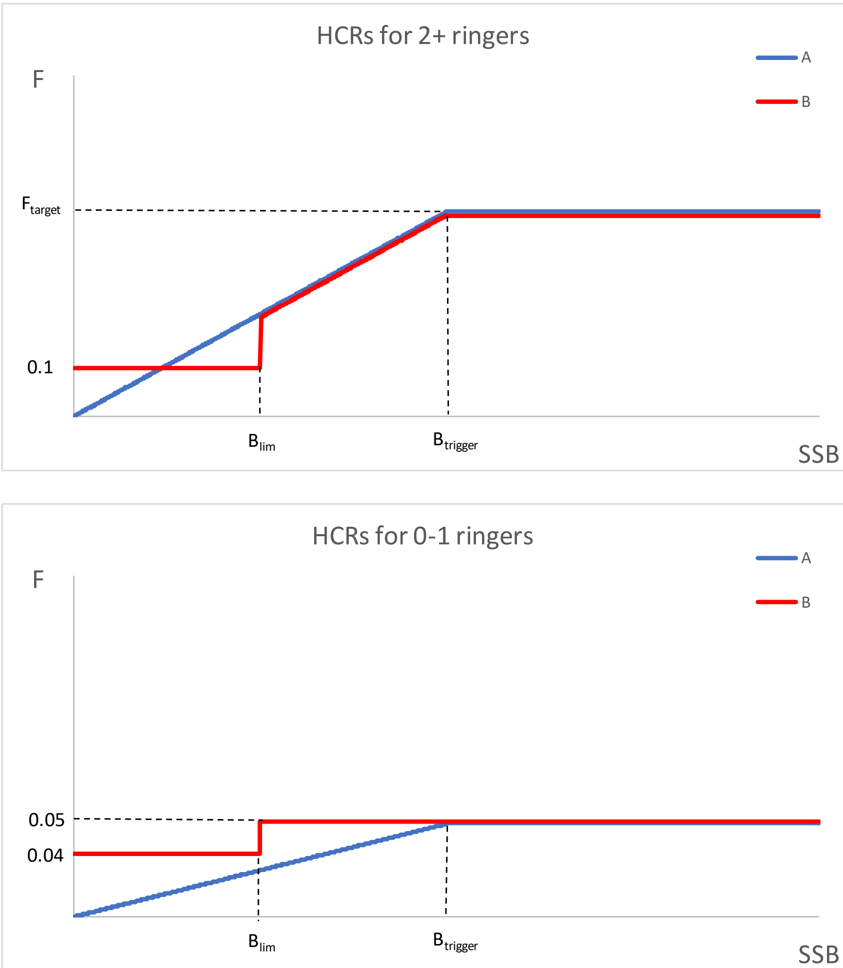


Figure 2.2. Harvest Control Rules for autumn-spawning herring 2+ ringers (top) and 0-1 ringers (bottom). The bottom left corner of both plots is the origin (F=0 and SSB=0).

Stability mechanisms for cod, haddock, whiting and saithe

For cod, haddock, whiting and saithe, in addition to HCRs A, B and C, illustrated in Figure 2.1, which did not include stability mechanisms, the request asks for versions of each of these that do include stability, as follows:

A+D: this is HCR A (Figure 2.1), with the addition of a TAC constraint (the TAC may not be more than 25% above or 20% below the previous TAC). In addition, banking and borrowing is allowed up to 10% of the TAC, according to paragraphs 1-3 in Annex 3. In this case, both the TAC constraint and the banking and borrowing scheme apply only when SSB at the start of the TAC year is at or above $B_{trigger}$; they are suspended when SSB<$B_{trigger}$. There is an additional requirement for saithe to consider a 15% TAC constraint (i.e. the TAC may not be more than 15% above or below the previous TAC) under the same conditions as the TAC constraint described above; this has been labelled A_1+D.

B+E: this is HCR B (Figure 2.1), with the addition of a TAC constraint (the TAC may not be more than 25% above or 20% below the previous TAC). In addition, banking and borrowing is allowed up to 10% of the TAC, according to paragraphs 1-3 and 5 in Annex 3. In this case, the TAC constraint applies only when SSB at the start of the TAC year is at or above $B_{trigger}$, and is suspended when SSB<$B_{trigger}$. In contrast to A+D, the banking and borrowing scheme applies throughout (i.e. regardless of whether SSB at the start of the TAC year is above or below $B_{trigger}$), but in order to offer additional protection, paragraph 5 of Annex 3 is invoked.

C+E: As described above for B+E, replacing HCR B with C (Figure 2.1).

Stability mechanisms for autumn-spawning herring

For autumn-spawning herring, in addition to HCRs A and B illustrated in Figure 2.2 for 2+ and 0-1 ringers, which do not include stability mechanisms, the request asks for versions of each of these that do include stability, as follows:

A+C: this is HCR A (Figure 2.2), with the addition of a TAC constraint (the TAC may not be more than 25% above or 20% below the previous TAC). In addition, banking and borrowing is allowed up to 10% of the TAC, according to paragraphs 1-3 in Annex 3. In this case, both the TAC constraint and the banking and borrowing scheme apply to the directed fishery only, and only when SSB at spawning time in the TAC year is at or above $B_{trigger}$; they are suspended when SSB<$B_{trigger}$.

A+D: this is the same as A+C, but both the TAC constraint and the banking and borrowing scheme apply to the entire fishery (i.e. not just to the directed fishery).

B+E: this is HCR B (Figure 2.2), with the addition of a TAC constraint (the TAC may not be more than 25% above or 20% below the previous TAC). In addition, banking and borrowing is allowed up to 10% of the TAC, according to paragraphs 1-3 and 5 in Annex 3. In contrast to A+D, both the TAC constraint and the banking and borrowing scheme apply throughout (i.e. regardless of whether SSB at spawning time of the TAC year is above or below $B_{trigger}$), but in order to offer additional protection, paragraph 5 of Annex 3 is invoked for banking and borrowing. Both the TAC constraint and the banking and borrowing scheme apply to the entire fishery (i.e. not just to the directed fishery). [Note, there is an error in the request, asking for B+D instead of B+E.]

Requested outputs

The request asks that for each of the management strategies (A, B, C, A+D, B+E, C+E for cod, haddock, whiting and saithe, and A, B, A+C, A+D and B+E for autumn-spawning herring), the combination of the control parameters F_{target} and $B_{trigger}$ be found that maximises long-term yield while also meeting the precautionary criterion that risk3≤5%. This requires a search over a grid of F_{target} and $B_{trigger}$ values. Once the "optimum" combination is found for each management strategy, the request then asks for the following four additional scenarios for each management strategy: $0.9F_{target}$, $1.1F_{target}$, $F_{MSY\text{-}lower}$, and $F_{MSY\text{-}upper}$, where the latter two are the reference points from the most recent benchmark (in the case of saithe, this would be from the latest inter-benchmark in January/February 2019 – see table below). It should be noted that $F_{MSY\text{-}lower}$ and $F_{MSY\text{-}upper}$ has not been defined for autumn-spawning herring, so these two options are not supplied for this stock. Furthermore, there is an additional request for haddock for management strategies A and A+D, namely that in combination with the "optimum" F_{target}, the following multiples of the "optimum" $B_{trigger}$ be given: $1.5B_{trigger}$ and $2B_{trigger}$.

Table 2.2. $F_{MSY\text{-}lower}$ and $F_{MSY\text{-}upper}$ values used as part of the additional scenarios in the request.

Stock	$F_{msy\text{-}lower}$	$F_{MSY\text{-}upper}$
Cod	0.198	0.46
haddock	0.167	0.194
whiting	0.158	0.172
saithe	0.210	0.536
autumn-spawning herring	N/A	N/A

An additional request was received for autumn-spawning herring late in the process (email received 11 February 2019) asking for an additional scenario where F_{target} is set to zero for 0-1 ringers for management strategy A+C (both for A1 and A2 in Annex 2 for herring). Because of the lateness of the request, this will be treated as a sensitivity test on the original A+C, rather than looking for the "optimum" combination of F_{target} and $B_{trigger}$ that maximise long-term yield and meets the precautionary criterion.

2.2 Interpretation of request

As is inevitable with written requests, it is often not possible to convert such requests directly into computer code without further clarification. This was indeed the case for this request. The obvious candidate was the text of paragraph 5 of the banking and borrowing scheme (Annex 3):

> *The inter-annual quota flexibility scheme should be terminated if the stock is estimated to be under the precautionary biomass level (B_{pa}) and the fishing mortality is estimated to be above the precautionary mortality level (F_{pa}) the following year, or if the SSB is estimated to be below B_{pa} in two consecutive years.*

In this text, it is not clear which year "the following year" refers to, and furthermore which years the "two consecutive years" refer to. Our interpretation was that "the following year" referred to the TAC year, and the "two consecutive years" were the TAC year and the year thereafter. For additional clarification, B_{pa} and F_{pa} were taken from the most recent benchmark (in the case of saithe from the inter-benchmark held in January/February 2019), as follows:

Table 2.3. B_{pa} and F_{pa} values used in paragraph 5 of the banking and borrowing scheme (Annex 3).

Stock	B_{pa}	F_{pa}
Cod	150 000 t	0.39
haddock	132 000 t	0.274
whiting	166 708 t	0.33
saithe	149 098 t	0.446
autumn-spawning herring	900 000 t	0.30

The request for herring included five management strategies, namely A, B, A+C, A+D and B+D. The way the request was structure implied that B+D was not correct and should have been B+E. We therefore only explored B+E (and not B+D). Furthermore, for herring, $F_{MSY\text{-}lower}$ and $F_{MSY\text{-}upper}$ are not defined for this stock, so the sensitivity analyses for these options were not possible.

2.3 General specifications of the MSE

We followed the general approach for "full" MSEs (i.e. we did not follow a "short-cut" approach), as described in ICES (2013) and Punt *et al.* (2016). A flowchart of the approach is provided in Figure 2.3.

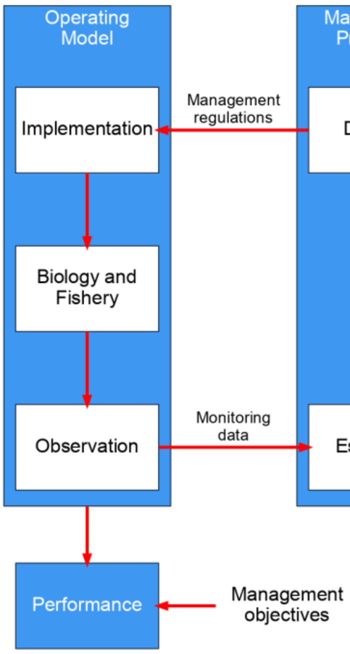


Figure 2.3. A flowchart of the Management Strategy Evaluation approach followed.

Under the terminology of Figure 2.3, the Operating Model (OM) represents the true underlying dynamics related to the biology and the fishery, and includes the observation model which adds observation error to OM quantities to derive monitoring data that is passed to the Management Procedure (MP), and the implementation model, which converts the management regulation (e.g. TAC) into a realised catch. The only communication between the OM and MP is through the monitoring data that the OM passes to the MP, and the management regulation that the MP passes back to the OM. The MP consists of an estimation model (e.g. the working group assessment model and forecast procedure), which is used to parameterise the decision model (the management strategies that are being evaluated). The performance of the management strategies is evaluated by performance statistics that are closely related to management objectives (e.g. maximising yield and minimising risk).

A key part of the MSE is the inclusion of uncertainty, and this is introduced through the OM by including parameter estimation error (using e.g. a variance-covariance matrix derived from fitting a model to data,), process error (e.g. in recruitment and survival), observation error (when deriving monitoring data), and implementation error (e.g. introduced by the banking and borrowing scheme). Uncertainty can also be introduced by defining alternative OMs, and from the fact that the estimation model in the MP does not have to be the same as the model the OM is conditioned on.

An important principle in our approach is that uncertainty is included in a self-consistent manner. For example, where 1000 replicates are used, each replicate will represent a single parameter set (typically obtained using a variance-covariance matrix) which represents a replicate population and its associated observation and process error parameters. A stock-recruit function is fitted to a given period of stock-recruit pairs from that replicate and future recruitment is generated for that replicate based on that stock-recruit function (see section 2.3.2). Survival process error will be defined for that replicate and used in projecting its associated population forward in time. Data will be generated from that replicate population based on the observation error parameters for that replicate. In this way, each replicate is self-consistent.

2.3.1 The baseline operating model and alternatives

Because of the amount of time available for the evaluations, pragmatic decisions were made during the first meeting for how to set up the MSE.

We decided to use the current ICES assessment (from the most recent benchmark, or in the case of saithe, from the January/February 2019 inter-benchmark meeting) as the baseline operating model (OM1). This would be the primary focus of the evaluation. The only exception was haddock, where it was demonstrated that SAM was an adequate approximation to TSA used for the ICES assessment, and was therefore used to condition the baseline assessment, while the TSA assessment was used to condition one of the alternative operating models (see haddock section for more details).

The search for combinations of F_{target} and $B_{trigger}$ that maximise long-term yield while fulfilling the ICES precautionary criterion (risk3≤5%), termed here the “optimal” combination, was only conducted for the baseline OM1 for each of the management strategies. Furthermore, because we were conducting full MSEs, each F_{target}-$B_{trigger}$ combination took almost 40 hours to run on a single core (although this time could be greatly improved with parallelised computing). It was therefore not always possible to obtain a full grid of F_{target}-$B_{trigger}$ combinations, and the search was mostly over an incomplete grid, focussing on the area where long-term yield was maximised while simultaneously meeting the precautionary criterion. The details of the search process are provided in the stock-specific sections.

We also considered a number of alternative operating models (OM2, OM3, etc.), which we treated as robustness tests to compare with OM1 (i.e. we would take the "optimal" combination of F_{target} and $B_{trigger}$ derived for each management strategy based on OM1, and check the impact of alternative OMs on the performance of the management strategies for these "optimal" combinations of F_{target} and $B_{trigger}$). It should be noted here that B_{lim} used in the OM (for calculation of the risk performance statistics) was re-estimated, if necessary, for the alternative OMs (i.e. if these OMs required the assessment model to be re-fitted). The B_{lim} used in the OM was therefore specific to that OM.

We also decided to conduct the projections for OM1 based on the same choices for modelling recruitment and other biological and fishery parameters as was made when estimating reference points for each stock (i.e. the same choices as used for EqSim). Details are provided in each stock-specific section, including any deviations from this general approach.

2.3.2 Modelling recruitment

Generally, the approach was to resample residuals (with replacement) from a stock-recruit function (e.g. segmented regression) fitted to stock-recruit pairs from a selected period in the recent past, where the fitting and resampling is done within each replicate. During discussions, concern was raised that this approach left gaps in the way the resampling was conducted, so an approach that smoothed over these gaps was derived. An example R-code to illustrate the approach used is given in the table below. Essentially, the approach fits a kernel density function to the selected residuals, and uses this function to resample for residuals that will be applied to the fitted stock-recruit relationship in future.

Table 2.4. Example R-code for generating smooth residuals.

```
# one start sample
x<-rnorm(20)

# smooth sampling function
smooth.sample <- function(N, x){
  bw <- density(x)$bw
  mu <- sample(x, N, replace = TRUE)
  rnorm(N, mu, sd=bw)
}

# test
xx<-smooth.sample(100000,x)
plot(density(x), lwd=10, col="red")
hist(xx, probability=T, add=TRUE, col="blue", 100)
rug(x, lwd=3)
```

Any deviations from this approach are covered in the stock-specific sections. The presence of significant autocorrelation is investigated, and if significant is included. A validation check is conducted in each case to ensure that recruitment that is generated in future is consistent with that "observed" in the past (for the given period of recruitment and associated SSBs).

2.3.3 Generating data from the Operating Model (observation error)

The general principle for generating data is that the same likelihood formulation that is used to fit to the data when conditioning the operating model would then be used for generating data. This includes any correlations among data that is assumed in the model fit. Details are provided in the stock-specific sections.

The way this has been coded in all cases is that the real historical data are passed to the estimation model in the management procedure (Figure 2.3), and as future data are generated in subsequent time-steps, these are added to the real historical data and they are together passed to the management procedure. Therefore, at the start of the projection period, the estimation model in the management procedure will have almost the identical data that was used in the most recent ICES assessment.

2.3.4 Implementation error (including banking and borrowing)

It is impossible to model exactly the behaviour of the banking and borrowing scheme (described in Annex 3), because we have no way of knowing to what extent it will be used each year, or what underlies the decision to bank/borrow each year. The approach we have taken has therefore been to model an extreme version of banking and borrowing, namely that of alternatively banking and borrowing (cod, haddock, whiting and saithe), or banking first and always borrowing thereafter (herring). The banking and borrowing algorithm used is explained below. Banking and borrowing is applied after the TAC constraint, and is modelled as implementation error (i.e. banking and borrowing does not affect the TAC from year to year, but rather the catch that is associated with the TAC).

Additional implementation error is included for herring because of the uncertainty related to the transfer of quota among fleets and quota uptake. Details of this are provided in the herring section.

Another form of implementation error sometimes encountered during simulations is that the TAC may imply an F in the operating model that is large – the a4a MSE framework includes a cap on F (it cannot exceed 2), which may mean that the catch realised in the operating model differs from that intended by the decision model in the MP. The number of times the cap is implemented is reported in each section (apart from herring where no cap was implemented).

Banking and borrowing algorithm:

Assume banking and borrowing scheme is tested for years 1,2,..., where "1" is the first year of application of the scheme.

Let Yhcr(y) denote the yield (=catch) that direct application of the management strategy gives for year y. It is assumed that the quota for year y is set accordingly (i.e. = Yhcr(y)).

The actual realised yield in year y, Y(y), is calculated by modifying Yhcr(y) to account for banking and borrowing, as follows:

Y(y) = Yhcr(y) (1 + ϱ(y)) – ϱ(y-1) Yhcr(y-1), for y=1,2,....

where ϱ(0)=0 and, for y≥1, ϱ(y) depends on the type of banking and borrowing scenario followed. In order to mimic alternate banking and borrowing, we assume that ϱ(y) = -0.1 for years 1,3,5,..., and ϱ(y) = 0.1 for years 2,4,6,... (cod, haddock, whiting, saithe), and in order to mimic banking first followed by continual borrowing, we assume ϱ(y) = -0.1 for year 1, and ϱ(y) = 0.1 for all subsequent years (herring).

Table 2.5 provides an illustration of what the banking and borrowing would be for the two extreme schemes tested, while Figure 2.4 provides an example application given some hypothetical TACs.

Table 2.5. Realisations of the two extreme banking and borrowing scenarios tested. In the examples shown, H_y represents the TAC from the decision model in year y(and following implementation of any TAC constraints that are applicable for that year).

year	1	2	3	4	5	6
Cod, haddock, whiting, saithe	$0.9H_1$	$1.1H_2 + 0.1H_1$	$0.9H_3 - 0.1H_2$	$1.1H_4 + 0.1H_3$	$0.9H_5 - 0.1H_4$	etc.
autumn-spawning herring	$0.9H_1$	$1.1H_2 + 0.1H_1$	$1.1H_3 - 0.1H_2$	$1.1H_4 - 0.1H_3$	$1.1H_5 - 0.1H_4$	etc.

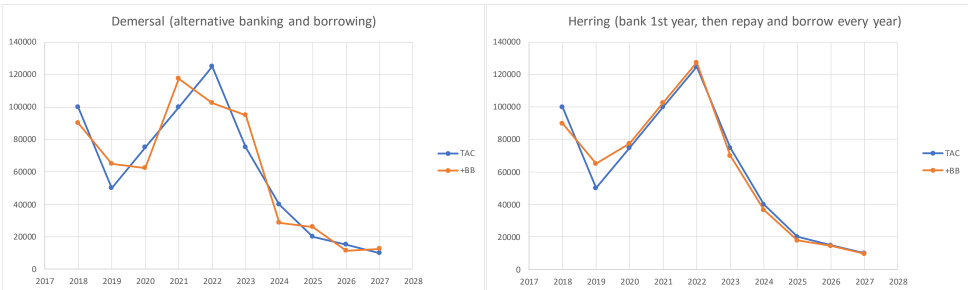


Figure 2.4. An illustration of the banking and borrowing scheme for demersal stocks (cod, haddock, whiting and saithe; left plot) and autumn-spawning herring (right plot) given a series of hypothetical TACs (blue line, same for both cases). The result of the application of the banking and borrowing scheme is shown in orange.

2.3.5 The management procedure

The management procedure is the component of the MSE that houses the estimation model and the decision model. The estimation model receives monitoring data from the operating model, in the same way that an assessment working group would collect data to fit to the assessment model. In our approach, the estimation model is exactly the assessment model that ICES would use to conduct annual assessments (following the stock annex), and would have exactly the same model setting and use exactly the same type of data. It would also incorporate, as far as possible, the same assumptions used for conducting a short-term forecast through the intermediate year to the start of the TAC year, after which the management strategy being evaluated in the decision model takes over for providing the TAC. It was not possible to reproduce the forecast procedure exactly in some cases (e.g. whiting and haddock) because the forecast is based on deterministic multi-fleet forecast software that was not possible to include in the management procedure, so the SAM stochastic forecast approach is used, taking the medians to represent the deterministic forecast. This is assumed to be a reasonable representation of the deterministic forecast. For herring, the forecast procedure was very similar, but not identical, to the one actually used (in reality, the selection pattern from a multi-fleet assessment is used, while the MSE uses proportional catch-at-age to divide the estimated single-fleet selection pattern into four fleets; differences are negligible).

The haddock estimation model in the management procedure is not the same as that used by ICES because it was simply impractical to evaluate TSA (the current assessment model) due of the amount of time this model takes to run, and due to its reliance on manual intervention. In this case, SAM (a closely-related model, both being state-space models) has been used to approximate the behaviour of TSA (see the haddock section for details).

2.3.6 Performance statistics and technical checks

Performance statistics

At a minimum, the request asks for a tabulation of the long-term yield, long-term SSB, interannual TAC variability and risk of SSB falling below B_{lim}, for the management strategies evaluated. We have recorded these performance statistics for the short- (herring: years 1-3, others: years 1-5), medium- (herring: years 4-8, others years 6-10) and long-term (final 10 years of the projection). In addition to these we also show the realised F (compared to F_{MSY} and F_{lim}) and SSB (compared to B_{lim} and B_{pa}).

Our long-term yield is defined as long-term catch, and interannual TAC variability as interannual catch variability (ICV), which would encompass the impact of the banking and borrowing scheme.

Both risk1 (average of the annual probabilities of SSB being below B_{lim} for a specified period) and risk3 (maximum of the annual probabilities of SSB being below B_{lim} for a specified period) has been calculated (ICES 2013), with risk3 being the main one of interest.

ICV has been calculated as follows:

$$ICV = median\ over\ y\ and\ i\ of\ \left|\frac{C_{y+1}^{i}}{C_{y}^{i}} - 1\right|$$

Technical checks

Technical check for the number of replicates for which the estimation model failed at least once in the MP, and for the number of times the cap on F (=2) was breached in the OM, were included, and statistics for these reported. Those replicates which included at least one failure of the estimation model were excluded from the calculation of performance statistics.

2.4 Tools for conducting the MSE

The a4a MSE framework (https://github.com/flr/mse), as developed by the JRC, has been used for four out of the five stocks (cod, haddock, whiting and saithe). Although this framework has not been used for autumn-spawning herring, FLR (Kell *et al.* 2007), which forms the basis of the a4a MSE framework, has been used in this case. All code has been stored on GitHub via the ICES TAF facility (https://github.com/ices-taf/wk_WKNSMSE).

2.5 Minimum requirements for MSE

The ICES MSE summary template was filled in for all stocks, and is given in Annex 5. This template helped ensure that the minimum requirements for conducting MSEs were carried out. Furthermore, several participants in this work attended the WKGMSE2 meeting (ICES 2019a), and the chair presented an outline of the work and approach used at this meeting, receiving a positive response and some useful input (e.g. regarding reference points for alternative OMs).

2.6 Discussion

This workshop was the first time that so many full MSEs were undertaken under one umbrella, an ambitious undertaking for any organisation. A full MSE means that the ICES assessments and forecasts, as conducted annually for each stock, are included in the simulation loop (resulting in 20000 assessments and forecasts for each management strategy tested based on 1000 replicates and a 20-year projection period). This posed some challenges for finding an "optimum" on an F_{target}-$B_{trigger}$ grid, and these have been reflected in the recommendations for future similar undertakings (Section 2.8). Several other issues were raised during this work, as discussed below.

Number of projection years

The number of projection years to use in the MSE was explored for cod, and to a limited extent for autumn-spawning herring (see those sections for more details). The conclusion of these investigations was that a 20-year projection period was long enough that the effects of initial numbers had largely disappeared by the time the long-term phase had been reached (final 10 years) and median SSB had stabilised; a 20-year period was therefore deemed adequate for our purposes, and this was adopted for all stocks considered.

Nevertheless, it was discovered that, even though the median of SSB stabilises in the long-term, the 5th percentile of the distribution does not necessarily stabilise. Figure 2.5 plots annual risk ($P(SSB<B_{lim})$) for the five stocks, which shows that for whiting and herring, there appears to be a trend in the medium- and long-term periods, which is not present to the same extent for cod, haddock and saithe. This may be due to the inclusion of auto-correlation in recruitment for whiting and herring that is not included for the other stocks; the additional inclusion of auto-correlation in biological parameters and the modelling of fishery selectivity as a correlated random walk may also contribute to this feature for herring. Extending the projections for a further 20 years for herring (for 200 replicates only) indicated the trend continued (see herring section for further details).

Results continue to be presented on the basis of a 20-year projection, where the long-term period (final 10 years) is used for "optimising" the management strategies, but the above feature should be noted; however, it should also be noted that results can be used to make relative comparisons among management strategies for the long-term period (final ten years), regardless of the above feature.

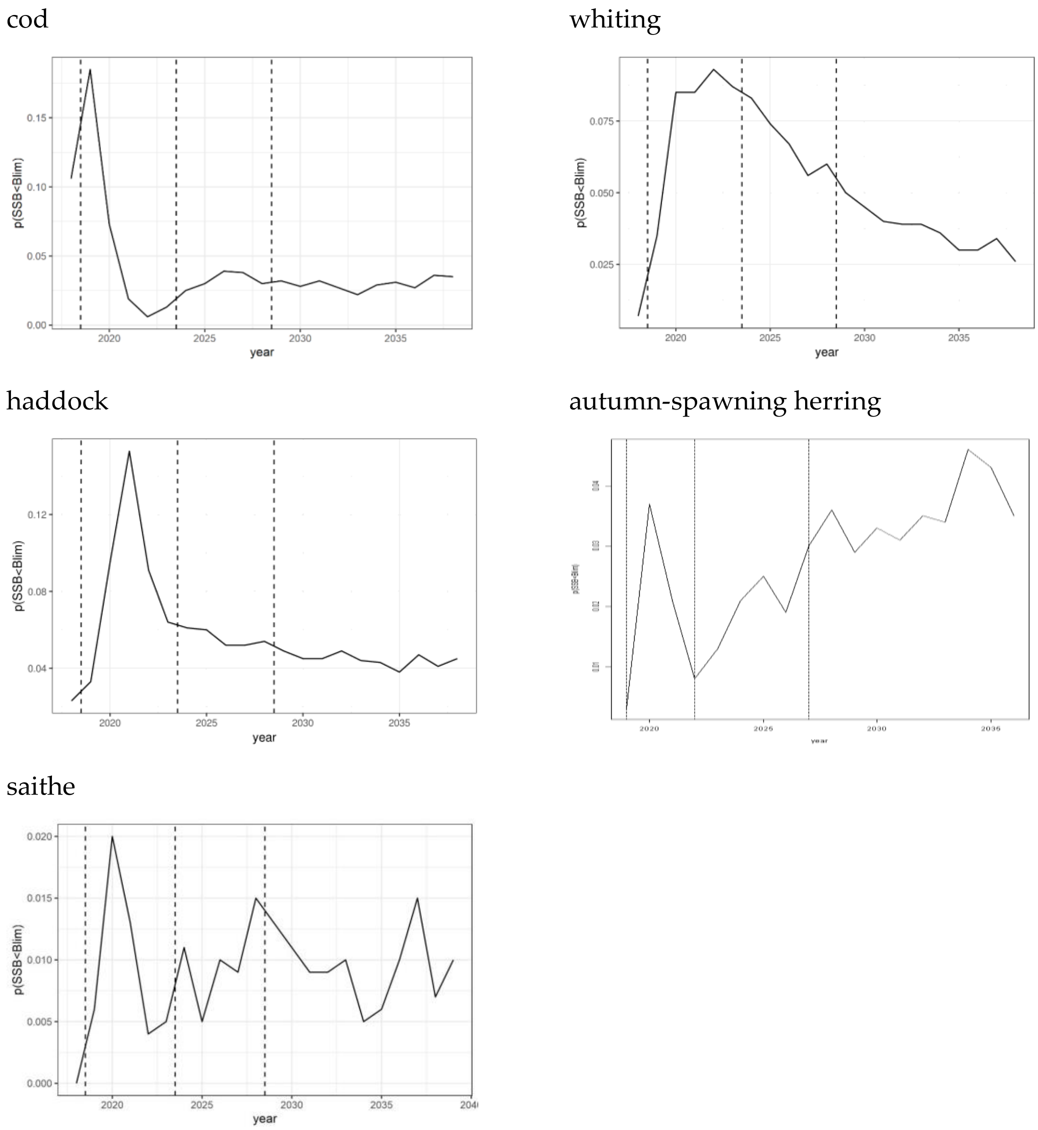


Figure 2.5. Annual risk (P(SSB<B_{lim})) for “optimised” management strategy A (except for herring, where F_{target}=0.23 and $B_{trigger}$=1.4MT were used for A instead of the “optimised” combination). The horizontal hashed lines separate the short- medium- and long-term projection periods used for the performance statistics for each stock. A total of 1000 replicates were used to produce these plots.

Number of replicates

The number of replicates to use in the MSE was explored for cod, and to a limited extend for autumn-spawning herring (see those sections for more details). Current guidelines suggest 1000 replicates should be the default. The conclusion of these investigations (based on considering risk1) was that 1000 replicates were adequate for our purposes, and this was adopted for all stocks considered.

However, on closer inspection (Figure 2.6), it appears that risk3 was both positively biased and relatively slow to converge, features that were noted by ICES (2013). Furthermore, it is not clear whether, even for a case which appears to stabilise (cod in Figure 2.5), risk3 will converge to risk1 (right-most plot in Figure 2.6, although note that the values are quite low). Given that risk3 becomes increasingly positively biased the lower the number of replicates, and given that risk3>risk1, by definition, the use of risk3 with 1000 replicates can be considered a conservative approach.

ICES defines risk3 as the appropriate measure for precaution, and we have adopted that for "optimising" the management strategies in all cases, based on 1000 replicates.

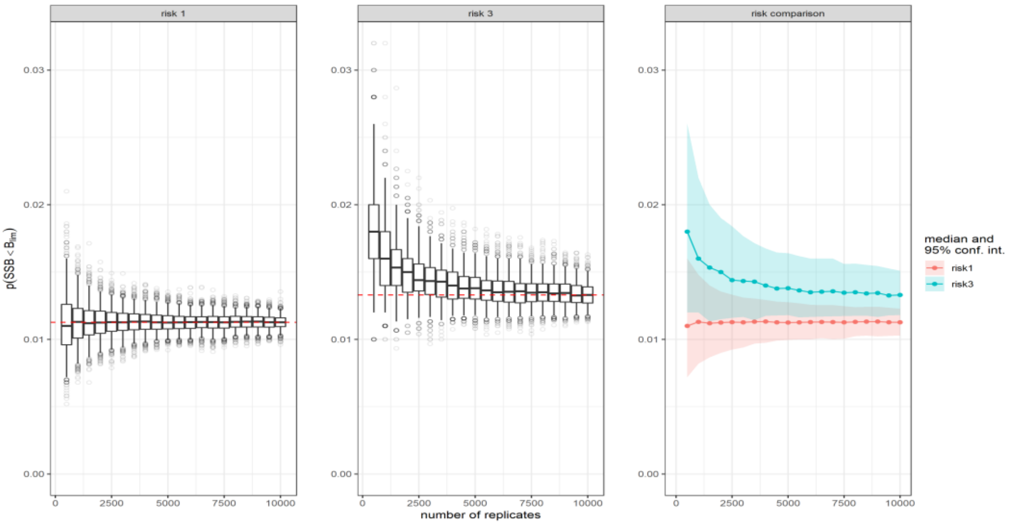


Figure 2.6. Calculation of risk1 (i.e. the average of the annual P(SSB<B_{lim})) and risk3 (i.e. the maximum of the annual P(SSB<B_{lim})) for years 11-20 of the projection period. A total of 10000 replicates based on OM1 and management strategy A* for cod were projected forward in time (see cod section for more details). The y-axis gives the distribution of 1000 calculations of risk1 (first plot) and risk3 (second plot), where each calculation uses the number of replicates shown on the x-axis that were re-sampled with replacement from the original 10000 replicates. In the box and whisker plots, the heavy horizontal line within the box indicates the median, the edges of the box the 25th and 75th percentiles, the whiskers the 2.5th and 97.5th percentiles, the remaining points the circles outside the whiskers, and the red hashed lines the median for 10000 replicates. The final plot combines the other two plots with linked dots indicating the medians, and shaded areas the 95% confidence bounds.

Precaution in the short- and long-term

Finding a management strategy precautionary in the long-term did not necessarily mean it was precautionary in the short term, even for a stock like saithe, that is considered to be in a healthy state currently (well above MSY $B_{trigger}$). Nevertheless, there are certain management strategies that have features in them (such as HCR B, with extra protection immediately below B_{lim}) that, when optimised for the long-term, can allow higher exploitation than otherwise (e.g. compared to HCR A) that ultimately affects short-term performance. In the saithe example, both A and B are precautionary in the long-term, but only A is precautionary in the short-term because its "optimised" combination of F_{target} and $B_{trigger}$ implies lower exploitation to start with compared to B.

In the case of cod, there exists no management strategy (not even F=0) that is precautionary in the short-term, simply because the stock is currently close to B_{lim}. Similarly, for whiting, none of the management strategies explored were precautionary in the short-term, although in this case F=0 would be precautionary in the short-term.

MSE and EqSim reference points

There are several differences between the MSE framework used here and EqSim that mean reference points between the two frameworks are likely to differ, despite making similar assumptions about biological parameters and recruitment. These differences include that the MSE is a much more comprehensive framework for handling uncertainty and includes the actual implementation of the ICES assessment and forecast, although EqSim performs a much longer projection. Table 2.6 highlights the $F_{P.05}$ value that can be extracted from the MSE for management strategy A* (which is similar to the ICES MSY approach for the stock, and the same as the advice rule used in EqSim), and compares this to the EqSim-based F reference points. In all cases except haddock, $F_{MSY\text{-upper}}$ (where available) would no longer be considered precautionary, and in the case of whiting, none of the EqSim-based reference points would be considered precautionary, and for herring, F_{MSY} would not be considered precautionary.

Table 2.6. Comparing fishing mortality reference points from the MSE (based on HCR A*, which is similar to the ICES MSY approach rule) and from EqSim. Those reference points not considered precautionary are coloured red. For the MSE reference point $F_{P.05}$, where a range is supplied, it is because the search grid is only partially filled in, so possible values are indicated.

Stock	**MSE** $F_{P.05}$	$F_{MSY\text{-lower}}$	**EqSim** F_{MSY}	$F_{MSY\text{-upper}}$
Cod	0.37	0.198	0.31	0.46
Haddock	0.23-0.26	0.167	0.194	0.194
Whiting	0.10-0.11	0.158	0.172	0.172
Saithe	0.37-0.42	0.210	0.363	0.536
Autumn-spawning herring	0.22	N/A	0.26	N/A

Ability to recover from low stock size

The MSEs conducted largely did not explore the lower end of the HCRs (region below B_{lim}; see Figures 2.1 and 2.2), resulting in not much discrimination between A and C, for example. In order to investigate further differences between A, B and C, and also test whether these HCRs were able to recover the stock from a very low stock size, additional projections were conducted for cod. Results indicated that when the stock was forced to a very low SSB (with recruitment failure), HCRs A, B and C reacted appropriately by reducing catch, and all three HCRs were able to recover the stock once recruitment improved. As expected (Figure 2.1), A is the most precautionary followed by B and C, with recovery to above B_{lim} being delayed for the latter two compared to A.

Discontinuities in the rule

Discontinuities exist in HCR B (the sudden drops shown in Figures 2.1 and 2.2), which is considered bad practice. This is because of the increase in variability to annual advice it introduces, and the arguments that ensue about which side of the cliff-edge the stock is. For this reason, discontinuities or sharp changes in HCRs are not recommended.

There are also sharp changes related to the application (or not) of the stability mechanisms, but the effect of these changes was not explored.

2.7 General conclusions

This MSE work on five North Sea stocks was an ambitious undertaking, and arguably not sufficiently resourced, both in terms of the time available to carry out the work, and the computing resources needed for high-performance computing. Both of these issues need to be addressed in any future, similar undertaking.

The a4a MSE framework used for four of the five stocks, and supported by the JRC, and the use of ICES' GitHub TAF facility worked well and meant that code could be shared amongst analysts (thus saving large amounts of time), facilitated easier cross-checking of code, and allowed all participants to freely check the code if they wished. Including relatively diverse stocks in this work also enhanced sharing of ideas and experience.

Stock-specific conclusions are covered in each of the stock sections.

2.8 Recommendations

It is recommended that:

- Guidelines be developed for when and how reference points should be extracted from an MSE when one is conducted. [ACOM]
- Guidelines be developed for how to treat the results of alternative operating models. In the current MSE approach, these have been used as robustness tests on the "optimised" combination for each management strategy. [ACOM]
- The relationship between estimated risk and assumed levels of uncertainty included in the MSE be investigated. Risk and uncertainty are closely related, and including more uncertainty affects the estimated level of risk from the MSE. [ACOM]
- More efficient ways of conducting searches over a grid to the required level of precision be investigated. This is needed because of the high-performance computing requirements for full MSEs. This work could include investigating statistical properties that relate sample size to required precision, GAMs to interpolate over an incomplete grid, etc. [WGMG, WKGMSE]
- The provision of high-performance computing facilities be investigated to ensure resources for conducting full MSEs are available when required. This was a significant problem for the work of WKNSMSE, caused substantial delays in obtaining results and limited the scope of the work [ACOM]

3 Cod (*Gadus morhua*) in Subarea 4, Division 7.d, and Subdivision 20 (North Sea, eastern English Channel, Skagerrak)

3.1 Baseline operating model (OM1)

3.1.1 Model and settings

The baseline operating model was conditioned on the latest SAM assessment for North Sea cod (ICES 2018a). For simulations, the assessment-estimated catch multipliers for the years 1993–2005 were used to adjust the catch in those years and estimation of the multipliers subsequently removed. The following plots show the assessment summaries and fits to data.

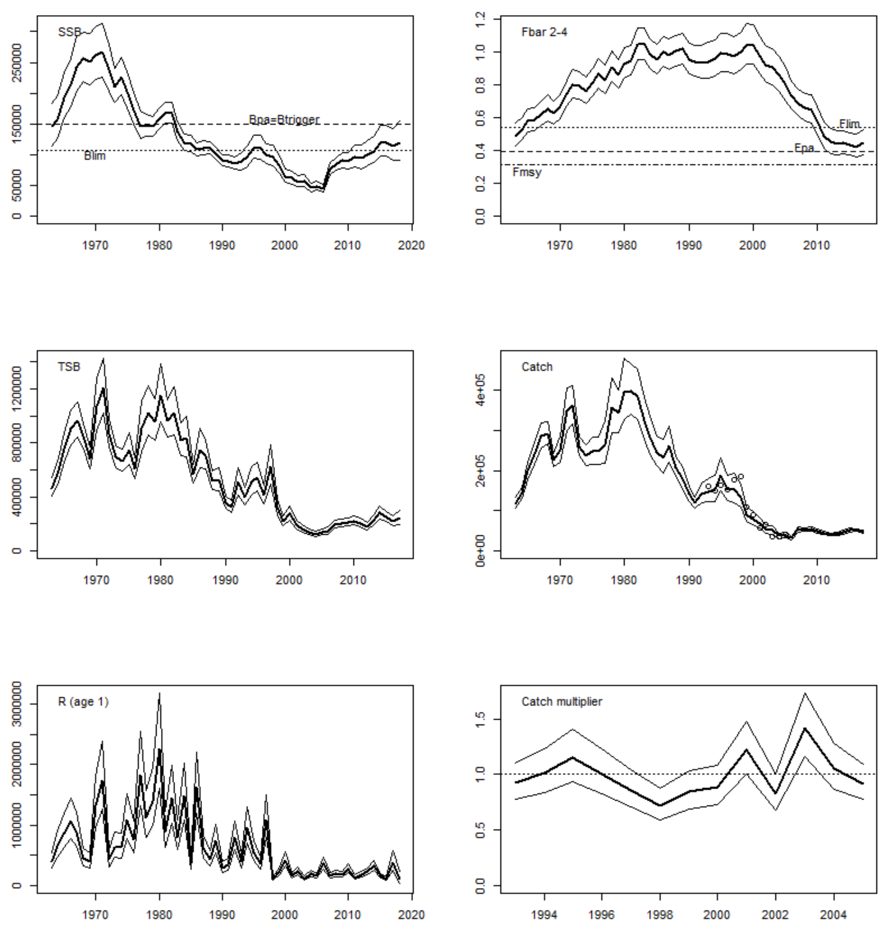


Figure 3.1.1. Cod in Subarea 4, Division 7.d and Subdivision 20: Anticlockwise from top left, point-wise estimates and 95% confidence intervals of spawning stock biomass (SSB), total stock biomass (TSB), recruitment (R(age 1)), the catch multiplier, catch and mean fishing mortality for ages 2–4 (F(2–4)), from the SAM final run (catch multiplier estimated for 1993–2005 only). The heavy lines represent the point-wise estimate, and the light lines point-wise 95% confidence intervals. The open circles given in the catch plot represent model estimates of the total catch excluding unaccounted mortality, while the solid lines represent the total catch including unaccounted mortality for 1993–2005. The horizontal broken lines in the SSB plot indicate Blim=107 000t and Bpa=150 000t, and in the Fbar plot Flim=0.54, Fpa=0.39 and Fmsy=0.31. The horizontal broken line in the catch multiplier plot indicates a multiplier of 1. Catch, SSB and TSB are in tonnes, and R in thousands.

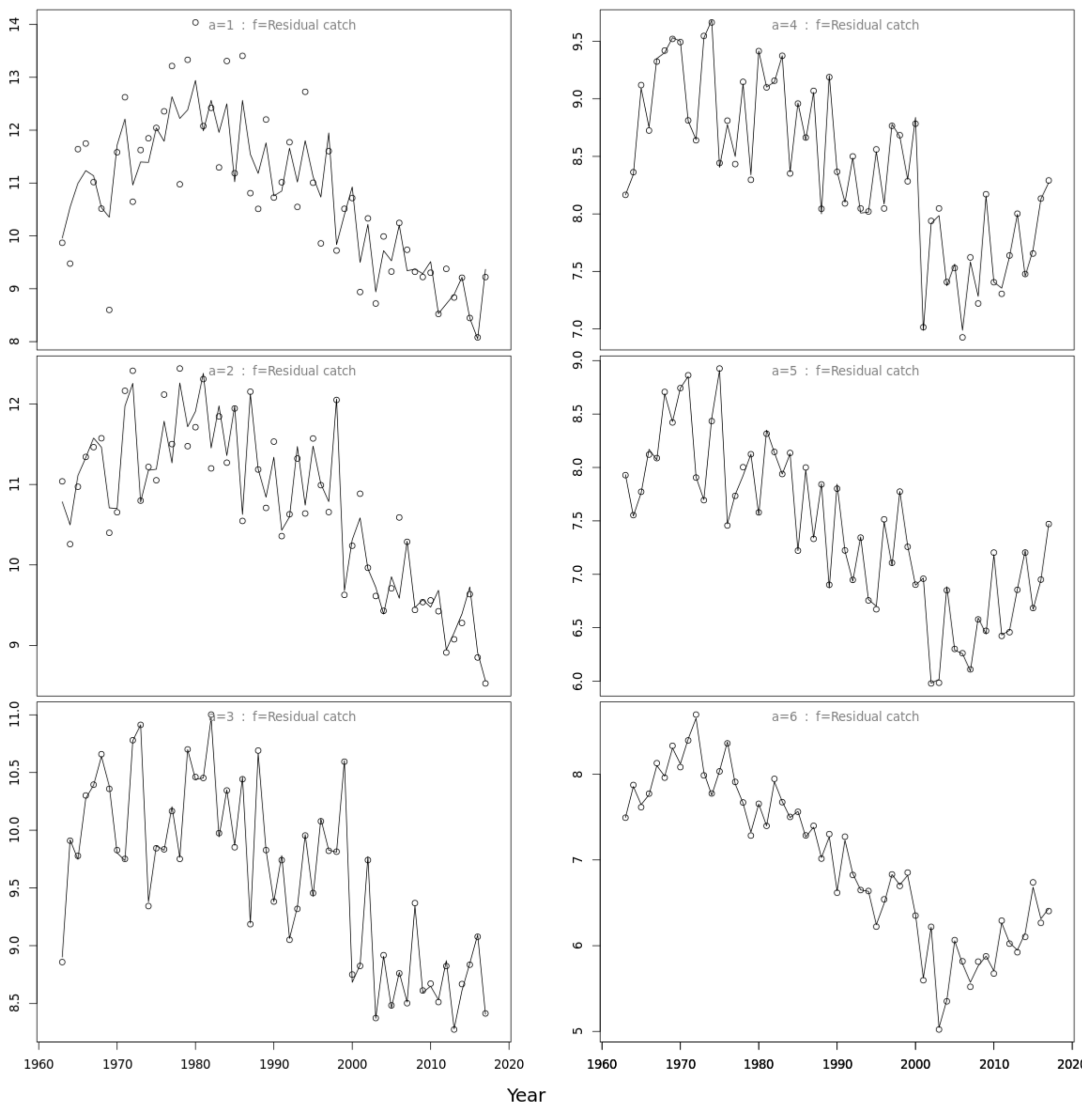


Figure 3.1.2. Cod in Subarea 4, Division 7.d and Subdivision 20: Fits to catch-at-age data.

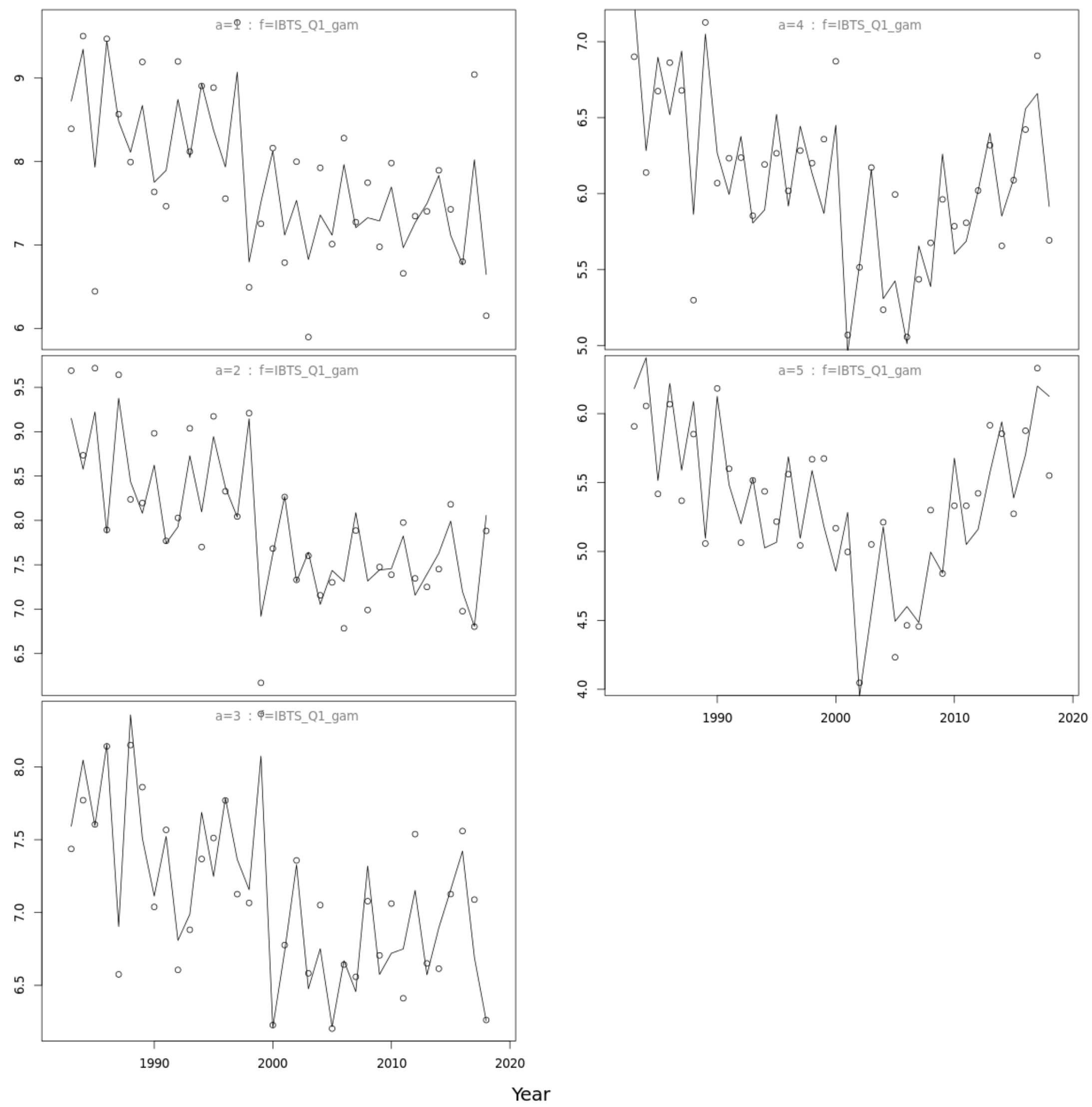


Figure 3.1.3. Cod in Subarea 4, Division 7.d and Subdivision 20: Fits to the IBTS–Q1 survey data.

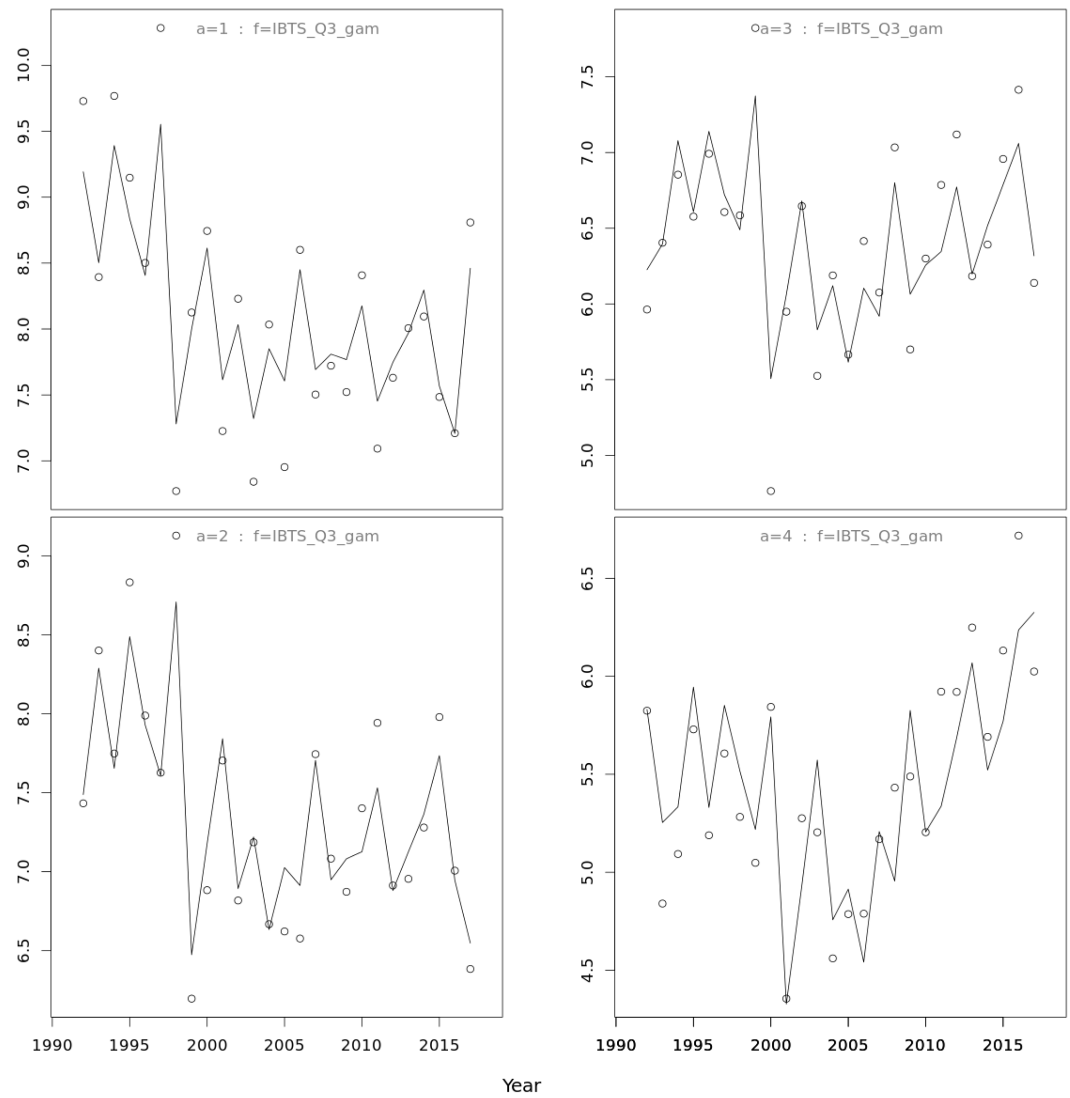


Figure 3.1.4. Cod in Subarea 4, Division 7.d and Subdivision 20: Fits to the IBTS–Q3 survey data.

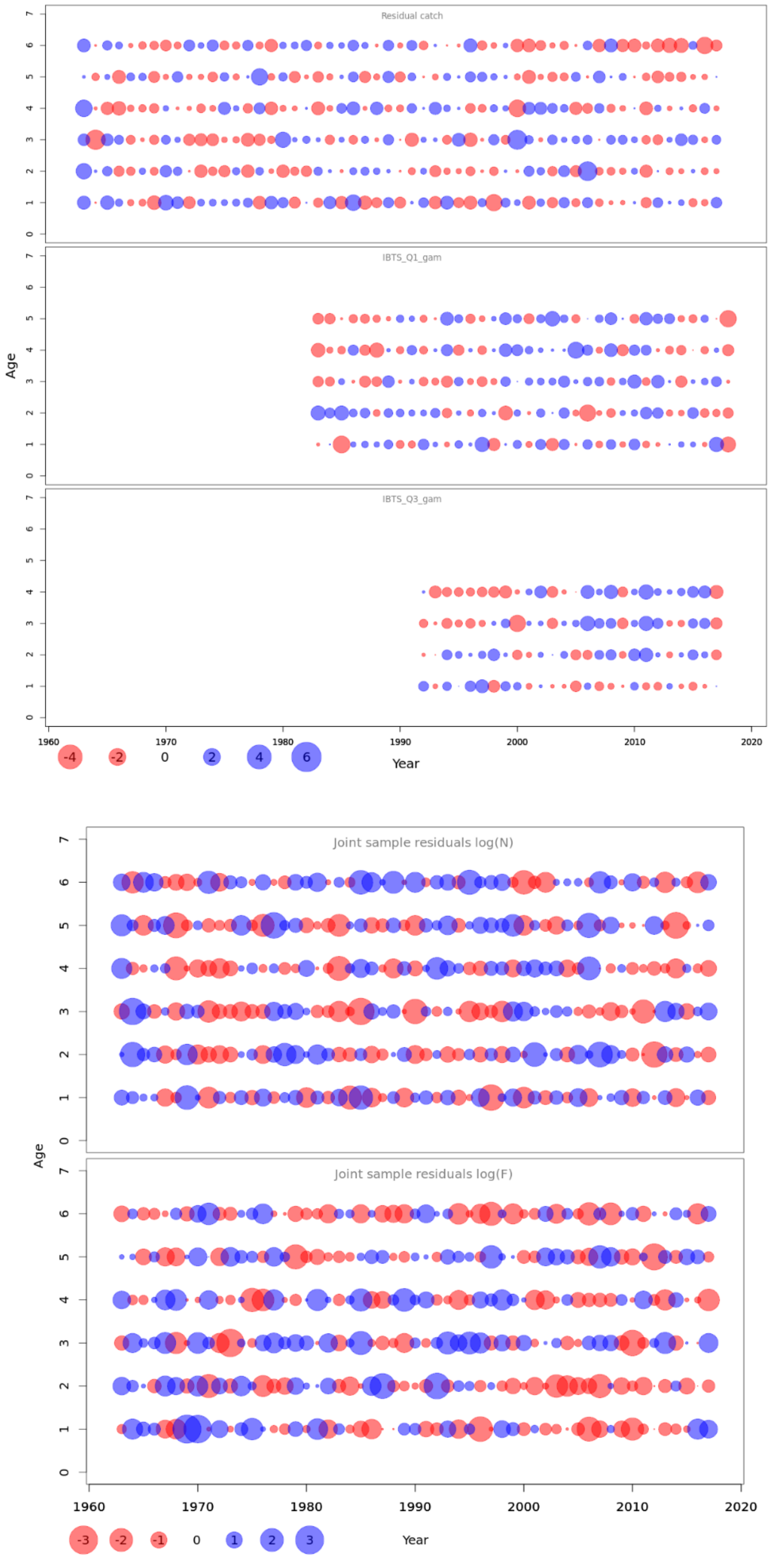


Figure 3.1.5. Cod in Subarea 4, Division 7.d and Subdivision 20: Normalized residuals for the SAM assessment, for total catch, IBTS–Q1, IBTS–Q3, the recruitment and survival process error, and the fishing mortality process error. Blue circles indicate a positive residual and red circles a negative residual.

3.1.2 Parameter uncertainty

Parameter uncertainty, including survival process error, is derived from the variance-covariance matrix of the estimable parameters from the SAM assessment. The variance-covariance matrix was used to derive 1000 parameter sets resulting in 1000 North Sea cod replicates reflecting the historical and current status of the stock and associated uncertainty.

3.1.3 Recruitment

Recruitment was generated based on a segmented regression curve from 1998 onwards. Although reference points for North Sea cod were calculated based on the period 1988+ (ICES 2015a), the very low recruitment period from 1998 is used as a precautionary check of the F_{MSY} range and to conduct short term forecasts. An alternative operating model (OM2) considers the period 1988+.

A segmented regression curve was fit to each of the 1000 replicates individually. The breakpoint of the segmented regression was estimated and there were only two replicates where the breakpoint was estimated to the right of the stock-recruit pairs. Residuals for future recruitments were drawn from smoothed distributions of the residuals for each replicate. Autocorrelation was not included because it was not significant (Figure 3.1.7).

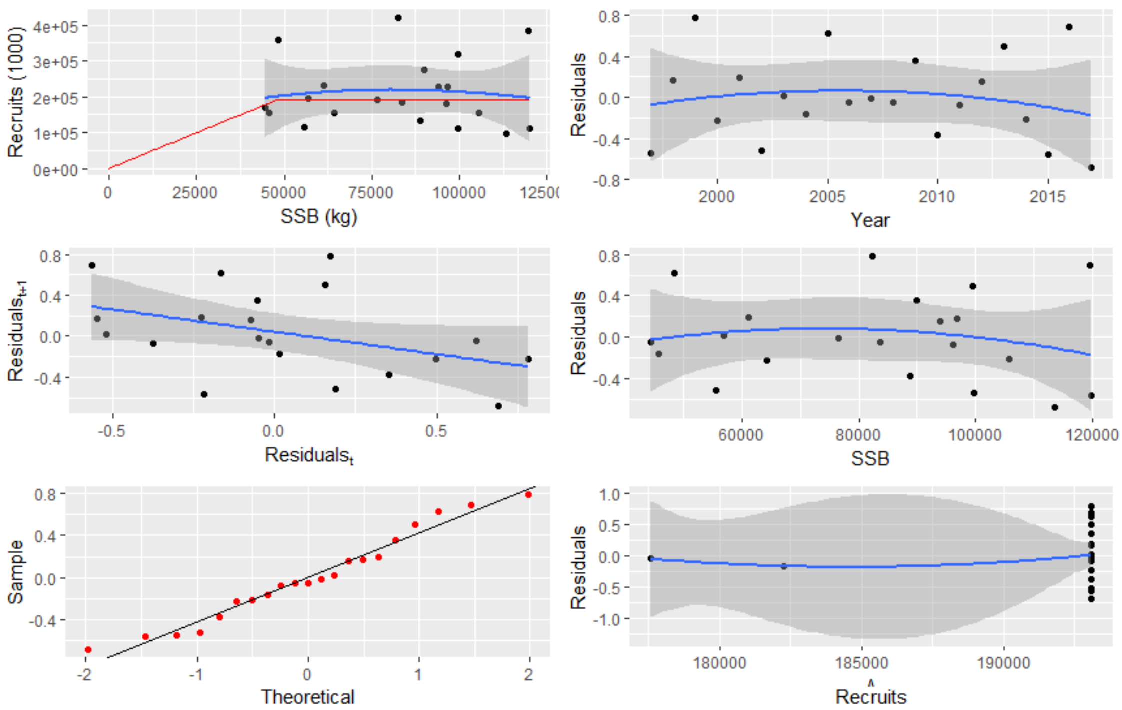


Figure 3.1.6. Cod in Subarea 4, Division 7.d and Subdivision 20: Fit of the segmented regression stock-recruit relationship to the original assessment point estimates for the recruitment period 1998+.

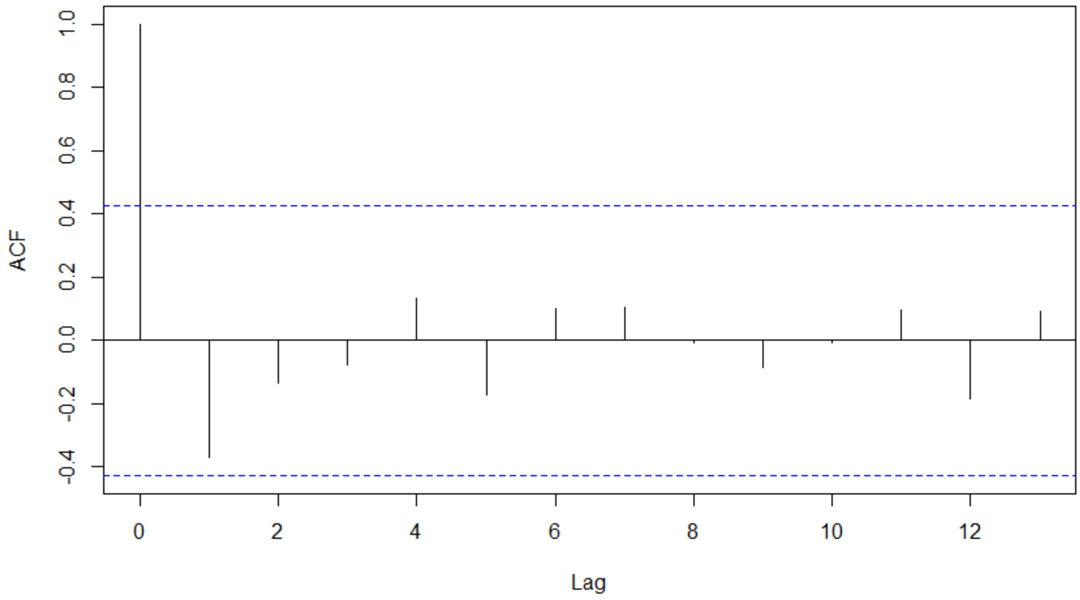


Figure 3.1.7. Cod in Subarea 4, Division 7.d and Subdivision 20: Autocorrelation function applied to the assessment estimates of recruitment for the period 1998+.

Figures 3.1.8-10 compare generated recruitments with corresponding (i.e. based on the same SSB) historical recruitments and indicate that the approach followed provides a plausible basis for generating recruitment.

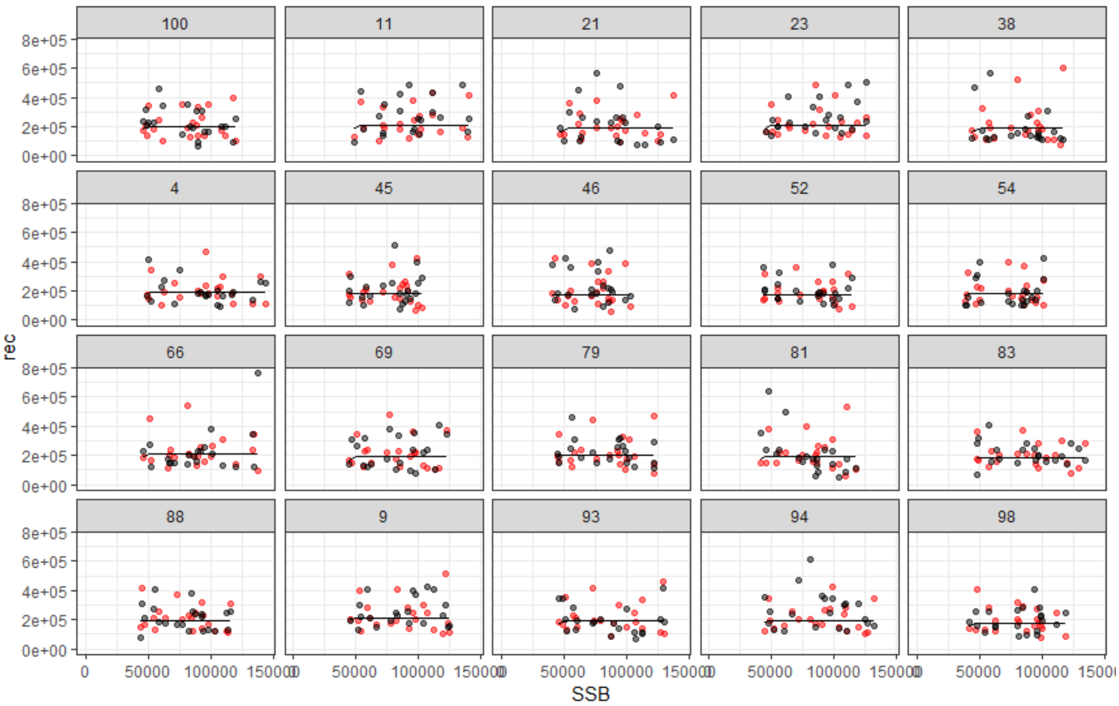


Figure 3.1.8. Cod in Subarea 4, Division 7.d and Subdivision 20: Historic stock-recruit pairs (red dots), with stock recruit relationships fitted to these (black lines) and generated recruitments (black dots) for a subset from 100 simulations.

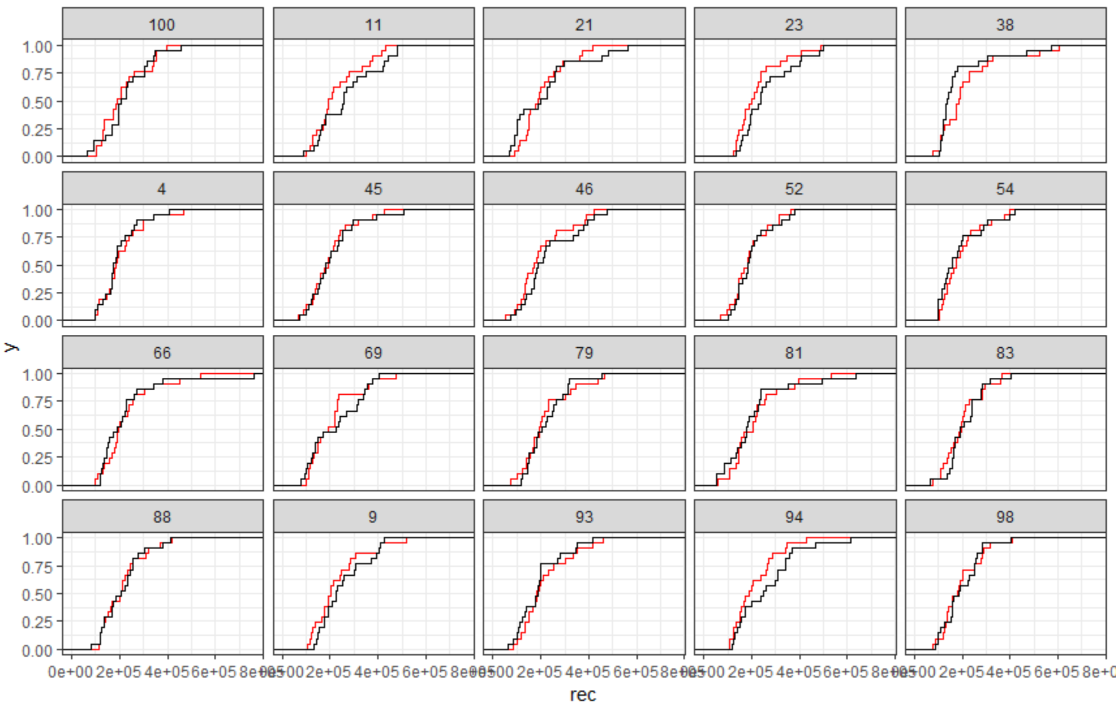


Figure 3.1.9. Cod in Subarea 4, Division 7.d and Subdivision 20: A comparison of historical and generated recruitments using empirical cumulative distribution function (ecdf in R) for the stock recruit pairs shown above.

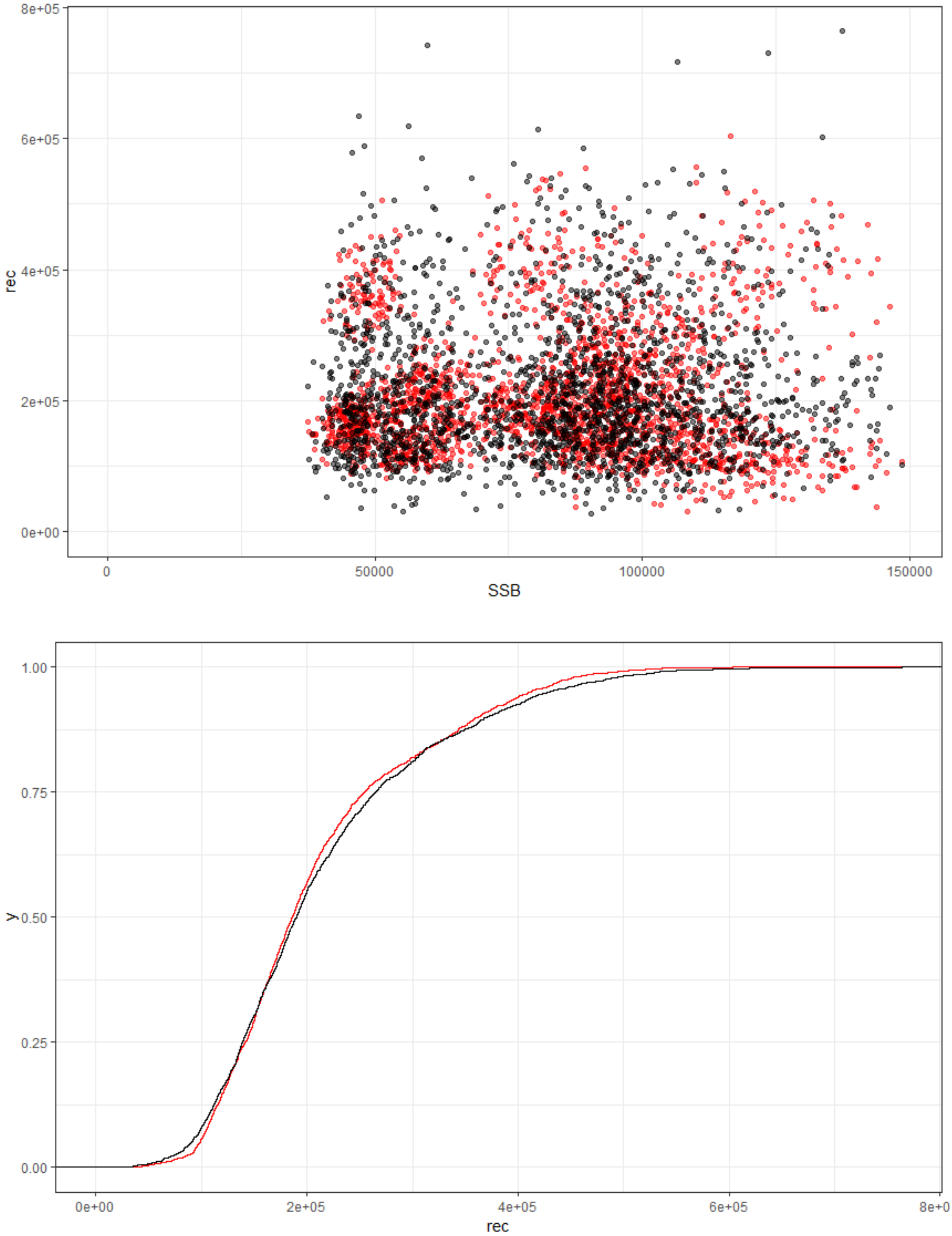


Figure 3.1.10. Cod in Subarea 4, Division 7.d and Subdivision 20: An overall comparison of historical (red) and generated (black) recruitment combining all 100 replicates.

3.1.4 Mean weights, maturity, natural mortality and selection

Simulation of biological parameters follows the same assumptions as in the estimation of reference points. Reference points for North Sea cod were last updated in 2017 (ICES 2017) on the same basis as for ICES (2015a; see WD2 in Annex 8 of that report). Future mean weights, maturity and natural mortalities were modelled by selecting a year at random with replacement from the period 2013–2017 for each future year and allocating the biological parameters for all ages in that year to the given future year. This process was done independently for each replicate and is consistent with the EqSim approach for estimating reference points, where a five-year time period was chosen for North Sea cod due to the increasing trends in mean weights and natural mortality observed at the time (ICES 2015a, WD2 in Annex 8 of that report). The only exception to this is maturity in 2018, for which IBTS–Q1 data are available.

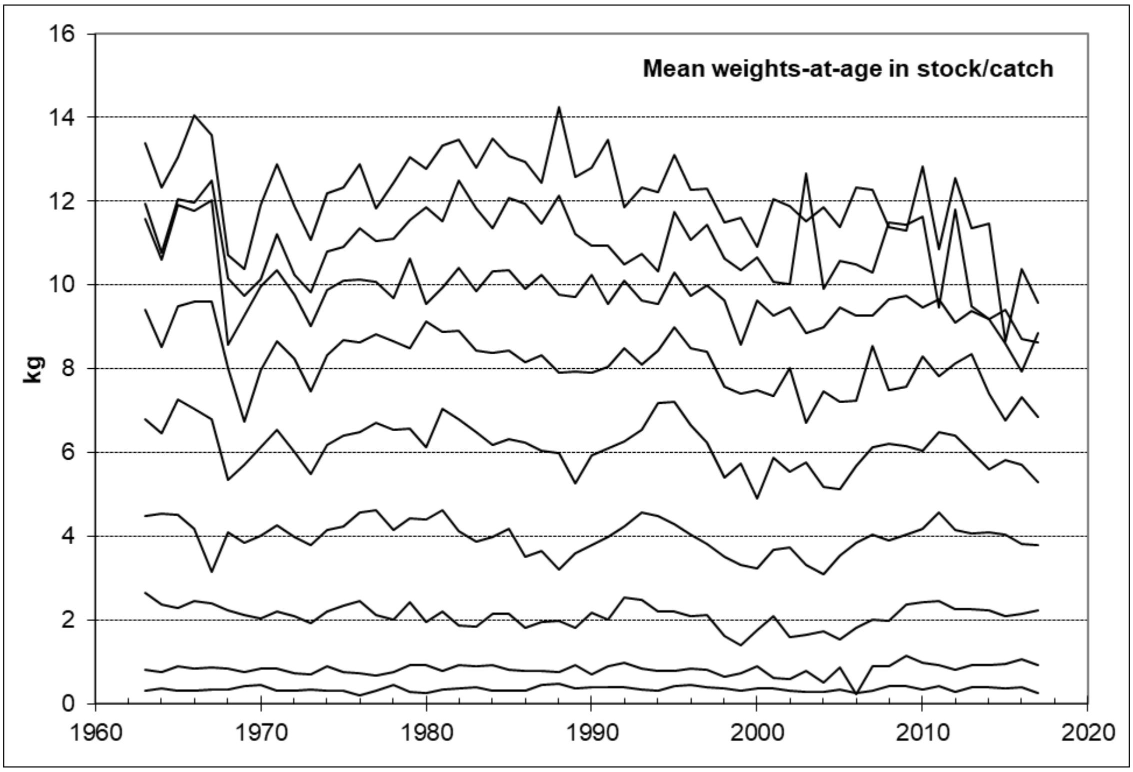


Figure 3.1.11. Cod in Subarea 4, Division 7.d and Subdivision 20: Mean weight at age in the catch for ages 1–9.

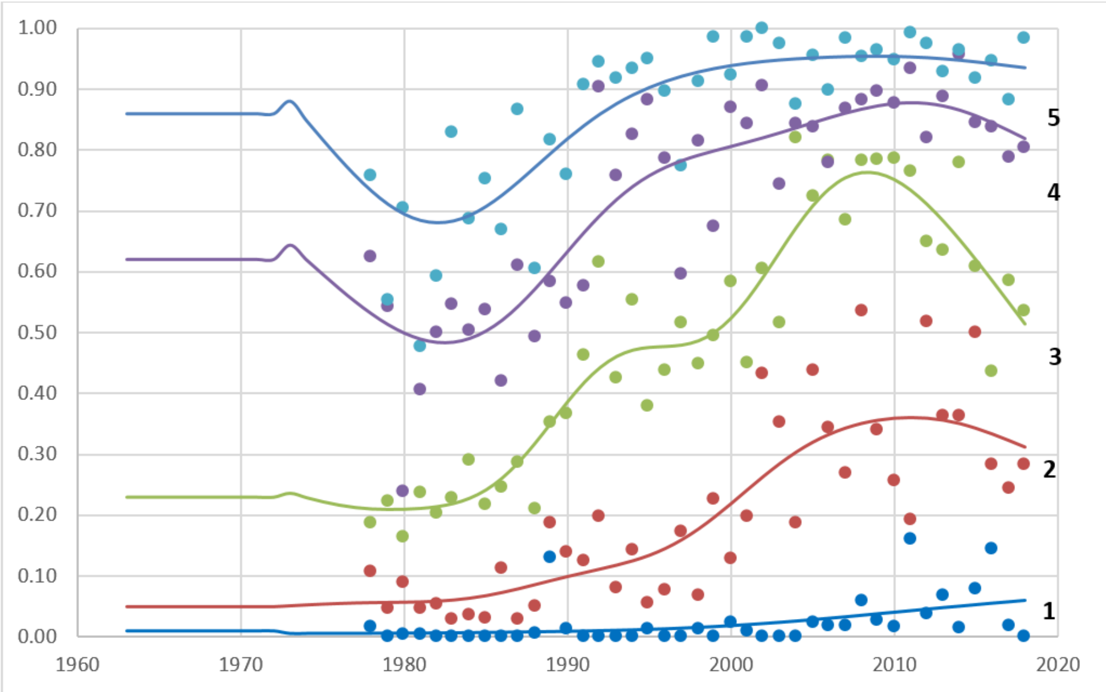


Figure 3.1.12. Cod in Subarea 4, Division 7.d and Subdivision 20: Annually varying maturity-at-age. Dots are the raw values estimated from IBTS–Q1 data while lines are the smoothed values that feed into the assessment. Values for 1963–1972 are the former constant maturity values used for cod.

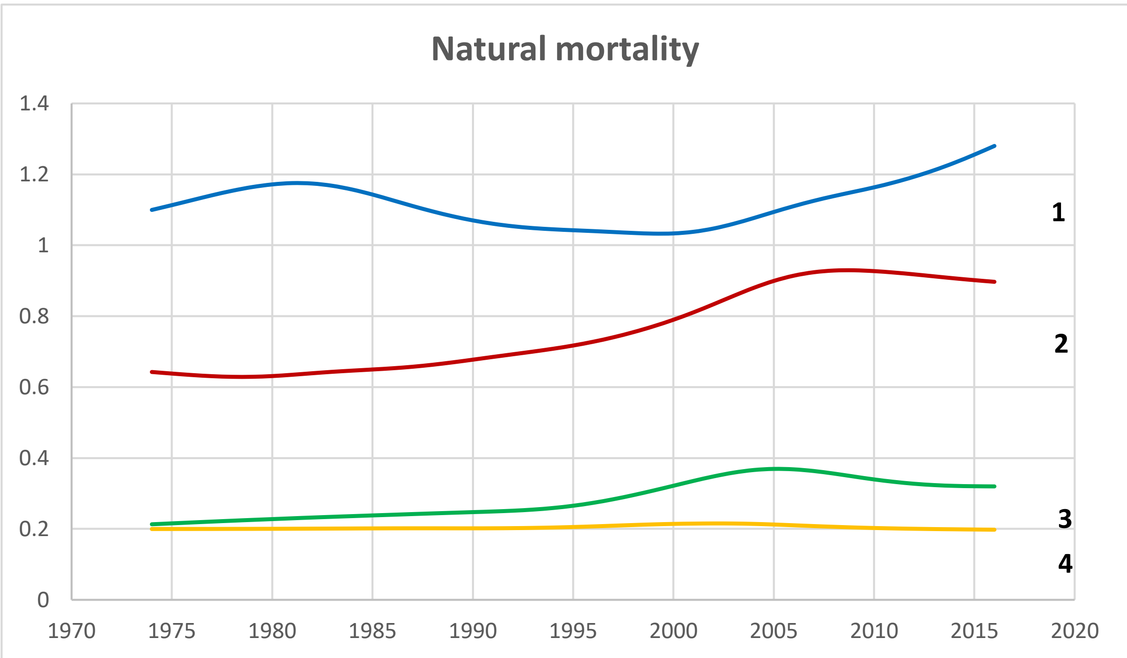


Figure 3.1.13. Cod in Subarea 4, Division 7.d and Subdivision 20: Smoothed, annually varying natural mortality from the 2017 key run (ICES 2018b). Values for 1963–1972 are set equal to the 1973 value, while 2017 is set equal to 2016.

Selection is also resampled with replacement from the period 2013–2017 but separately to the biological parameters, following the EqSim approach for estimating reference points. Although no change in exploitation pattern was detected in the preceding 10 years, a five-year time period was chosen to avoid the years 2004–2005, which had substantial unallocated removals (ICES 2015a, WD2 in Annex 8 of that report).

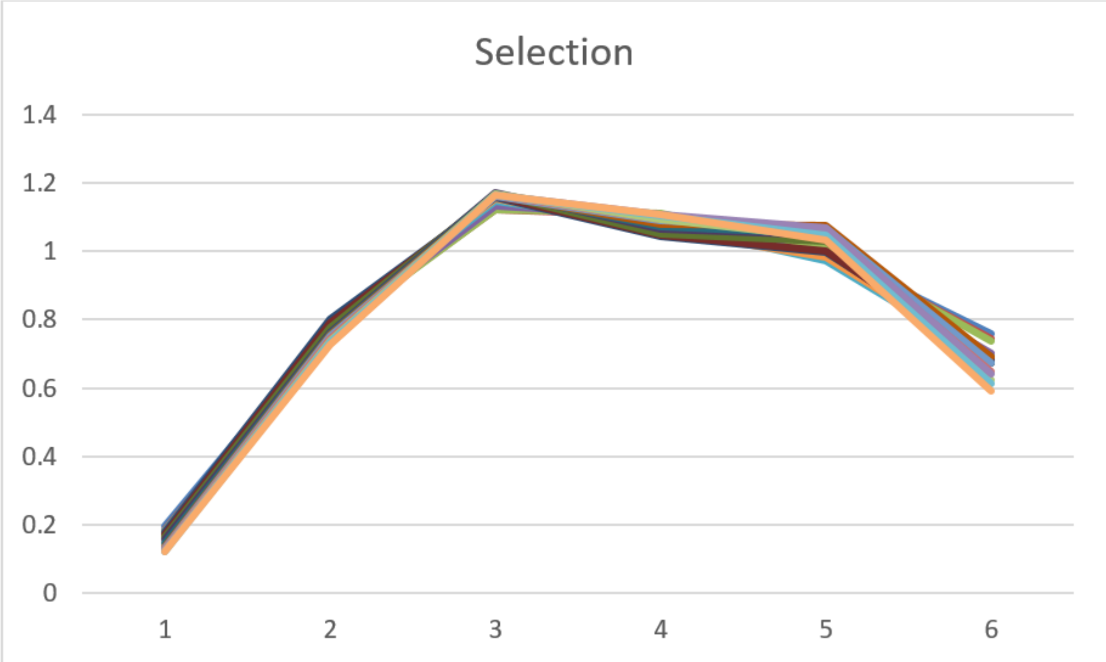


Figure 3.1.14. Cod in Subarea 4, Division 7.d and Subdivision 20: Selection pattern for the years 2000–2017.

3.1.5 Generating data from the operating model

Catch was generated when projecting the stock with the fwd function in FLR package FLash. Catches from the operating model were multiplied by an error term $e^{\varepsilon_{a,y}}$ when being passed to the management procedure, where $\varepsilon_{a,y} \sim N(0, \sigma_a^2)$ and σ are observation standard deviations for catch as estimated by SAM.

Survey observations were generated from the operating model as follows:

$$I_{a,y,i} = q_{a,i} N_{a,y} e^{-t_i Z_{a,y}} \, e^{\varepsilon_{a,y,i}}$$

where N and Z are stock numbers and total mortalities from the operating model, the a, y and i subscripts denote age, year and survey (IBTS-Q1 or IBTS-Q3) respectively, q are survey catchabilities and $\varepsilon_{a,y,i} \sim N(0, \sigma_{a,i}^2)$ with σ standard deviations as estimated by SAM, and t is the timing of the survey (0.125 for Q1 and 0.625 for Q3) (Nielsen and Berg 2014).

Biological parameters for the management procedure were taken as the mean of those parameters in the operating model for the years 2013–2017.

3.1.6 Implementation error

Banking and borrowing has been introduced as implementation error. Once the management strategy produces a TAC, this TAC is adjusted by the effects of the banking and borrowing scheme (see Annex 3). Implementation error also occurs because of a cap on the operating model F of 2.

3.1.7 Number of replicates and projection years

The number of replicates to be used for the MSE was justified using an MSE with 10000 replicates (based on OM1 and management strategy A*). Figure 3.1.15 gives the distributions of risk1 (i.e. average P(SSB<B_{lim})) calculated for a set period of years and for increasing numbers of replicates resampled 1000 times each. Although this performance statistic is quite variable in the short-term, 1000 replicates appeared to be an adequate number for the period of interest (years 11-20 of the projection period).

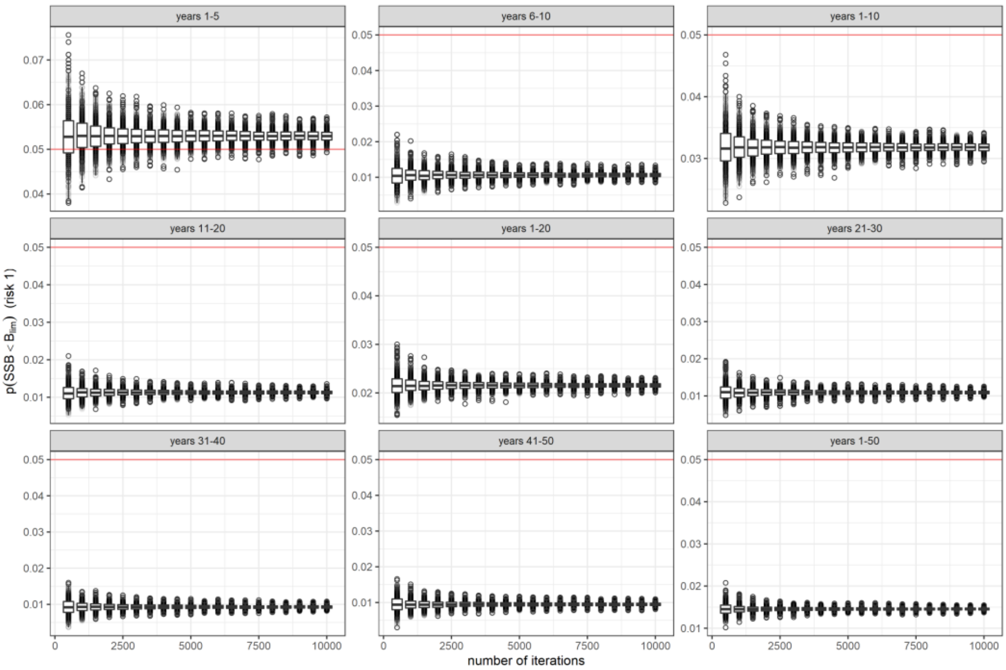


Figure 3.1.15. Calculation of risk1 (i.e. the average annual P(SSB<B_{lim})) for a given range of years. A total of 10000 replicates based on OM1 and management strategy A (with F_{target}=0.31 and $B_{trigger}$=150000, labelled A*; note that this is not the "optimal" combination of these control parameters), were projected forward in time. The y-axis gives the distribution of 1000 calculations of risk1, where each calculation uses the number of replicates shown on the x-axis that were resampled with replacement from the original 10000 replicates.

The number of years to use in the projection period was also investigated by projecting the operating model (OM1) forward with F=0, and based on management strategy A (Figure 3.1.16). The F=0 projection indicates that SSB reaches a plateau within a 20-year projection period, and following management strategy A for an arbitrary combination of F_{target} and $B_{trigger}$, this is reached even sooner. A projection period of 20 years was therefore considered adequate for cod.

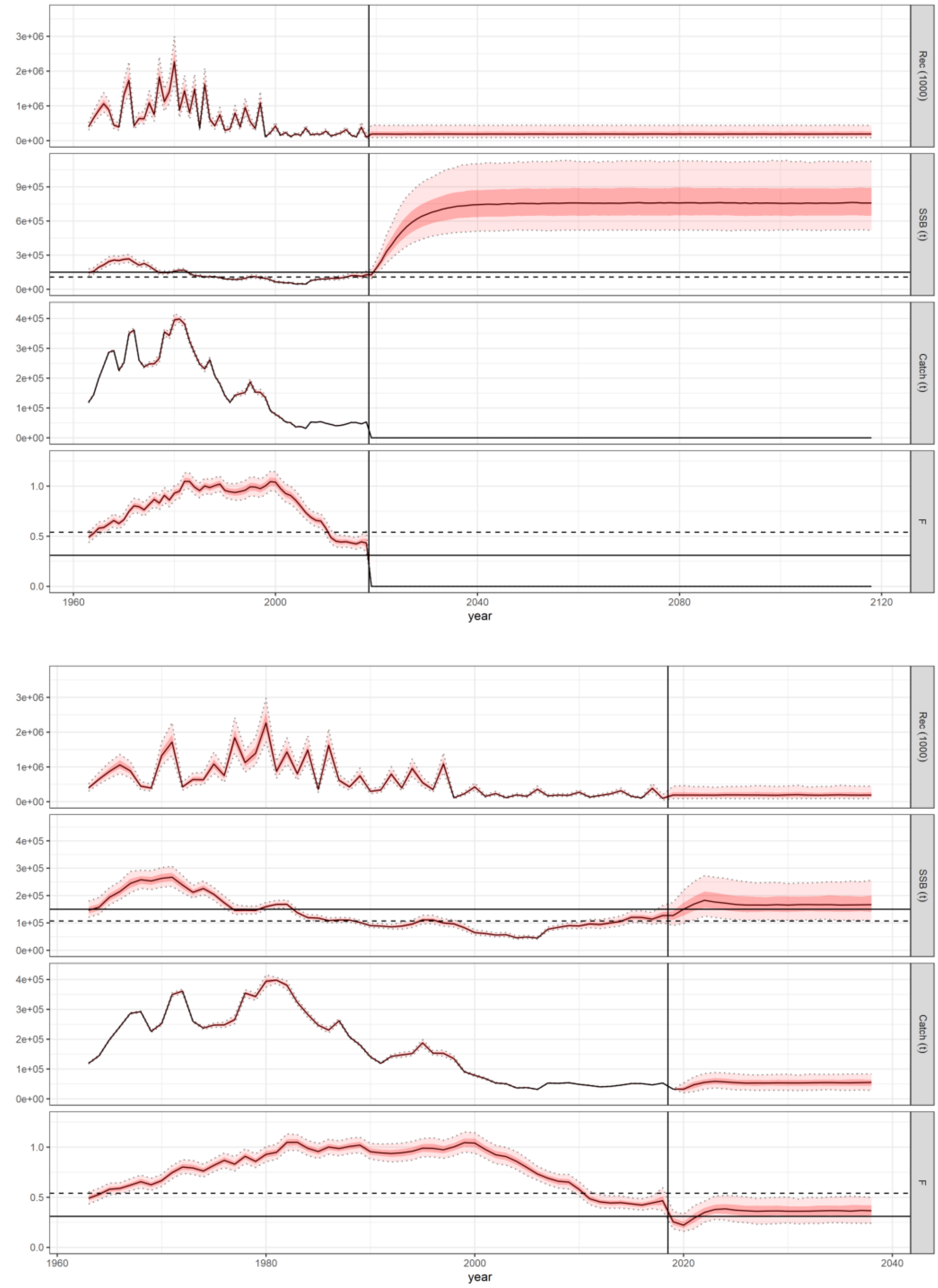


Figure 3.1.16. Summary projections (Rec, SSB, Catch and F(2-4)) based on OM1 for the case where F=0 (top four plots) and for management strategy A (with arbitrary F_{target}=0.37 and $B_{trigger}$=150000; note that this is for illustrative purposes only and is not the "optimal" combination of these control parameters).

3.2 Alternative operating models

3.2.1 OM2 - Alternative recruitment period (1988+)

The first alternative operating model (OM2) bases recruitment on the period from 1988 onwards. This recruitment period was used to derive F_{MSY} reference points for North Sea cod and includes the SSB used to set B_{lim} (=SSB in 1996, the last reasonably sized recruitment; ICES 2015a).

As for OM1, a segmented regression curve was fit to each replicate individually with breakpoint estimated. For 62 replicates, the breakpoint was estimated to the right of the stock-recruit pairs. Serial correlation was shown to be significant only at the third and fifth lags and was therefore not included (Figure 3.2.1.2). Residuals for future recruitments were again drawn from smoothed distributions of the residuals for each replicate.

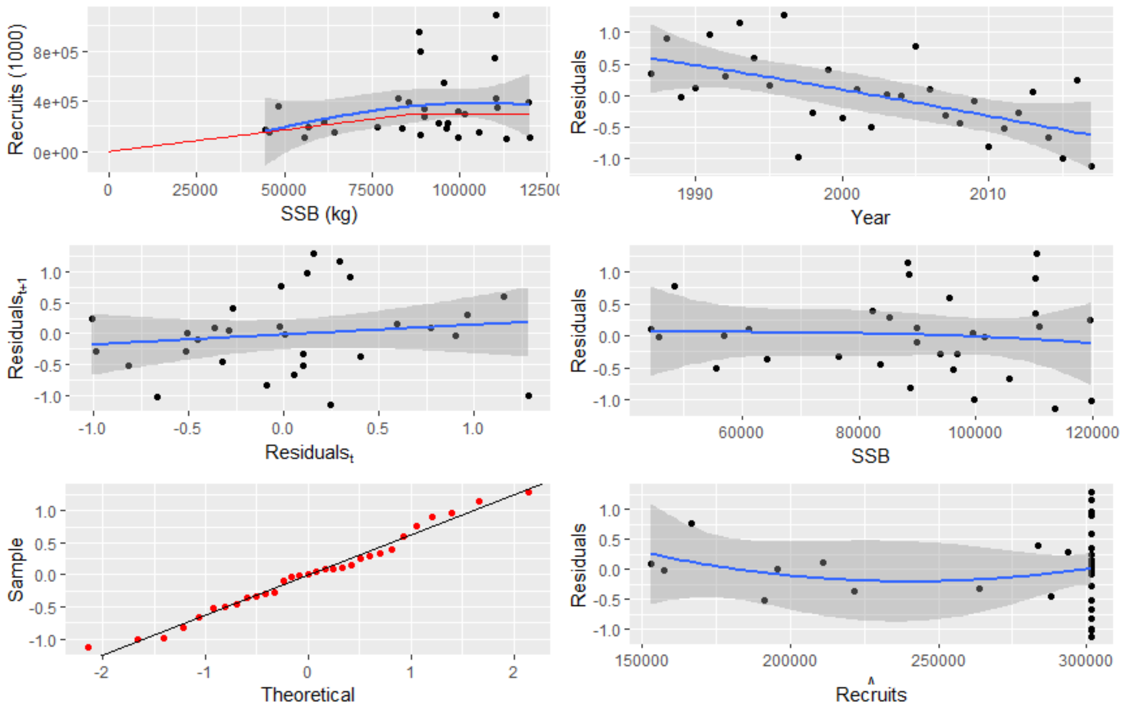


Figure 3.2.1.1. Cod in Subarea 4, Division 7.d and Subdivision 20: Fit of the segmented regression stock-recruit relationship to the original assessment point estimates for the recruitment period 1988+.

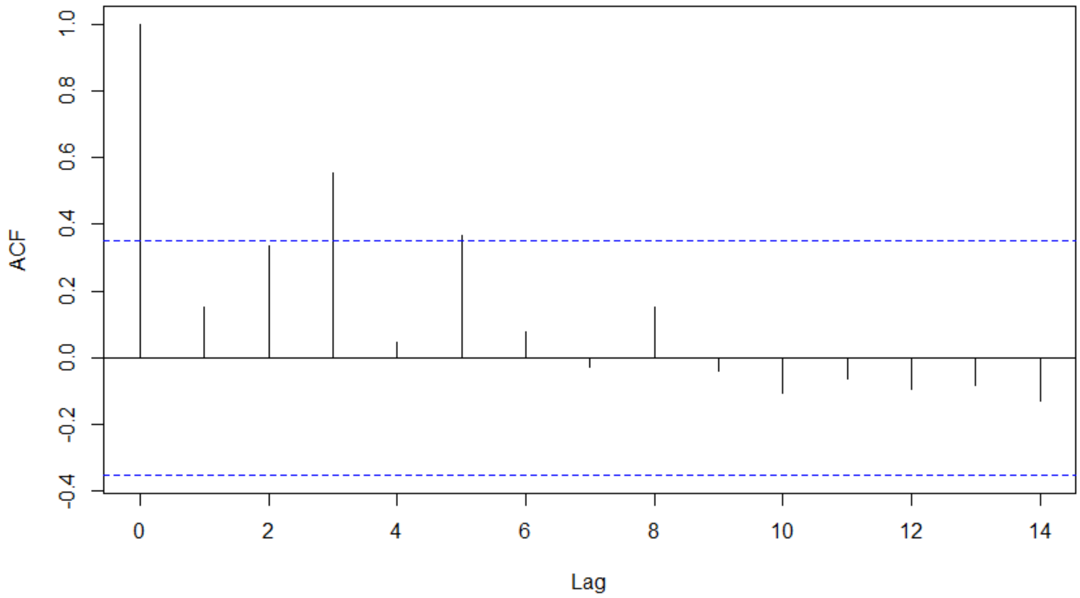


Figure 3.2.1.2. Cod in Subarea 4, Division 7.d and Subdivision 20: Autocorrelation function applied to the assessment estimates of recruitment for the period 1988+.

Figures 3.2.1.3-5 compare generated recruitments with corresponding (i.e. based on the same SSB) historical recruitments and indicate that the approach followed provides a plausible basis for generating recruitment.

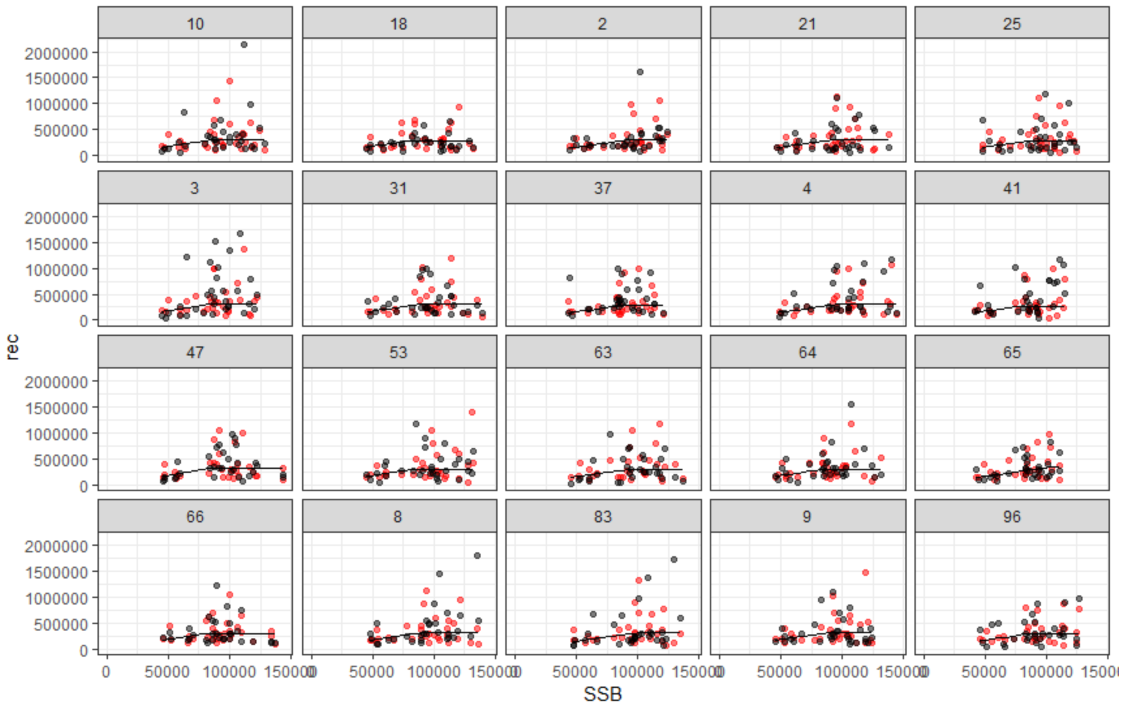


Figure 3.2.1.3. Cod in Subarea 4, Division 7.d and Subdivision 20: Historic stock-recruit pairs (red dots), with stock recruit relationships fitted to these (black lines) and generated recruitments (black dots) for a subset from 100 simulations.

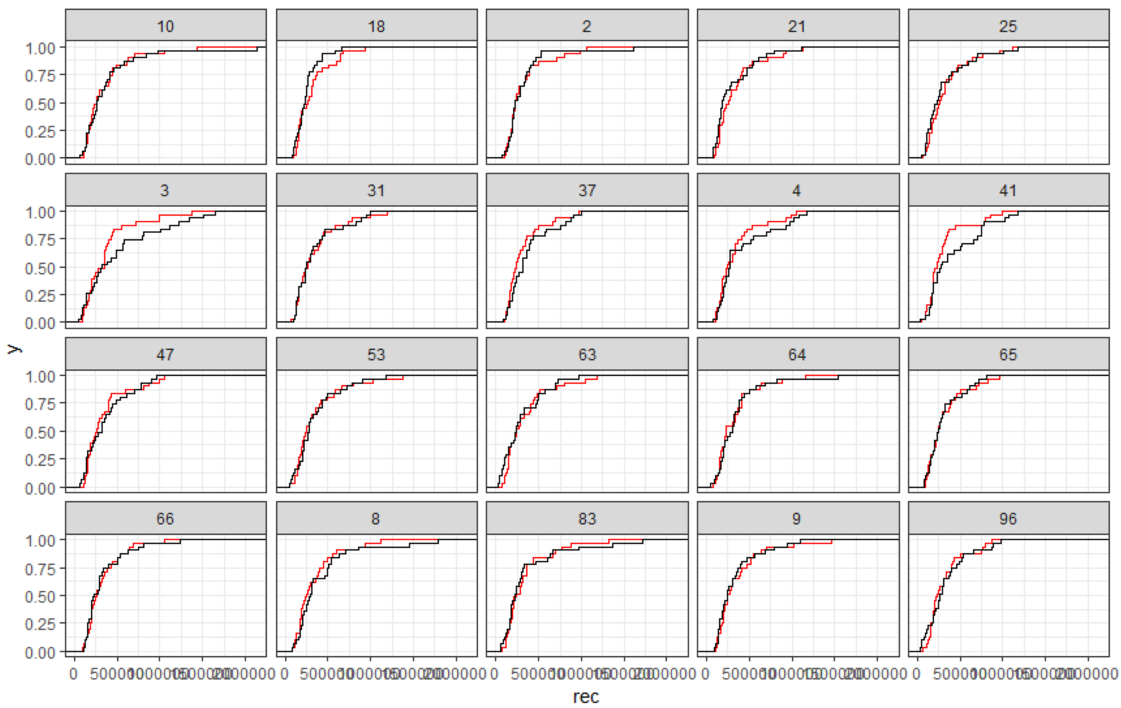


Figure 3.2.1.4. Cod in Subarea 4, Division 7.d and Subdivision 20: A comparison of historical and generated recruitments using empirical cumulative distribution function (ecdf in R) for the stock recruit pairs shown above.

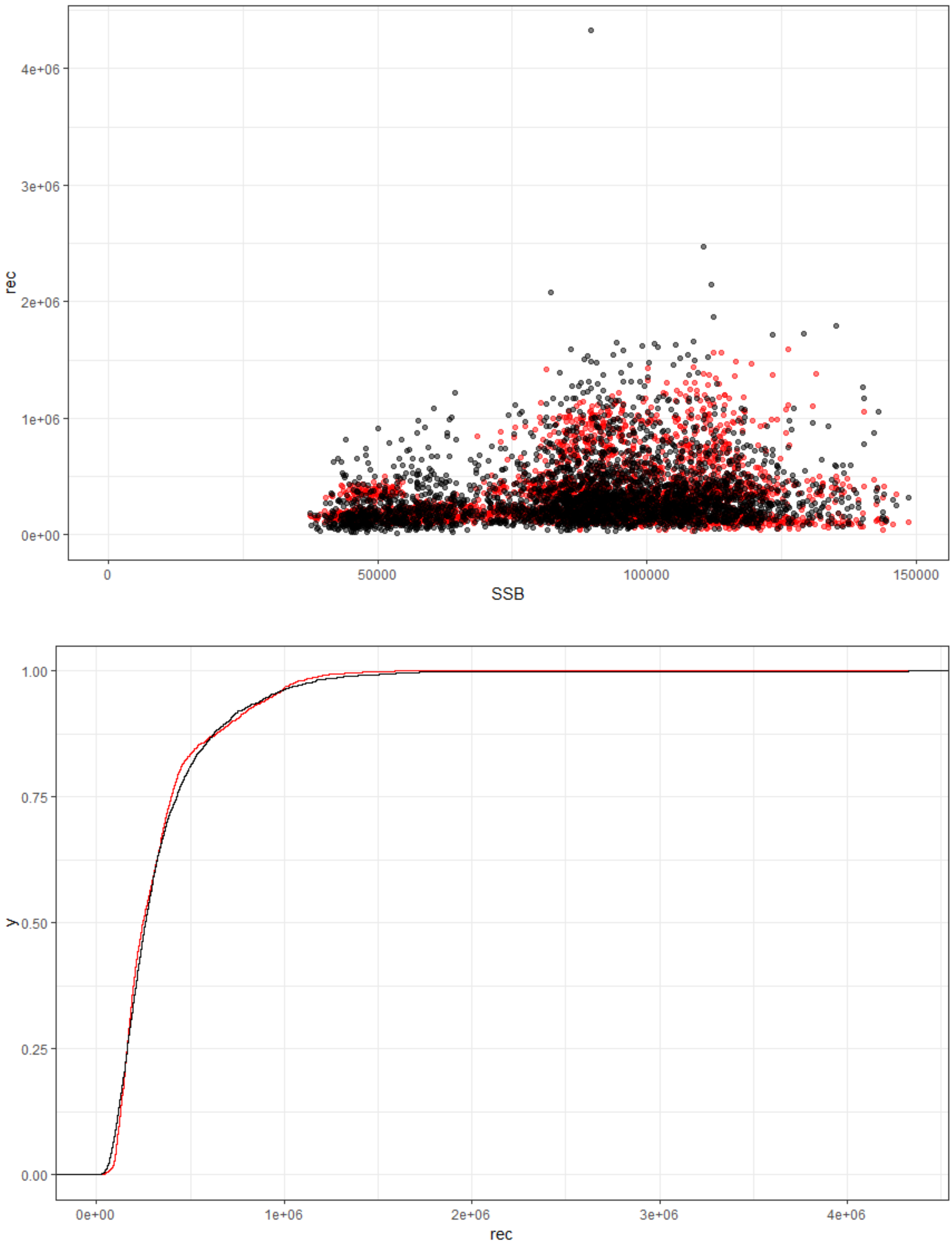


Figure 3.2.1.5. Cod in Subarea 4, Division 7.d and Subdivision 20: An overall comparison of historical (red) and generated (black) recruitment combining all 100 replicates.

3.2.2 OM3 – Year effects in the IBTS surveys

The second alternative operating model (OM3) includes year effects in the surveys. This is justified by the latest assessment of North Sea cod, which saw a downscaling of SSB in recent years, partially caused by lower-than-expected catch rates of older cod in the 2018 IBTS–Q1, and to a lesser extent the 2017 IBTS–Q3 surveys (ICES 2018a). Data analyses conducted by WGISDAA

2018 (report not yet available) found year effects in the recent survey indices, although the reasons for this remain unclear.

Year effects were included by introducing correlated errors between age classes for the survey indices (Berg and Nielsen 2016). A single correlation parameter was estimated for each survey (Table 3.2.2.1) and, although this made little improvement to the observation residuals (which are still mostly negative in the last instance), led to a significant improvement in negative log likelihood terms, and to a better AIC (Table 3.2.2.2).

Table 3.2.2.1. Cod in Subarea 4, Division 7.d and Subdivision 20: Observation covariance structure configuration for the alternative OM with year effects in the survey indices.

	1–2	2–3	3–4	4–5	5–6+
Catch	ID	ID	ID	ID	ID
IBTS–Q1	0	0	0	0	-
IBTS–Q3	1	1	1	-	-

Table 3.2.2.2. Cod in Subarea 4, Division 7.d and Subdivision 20: Model fitting diagnostics for the alterative assessment with correlated residuals and the accepted assessment for 2018 (baseline).

Model	log(L)	No.par	AIC	Pval
Correlated survey residuals (OM3)	-164.98	36	401.96	
Assessment 2018 (OM1)	-169.79	34	407.57	0.008176

Figures 3.2.2.1-6 compare assessment summaries from the alternative and baseline models and show fits of the alternative SAM model to data.

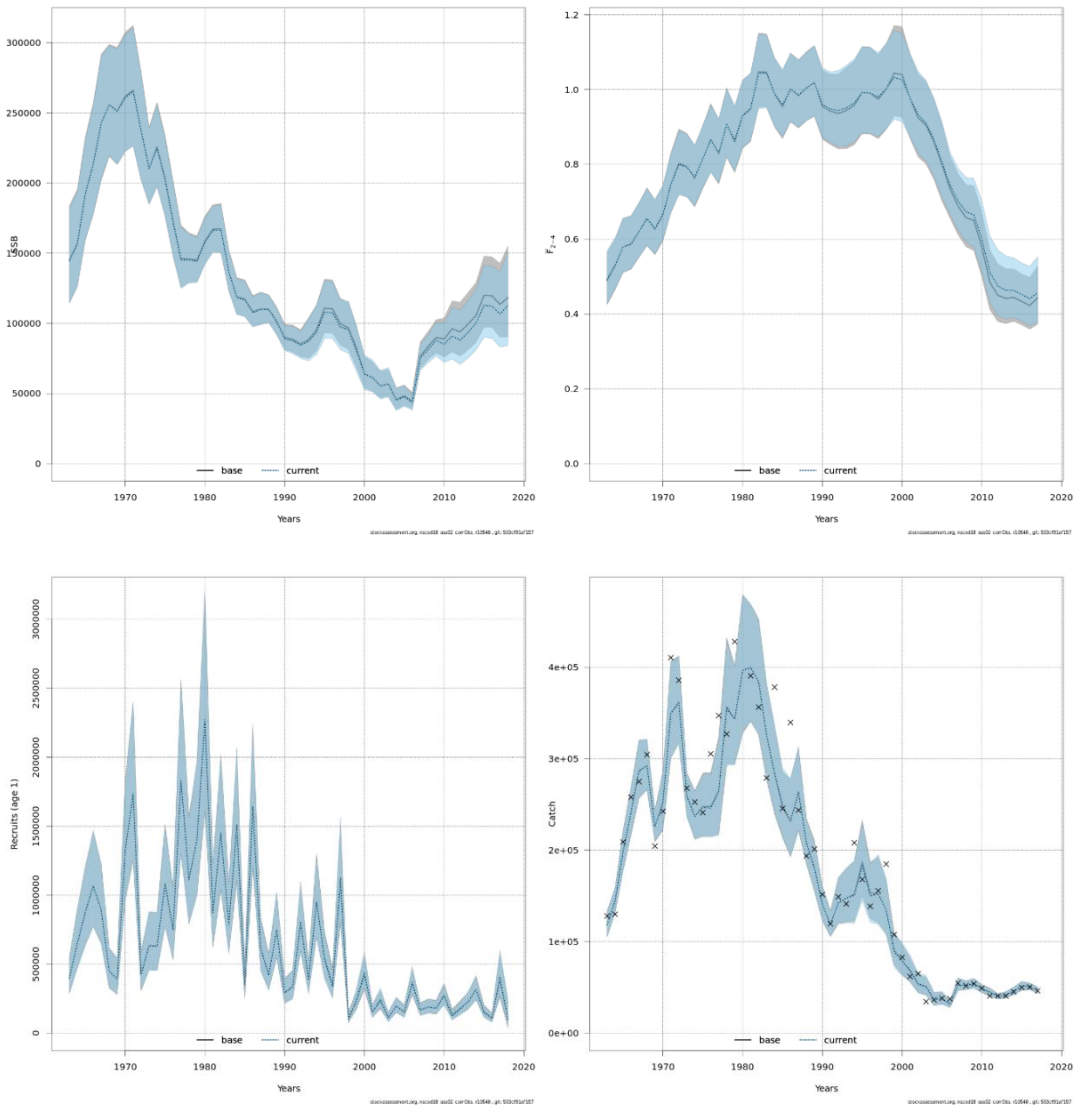


Figure 3.2.2.1. Cod in Subarea 4, Division 7.d and Subdivision 20: SSB, F2-4, recruitment and catch as estimated by the alterative assessment with correlated residuals (blue) and the accepted assessment for 2018 (baseline; grey).

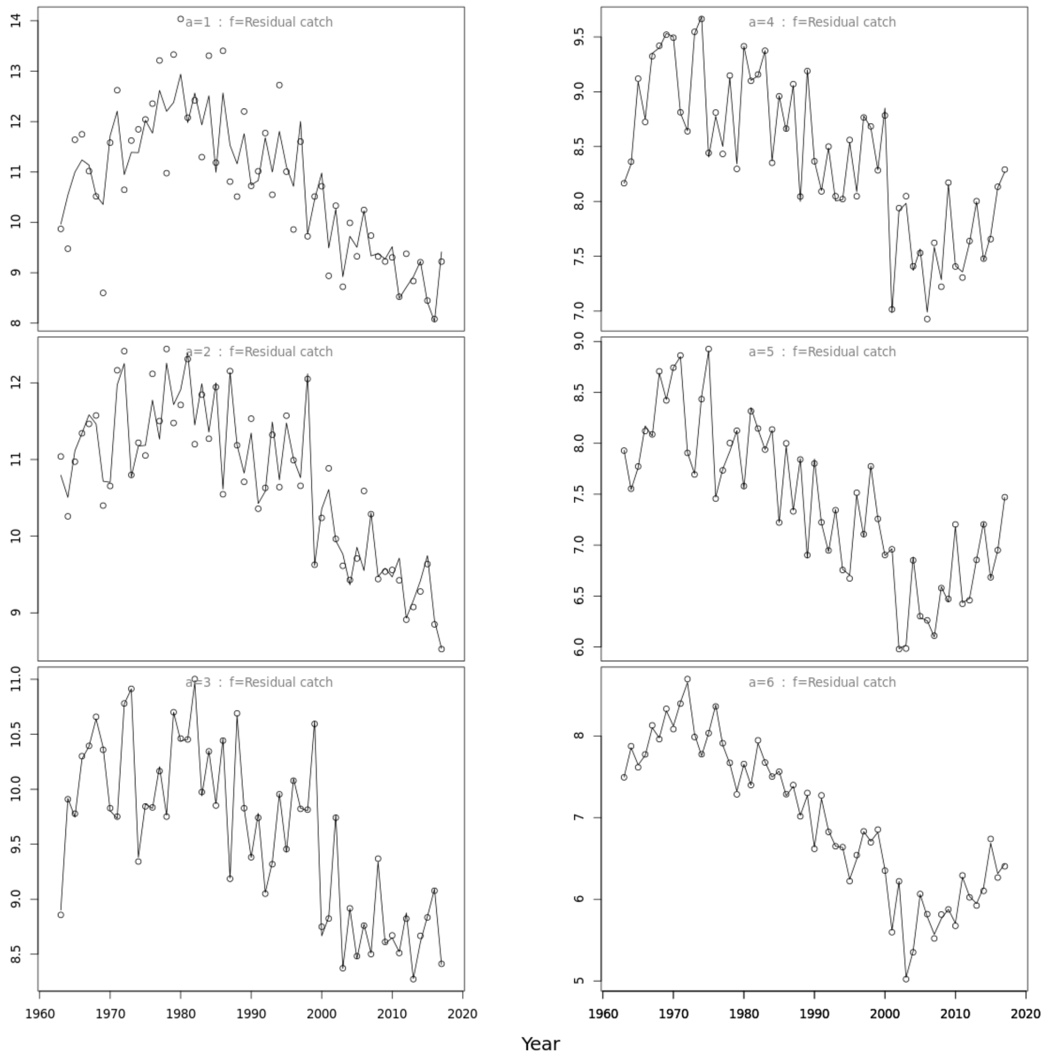


Figure 3.2.2.2. Cod in Subarea 4, Division 7.d and Subdivision 20: Fits to catch-at-age data.

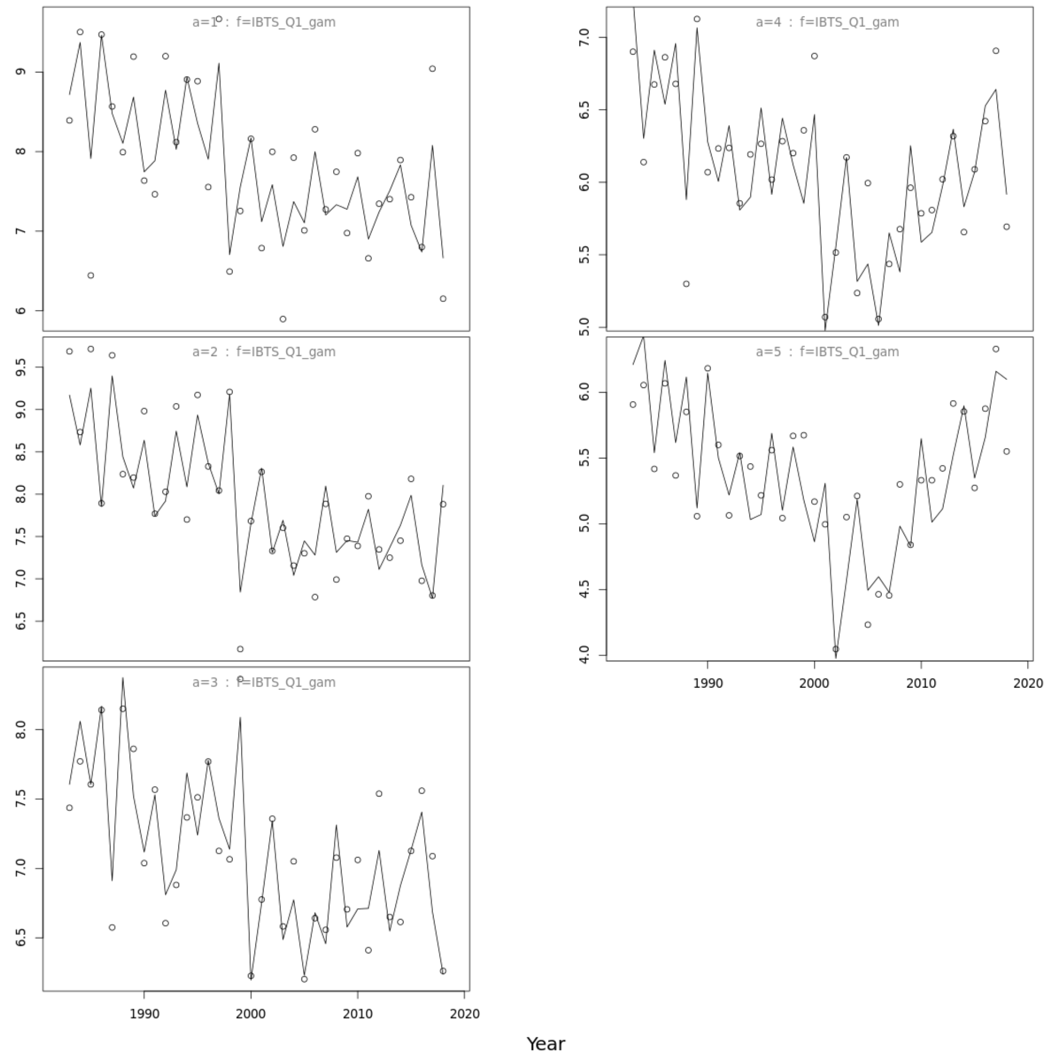


Figure 3.2.2.3. Cod in Subarea 4, Division 7.d and Subdivision 20: Fits to the IBTS–Q1 survey data.

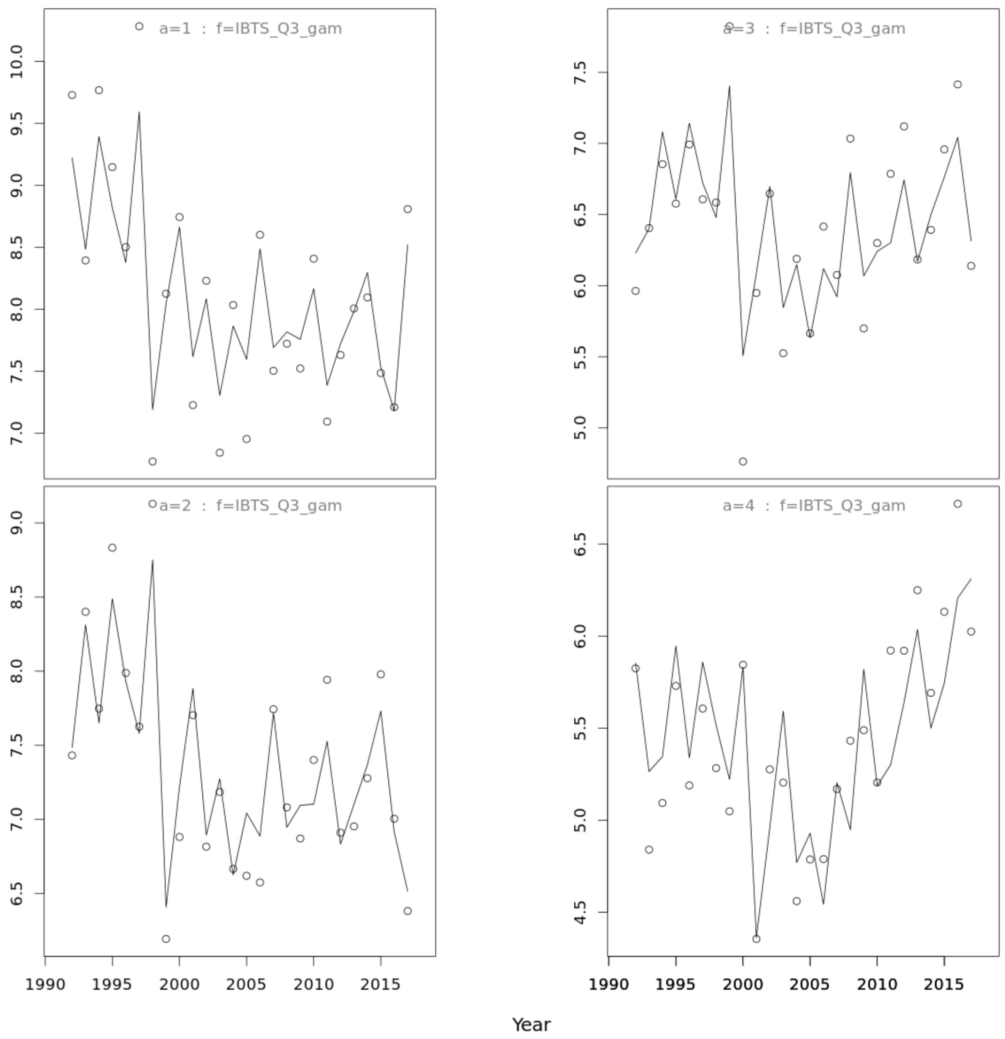


Figure 3.2.2.4. Cod in Subarea 4, Division 7.d and Subdivision 20: Fits to the IBTS–Q3 survey data.

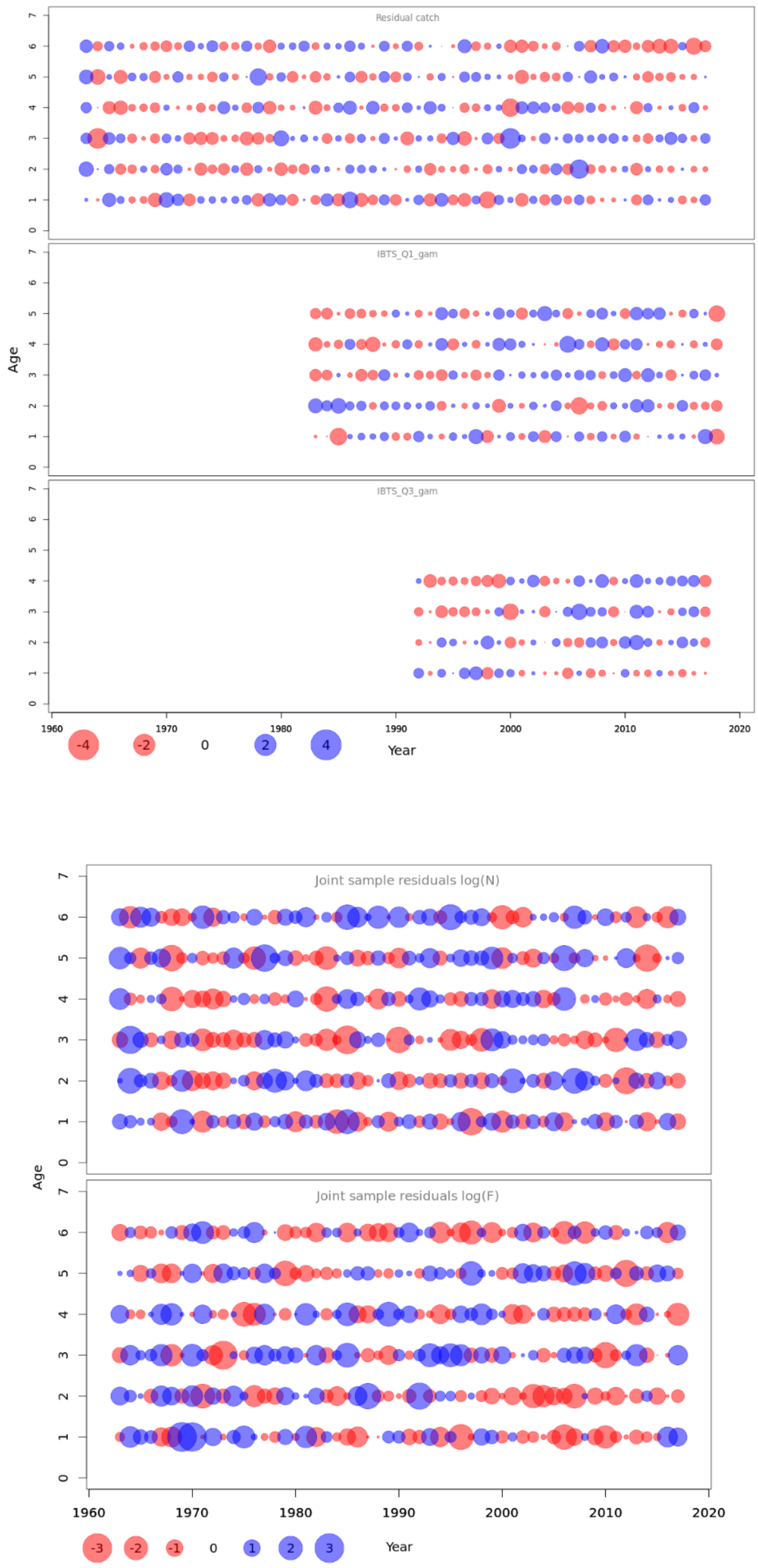


Figure 3.2.2.5. Cod in Subarea 4, Division 7.d and Subdivision 20: Normalized residuals for total catch, IBTS–Q1, IBTS–Q3, the recruitment and survival process error, and the fishing mortality process error. Blue circles indicate a positive residual and red circles a negative residual.

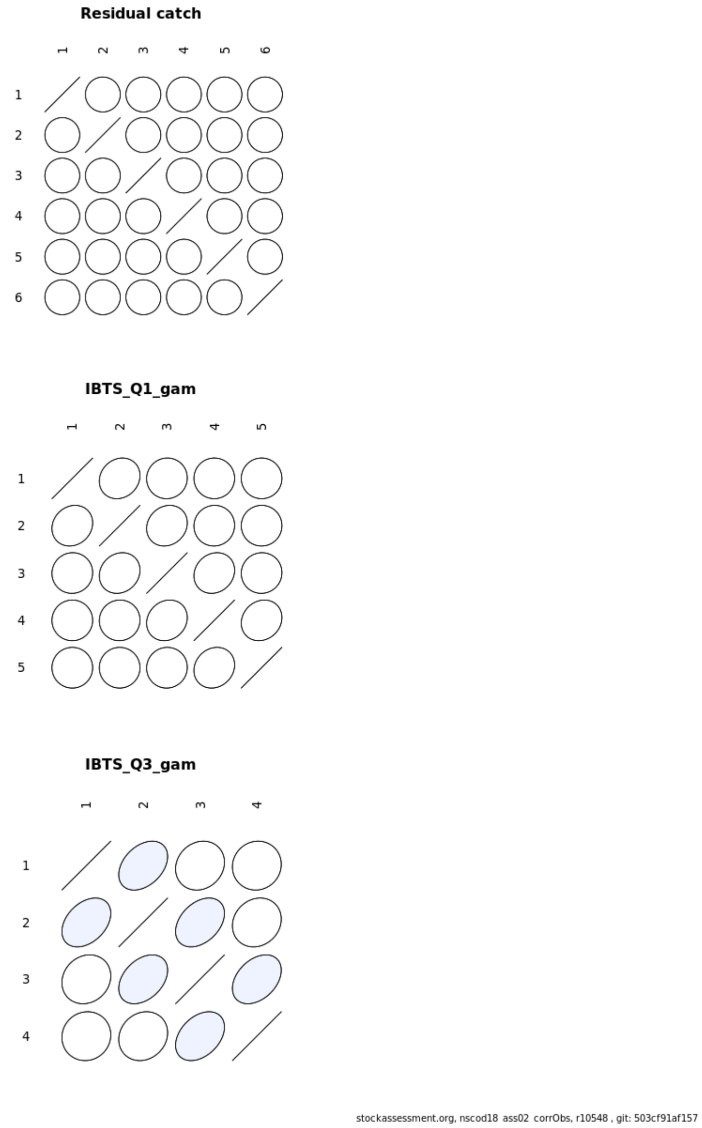


Figure 3.2.2.6. Cod in Subarea 4, Division 7.d and Subdivision 20: Estimated observation correlation matrices.

Survey observations were generated in a similar way to the other OMs except that observation errors were drawn from a multivariate normal distribution:

$$\varepsilon_{y,i} \sim N(0, \Sigma_i)$$

Where Σ_i are the covariance matrices between age classes within years for each survey i, obtained from the SAM fit.

B_{lim} was re-estimated because OM3 is based on an alternative SAM configuration, and therefore an alternative assessment. As for the accepted assessment (OM1), B_{lim} was taken as the SSB associated with the last reasonably sized year class (SSB in 1996 = 108,000 t). This new B_{lim} was used for the purposes of calculating performance statistics, while the management procedure component of the MSE continued to employ the current value of B_{lim} = 107,000 t, on the basis that the management procedure should mimic current practices for assessment and advice.

3.2.3 OM4 – Density-dependent M

Cannibalism is an important part of natural mortality for younger cod and predation levels on these early age classes may change as the stock recovers. The third alternative operating model (OM4) considers density-dependence in natural mortality. The stock assessment of cod uses estimates of natural mortality derived from multispecies analysis, updated by the Working Group on Multispecies Stock Assessment Methods (WGSAM) every three years in so called "key runs".

Future Ms were simulated according to relationships of partial predation mortality ($pM2$) between younger age classes of cod (1–3) and their main predators (cod, whiting, grey seal and porpoise). These relationships were obtained by fitting GLMs to data for each combination of predator and prey from the last SMS key run (ICES 2018b):

$$\ln\left(pM2_{a,pr}\right) = c_{a,pr} + b_{1,a,pr}\ln(N_a) + b_{2,a,pr}\ln\left(N_{pr}\right)$$

where the subscripts denote cod prey aged a and predator pr and N are abundances, b regression coefficients and c the intercept. Abundances of external predators (whiting, grey seal and porpoise) are fixed at their 2016 abundances while abundances of cod are updated in each time step of the simulation.

Table 3.2.3.1. Cod in Subarea 4, Division 7.d and Subdivision 20: Parameters describing the partial predation mortalities of cod and their main predators. Note that the intercept and regression coefficients are given on a log scale.

Interaction	$c_{a,pr}$	$b_{1,a,pr}$	$b_{2,a,pr}$	N_{pr} (000)
Cod1~Grey seal1	-5.050965689	-0.246109496	1.410438034	88
Cod2~Grey seal1	-6.862945372	-0.166796428	1.554528004	88
Cod3~Grey seal1	-6.958168035	-0.122533958	1.38999513	88
Cod1~H. porpoise1	2.324555922	-0.250388948	NA	224
Cod2~H. porpoise1	2.585418729	-0.301430919	NA	224
Cod1~Cod2	-13.3757484	-0.124047368	1.075964403	
Cod1~Cod3	-10.48454551	-0.088211003	0.923879933	
Cod1~Cod4	-9.684056523	-0.074631755	0.884622061	
Cod1~Cod5	-9.237195478	-0.060384673	0.83574969	Dynamic
Cod1~Cod6	-9.353143483	-0.059836816	0.860453772	
Cod2~Cod5	-11.9181104	0.18738728	0.768133054	
Cod2~Cod6	-9.734754887	-0.038695018	0.864268236	
Cod1~Whiting5	-18.49326447	-0.459320543	1.919397959	27701
Cod1~Whiting6	-11.39386054	-0.242620422	0.971044622	20949
Cod1~Whiting7	-10.20859553	-0.230527818	0.808415326	9388
Cod1~Whiting8	-10.56068345	-0.240002154	0.854289965	8150

Total predation mortality ($M2$) on each age class is given by summing the partial M2s over all predators:

$$M2_a = \sum_{pr} pM2_{a,pr}$$

And total natural mortality as the sum of non-predation ($M1$ = 0.2 for all ages) and predation ($M2$) mortality:

$$M_a = 0.2 + M2_a$$

Three-year means of natural morality were generated from the operating model to simulate the process of key runs. Each key run year mean Ms from the previous three years were generated from the operating model and passed to the management procedure, with these mean Ms being retained until the next key run year. The R code in Table 3.2.3.2 demonstrates this process.

Table 3.2.3.2. Cod in Subarea 4, Division 7.d and Subdivision 20: R code to generate three-year means of M from the operating model on key run years. "ay" is the current assessment year within the MSE, "observations$stock" the observed stock and "stk" the operating model.

```
if (!is.null(dd_M) & (ay %% 3 == 1)) {
  m(observations$stk)[, ac(ay:(ay+2))] <- yearMeans(m(stk)[, ac((ay-3):(ay-1))])
}
```

3.3 Management procedure

The management procedure (MP) comprises of the estimation model and the decision model. The decision model comprises the management strategies that are being evaluated (Section 2.1), and the estimate of SSB needed by the decision model is supplied by the estimation model. For cod, the estimation model is identical to the SAM model used on an annual basis for advice, and includes the forecasting procedure needed to derive the annual advice. The model settings and forecast assumptions are therefore the same, and are as described in the stock annex for this stock.

3.4 Results

3.4.1 Search grid for "optimal" combination of F_{target} and $B_{trigger}$

The search for "optimal" combinations of F_{target} and $B_{trigger}$ (i.e. those that maximise long-term yield while fulfilling the ICES precautionary criterion of risk3≤5%), was only conducted for the baseline OM1 for each of the six management strategies. The grid searches are shown in Figures 3.4.1.1-6. Most of the grids are only partial because each cell in the grid takes just under 40 hours on a single core computer. Furthermore, the search was conducted in steps of 0.01 for F_{target}, and 10000 t for $B_{trigger}$. The "optimal" combination is highlighted in each plot with a black border around the corresponding cell. Table 3.4.1.1 summarises the result of the search for the "optimal" combinations. The grid for management strategy A (Figure 3.4.1.1) came at the cost of a total CPU runtime of around 18,500 hours (i.e. 2.1 years) and used exclusively 40 high performance computing nodes with a total of 1,600 CPU cores and 15 terabytes of memory for more than 10 hours.

Table 3.4.1.1. Cod in Subarea 4, Division 7.d and Subdivision 20: "optimal" combinations for F_{target} and $B_{trigger}$ for the baseline OM1 and six management strategies. Also reported are the median long-term values for catch, SSB, realized mean F (ages 2-4), interannual catch variability (ICV), interannual TAC variability (ITV), risk3, risk1, the number of times the SAM assessment did not converge during the simulation and the number of times mean F reached the maximum of 2.0.

Management strategy	F_{target}	$B_{trigger}$	Catch	SSB	F(2-4)	ICV	ITV	risk3	risk1	convergence failed	F_{maxed}
F=0	0.00	-	0	701275	0.000	0.000	0.000	0.0%	0.0%	-	0
A*	0.31	150000	52610	195959	0.311	0.113	0.113	1.1%	0.7%	0	0
A*+D	0.31	150000	51880	195477	0.305	0.315	0.128	1.1%	0.7%	0	0
A	0.38	170000	54597	167536	0.362	0.171	0.171	3.6%	3.0%	0	0
B	0.38	160000	54790	165561	0.369	0.166	0.166	4.0%	3.6%	0	0
C	0.38	170000	54597	167536	0.362	0.171	0.171	3.6%	3.0%	0	0
A+D	0.4	190000	52532	167587	0.351	0.260	0.211	3.8%	3.1%	0	0
B+E	0.36	130000	52728	168381	0.356	0.329	0.151	4.6%	3.6%	0	0
C+E	0.36	140000	52440	168157	0.353	0.318	0.149	4.9%	3.6%	0	0

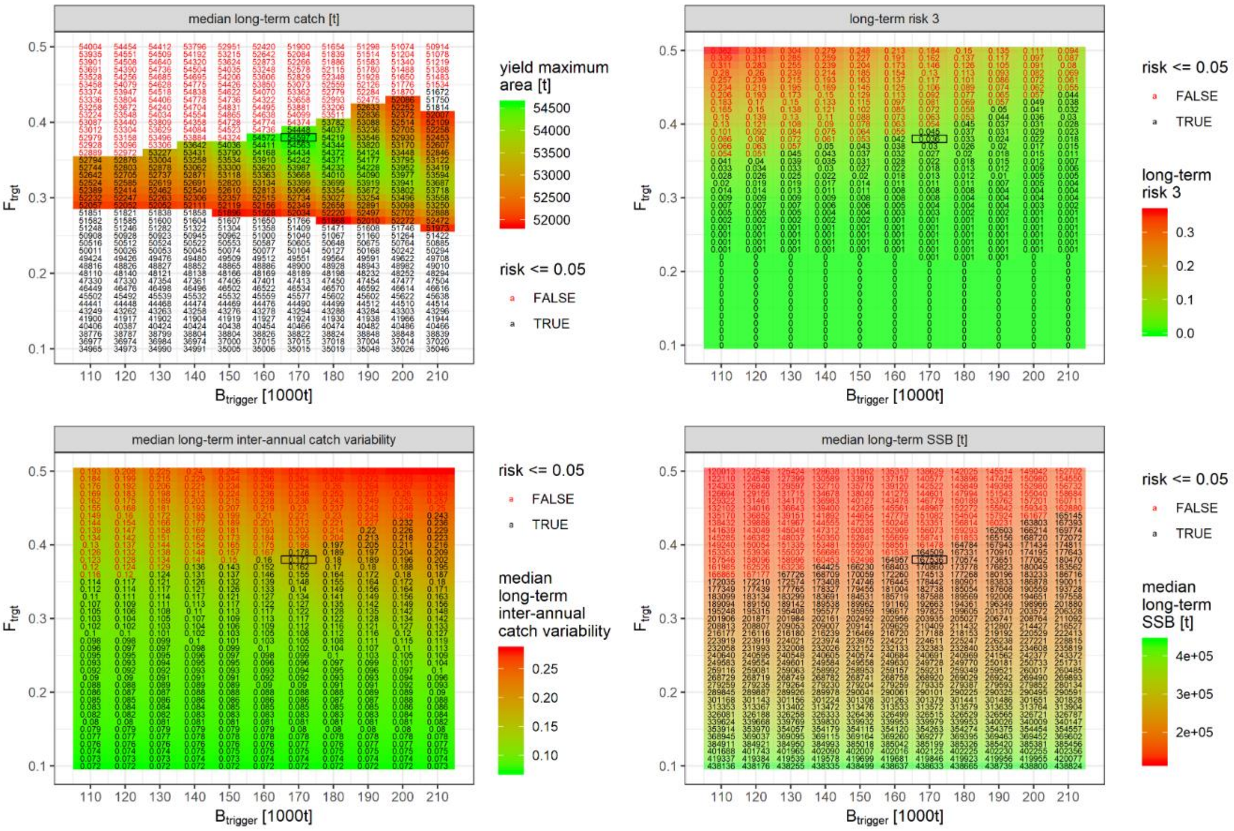


Figure 3.4.1.1. Cod in Subarea 4, Division 7.d and Subdivision 20: Grid search for "optimal" combination of F_{target} and $B_{trigger}$ for management strategy A for the long-term (i.e. final 10 years of the 20-year projection). The top-left plot is median long-term catch, top-right the long-term risk3, bottom left the median long-term inter-annual catch variability and bottom right the median long-term SSB. The "optimal" combination is surrounded by a black box. The combinations that meet the precautionary criterion (risk3≤5%) are in black text, while those that do not are in red.

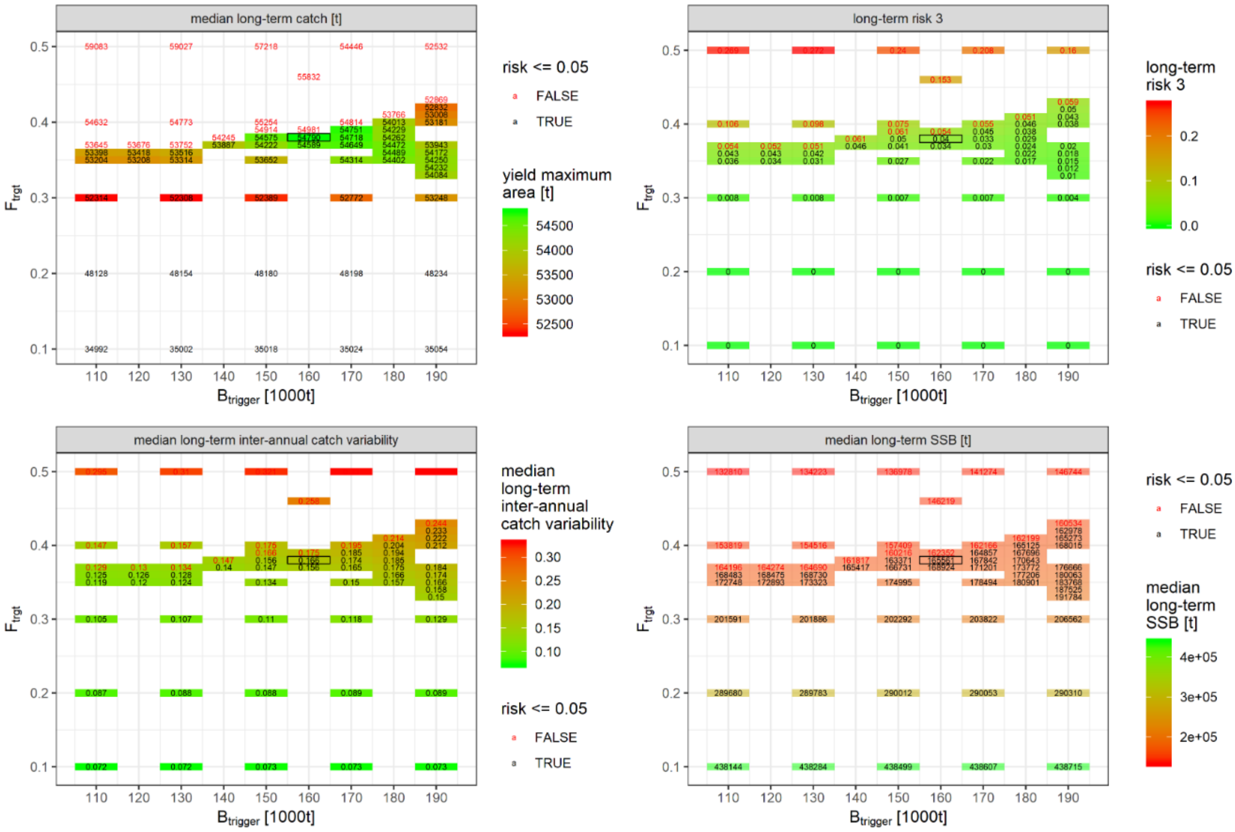


Figure 3.4.1.2. Cod in Subarea 4, Division 7.d and Subdivision 20: Grid search for "optimal" combination of F_{target} and $B_{trigger}$ for management strategy B for the long-term (i.e. final 10 years of the 20-year projection). See caption to Figure 3.4.1.1 for further details.

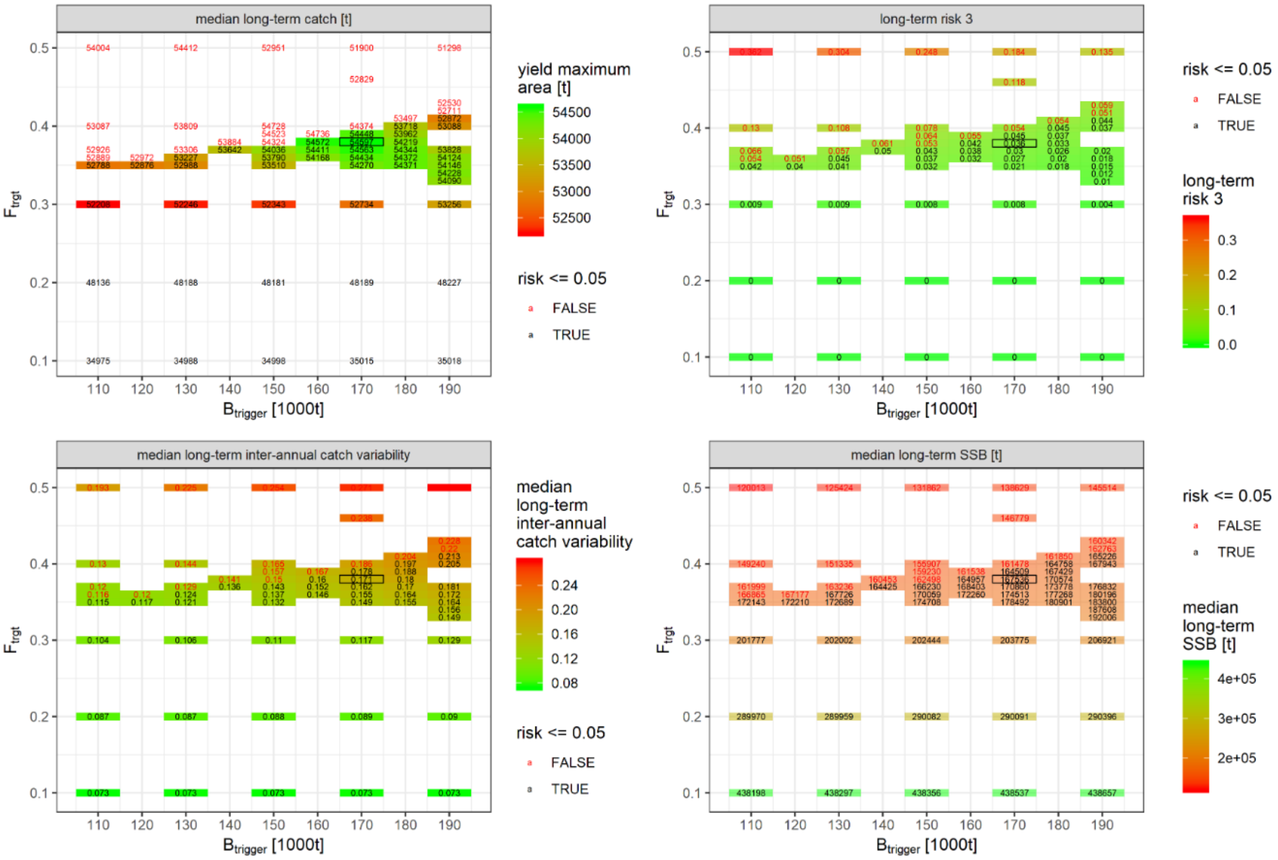


Figure 3.4.1.3. Cod in Subarea 4, Division 7.d and Subdivision 20: Grid search for "optimal" combination of F_{target} and $B_{trigger}$ for management strategy C for the long-term (i.e. final 10 years of the 20-year projection). See caption to Figure 3.4.1.1 for further details.

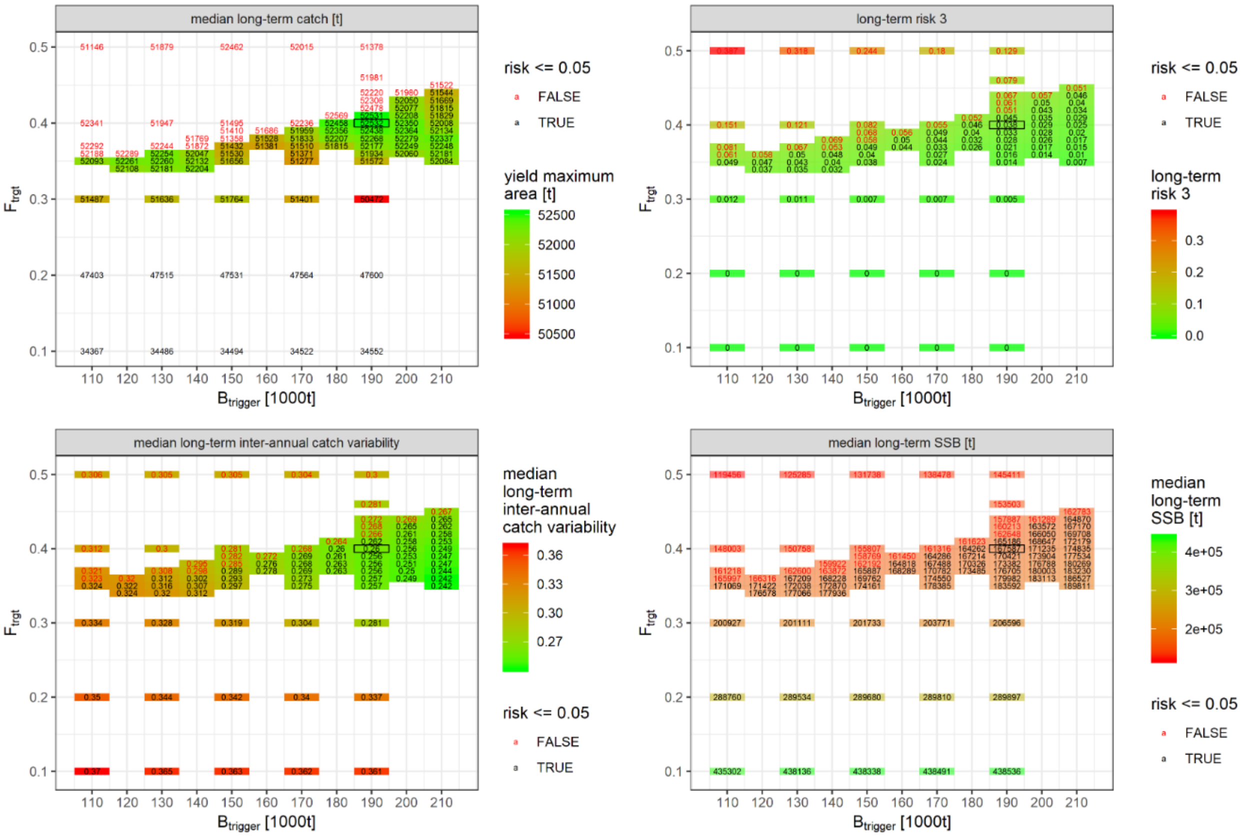


Figure 3.4.1.4. Cod in Subarea 4, Division 7.d and Subdivision 20: Grid search for "optimal" combination of F_{target} and $B_{trigger}$ for management strategy A+D for the long-term (i.e. final 10 years of the 20-year projection). See caption to Figure 3.4.1.1 for further details.

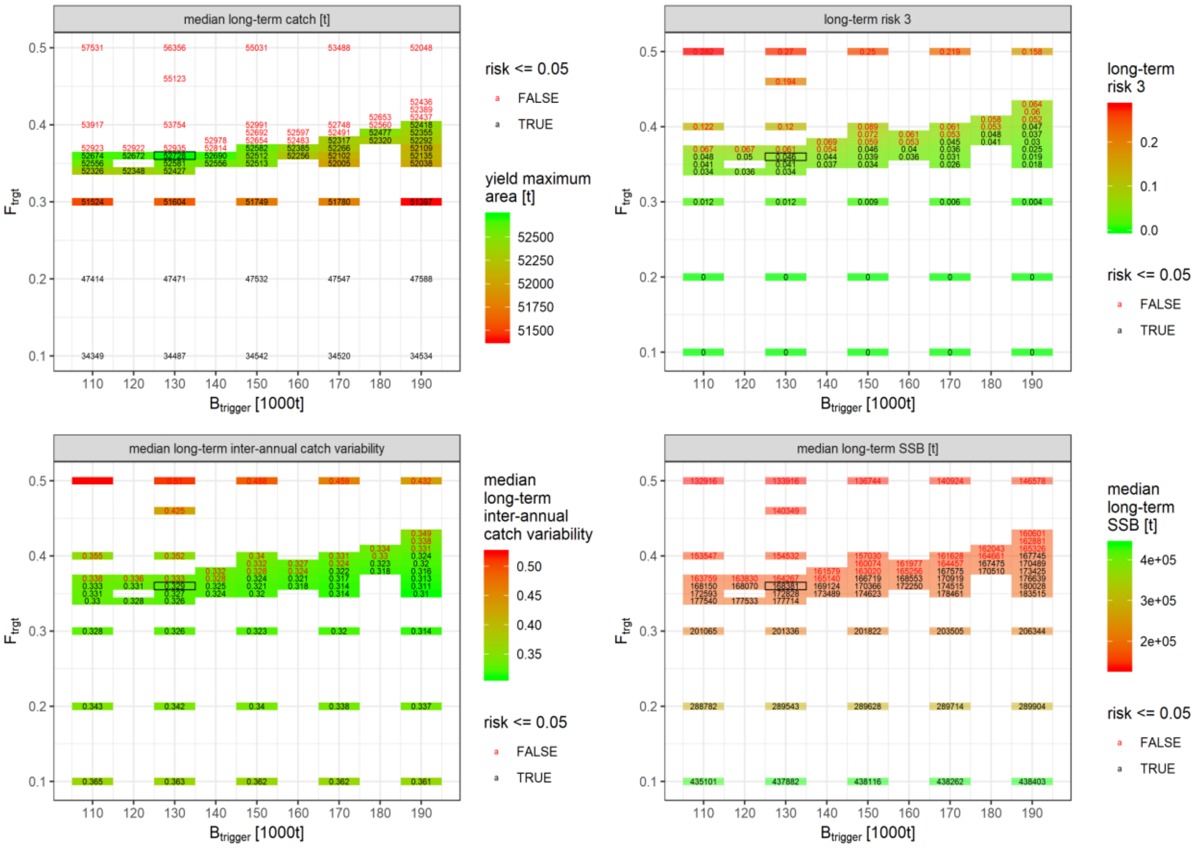


Figure 3.4.1.5. Cod in Subarea 4, Division 7.d and Subdivision 20: Grid search for "optimal" combination of F_{target} and $B_{trigger}$ for management strategy B+E for the long-term (i.e. final 10 years of the 20-year projection). See caption to Figure 3.4.1.1 for further details.

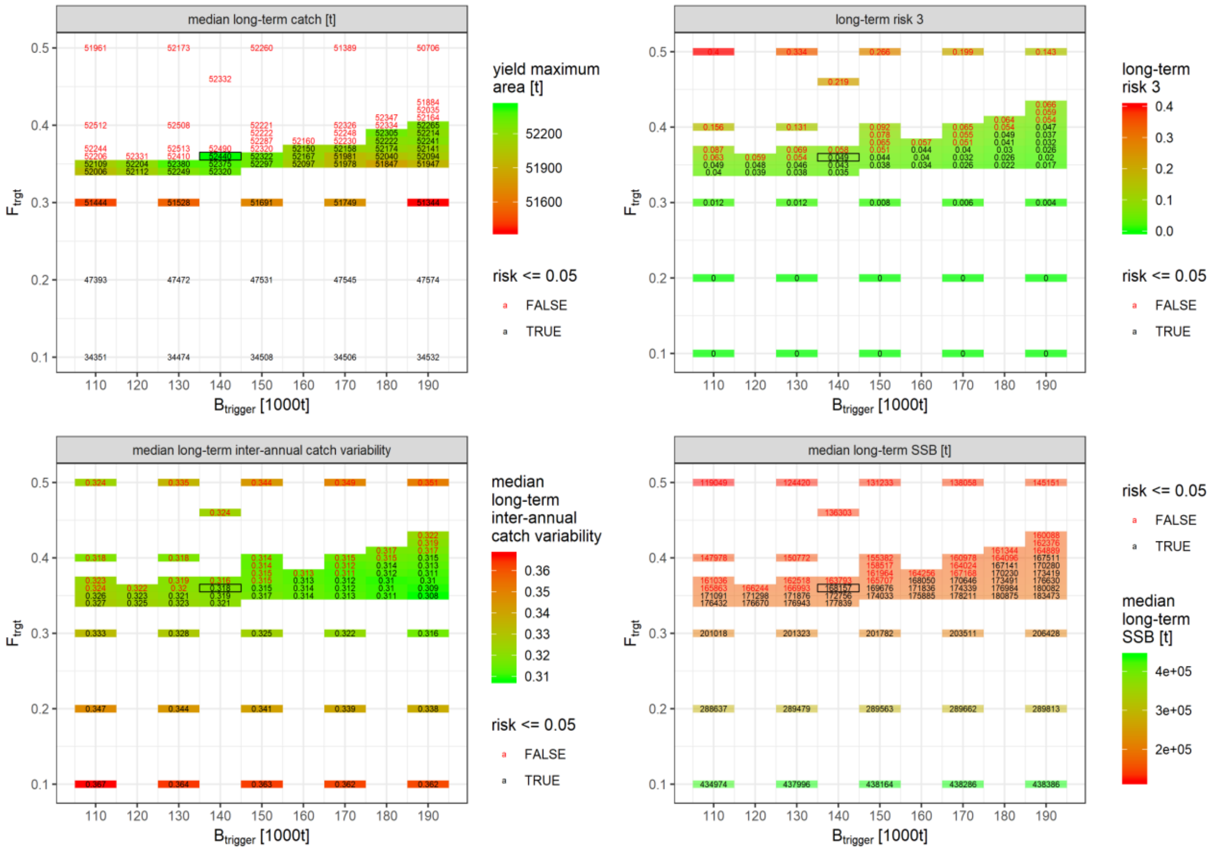


Figure 3.4.1.6. Cod in Subarea 4, Division 7.d and Subdivision 20: Grid search for "optimal" combination of F_{target} and $B_{trigger}$ for management strategy C+E for the long-term (i.e. final 10 years of the 20-year projection). See caption to Figure 3.4.1.1 for further details.

3.4.2 Summary projections

Summary projections for recruitment (age 1), SSB, catch and mean F (ages 2-4) for the baseline OM1 are given for F=0 in Figure 3.4.2.1, for a version of management strategy A that sets $F_{target}=F_{MSY}=0.31$ and $B_{trigger}$=MSY $B_{trigger}$=150000 t (labelled A*) in Figure 3.4.2.2, and for a version of A* that includes the stability mechansims (labelled A*+D) in Figure 3.4.2.3. Summary projections for the six "optimised" management strategies (see Table 3.4.1.1) are given in Figures 3.4.2.4-9. Figure 3.4.2.10 plots the annual risk for "optimised" management strategy A, which indicates that annual risk has stabilised from around 2025 onwards.

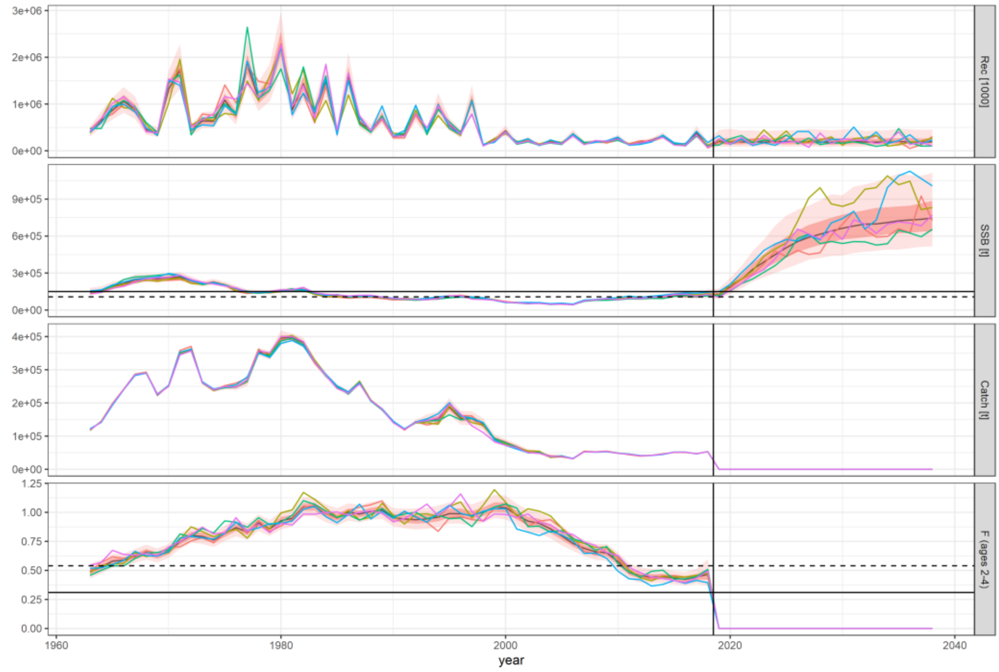


Figure 3.4.2.1. Cod in Subarea 4, Division 7.d and Subdivision 20: Summary projections for F=0. Top plot is recruitment (age 1), second plot SSB, third plot catch and bottom plot mean F (ages 2-4). The vertical black line separates the historical period from the projection period. The SSB plot includes B_{pa}=MSY $B_{trigger}$ (horizontal solid line) and B_{lim} (horizontal hashed line), while the mean F plot includes F_{msy} (horizontal solid line) and F_{lim} (horizontal dashed line). The actual plots show medians (solid black line) with the darker shaded area indicating the 25th and 75th percentiles, and the light shaded area the 5th and 95th percentiles. The coloured lines represent the values from the first five replicates.

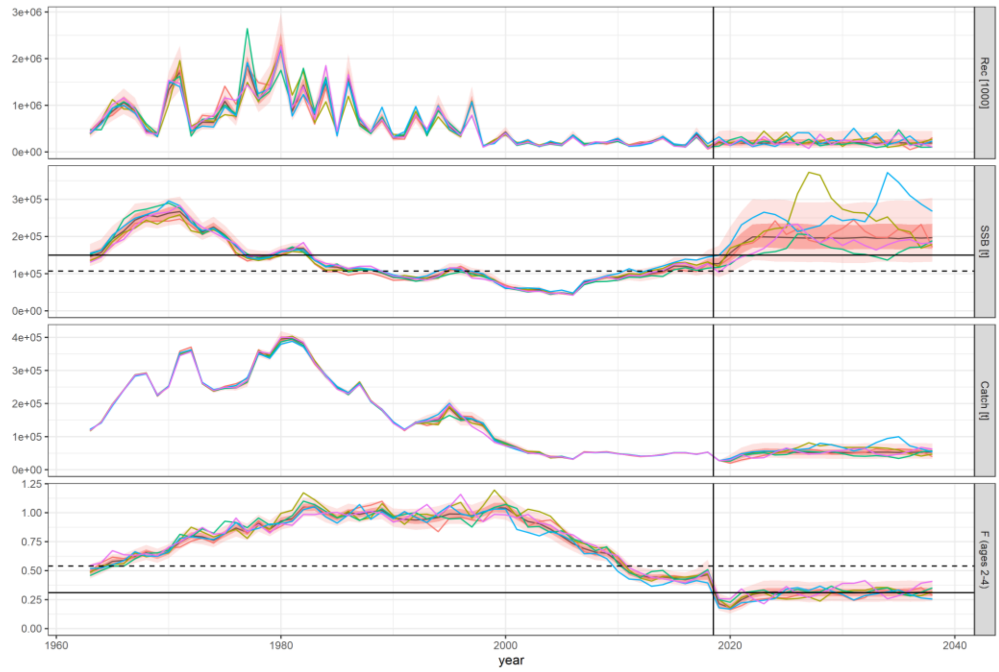


Figure 3.4.2.2. Cod in Subarea 4, Division 7.d and Subdivision 20: Summary projections for <u>management strategy A*</u> (i.e. with F_{target}=F_{msy}=0.31 and $B_{trigger}$=MSY $B_{trigger}$=150000 t). See the caption to Figure 3.4.2.1 for further details.

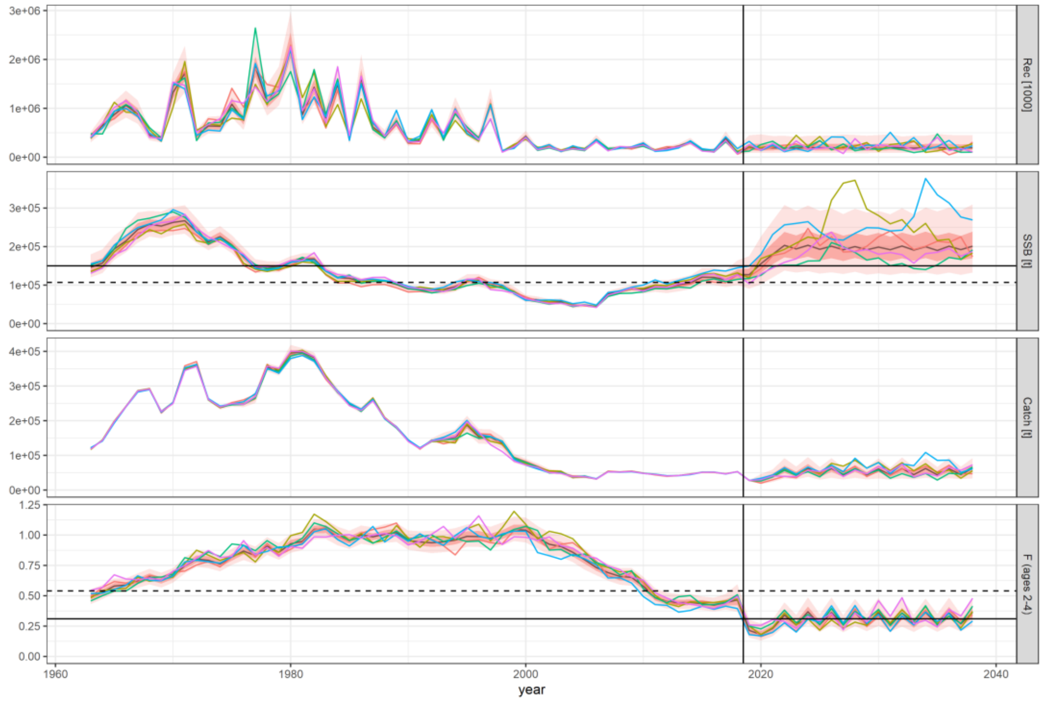


Figure 3.4.2.3. Cod in Subarea 4, Division 7.d and Subdivision 20: Summary projections for <u>management strategy A*+D</u> (i.e. A+D, but with F_{target}=F_{msy}=0.31 and $B_{trigger}$=MSY $B_{trigger}$=150000 t,). See the caption to Figure 3.4.2.1 for further details.

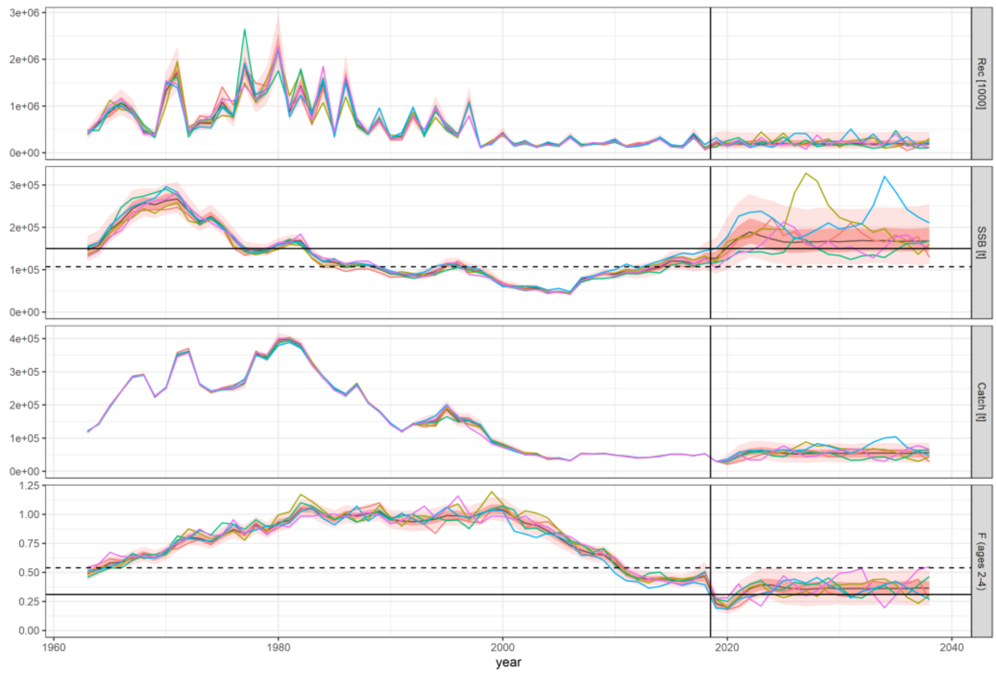


Figure 3.4.2.4. Cod in Subarea 4, Division 7.d and Subdivision 20: Summary projections for "optimised" <u>management strategy A</u> (see Table 3.4.1.1). See the caption to Figure 3.4.2.1 for further details.

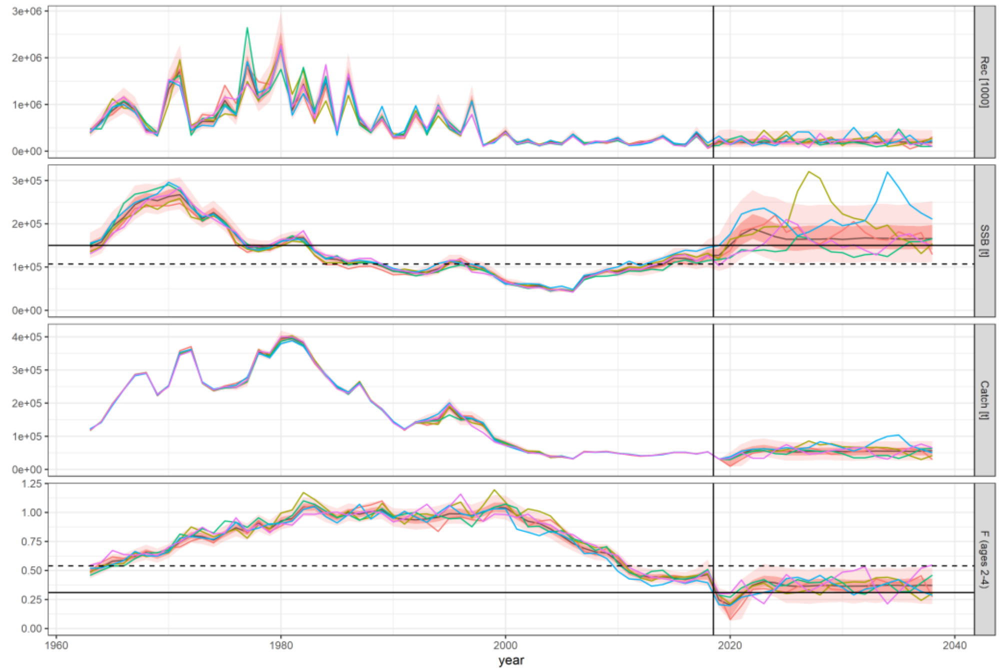


Figure 3.4.2.5. Cod in Subarea 4, Division 7.d and Subdivision 20: Summary projections for "optimised" management strategy B (see Table 3.4.1.1). See the caption to Figure 3.4.2.1 for further details.

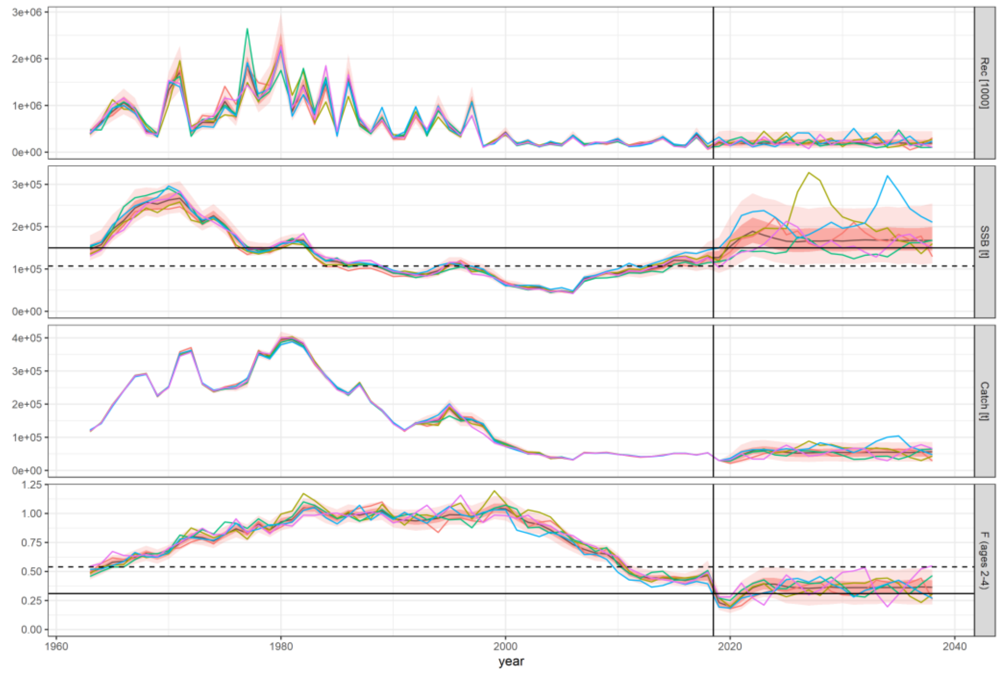


Figure 3.4.2.6. Cod in Subarea 4, Division 7.d and Subdivision 20: Summary projections for "optimised" management strategy C (see Table 3.4.1.1). See the caption to Figure 3.4.2.1 for further details.

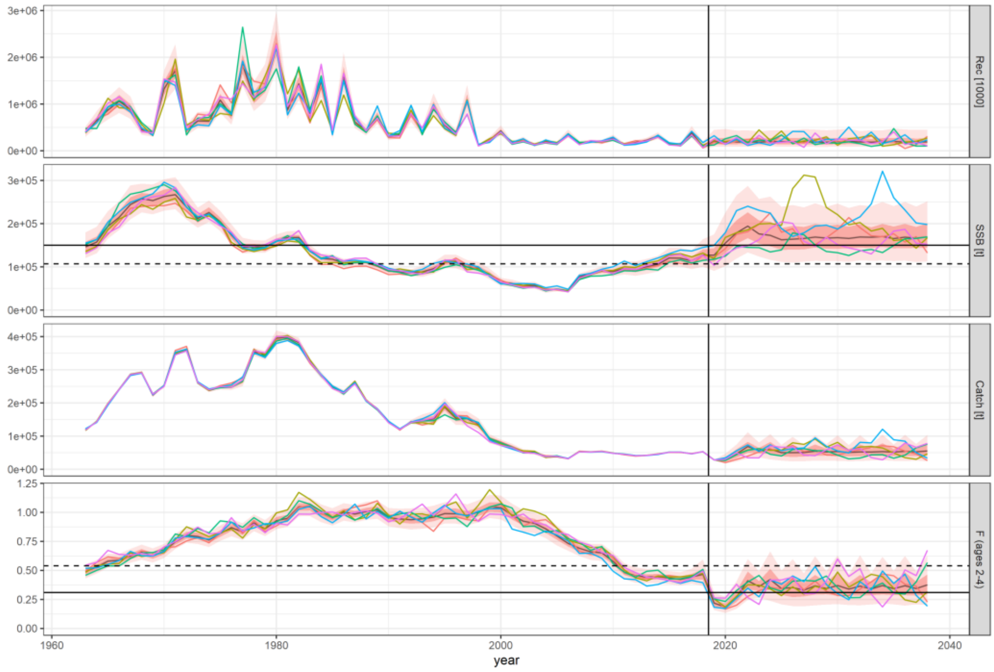


Figure 3.4.2.7. Cod in Subarea 4, Division 7.d and Subdivision 20: Summary projections for "optimised" management strategy A+D (see Table 3.4.1.1). See the caption to Figure 3.4.2.1 for further details.

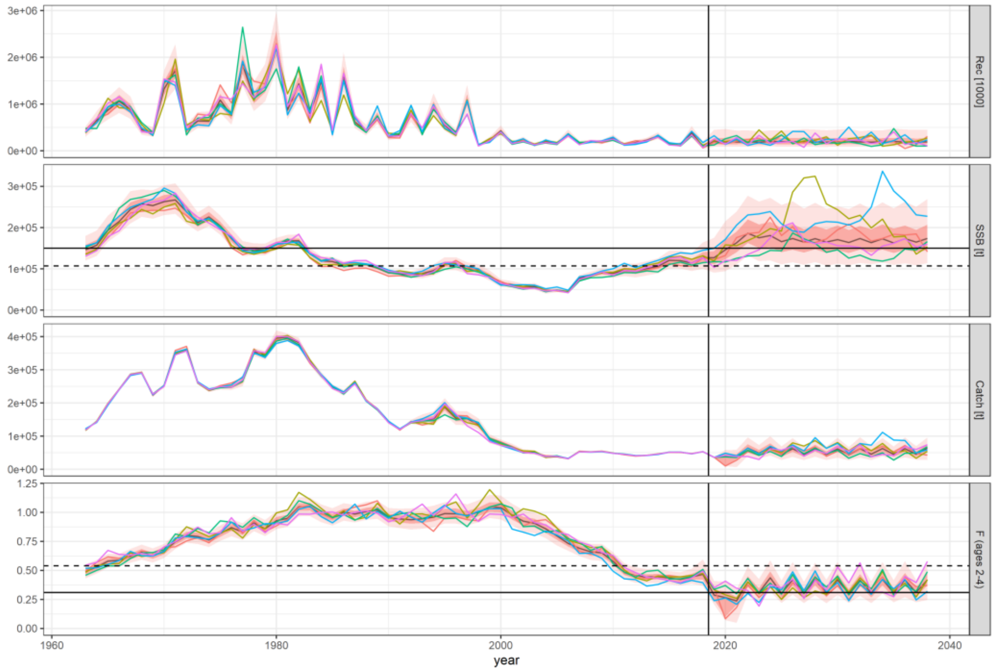


Figure 3.4.2.8. Cod in Subarea 4, Division 7.d and Subdivision 20: Summary projections for "optimised" management strategy B+E (see Table 3.4.1.1). See the caption to Figure 3.4.2.1 for further details.

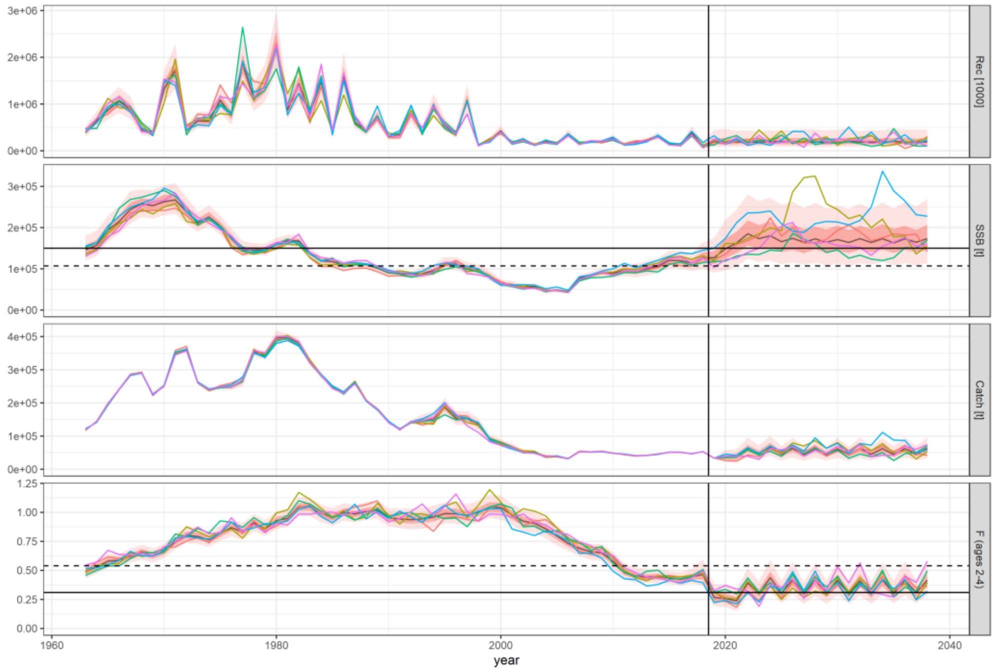


Figure 3.4.2.9. Cod in Subarea 4, Division 7.d and Subdivision 20: Summary projections for "optimised" management strategy C+E (see Table 3.4.1.1). See the caption to Figure 3.4.2.1 for further details.

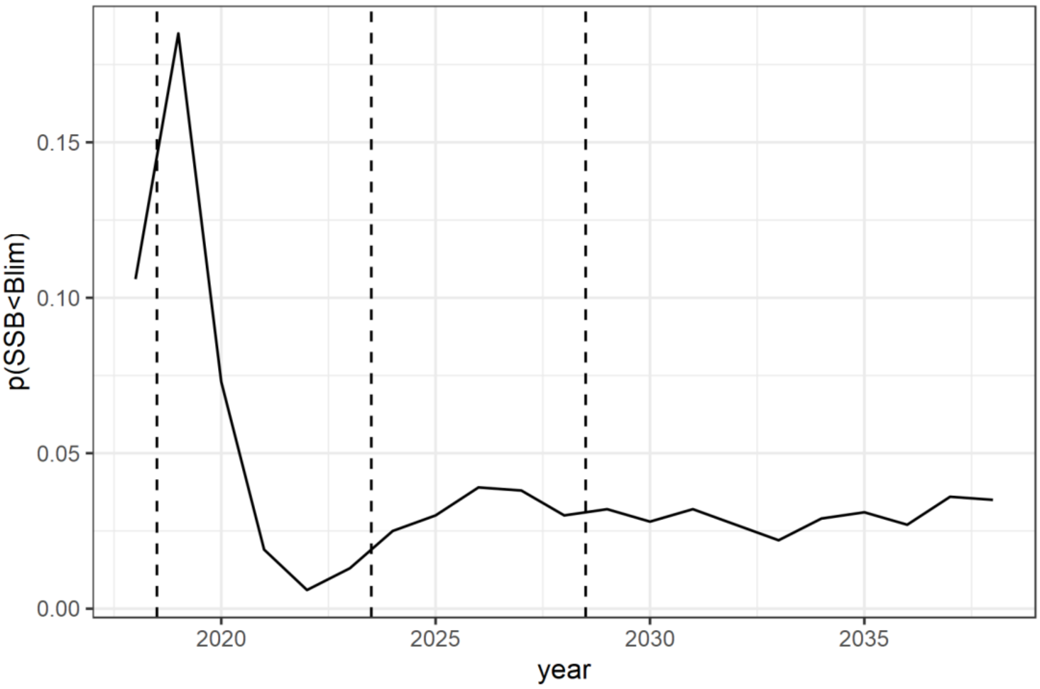


Figure 3.4.2.10. Cod in Subarea 4, Division 7.d and Subdivision 20: Annual risk (P(SSB<B_{lim})) for "optimised" management strategy A. The horizontal hashed lines separate the short- medium- and long-term projection periods used for the performance statistics.

3.4.3 Comparison of management strategies for the baseline OM1

The performance of F=0, a version of management strategy A that sets $F_{target}=F_{MSY}=0.31$ and $B_{trigger}$=MSY $B_{trigger}$=150000 t (labelled A*), and the six “optimised” management strategies are compared in terms of catch, risk1 and risk3, inter-annual catch variability and SSB in the short- (first five years), medium- (years 6–10) and long-term (final 10 years) in Figures 3.4.3.1–3.4.3.3. Two additional performance statistics were calculated for cod to account for the fact that the latest assessment predicts the stock to be below MSY $B_{trigger}$ (ICES 2018a): the proportion of replicates that recover to above B_{pa}=MSY $B_{trigger}$=150000 t within the 20-year simulation period and the number of years it takes for each replicate to recover above B_{pa}=MSY $B_{trigger}$. These results are presented for F=0, A* and the six “optimised” management strategies in Figure 3.4.3.4.

Short-term comparisons (Figure 3.4.3.1) indicate that none of the management strategies (and not even closing the fishery) has an associated risk3 lower than 5%, which is an indication of current stock status (SSB close to B_{lim}). This implies that there are no management strategies that would be deemed precautionary in the short-term for cod. Recovery is quick, however, and all management strategies are precautionary in the medium- (Figure 3.4.3.2) and long-term (Figure 3.4.3.3). An interesting result is that management strategy A* (essentially the current MSY approach for cod) results in similar long-term catch as the other six “optimised” management strategies, but at much lower risk and interannual catch variability, and higher long-term SSB (Figure 3.4.3.3).

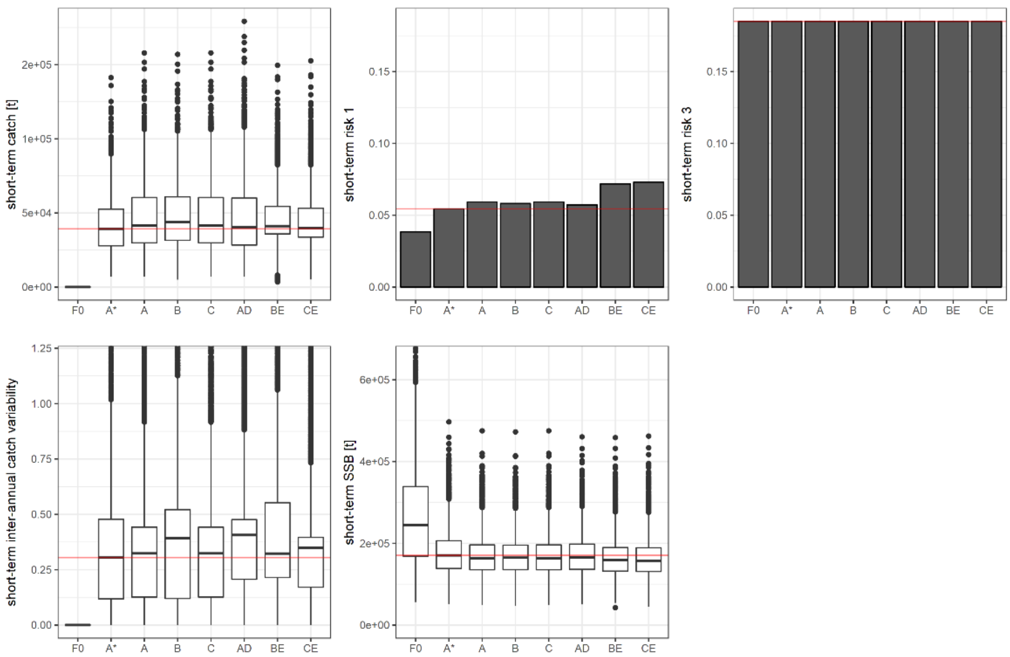


Figure 3.4.3.1. Cod in Subarea 4, Division 7.d and Subdivision 20: Comparing the performance of management strategies in the short-term (first five years). Individual plots are as indicated by the label on the y-axis. Within each plot, the management strategies are F0 (i.e. F=0), A* (i.e. management strategy A with $F_{target}=F_{msy}=0.31$ and $B_{trigger}$=MSY $B_{trigger}$=150000 t, and the six “optimised” management strategies (A, B, C, A+D, B+E and C+E). In the box and whisker plots, the heavy horizontal line within the box indicates the median, the edges of the box indicate the 25th and 75th percentiles, and the whiskers extend to the largest and smallest values within 1.5 times the inter-quartile range (IQR) from the edges, and the remaining points indicated as dots outside the whiskers are the outliers to 1.5*IQR from the edges. The red horizontal line corresponds to the median (box and whisker plots) or actual value (risk plots) for management strategy A* for comparison.

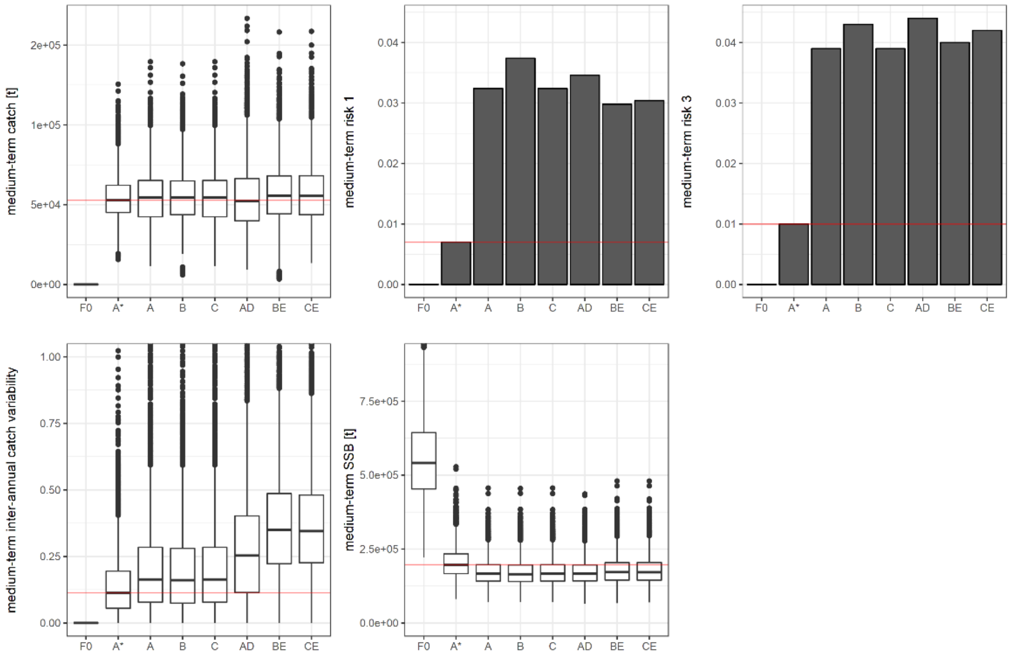


Figure 3.4.3.2. Cod in Subarea 4, Division 7.d and Subdivision 20: Comparing the performance of management strategies <u>in the medium-term (years 6-10)</u>. See Figure 3.4.3.1 for more details.

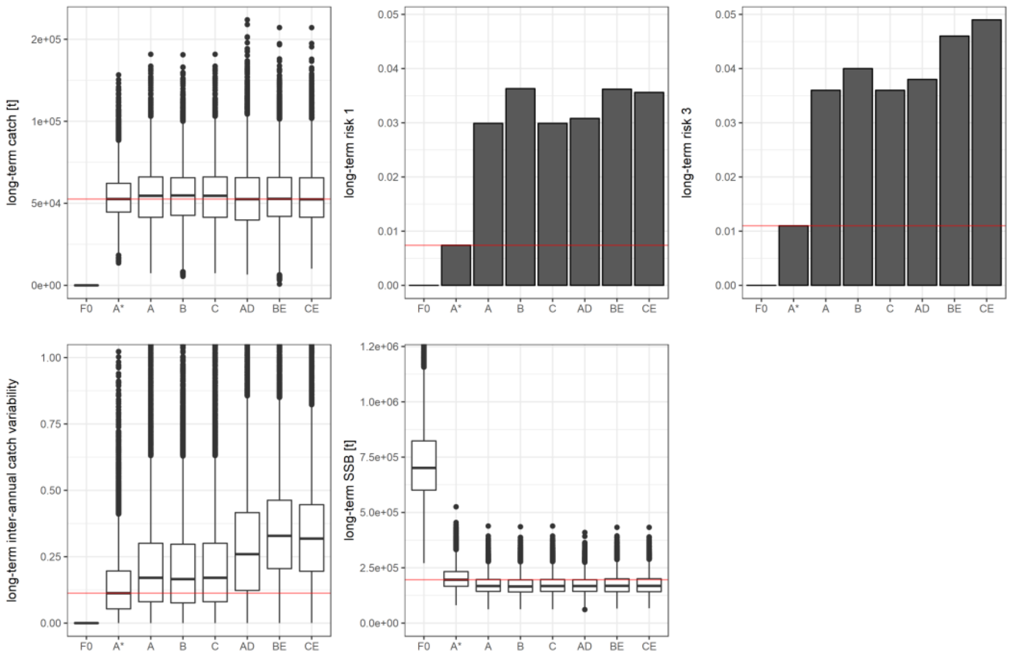


Figure 3.4.3.3. Cod in Subarea 4, Division 7.d and Subdivision 20: Comparing the performance of management strategies <u>in the long-term (final 10 years)</u>. See Figure 3.4.3.1 for more details.

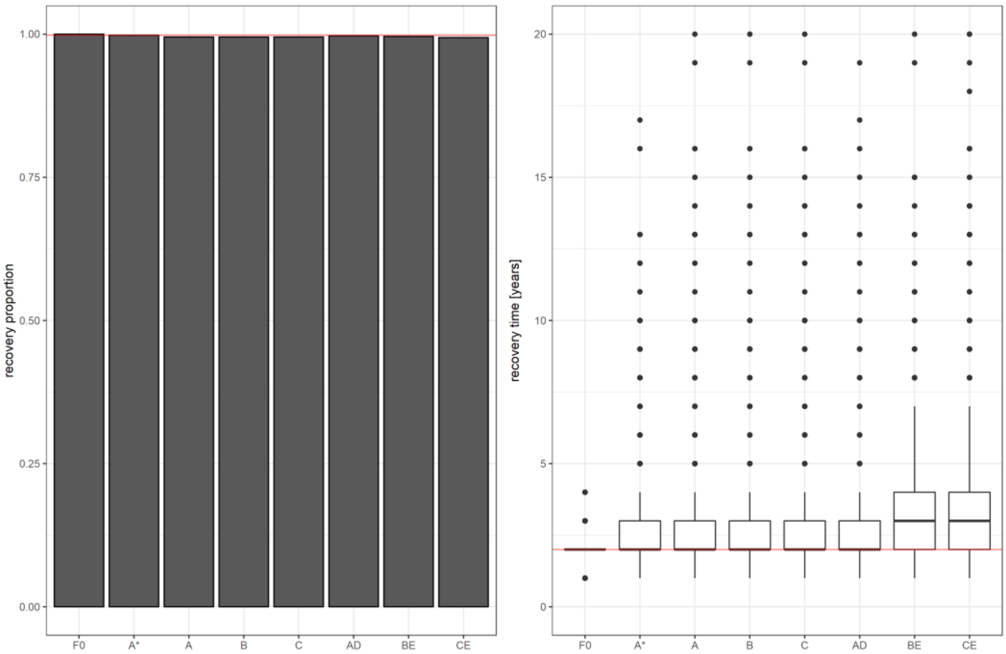


Figure 3.4.3.4. Cod in Subarea 4, Division 7.d and Subdivision 20: Recovery statistics for the various management strategies (as described in Figure 3.4.3.1). The left plot indicates the proportion of replicates that recover above B_{pa}=MSY $B_{trigger}$, while the right plot indicates the number of years taken to recover above B_{pa}=MSY $B_{trigger}$ for the first time, indicated as box and whisker plots (see Figure 3.4.3.1 for a description).

3.4.4 Sensitivity of management strategies for the baseline OM1

The sensitivity of performance statistics for the six "optimised" management strategies (A, B, C, A+D, B+E and C+E) to five fishing pressure scenarios (0.9*F_{target}, F_{target}, 1.1*F_{target}, $F_{MSY\ lower}$=0.198 and $F_{MSY\ upper}$=0.46) in the short- (first five years), medium- (years 6–10) and long-term (final 10 years) are presented in Figures 3.4.4.1–3.4.4.3. Sensitivity of recovery statistics for the management strategies to the same fishing pressure scenarios are presented in Figure 3.4.4.4.

The management strategies have been tuned (using control parameters F_{target} and $B_{trigger}$) to maximise catch in the long-term, but with a check that the ICES precautionary criterion is met (risk3≤5%). For cod, this often meant that the "optimal" combination of F_{target} and $B_{trigger}$ was on the edge of the precautionary and non-precautionary zones of the grid for risk3 (see e.g. Figure 3.4.1.1), and consequently that there was not a lot of slack for F (i.e. selection of a slightly higher F than the "optimal" F_{target} would quickly become non-precautionary). For this reason, none of the management strategies are precautionary when F is increased to 1.1F_{target} and $F_{MSY-upper}$. On the other hand, long-term catch is hardly affected when decreasing F to 0.9F_{target}., but setting it at $F_{MSY-lower}$ leads to markedly lower long-term catch.

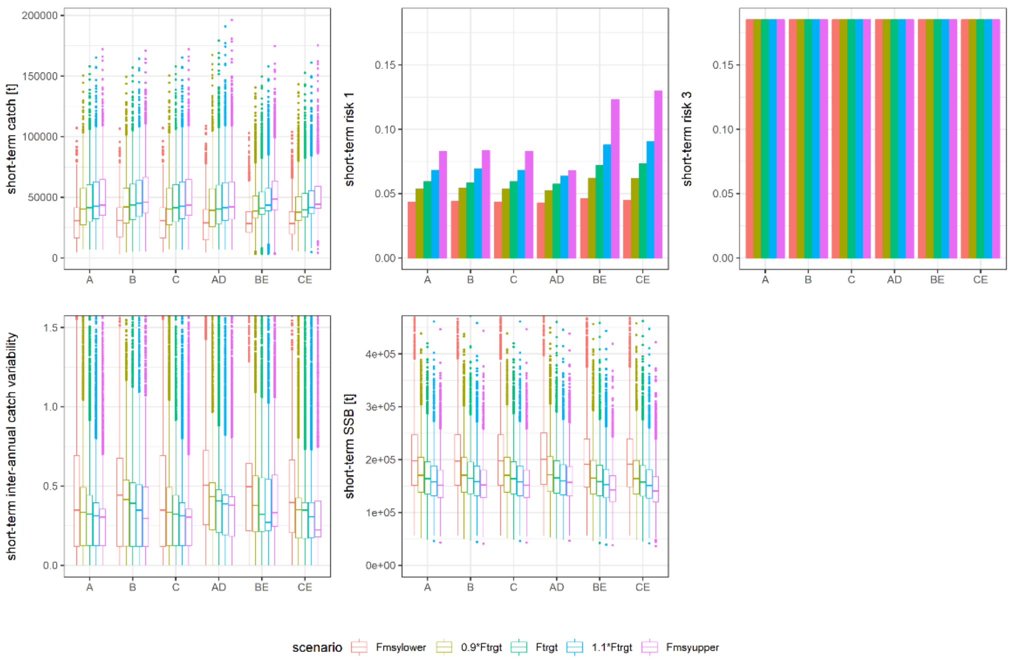


Figure 3.4.4.1. Cod in Subarea 4, Division 7.d and Subdivision 20: Sensitivity of performance statistics for the "optimised" management strategies to changes in F in the short-term (first five years). Individual plots are as indicated by the label on the y-axis. In the box and whisker plots, the heavy horizontal line within the box indicates the median, the edges of the box indicate the 25th and 75th percentiles, and the whiskers extend to the largest and smallest values within 1.5 times the inter-quartile range (IQR) from the edges, and the remaining points indicated as dots outside the whiskers are the outliers to 1.5*IQR from the edges.

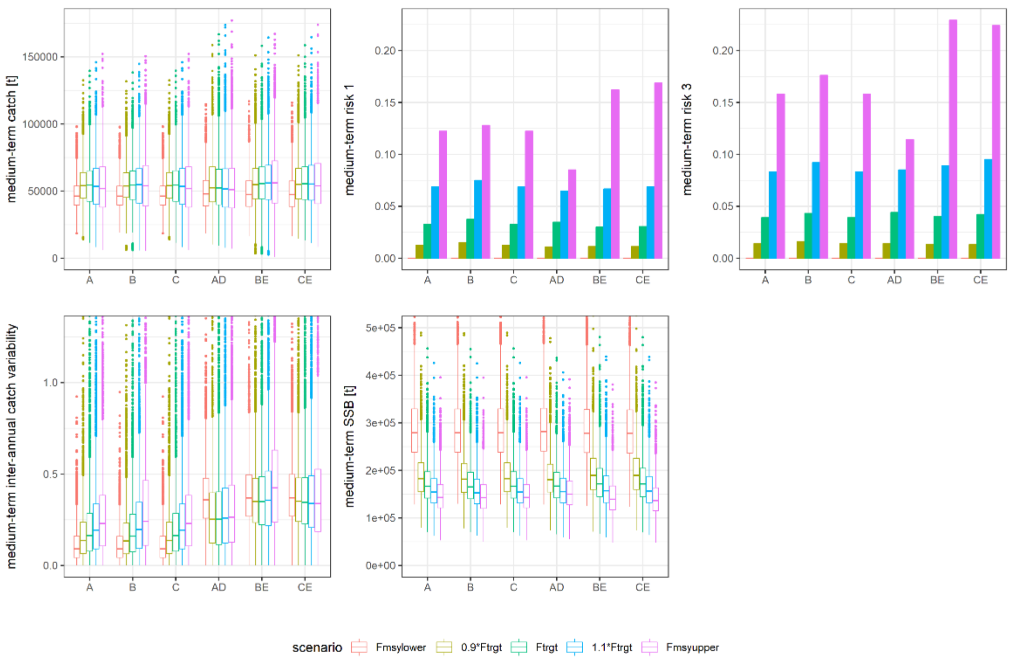


Figure 3.4.4.2. Cod in Subarea 4, Division 7.d and Subdivision 20: Sensitivity of performance statistics for the "optimised" management strategies to changes in F in the medium-term (years 6-10). See Figure 3.4.4.1 for more details.

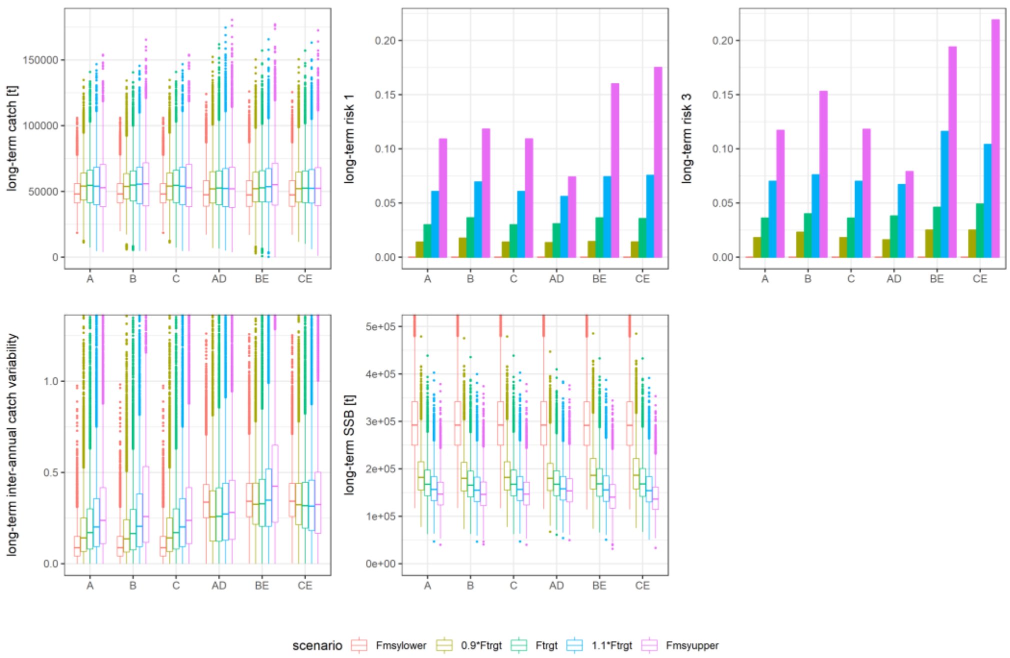


Figure 3.4.4.3. Cod in Subarea 4, Division 7.d and Subdivision 20: Sensitivity of performance statistics for the "optimised" management strategies to changes in F in the long-term (final 10 years). See Figure 3.4.4.1 for more details.

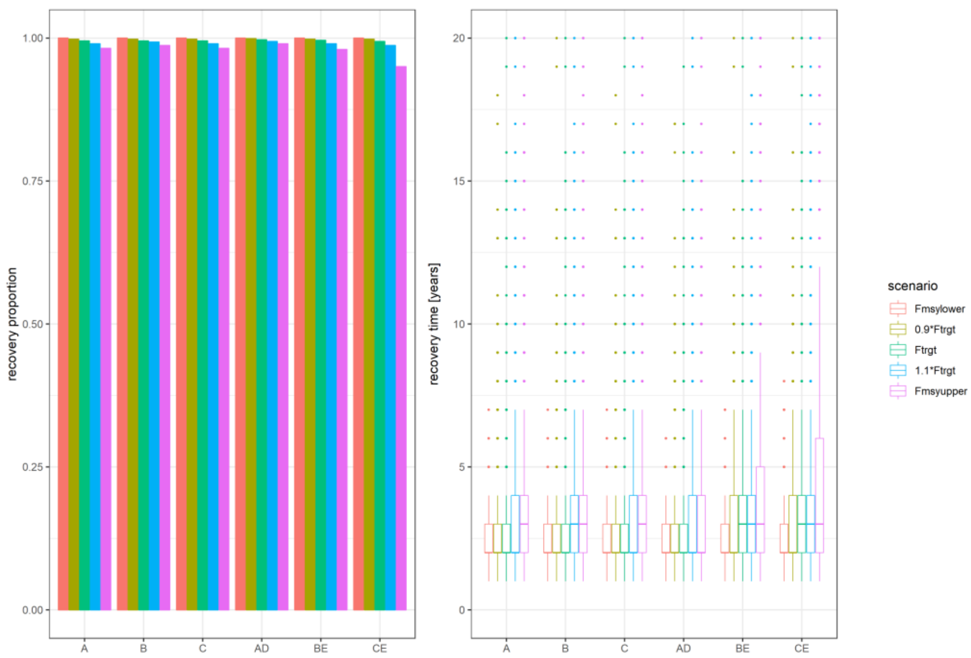


Figure 3.4.4.4. Cod in Subarea 4, Division 7.d and Subdivision 20: Sensitivity of recovery statistics for the "optimised" management strategies (as described in Figure 3.4.4.1) to changes in F. The left plot indicates the proportion of replicates that recover above B_{pa}=MSY $B_{trigger}$, while the right plot indicates the number of years taken to recover above B_{pa}=MSY $B_{trigger}$ for the first time, indicated as box and whisker plots (see Figure 3.4.4.1 for a description).

3.4.5 Robustness of management strategies across alternative OMs

Robustness of the "optimised" management strategies (A, B, C, A+D, B+E and C+E) across alternative operating models (OMs 1–4, described in Sections 3.1–3.2) is evaluated in the short (first five years), medium (years 6–10) and long (final 10 years) term. Performance statistics for each "optimised" management strategy are compared across operating models and to performance statistics for F=0 and a version of management strategy A that sets F_{target}=F_{MSY}=0.31 and $B_{trigger}$=MSY $B_{trigger}$=150000 t (labelled A*) in Figures 3.4.5.1–3.4.5.3. Similar plots comparing recovery statistics for the various management strategies across alternate operating models are presented in Figure 3.4.5.4.

Figure 3.4.5.3 reveals that none of the "optimised" management strategies are precautionary in the long-term under alternative operating model OM3 (year-effects in the IBTS surveys); however, management strategy A* (the current MSY approach for cod) remains precautionary in the medium- and long-term under all alternative operating models.

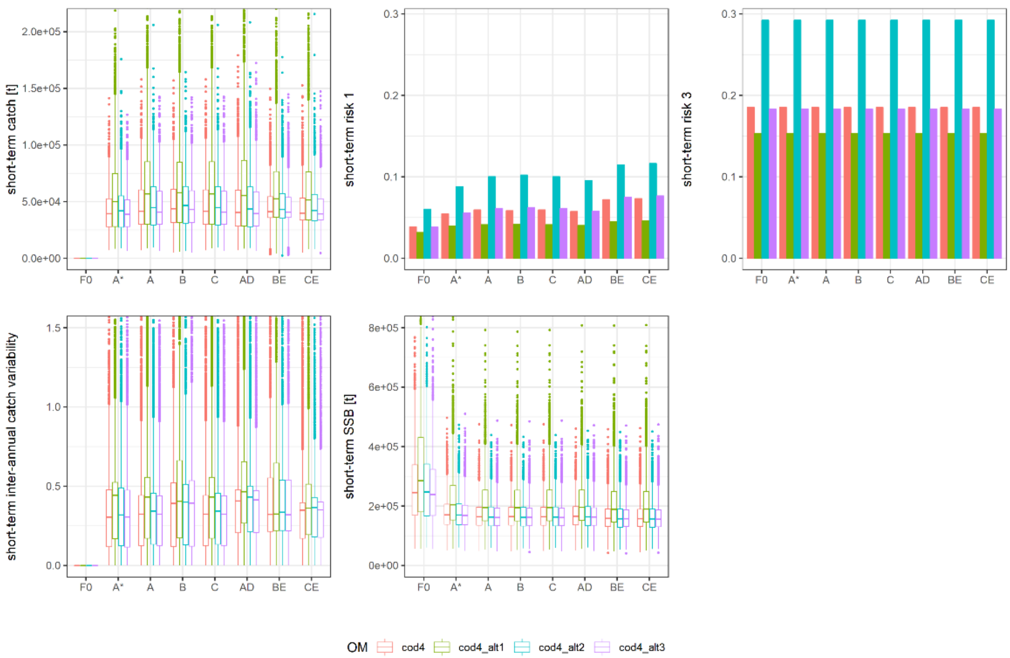


Figure 3.4.5.1. Cod in Subarea 4, Division 7.d and Subdivision 20: Performance statistics for the various management strategies with alternate operating models in the short-term (first five years). Individual plots are as indicated by the label on the y-axis. Within each plot, the management strategies are F0 (i.e. F=0), A* (i.e. management strategy A with F_{target}=F_{msy}=0.31 and $B_{trigger}$=MSY $B_{trigger}$=150000 t, and the six "optimised" management strategies (A, B, C, A+D, B+E and C+E). The operating models are OM1 (cod4), OM2 (cod4_alt1), OM3 (cod4_alt2) and OM4 (cod4_alt3) described in Sections 3.1–3.2. In the box and whisker plots, the heavy horizontal line within the box indicates the median, the edges of the box indicate the 25th and 75th percentiles, and the whiskers extend to the largest and smallest values within 1.5 times the inter-quartile range (IQR) from the edges, and the remaining points indicated as dots outside the whiskers are the outliers to 1.5*IQR from the edges.

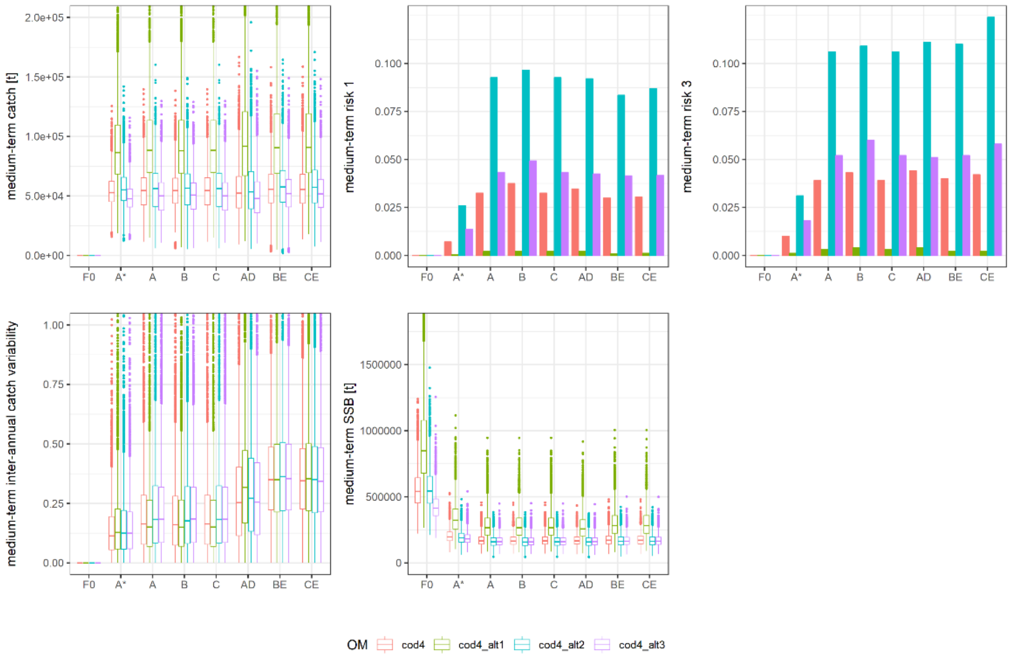


Figure 3.4.5.2. Cod in Subarea 4, Division 7.d and Subdivision 20: Performance statistics for the various management strategies with alternate operating models <u>in the medium-term (years 6-10)</u>. See Figure 3.4.5.1 for more details.

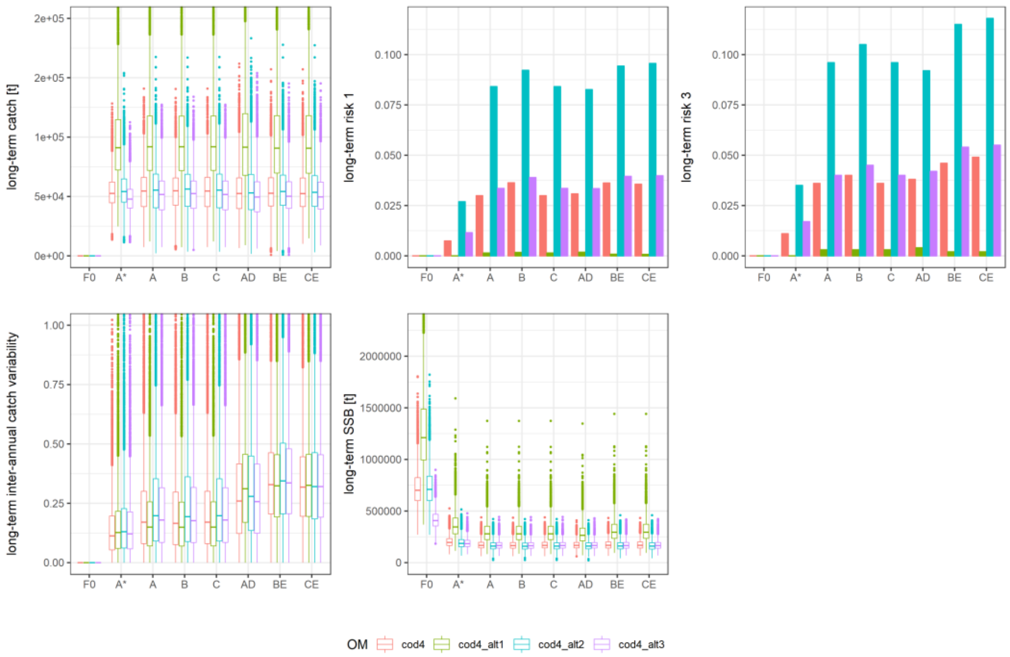


Figure 3.4.5.3. Cod in Subarea 4, Division 7.d and Subdivision 20: Performance statistics for the various management strategies with alternate operating models <u>in the long-term (final 10 years)</u>. See Figure 3.4.5.1 for more details.

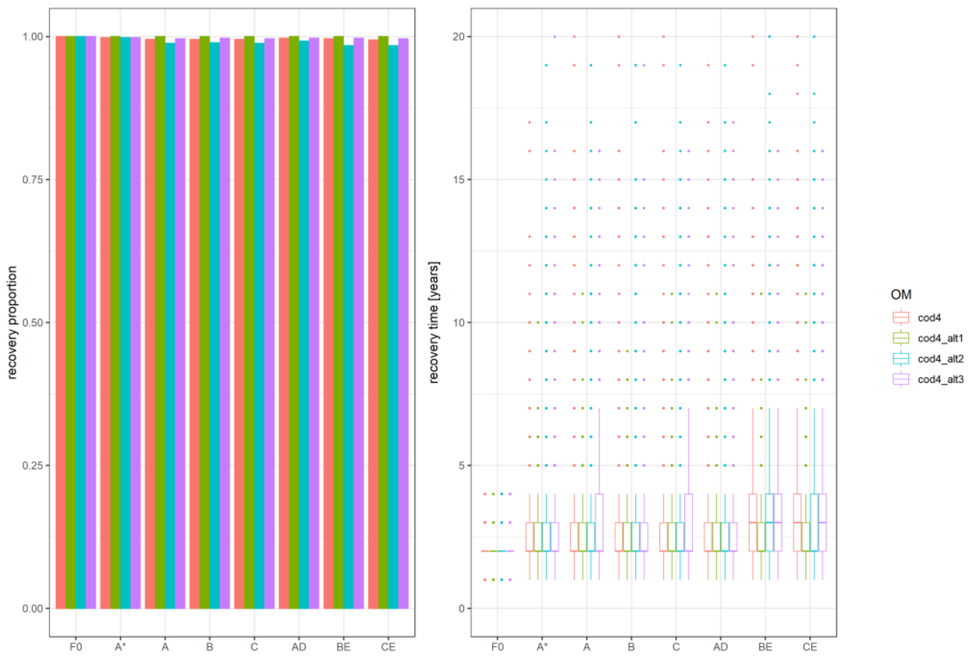


Figure 3.4.5.4. Cod in Subarea 4, Division 7.d and Subdivision 20: Recovery statistics for the various management strategies (as described in Figure 3.4.5.1) with alternate operating models (see Figure 3.4.5.1 for definitions). The left plot indicates the proportion of replicates that recover above B_{pa}=MSY $B_{trigger}$, while the right plot indicates the number of years taken to recover above B_{pa}=MSY $B_{trigger}$ for the first time, indicated as box and whisker plots (see Figure 3.4.5.1 for a description). [Note for OM3 (labelled cod4_alt2), MSY $B_{trigger}$ was not re-calculated, but because B_{lim} for OM3 was so close to the B_{lim} for OM1, MSY Btrigger were almost the same.]

Figure 3.4.5.5a plots the discrepancy between the management procedure and the underlying "truth" for each alternate operating model under "optimised" management strategy A. Because the estimation model component of the management procedure revises historical estimates of stock numbers, fishing mortality and any derived metrics with each new estimation, only the final year of the management procedure is plotted in each time step. The peak in F near the beginning of the projection period results from the slow response of the management procedure to the sharp decline in F under "optimised" management strategy A: this slow reaction is a consequence of the high correlation parameter for increments of log(F) across ages estimated by SAM ($\rho = 0.86$).

There is some indication of a slight positive bias in SSB when comparing the MP to the OM (Figure 3.4.5.5a). This is not unexpected for cod given the slight tendency to overestimate SSB, as highlighted by the 5-year retrospective plot from the most recent SAM assessment (Figure 3.4.5.5b).

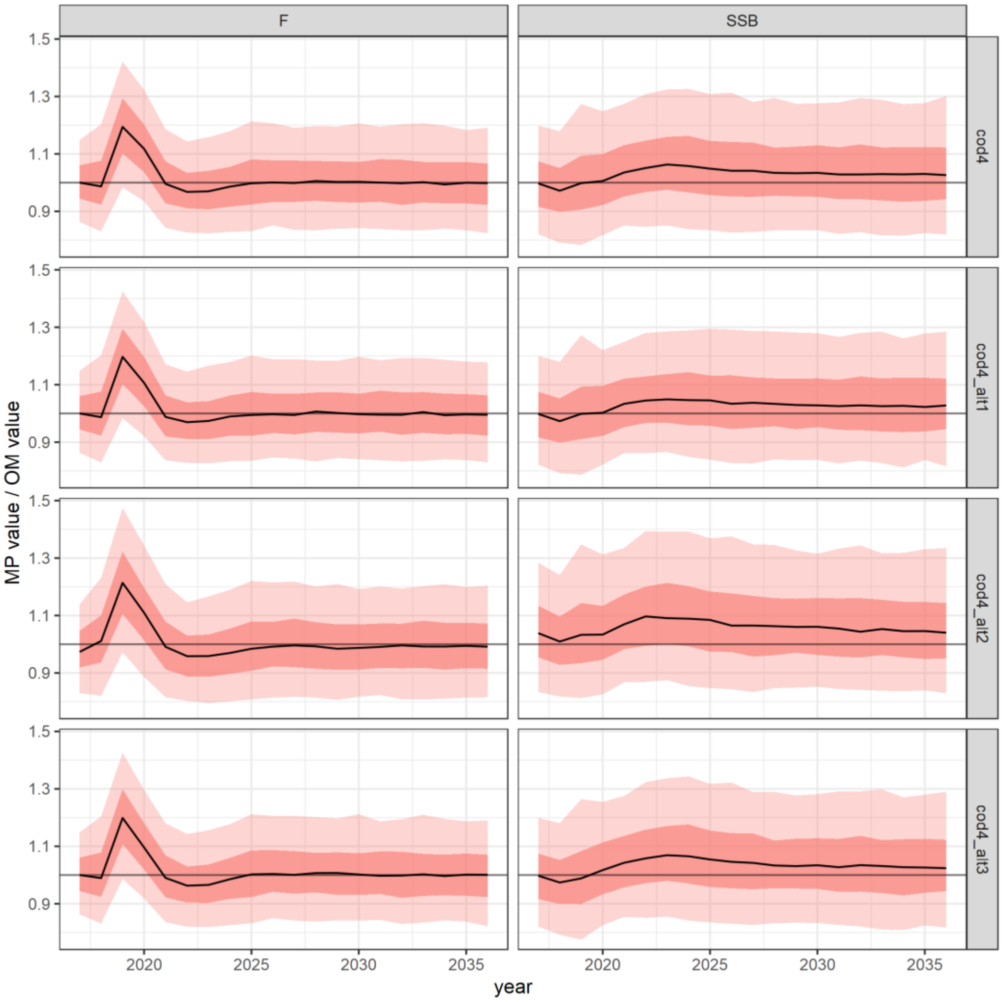


Figure 3.4.5.5a. Cod in Subarea 4, Division 7.d and Subdivision 20: Discrepancy in estimates of F and SSB from the management procedure compared to the underlying “truth” for each alternative operating model (see Figure 3.4.5.1 for definitions). Values > 1 indicate an overestimation by the management procedure while values < 1 indicate an underestimation.

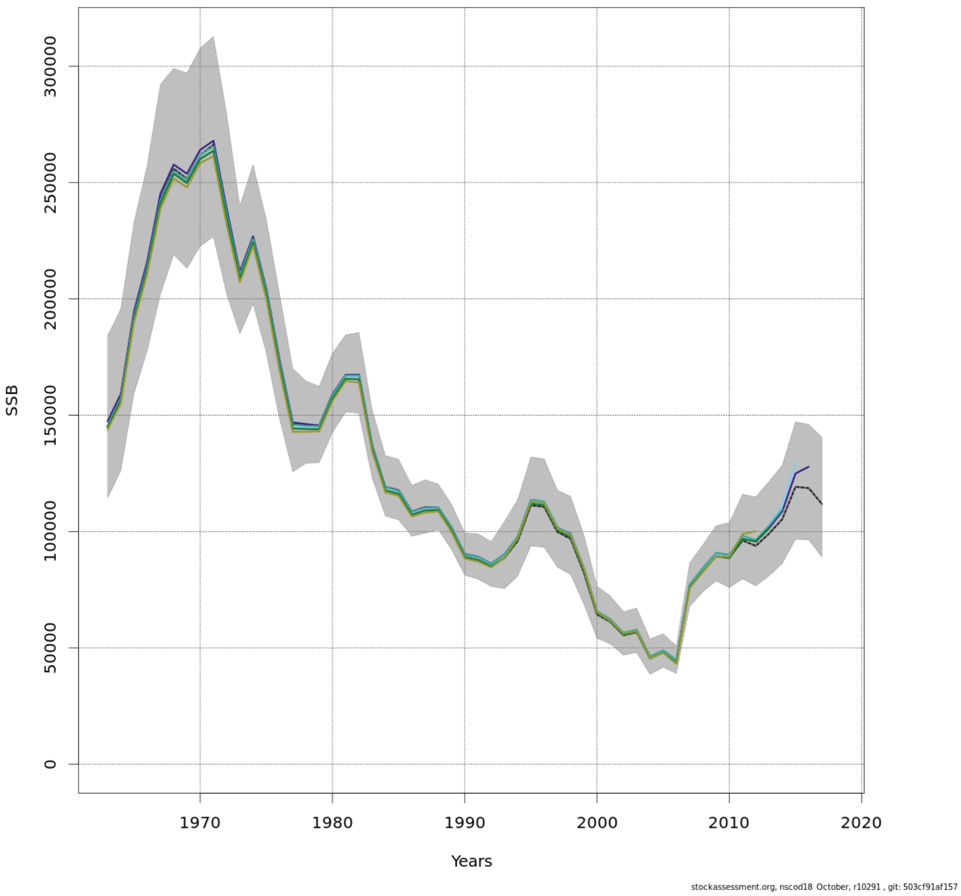


Figure 3.4.5.5b Cod in Subarea 4, Division 7.d and Subdivision 20: Retrospective estimates (5 years) from the SAM assessment (October update assessment; ICES 2018a). Estimated yearly SSB together with corresponding point-wise 95% confidence intervals.

Figure 3.4.5.6 plots natural mortality-at-age and SSB for the baseline operating model (OM1) and the alternative operating model considering density-dependent M (OM4; see Section 3.2) both for “optimised” management strategy A, showing Ms for ages 1–3 to be higher and more variable when including density-dependence.

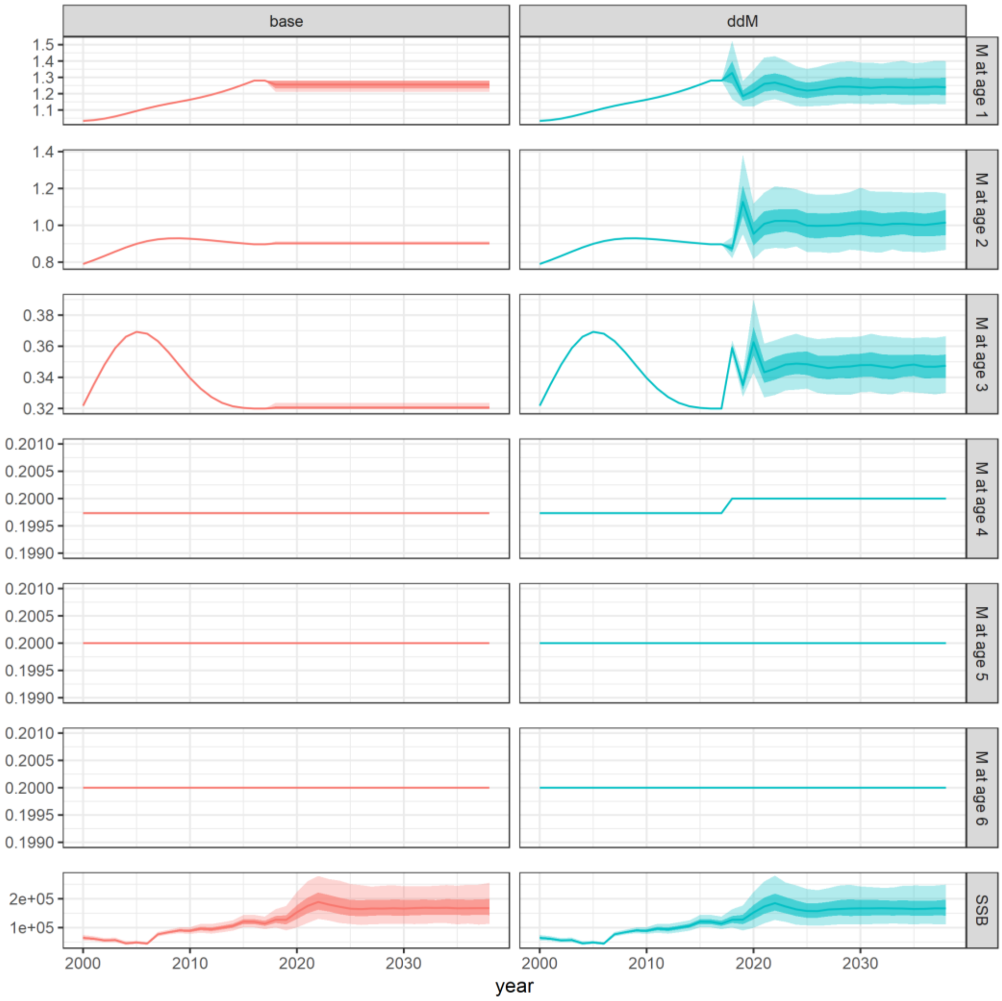


Figure 3.4.5.6. Cod in Subarea 4, Division 7.d and Subdivision 20: Natural mortality-at-age and SSB for the baseline (base=OM1) and density-dependent M (ddM=OM4) operating models under "optimised" management strategy A. Note that M-at-age for OM2 and OM3 will be the same as for the baseline OM1.

Given that "optimised" management strategies A and C yield the same results (Table 3.4.1.1), a fourth alternative operating model (OM5) was considered to explore the space where the three harvest control rules differ (i.e. where SSB < B_{lim} for HCR B and SSB < 0.25*$B_{trigger}$ for HCRs A and C; see Figure 2.1). Generated recruitments (see Section 3.1.3) were reduced by 99% for the first 15 years of the projection period and the time taken from the following year for the SSB of each replicate to exceed B_{lim} recorded. The distribution of SSBs when at the lowest (2034; the year after the last low recruitment) and of time taken for SSB to exceed B_{lim} are shown in Figure 3.4.5.7. Summary projections for recruitment (age 1), SSB, catch and mean F (ages 2-4) are given for the three HCRs (A, B and C) in Figure 3.4.5.8.

These results indicate that when the stock is forced to a very low SSB (with recruitment failure), HCRs A, B and C react appropriately by reducing catch, and all can recover the stock once recruitment improves. As expected, A is the most precautionary followed by B and C, with recovery to above B_{lim} being delayed for the latter two compared to A.

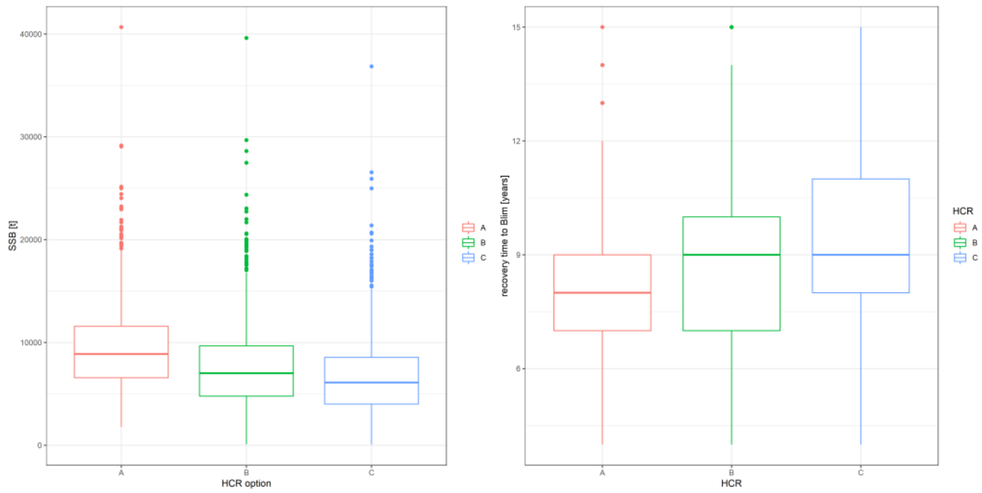


Figure 3.4.5.7. Cod in Subarea 4, Division 7.d and Subdivision 20: Distributions of SSB in 2034 and time taken from 2034 for SSB to exceed B_{lim} for OM5 with "optimised" management strategies A, B and C. In the box and whisker plots, the heavy horizontal line within the box indicates the median, the edges of the box indicate the 25th and 75th percentiles, and the whiskers extend to the largest and smallest values within 1.5 times the inter-quartile range (IQR) from the edges, and the remaining points indicated as dots outside the whiskers are the outliers to 1.5*IQR from the edges.

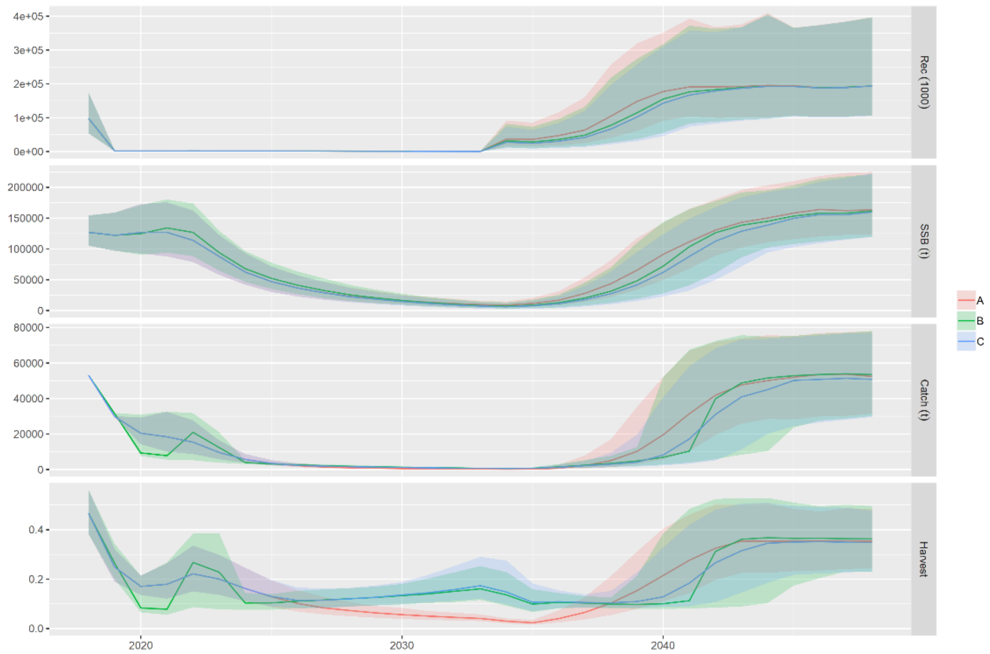


Figure 3.4.5.8. Cod in Subarea 4, Division 7.d and Subdivision 20: Summary projections for OM5 under the three different HCRs ("optimised" management strategies A, B and C). Top plot is recruitment (age 1), second plot SSB, third plot catch and bottom plot mean F (ages 2-4). The actual plots show medians (solid lines) with the shaded areas the 80% confidence interval.

3.5 Conclusions

"Optimised" combinations without stability

- A and C have identical "optimised" control parameters because SSBs do not drop low enough to result in a difference. $B_{trigger}$=170000 t and F_{target}=0.38 in both cases.

- B results in a slightly higher median long-term catch, but also lower SSB and higher risk. $B_{trigger}$=160000 t and F_{target}=0.38.
- When the stock is forced to a very low SSB (with recruitment failure), all rules react appropriately by reducing catch, and all can recover the stock once recruitment improves. As expected, A is the most precautionary followed by B and C, with recovery to above B_{lim} being delayed for the latter two compared to A.
- In all three cases, the median long-term SSB is close to the $B_{trigger}$ value, implying that the rule will often operate "on the slope", resulting in ICVs of around 17%.

"Optimised" Combinations with stability

- When stability mechanisms are included, median long-term catch is slightly reduced, and ICV substantially increased in all cases. The increase in ICV is due to the extreme banking and borrowing scenario implemented.
- F_{target} and $B_{trigger}$ are increased for A+D, but reduced for B+E and C+E. This is likely due to the differences in the application of the banking and borrowing scheme (only when SSB≥$B_{trigger}$ for A, but throughout for B and C; additional safeguards [paragraph 5] for B and C compared to A).

Compared to MSY advice rule approach and F=0

- The MSY approach advice rule produces a similar long-term yield as the six management strategies, but with a much lower risk and ICV, and higher SSB.
- None of the management strategies are precautionary in the short-term: short-term risk is much higher than 5% for all management strategies, including the MSY approach advice rule and F=0; this is because the SSB for cod is currently close to B_{lim}.
- Recovery to above B_{pa} is 2-3 years in all cases, but with a slight delay for B+E and C+E

Sensitivity for "Optimised" Combinations

- Short-, medium- and long-term catches are similar across the F ranges for the sensitivity tests, except for $F_{MSY\text{-}lower}$, which has a consistently lower value.
- Long-term risk is above 5% for 1.1F_{target} and $F_{MSY\text{-}upper}$.
- For $B_{trigger}$=150000 t (MSY $B_{trigger}$), $F_{MSY\text{-}upper}$, would not be considered precautionary. This is in direct contrast to EqSim, which concludes that $F_{MSY\text{-}upper}$ is precautionary. From this study the equivalent to $F_{P.05}$ is 0.37, whereas $F_{MSY\text{-}upper}$ is 0.46.

Robustness tests against alternative operating models

- All optimised management strategies fail the precautionary check (i.e. risk3>5%) under the alternative operating model that includes year effects in the IBTS surveys.
- This result indicates that were future assessments of cod to indicate that year effects in the survey should be included, then more precautionary combinations of F_{target} and $B_{trigger}$ would be needed than the "optimised" combinations derived for the baseline operating model.

Computational considerations

- The simulations required for this MSE were computationally very expensive and it was not possible to run the full grid for all management strategies. During the workshop, an opportunity arose to test a commercial state-of-the-art high-performance computing system and a full grid search was conducted for management strategy A for cod (as shown in Figure 3.4.1.1). This simulation alone, however, came at the cost of a total CPU runtime of around 18,500 hours (i.e. 2.1 years) and used exclusively 40 high performance computing nodes with a total of 1,600 CPU cores and 15 terabytes of memory for more than 10 hours.

4 Haddock (*Melanogrammus aeglefinus*) in Subarea 4, Division 6.a, and Subdivision 20 (North Sea, West of Scotland, Skagerrak)

4.1 Baseline operating model (OM1)

4.1.1 Model and settings

The baseline operating model has been conditioned using a version of SAM that is based on the same data and approximates well the latest TSA stock assessment for Northern Shelf haddock (WGNSSK ICES, 2018a). The reason why this approach is used is because TSA cannot be used in the MP because it takes a long time to converge and requires manual input. An approach was attempted where the OM was conditioned on the TSA assessment, while SAM was used to approximated TSA in the MP, but this approach led to a systematic bias between the OM and the MP that is not representative of the retrospective pattern in the TSA assessment, and therefore TSA cannot be used as the baseline OM either. The approach used here was therefore to condition the OM with SAM (baseline OM1), and use SAM to approximate TSA in the MP, and to introduce, as a robustness test, an alternative OM (OM2) that is conditioned on TSA, but is used together with SAM in the MP. Section 4.3.1 provides a comparison between SAM and TSA.

A comparison of Figure 4.1.1.1 below with the 2018 assessment results for haddock indicates that reference points will be very similar between TSA and SAM, so the current reference points for haddock (ICES, 2018a) have been adopted for all three OMs for the calculation of performance statistics.

The stock spawning biomass has been above the MSY $B_{trigger}$ value of 132 000 t for most years since 2002 and fishing mortality has fluctuated mostly above F_{MSY} but remains at a historical minimum (ICES, 2018a). The SAM assessment results and fit to data are shown in the following plots (Figures 4.1.1.1–5).

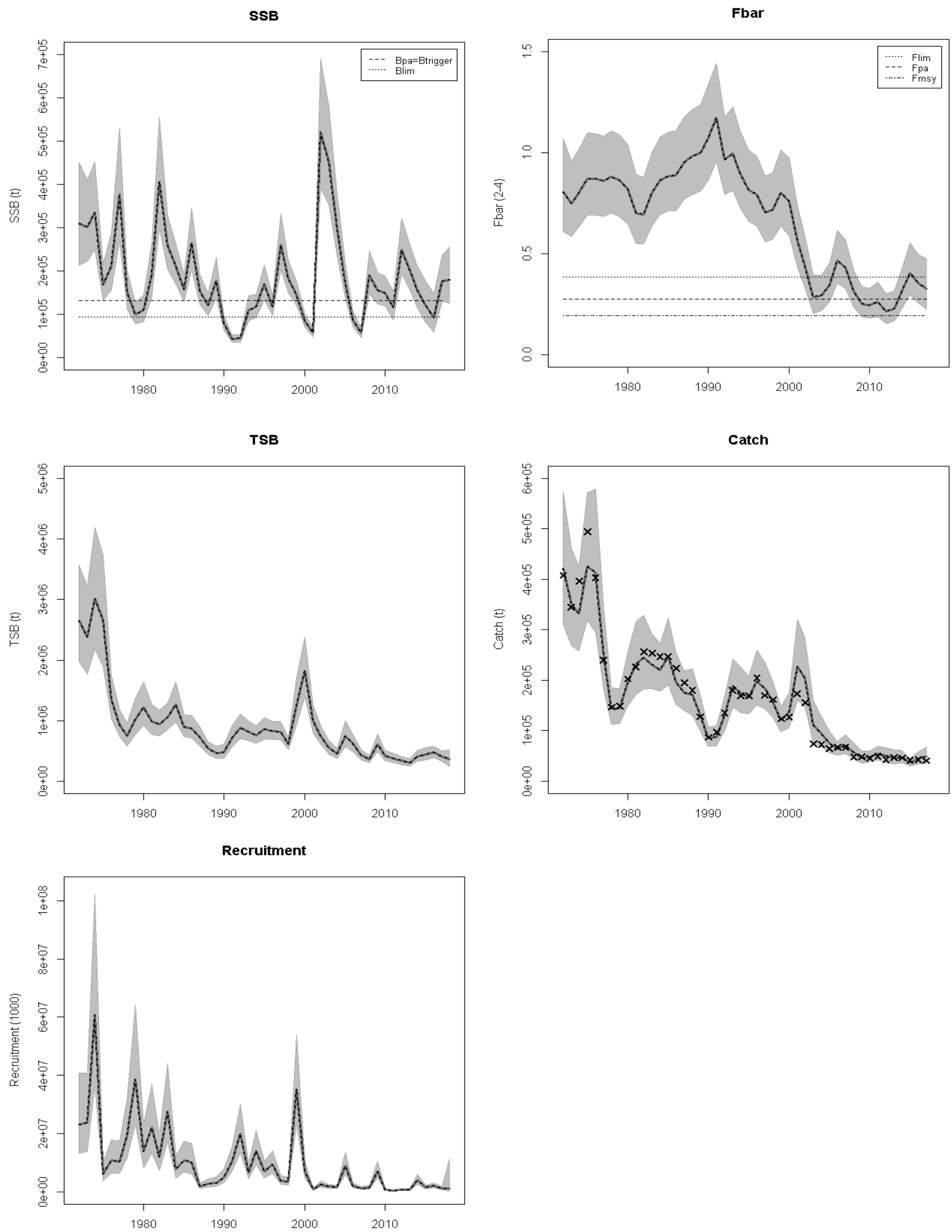


Figure 4.1.1.1. Haddock in Subarea 4, Division 6.a and Subdivision 20: Anticlockwise from top left, point-wise estimates and approximate 95% confidence intervals of spawning stock biomass (SSB), mean fishing mortality for ages 2-4 (F(2-4)), catch, recruitment (R(age 0)), and total stock biomass (TSB) from the SAM final run. The black lines represent the point-wise estimate, and the grey shading represent the approximate point-wise 95% confidence intervals. The black crosses represent the observed values of catch. The horizontal broken lines in the SSB plot indicate B_{lim}=94 000t and MSY $B_{trigger}$=B_{pa}=132 000t, and in the Fbar plot F_{lim}=0.384, F_{pa}=0.274 and F_{MSY}=0.194. Catch, TSB and SSB are in tonnes, and R in millions.

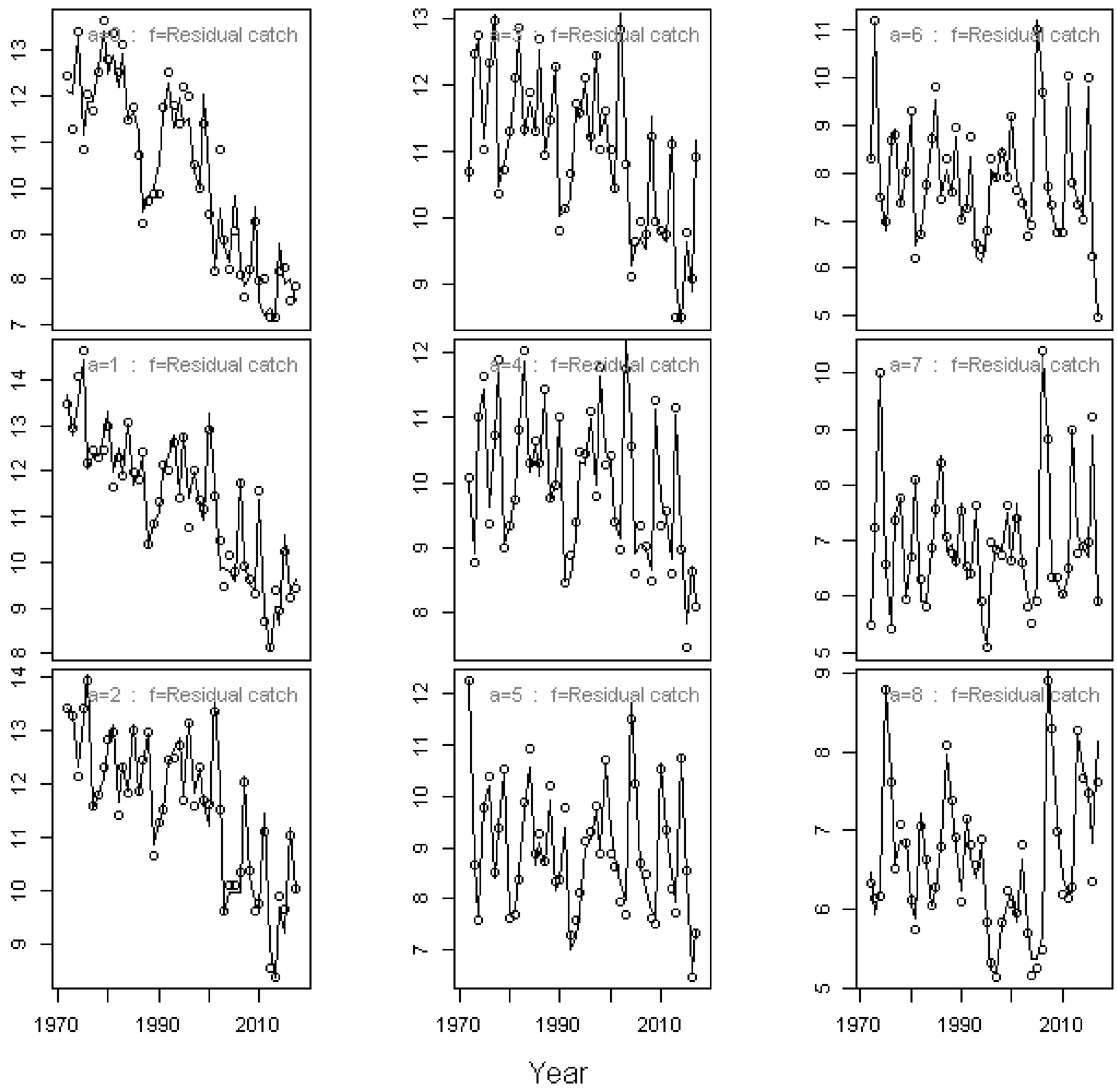


Figure 4.1.1.2. Haddock in Subarea 4, Division 6.a and Subdivision 20: Fits to catch-at-age data.

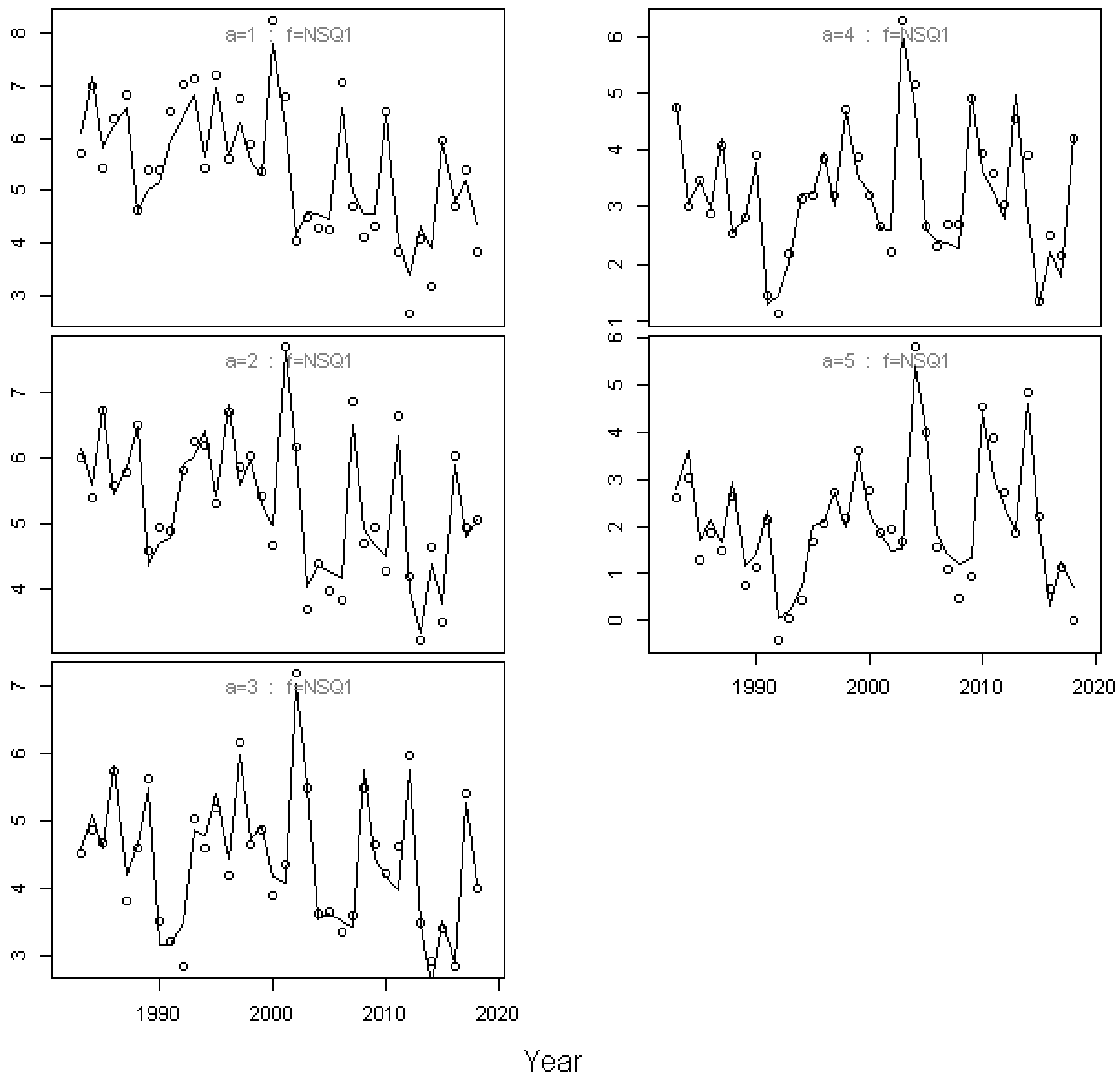


Figure 4.1.1.3. Haddock in Subarea 4, Division 6.a and Subdivision 20: Fits to the IBTS–Q1 survey data.

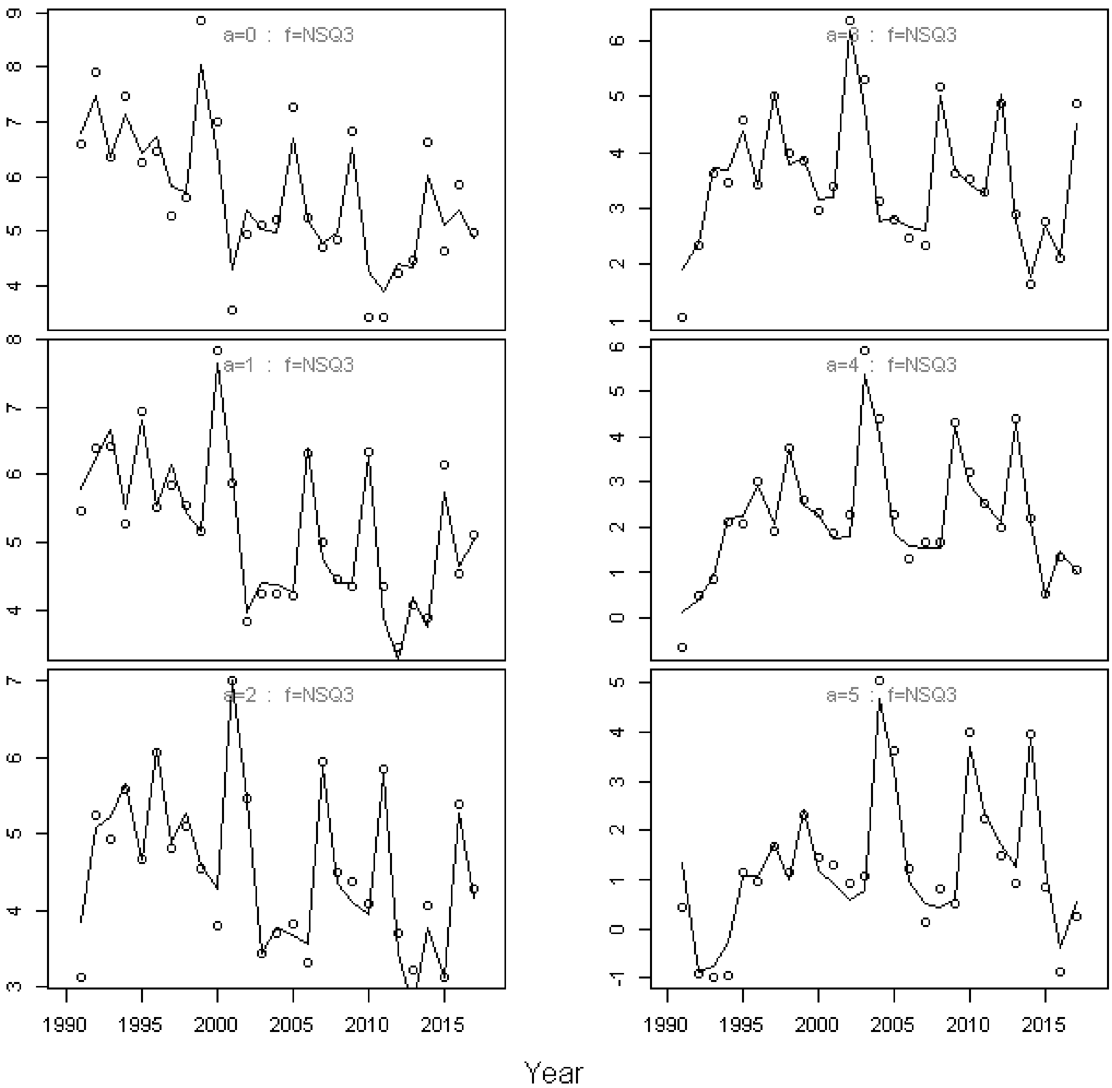


Figure 4.1.1.4. Haddock in Subarea 4, Division 6.a and Subdivision 20: Fits to the IBTS–Q3 survey data.

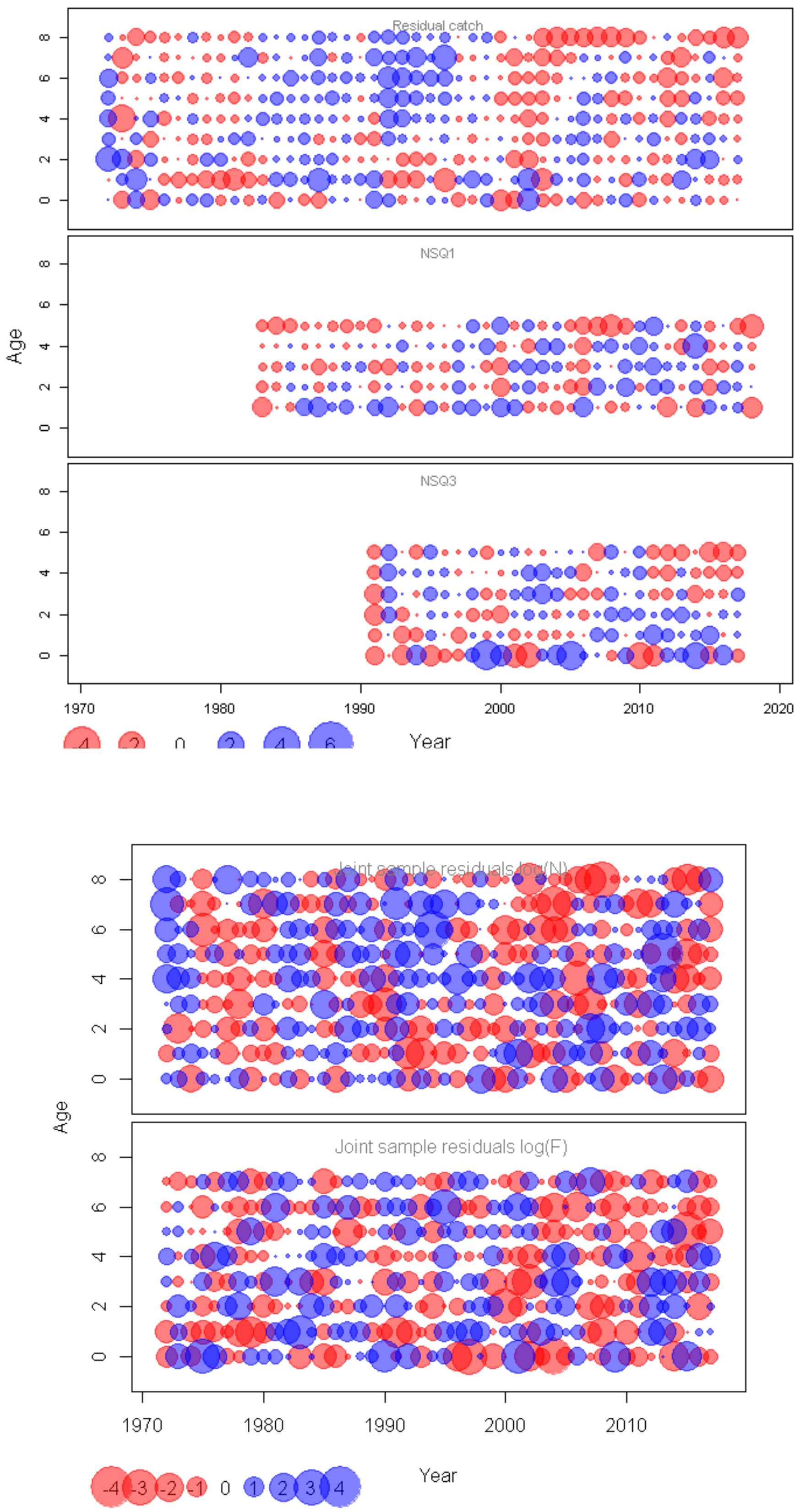


Figure 4.1.1.5. Haddock in Subarea 4, Division 6.a and Subdivision 20: Normalized residuals for the SAM assessment, for total catch, IBTS–Q1, IBTS–Q3, the recruitment and survival process error, and the fishing mortality process error. Blue circles indicate a positive residual and red circles a negative residual.

Northern Shelf haddock comprises of 4 catch components of which 3 are pooled together before conducting the stock assessment. The same method is used here so that the operating model comprises of landings and discards where discards include industrial bycatch and BMS (below minimum size landings). While industrial bycatch of haddock represented 10-15% of the catch in the 1970s it has decreased in importance over time and represents less than 0.2% of the total catch in recent years (Figure 4.1.1.6). BMS landings have only been reportable for haddock since 2016 and so far represent less than 0.5% of the total catch. TAC advice arising from the stock assessment is given as total catch.

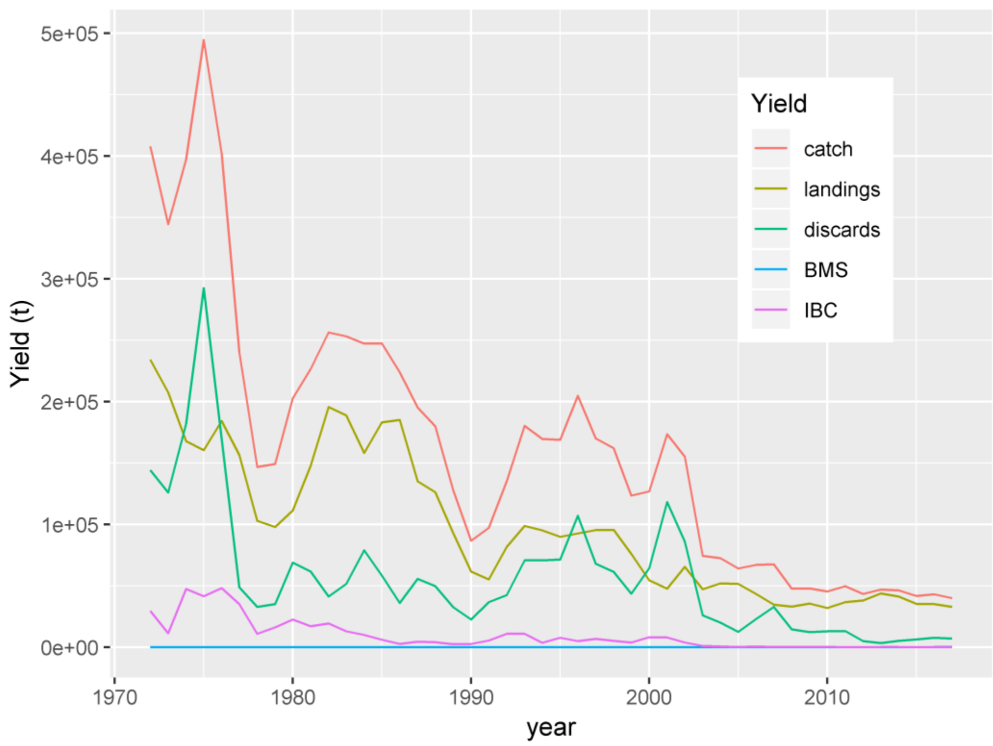


Figure 4.1.1.6. Haddock in Subarea 4, Division 6.a and Subdivision 20: Yield from each catch components

4.1.2 Parameter uncertainty

Parameter uncertainty, including survival process error, is derived from the variance-covariance matrix of the estimable parameters from the SAM assessment. The variance-covariance matrix was used to derive 1000 parameter sets resulting in 1000 Northern Shelf haddock replicates reflecting the historical and current status of the stock and associated uncertainty.

4.1.3 Recruitment

Northern Shelf haddock is characterised by sporadically high recruitment which leads to dominant year classes in the fishery (Figure 4.1.1.1). These large year classes occur in 1974, 1979 and 1999; however, smaller peaks in recruitment seem to occur throughout the time series. Recruitment has been markedly reduced in recent years, specifically in the size of the recruitment peaks which have diminished in magnitude over time (ICES 2018a). The period since 2000 encapsulates this reduced recruitment.

Future residuals for recruitment were generated by fitting a segmented regression curve and sampling from a smoothed distribution of the residuals. The segmented regression was fitted to a recent period of recruitment (2000 onwards) following the EqSim assumptions used for calculating reference points for Northern Shelf haddock (IBPHaddock ICES, 2016).

No significant autocorrelation was found in the 2000+ period (Figure 4.1.3.1) and so is not accounted for in this OM. The model fit diagnostics to the original assessment point estimates are shown in Figure 4.1.3.2. Stock-recruit pairs and empirical cumulative distributions for individual replicates are shown in Figures 4.1.3.3 and 4.1.3.4 respectively, which compare estimates from the recruitment period to the recruitment generated from the future residuals. Overall, the recruitments generated from the smoothed distribution of residuals compare well with historical data. The median breakpoint value is 84 435 tonnes with an interquartile range of 11 909 tonnes. The residuals for future recruitment to be used in the MSE are shown in Figure 4.1.3.5 and the residuals for 10 replicates are shown in Figure 4.1.3.6.

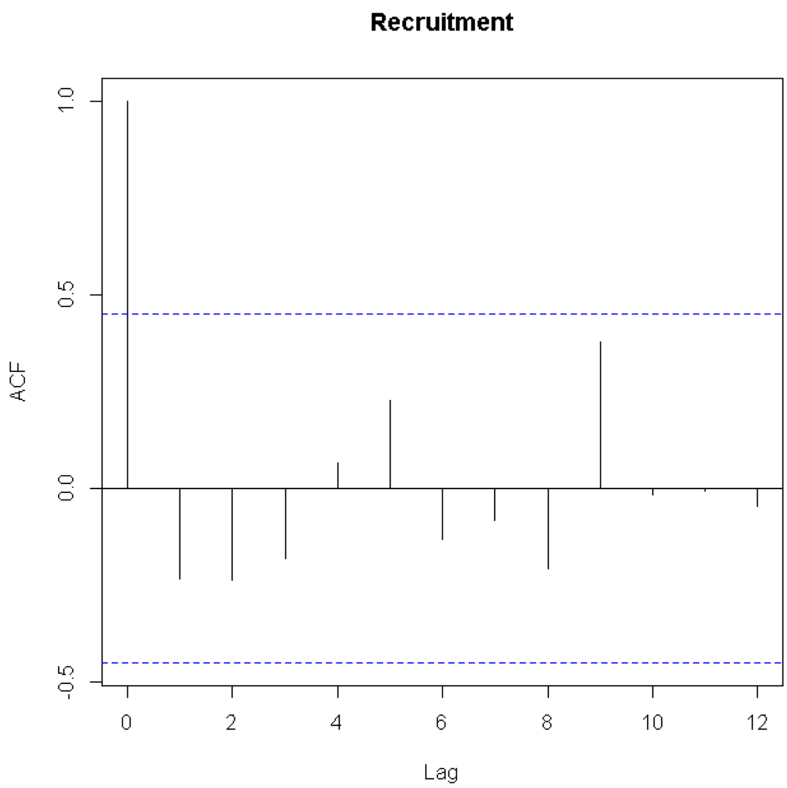


Figure 4.1.3.1. Haddock in Subarea 4, Division 6.a and Subdivision 20: Autocorrelation function applied to the assessment estimates of recruitment for the period 2000 onwards

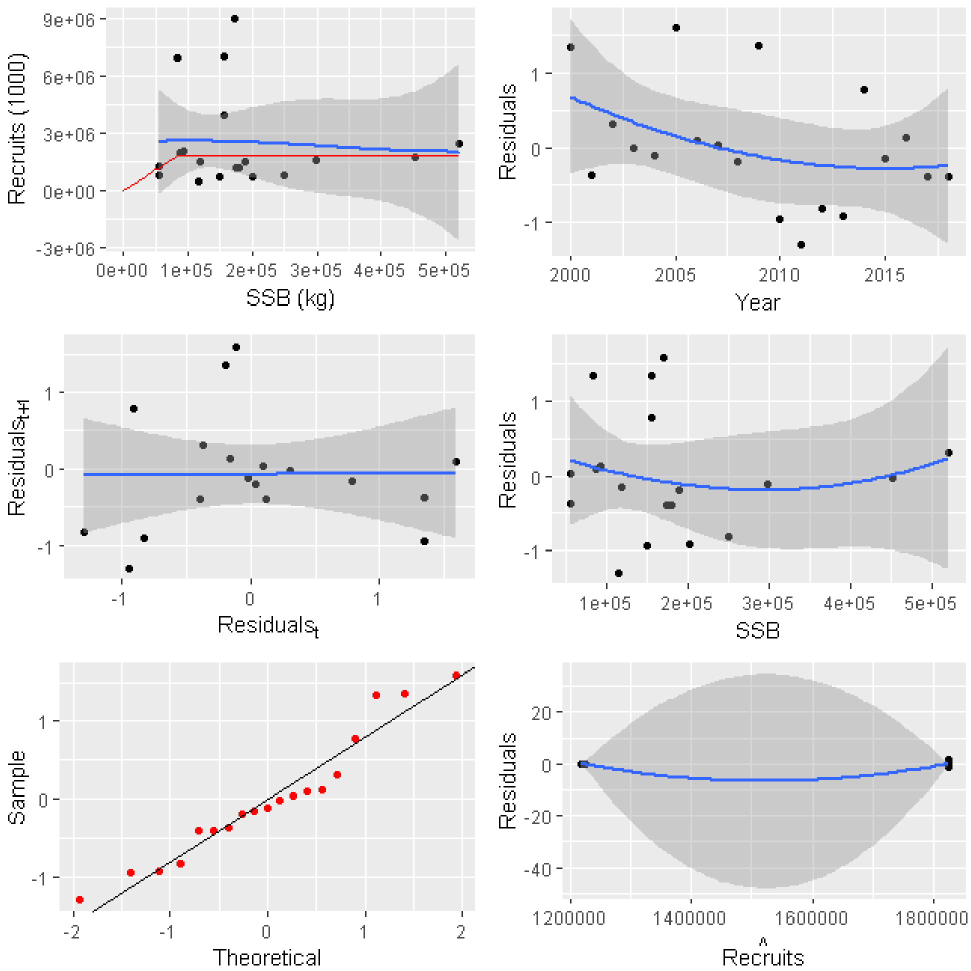


Figure 4.1.3.2. Haddock in Subarea 4, Division 6.a and Subdivision 20: Fit of the segmented regression stock recruit relationship to the original assessment point estimates for the recruitment period 2000 onwards.

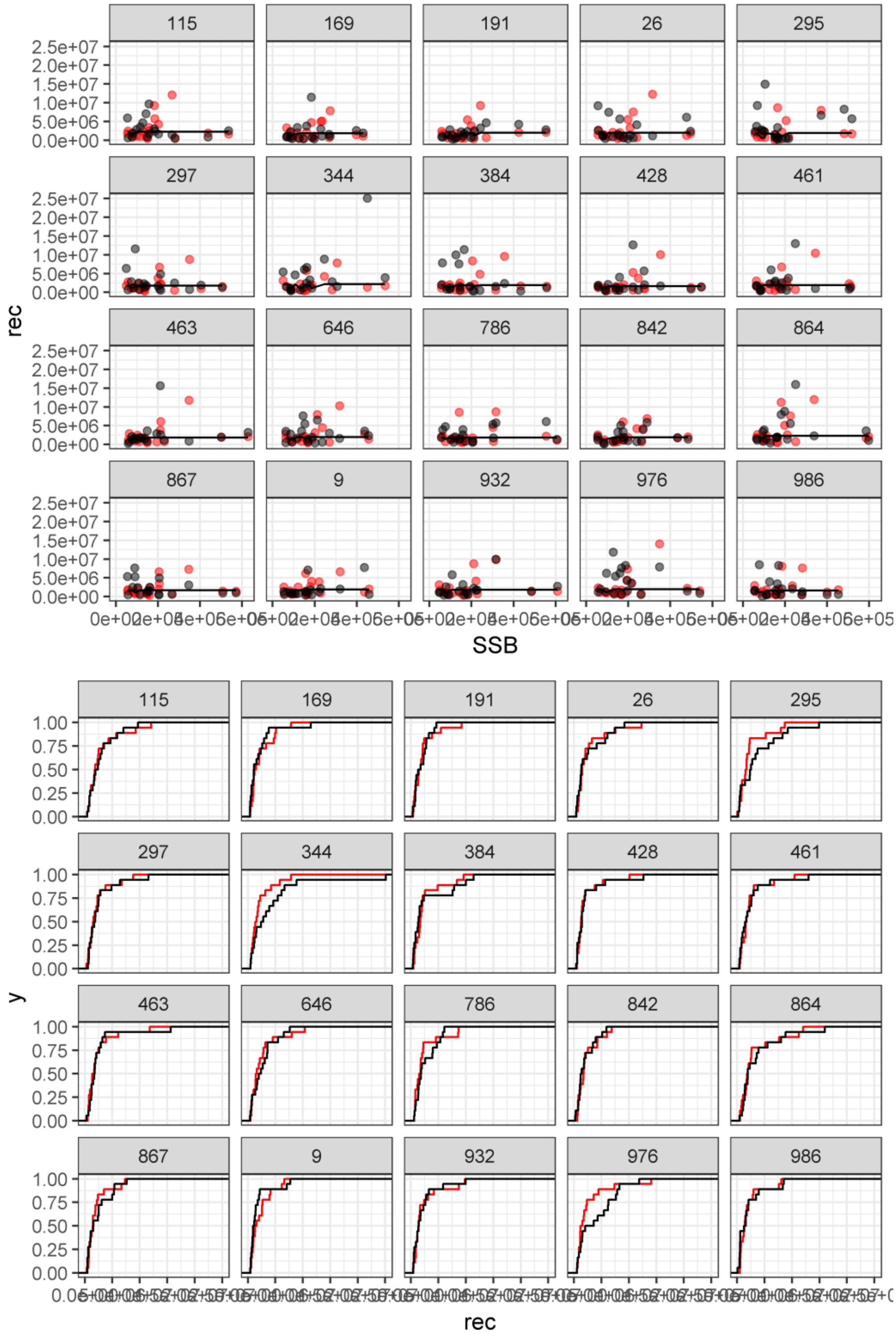


Figure 4.1.3.3. Haddock in Subarea 4, Division 6.a and Subdivision 20: Stock-recruit pairs (top) and empirical cumulative distributions (bottom) of recruitment for recruitment period 2000–2017 (red) and future recruitments sampled from smoothed distribution (black). Title indicates the replicate number which were chosen at random.

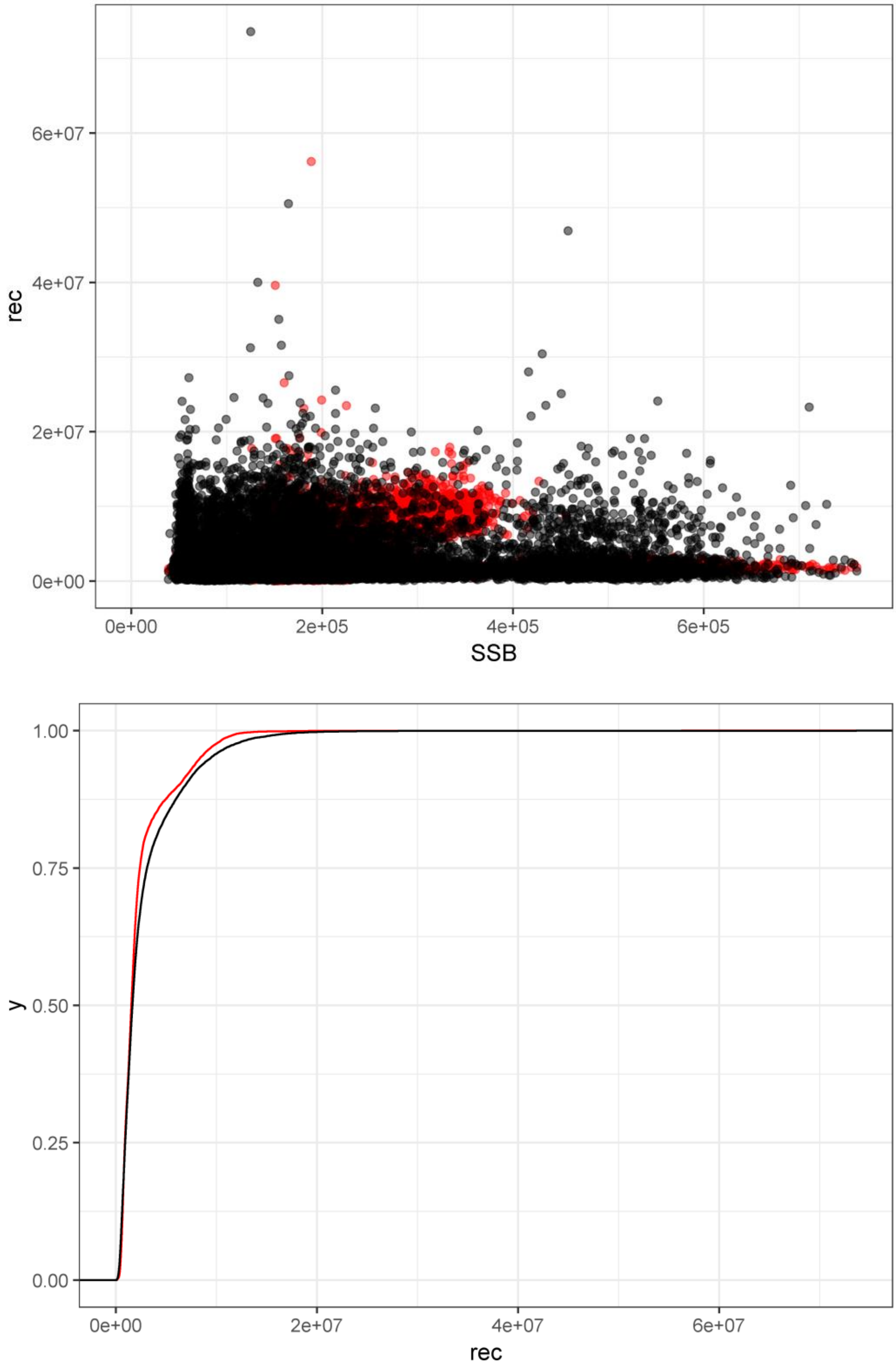


Figure 4.1.3.4. Haddock in Subarea 4, Division 6.a and Subdivision 20: Stock-recruit pairs (top) and empirical cumulative distributions (bottom) of recruitment for recruitment period 2000–2017 (red) and future recruitments sampled from smoothed distribution (black). All replicates listed in Figure 6 are combined on this plot (20 in total).

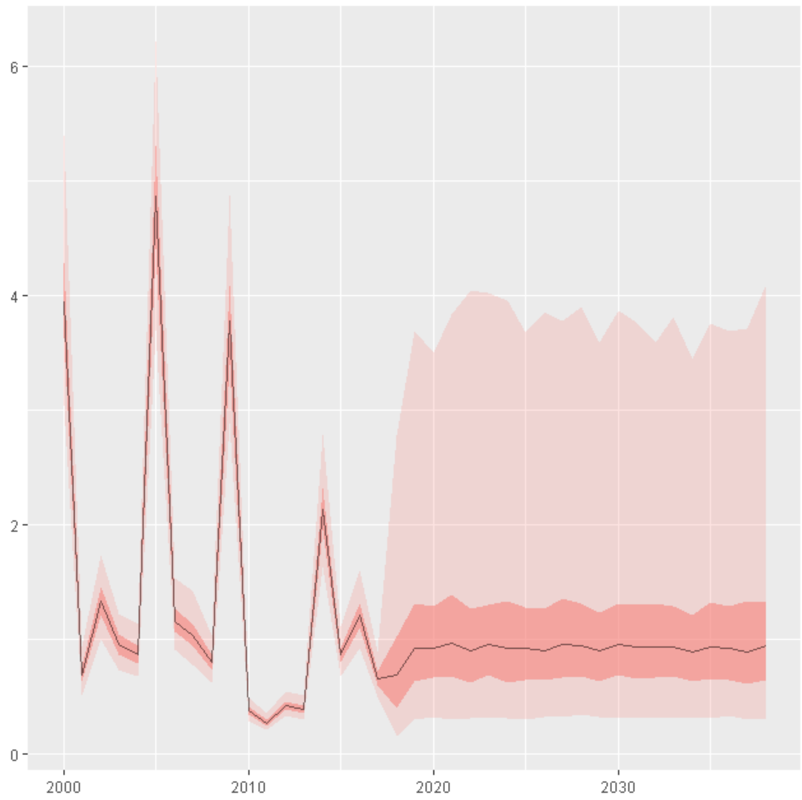


Figure 4.1.3.5. Haddock in Subarea 4, Division 6.a and Subdivision 20: Distribution of recruitment residuals for all replicates for the recent recruitment period (2000 to 2017) from which future recruitment residuals (2018–2038) are resampled.

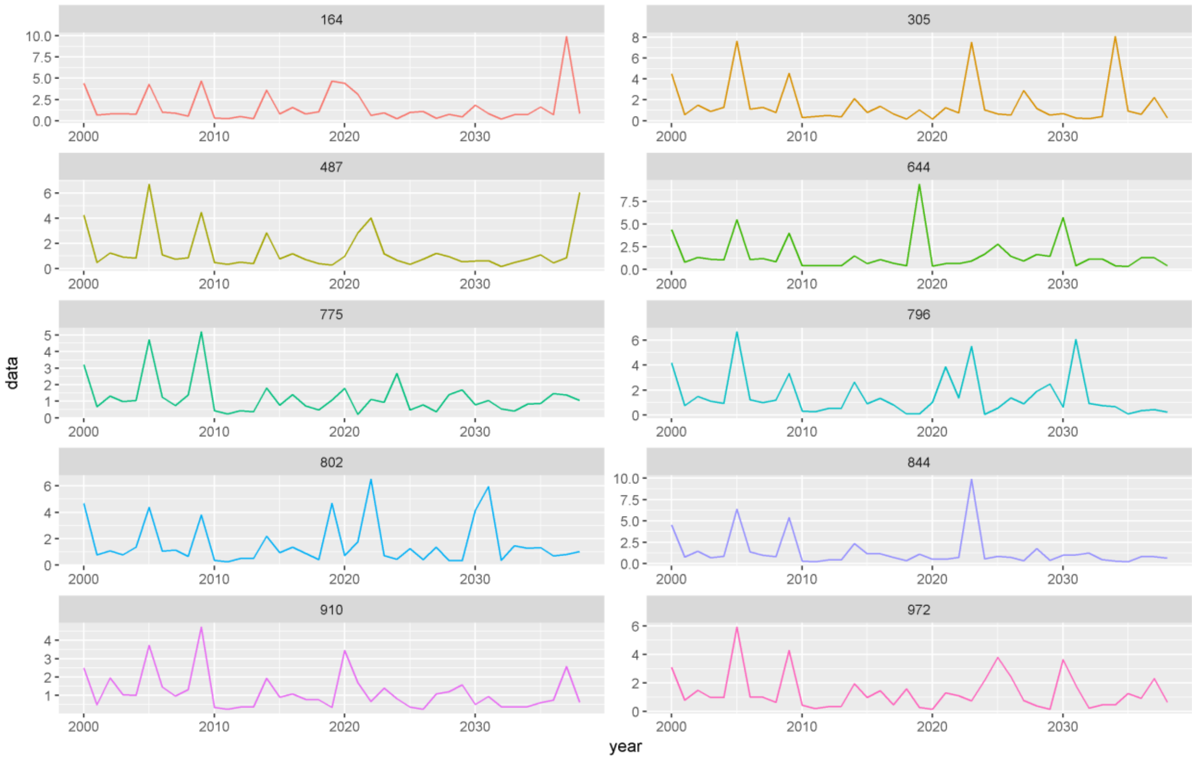


Figure 4.1.3.6. Haddock in Subarea 4, Division 6.a and Subdivision 20: Recruitment residuals for randomly selected replicates (2000–2038)

4.1.4 Mean weights, maturity, natural mortality and selection

Future biological parameters (mean weights-at-age, maturity, natural mortality) were generated by random resampling, with replacement, from the last 10 years (2008–2017) (Figure 4.1.4.1–2). The values across all ages in each sampled year were allocated to the future year. This is consistent with the EqSim procedure for calculating reference points for Northern Shelf haddock (ICES, 2016). Each parameter was checked for autocorrelation and nothing significant was found. There were some notable increases in mean weights in the most recent years; however, this was only seen in some ages and the last 10-year period encapsulates most of the range in mean weight at age over the entire time series. The effect of larger year classes in recent years (2005, 2009, 2014) on growth was also examined (Figures 4.1.4.3–4). It would be expected that larger year classes would grow more slowly and have lower weights at age compared to other cohorts due to density dependent effects. However, though the 2005 and 2009 cohorts are amongst the slower-growing cohorts, they do not appear to be considerably different to other cohorts. Furthermore, the 2014 cohort has a relatively average growth rate. Therefore, it was decided there wasn't enough evidence to deviate from the standard method of following the EqSim settings, so the last 10-year time period was used to remain consistent with these settings.

Future selectivities were generated in a similar way to the biological parameters (i.e. resampling with replacement) though the sampling was performed separately to the biological parameters to produce a different sequence of years in addition to using only the last 5 years of data (2013–2017). This approach differs from the EqSim approach which uses a 10-year period. The selection curves for 2008–2017 are shown in Figure 4.1.4.5 and a considerable difference is seen in the selectivities for 2008–2012 and 2013–2017. Due to this trend, only the last 5 years are used in the resampling. Another check was performed to assess if variability in the selection curves might be being driven by the occurrence of the moderately large 2005, 2009 and 2014 year-classes. This comprised of a paired t-test between the selection curves for each year and the 5-year mean (2013–2017). No statistical difference was found between the selection curves for 2013–2017 and the 5-year mean.

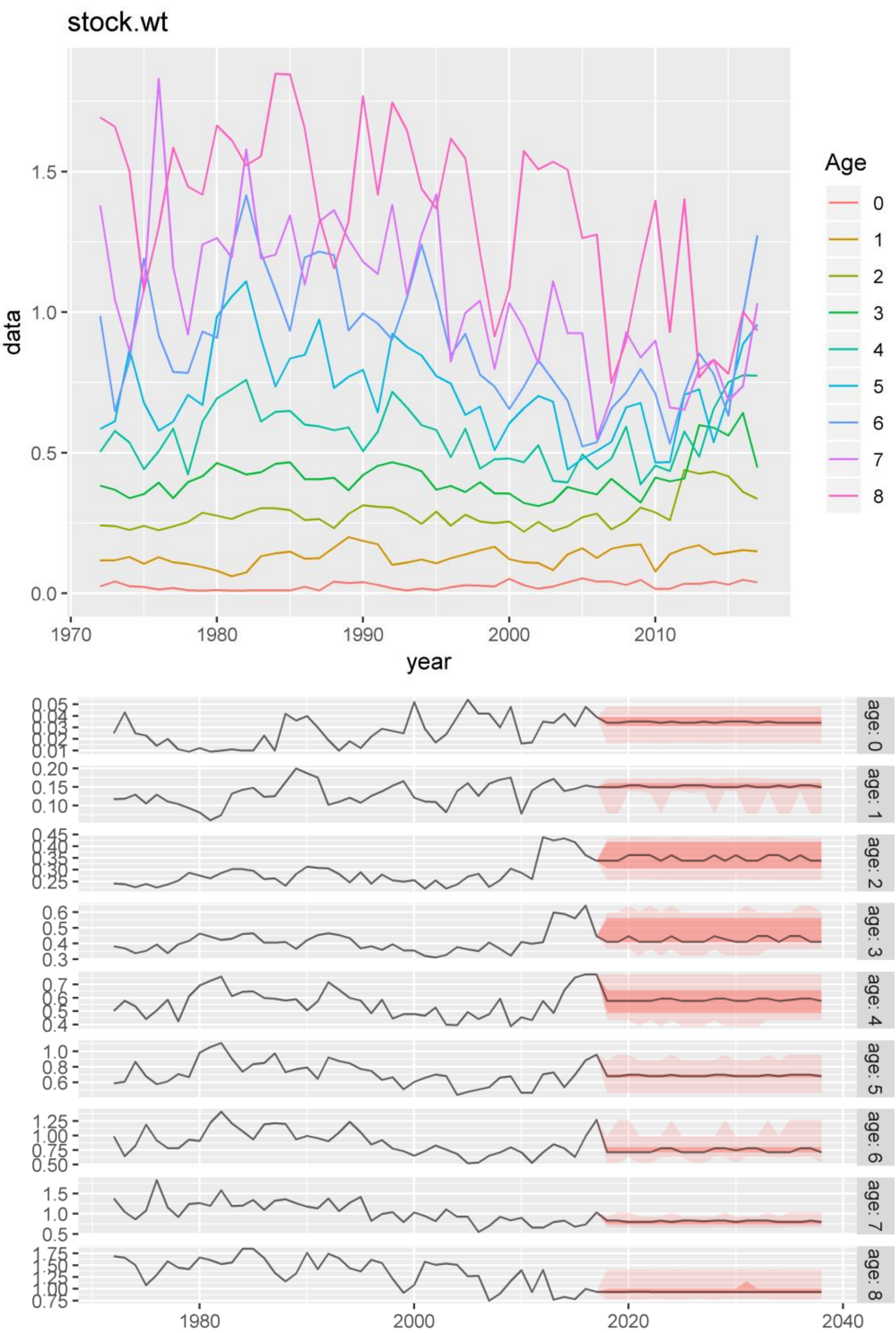


Figure 4.1.4.1. Haddock in Subarea 4, Division 6.a and Subdivision 20: Top – time series of mean weight-at-age in the stock and catch (ages 0 to 8+). Bottom – time series of mean weight-at-age and distribution of future values. The mean weight-at-age in the stock is assumed to be the same as in the catch.

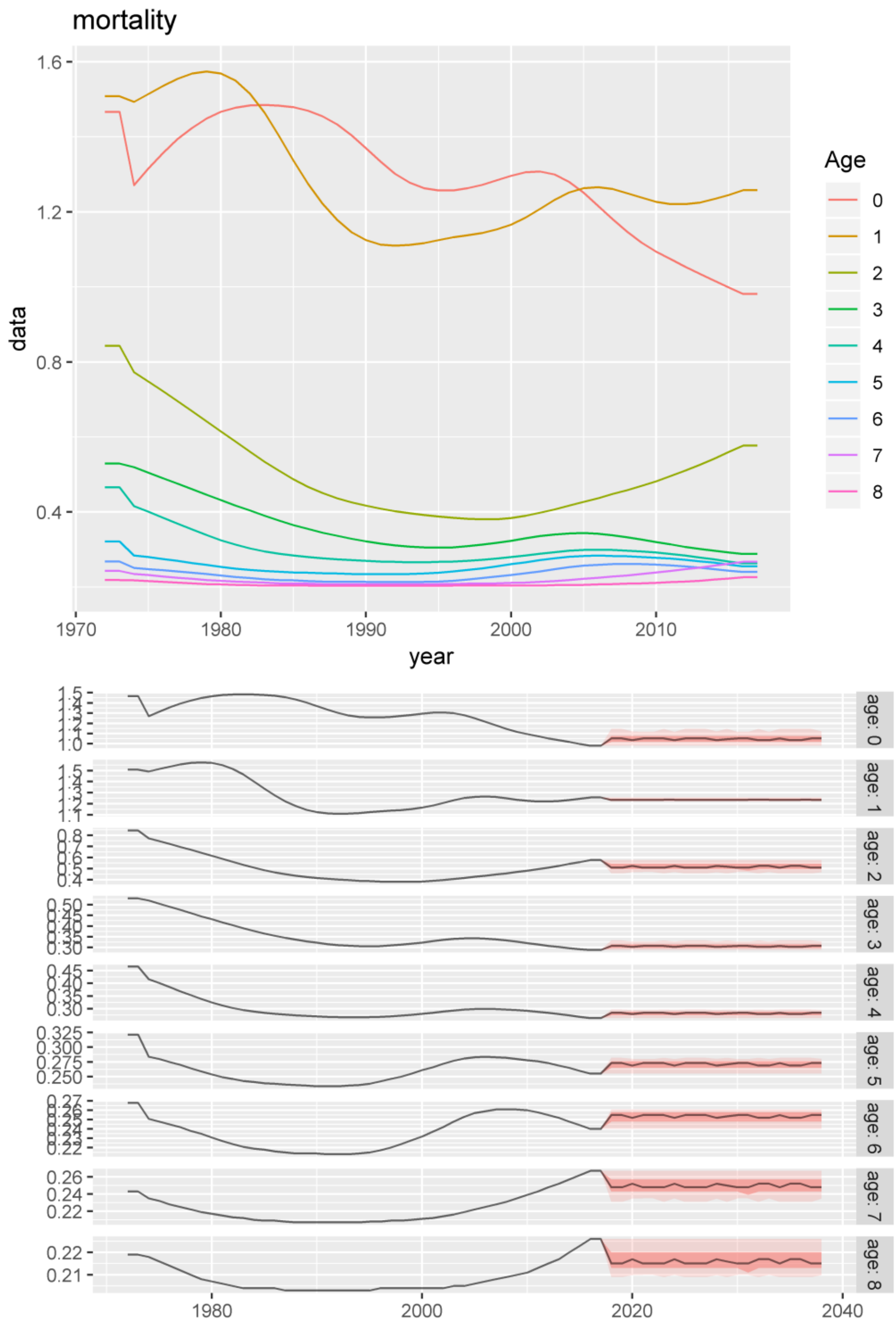


Figure 4.1.4.2. Haddock in Subarea 4, Division 6.a and Subdivision 20: Top – time series of natural mortality (ages 0 to 8+). Bottom – time series of natural mortality and distribution of future values.

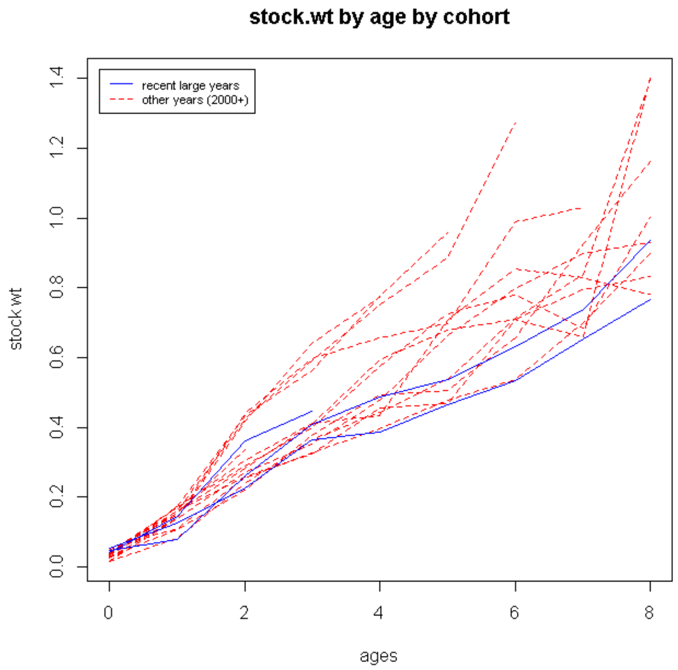


Figure 4.1.4.3. Haddock in Subarea 4, Division 6.a and Subdivision 20: Comparison of weights at age for cohorts of recent large year classes (2005, 2009, 2014) and other years since 2000. Cohorts from 2000 onwards used as these cohorts will contribute to the weights at age in the last 10 years of the time series from which future mean weights are resampled.

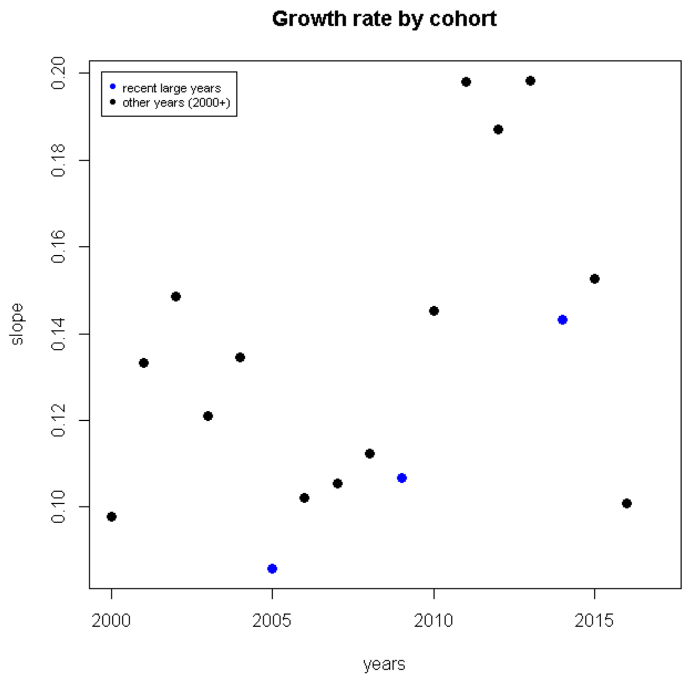


Figure 4.1.4.4. Haddock in Subarea 4, Division 6.a and Subdivision 20: Growth rate for each cohort since 2000 with recent large year classes (2005, 2009 and 2014) highlighted in blue.

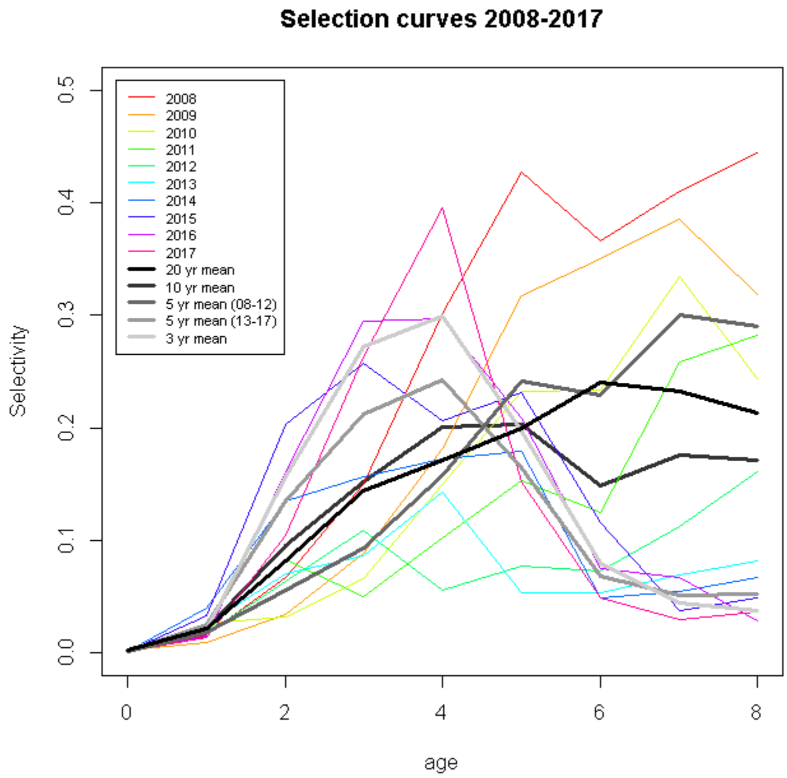


Figure 4.1.4.5. Haddock in Subarea 4, Division 6.a and Subdivision 20: Selection curves for 2008–2017. 10 year, 5 year (2008–2012 and 2013–2017) and 3-year means are also shown. The 20-year mean is also shown for comparison.

4.1.5 Generating data from the operating model

Catch was generated when projecting the stock with the fwd function in FLR package FLash. Catches from the operating model were multiplied by an error term $e^{\varepsilon_{a,y}}$ when being passed to the management procedure, where $\varepsilon_{a,y} \sim N(0, \sigma_a^2)$ and σ are observation standard deviations for catch as estimated by SAM.

Survey observations were generated from the operating model as follows:

$$I_{a,y,i} = q_{a,i} N_{a,y} e^{-t_i Z_{a,y}} \, e^{\varepsilon_{a,y,i}}$$

where N and Z are stock numbers and total mortalities from the operating model, the a, y and i subscripts denote age, year and survey (IBTS-Q1 or IBTS-Q3) respectively, q are survey catchabilities and $\varepsilon_{a,y,i} \sim N(0, \sigma_{a,i}^2)$ with σ standard deviations as estimated by SAM, and t is the timing of the survey (0.125 for Q1 and 0.625 for Q3) (Nielsen and Berg 2014).

Biological parameters for the management procedure were taken as the mean of those parameters in the operating model for the years 2008–2017.

4.1.6 Implementation error

Banking and borrowing has been introduced as implementation error. Once the management strategy produces a TAC, this TAC is adjusted by the effects of the banking and borrowing scheme (see Annex 3).

4.1.7 Number of replicates and projection years

The operating model is set up with 1000 replicates and 20 projection years. There was not time to conduct runs to test for the ideal number of replicates and simulation years for Northern Shelf haddock and so the decision was made to use 1000 replicates and 20 projection years respectively in line with what was decided for North Sea cod. However, during the runs, one replicate in OM2 was found to consistently fail during the stock assessment in the estimation model. Therefore, OM2 was run with 1001 replicates from which the failed replicate was removed added as time constraints prevented a thorough investigation into why this replicate failed.

4.2 Alternative operating models

4.2.1 OM2 - Alternative assessment model – TSA

This alternative operating model (OM2) has been conditioned using the latest stock assessment for Northern Shelf haddock (ICES, 2018a). Full details of the assessment results can be found in the WGNSSK 2018 report (ICES, 2018a). The assessment results and fit to data are shown in the following plots (Figure 4.2.1.1–8).

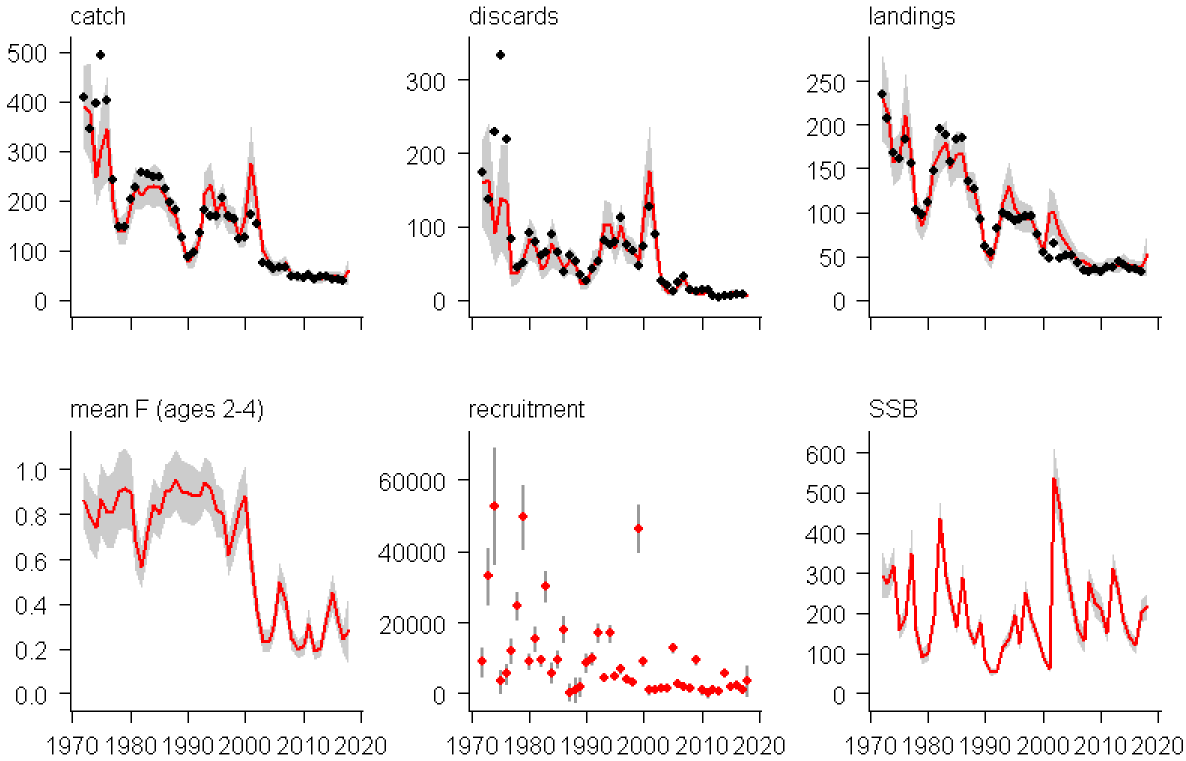


Figure 4.2.1.1. Haddock in Subarea 4, Division 6.a and Subdivision 20: Anticlockwise from top left, point-wise estimates and approximate 95% confidence intervals of catch, mean fishing mortality for ages 2–4 (F(2-4)), recruitment (R(age 0)), spawning stock biomass (SSB), landings and discards, from the TSA final run. The red lines (or points) represent the point-wise estimate, and the grey shading/bars represent the approximate point-wise 95% confidence intervals. The black circles represent the observed values of catch, landings and discards. Catch, landings, discards and SSB are in tonnes, and R in millions.

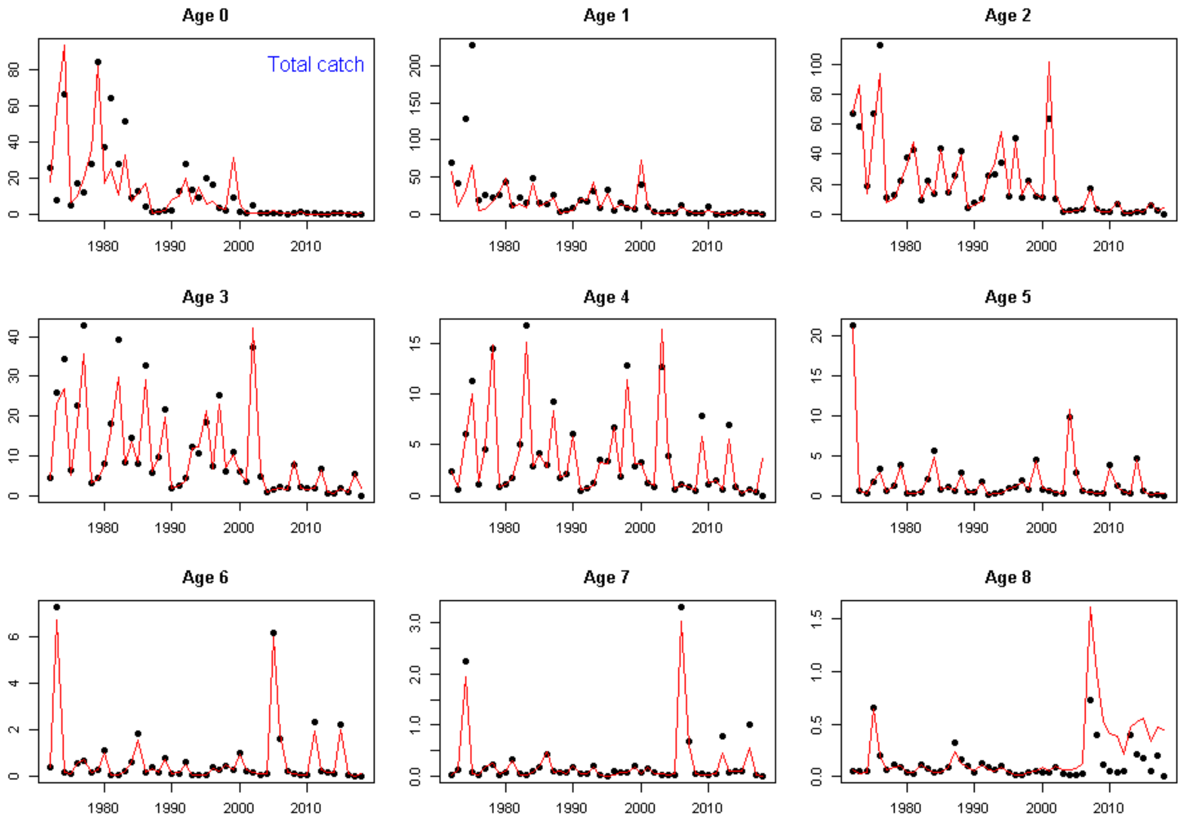


Figure 4.2.1.2. Haddock in Subarea 4, Division 6.a and Subdivision 20: Fits to catch-at-age data.

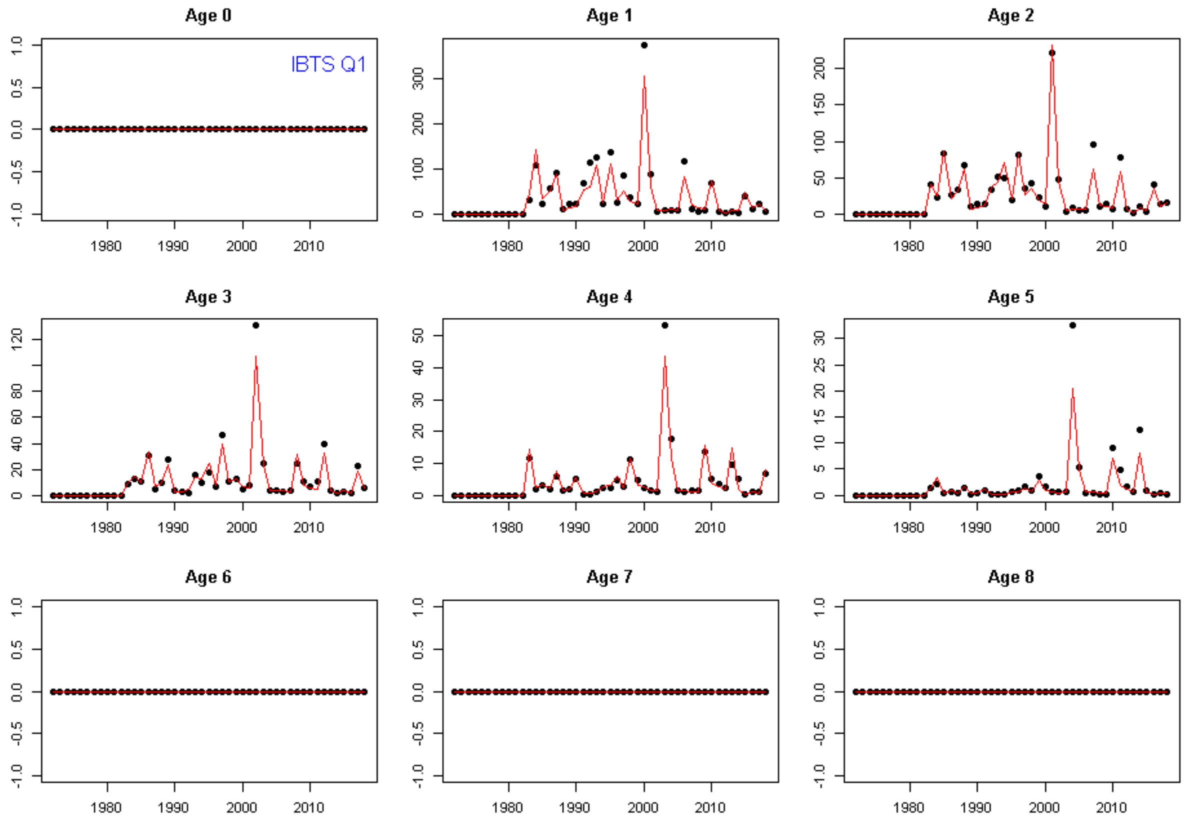


Figure 4.2.1.3. Haddock in Subarea 4, Division 6.a and Subdivision 20: Fits to the IBTS–Q1 survey data.

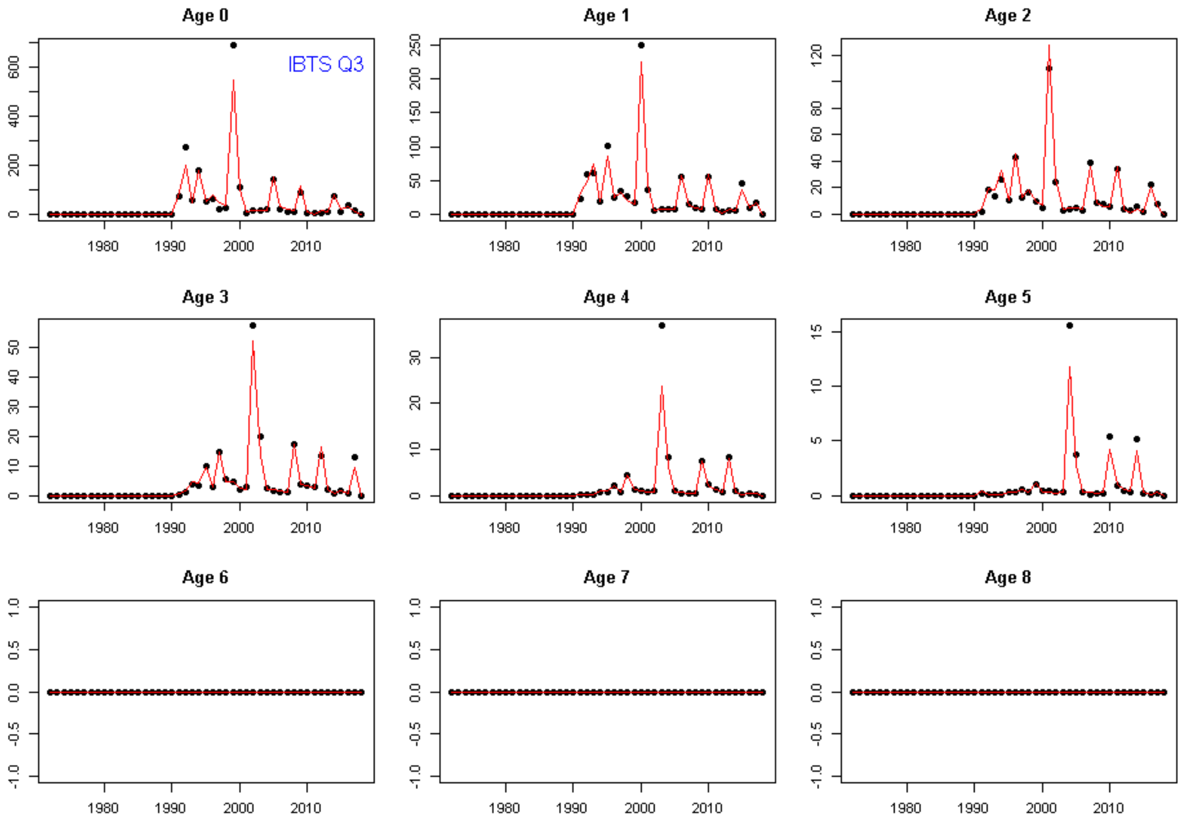


Figure 4.2.1.4. Haddock in Subarea 4, Division 6.a and Subdivision 20: Fits to the IBTS–Q3 survey data.

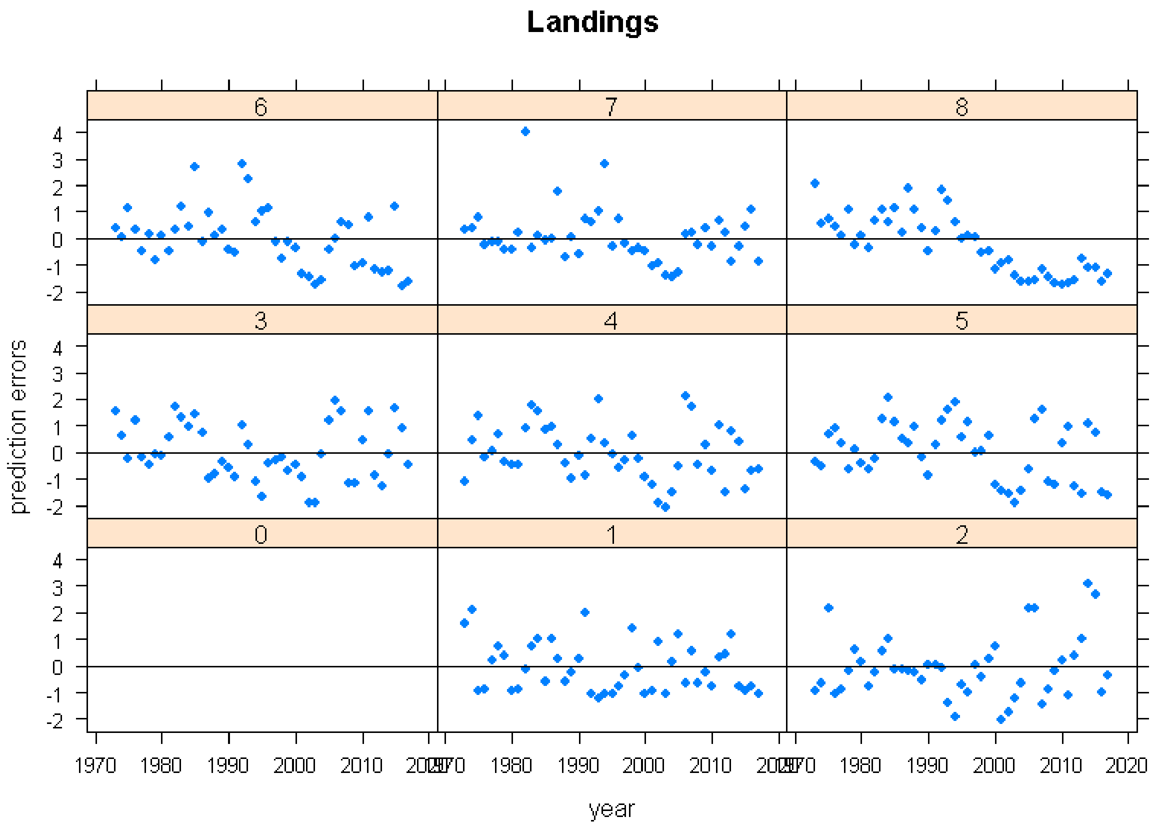


Figure 4.2.1.5. Haddock in Subarea 4, Division 6.a and Subdivision 20: Standardized TSA landings prediction errors by age. These indicate the discrepancy between the model prediction and observation as the model steps through the data from the start to the end.

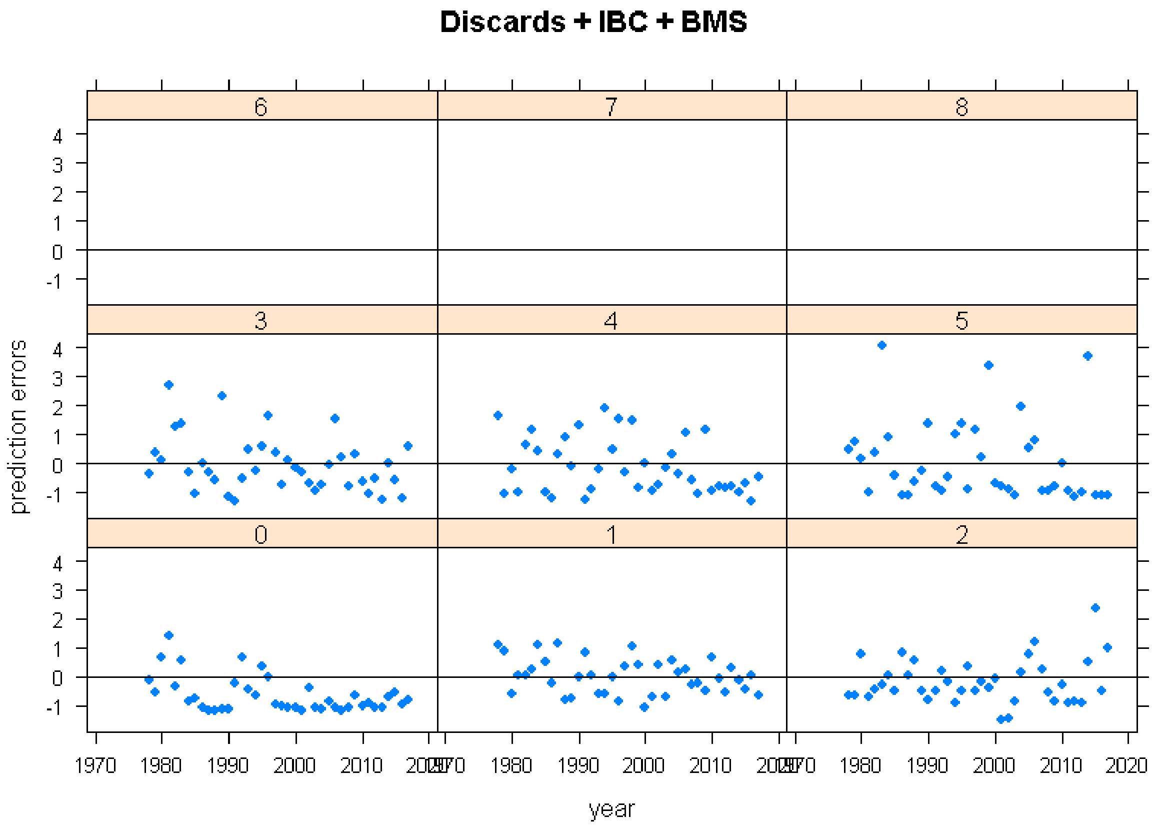


Figure 4.2.1.6. Haddock in Subarea 4, Division 6.a and Subdivision 20: Standardized TSA discards (discards+BMS+IBC) prediction errors by age. These indicate the discrepancy between the model prediction and observation as the model steps through the data from the start to the end.

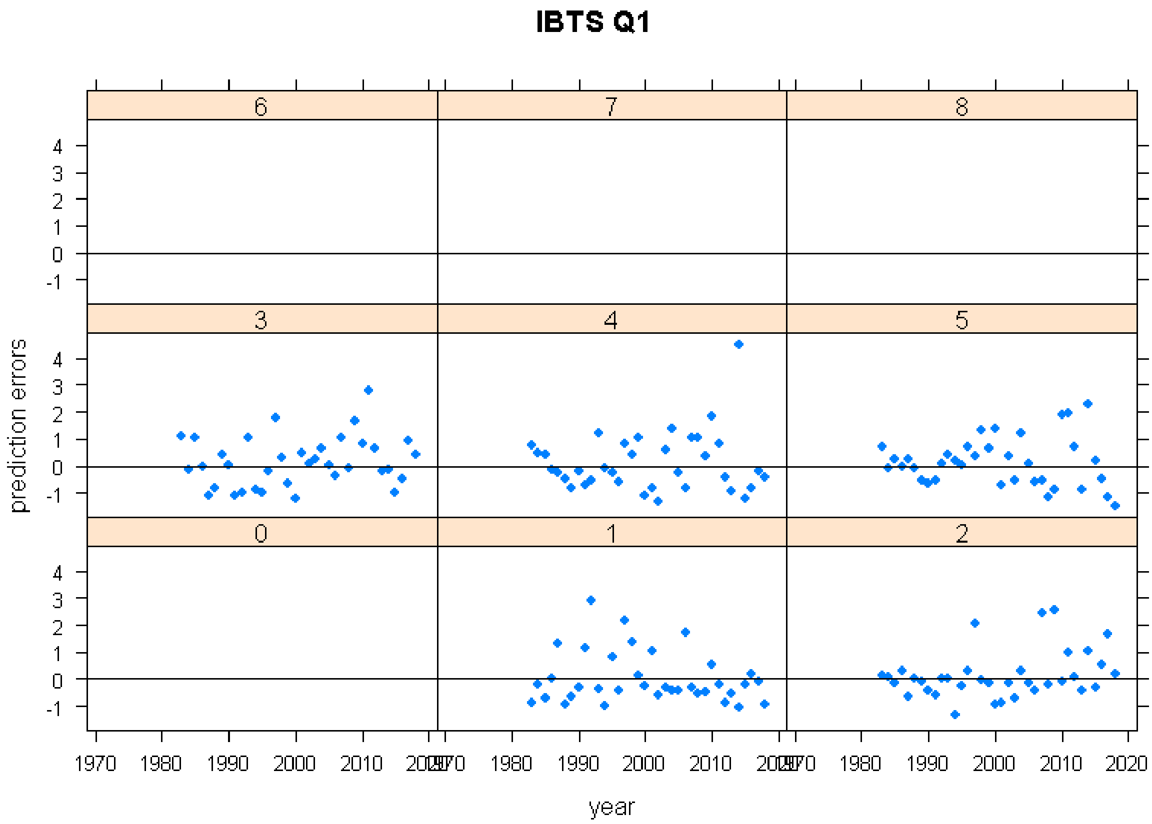


Figure 4.2.1.7. Haddock in Subarea 4, Division 6.a and Subdivision 20: Standardized TSA IBTS Q1 prediction errors by age. These indicate the discrepancy between the model prediction and observation as the model steps through the data from the start to the end.

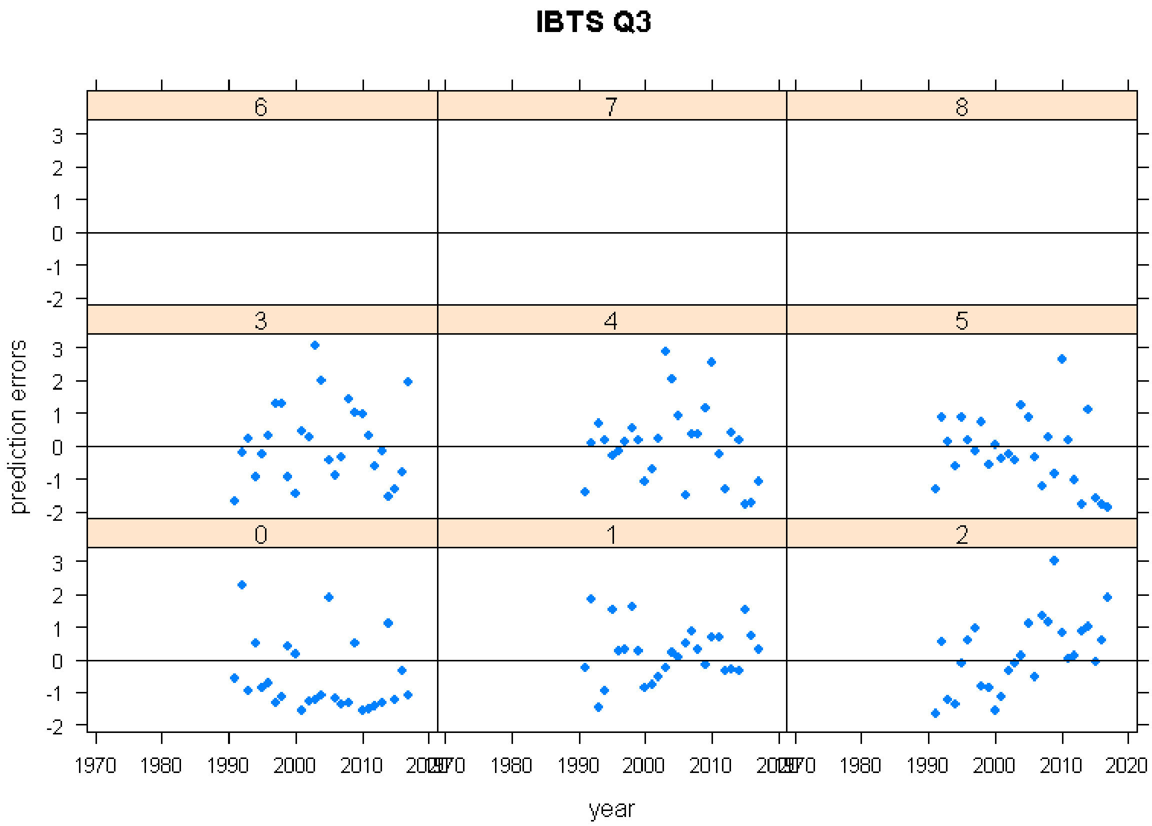


Figure 4.2.1.8. Haddock in Subarea 4, Division 6.a and Subdivision 20: Standardized TSA IBTS Q3 prediction errors by age. These indicate the discrepancy between the model prediction and observation as the model steps through the data from the start to the end.

Parameter uncertainty

Replicates for the initial populations were simulated from TSA. This was done by first generating replicates for f-at-age and using those to simulate forwards from replicates of recruitment (age 0) and n-at-age in the first year of the time series (1972) (Figures 4.2.1.9–10). The replicates of recruitment and first-year n-at-age were generated using their estimate and standard error from the latest TSA stock assessment (ICES, 2018a).

Replicates of f-at-age were generated using the variances of transitory effects in f-at-age estimated by TSA. Variability in fishing mortalities in TSA comprises of persistent and transitory effects in both the age component and year component of the model. Replicates in f-at-age were generated using the variances in the transitory effects and adding them to the estimates of persistent changes of fishing mortalities. Temporal correlations in the fishing mortalities are included implicitly in using this method. This method was chosen as using a variance-covariance matrix to generate parameter uncertainty is not feasible with TSA. This process is described in more detail below and is taken from the description of TSA given in Fryer (2002). Some simple checks were conducted to check the replicates looked reasonable. These included checking for negative values, checking that maxima and minima occurred at realistic ages and years and checking that cohorts decreased in size over time.

Generating f-at-age replicates

The state equations for fishing mortalities in TSA are given by:

$$\log F(a,y) = U(a,y) + V(y) + NID(0,(H(a)\sigma_F)^2) \quad (1)$$

$$U(a,y) = U(a,y-1) + NID(0,\sigma_U^2) \quad a \le a_m < A \quad (2)$$

$$U(a,y) = U(a_m,y) \quad a > a_m \quad (3)$$

With the constraint that $\sum_1^{a_m} U(a,y) = 0$. This is necessary for identification purposes.

$$V(y) = Y(y) + NID(0,\sigma_V^2) \quad (4)$$

$$Y(y) = Y(y-1) + NID(0,\sigma_Y^2) \quad (5)$$

The key features of these equations are:

- Log fishing mortality is separated into an age component (U(a,y)) and a year component (V(y)) and both evolve over time (equation 1)
- a_m is the age above which fishing mortality is assumed to be constant except for local transitory departures. This is set to age 7 for Northern Shelf haddock.
- H(a) allows the variability at specific ages to be adjusted. For Northern Shelf haddock, its value is set to 2 for ages 0 and 1 and 1 for all other ages as the fishing mortalities for these younger ages are more variable than at older ages.

Variance terms:

- The σ_Y^2 term induces persistent changes in fishing mortality through the year component, V
- The σ_V^2 term induces transitory changes in fishing mortality through the year component, V
- The σ_U^2 term induces persistent changes in fishing mortality through the age component, U
- The σ_F^2 term induces transitory changes in fishing mortality around the separable model U+V

These steps were taken to generate the replicates of fishing mortality at age:

1. 1000 replicates of the variance terms inducing transitory changes $(NID(0,\sigma_V^2)\ and\ NID(0,(H(a)\sigma_F)^2))$ were generated by randomly sampling from a normal distribution with mean of 0 and standard deviation of $\sqrt{\sigma_V^2}$ and $\sqrt{\sigma_F^2}$ respectively.
2. The $H(a)$ term is a multiplier used to account for more variability in the fishing mortalities at younger ages.
3. The parameter estimates of $U(a,y)\ and\ Y(y)$ were extracted from the latest TSA fit (ICES 2018a). The sum of these parameters describe the persistent changes in fishing mortality at age over time. These were then summed together with the 1000 replicates of $NID(0,\sigma_V^2)\ and\ NID(0,(H(a)\sigma_F)^2)$ and the exponent taken to get 1000 replicates of f-at-age over time.

Generating n-at-age replicates

The 1000 replicates of n-at-age were generated using these fishing mortalities replicates. The n-at-age time series was initiated by generating 1000 replicates of the recruits (age 0, all years) and n-at-age in the first year of the time series (all ages in 1972) by randomly sampling from a normal distribution using the n-at-age estimate as the mean and it's standard error as the standard deviation. The n-at-age estimates and standard errors used came from the TSA fit arising from the latest stock assessment (ICES 2018a).

The time series is then filled by simulating forward with the f-at-age replicates. The f-at-age replicates are first summed together with the natural mortality time series used as input to the assessment and this total mortality is used to calculate n-at-age for each cohort, through time, using the usual equation (with the usual adjustments for plus groups).

$$N(a+1, y+1) = \exp(-Z(a, y))N(a, y) \quad (6)$$

Process error

The way the replicates of f-at-age and n-at-age are generated mean that the n-at-age and f-at-age in a specified replicate correspond to each other and therefore process error does not need to be accounted for. This is different to other stocks which condition the OMs on SAM, where the method used to generate the initial populations needs an estimate of process error. Despite this, it has been shown in Section 4.3.1 that SAM (and everything that occurs within SAM) can be used as a close approximation of TSA and so process error does not explicitly need to be considered further as a component of the OM based on TSA.

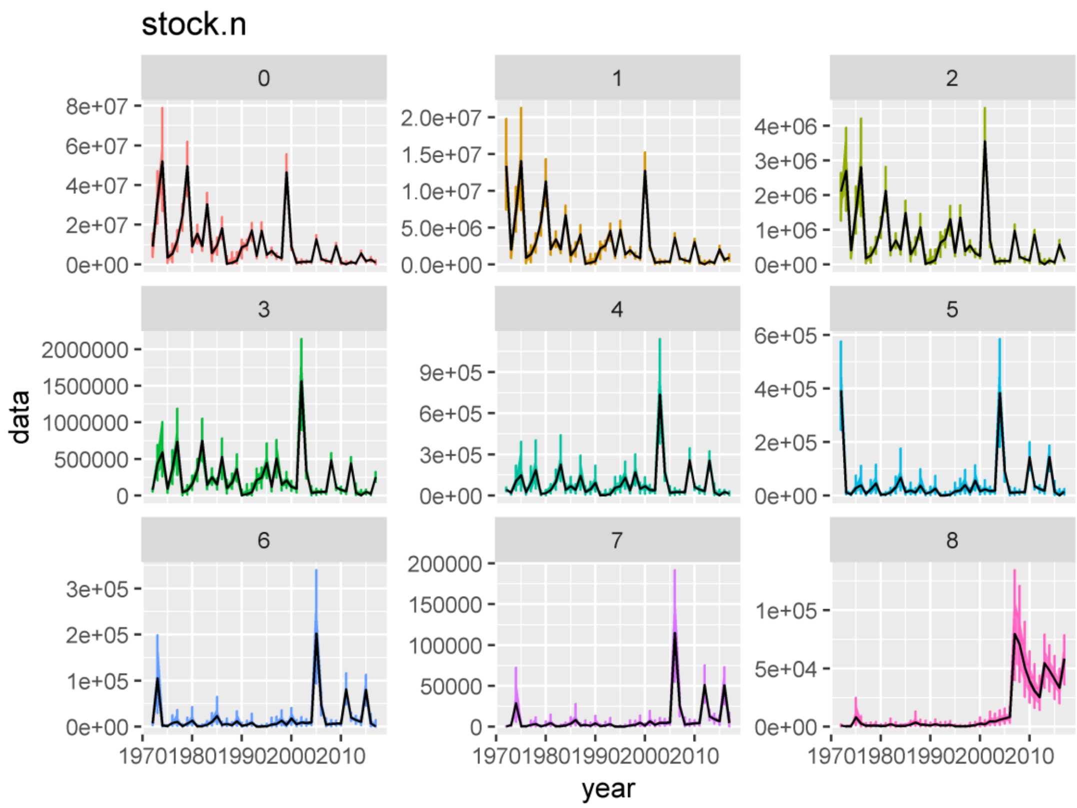


Figure 4.2.1.9. Haddock in Subarea 4, Division 6.a and Subdivision 20: stock n-at-age (age indicated in plot heading. Age 8 is a plus group). Coloured bars denote the 5% and 95% confidence intervals.

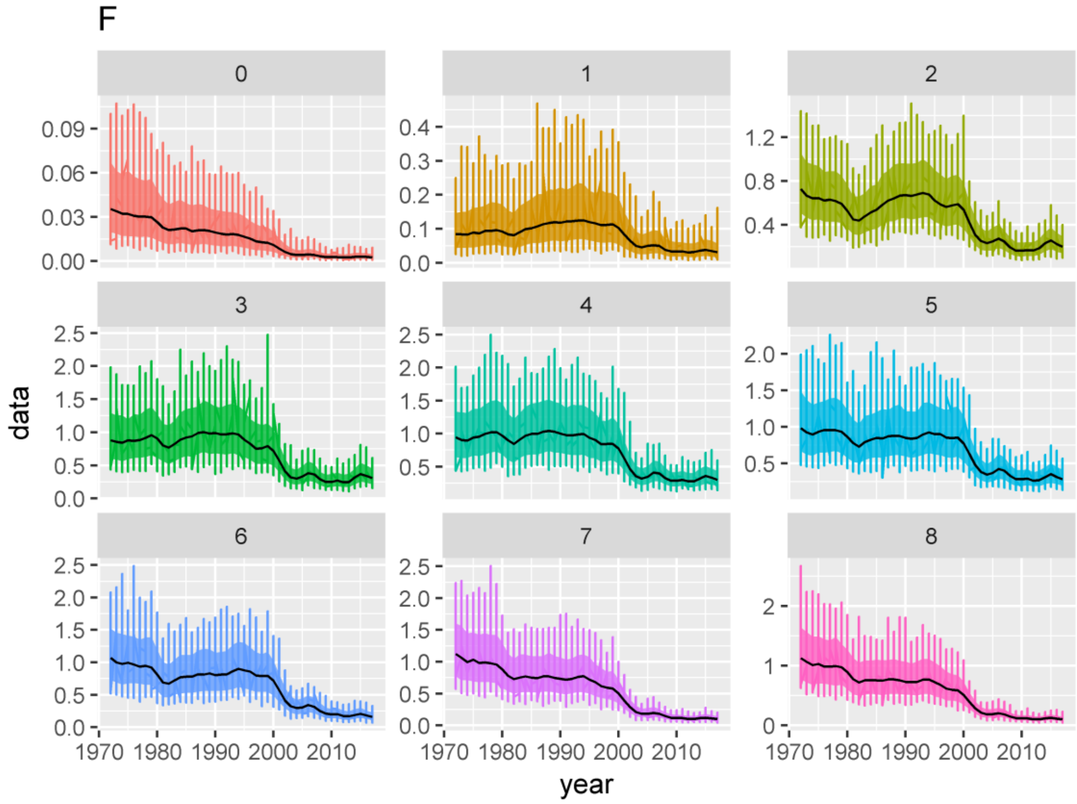


Figure 4.2.1.10. Haddock in Subarea 4, Division 6.a and Subdivision 20: fishing mortality at age (age indicated in plot heading. Age 8 is a plus group). Coloured bars denote the 5% and 95% confidence intervals.

Recruitment

Future residuals for recruitment for OM2 were generated in the same way as for the baseline OM (OM1) though using the results from the TSA stock assessment. The corresponding diagnostic plots are shown in the following plots (Figures 4.2.1.11–16).

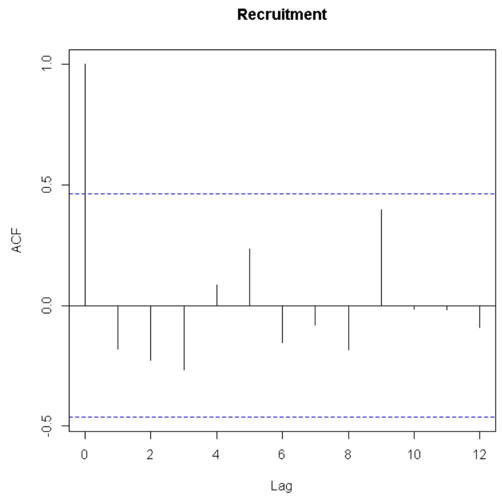


Figure 4.2.1.11. Haddock in Subarea 4, Division 6.a and Subdivision 20: Autocorrelation function applied to the assessment estimates of recruitment for the period 2000 onwards

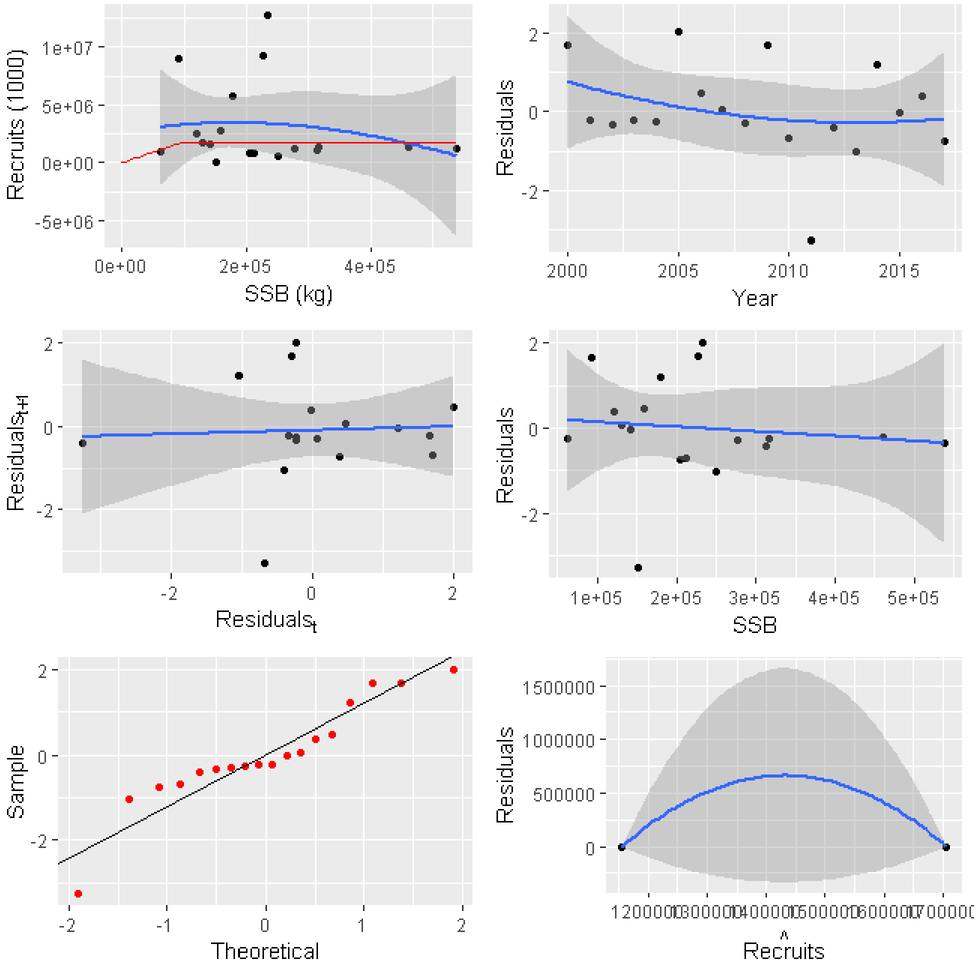


Figure 4.2.1.12. Haddock in Subarea 4, Division 6.a and Subdivision 20: Fit of the segmented regression stock recruit relationship to the original assessment point estimates for the recruitment period 2000 onwards.

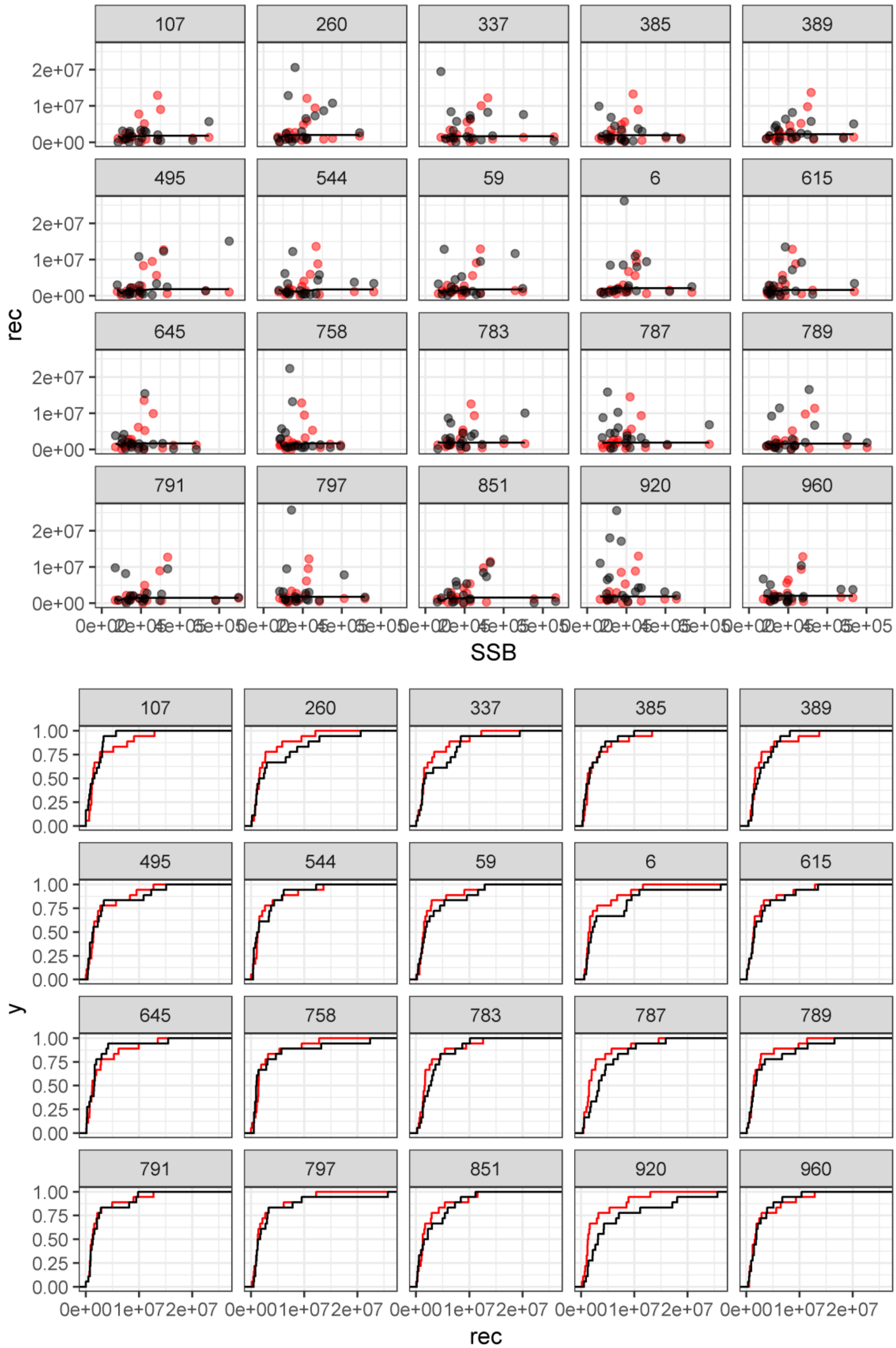


Figure 4.2.1.13. Haddock in Subarea 4, Division 6.a and Subdivision 20: Stock-recruit pairs (top) and empirical cumulative distributions (bottom) of recruitment for recruitment period 2000–2017 (red) and future recruitments sampled from smoothed distribution (black). Title indicates the replicate number which were chosen at random

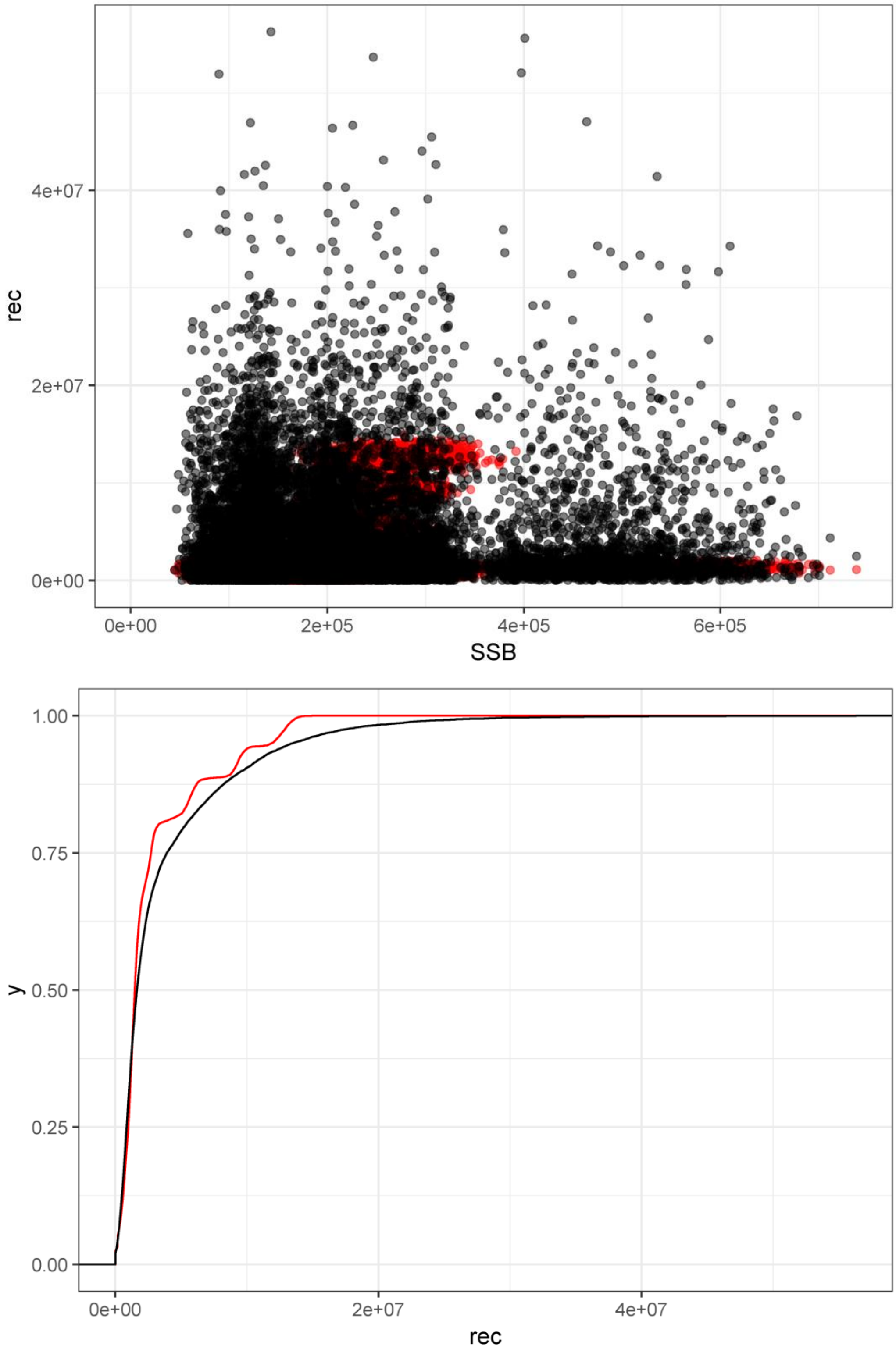


Figure 4.2.1.14. Haddock in Subarea 4, Division 6.a and Subdivision 20: Stock-recruit pairs (top) and empirical cumulative distributions (bottom) of recruitment for recruitment period 2000–2017 (red) and future recruitments sampled from smoothed distribution (black). All replicates are combined on this plot (1000 in total).

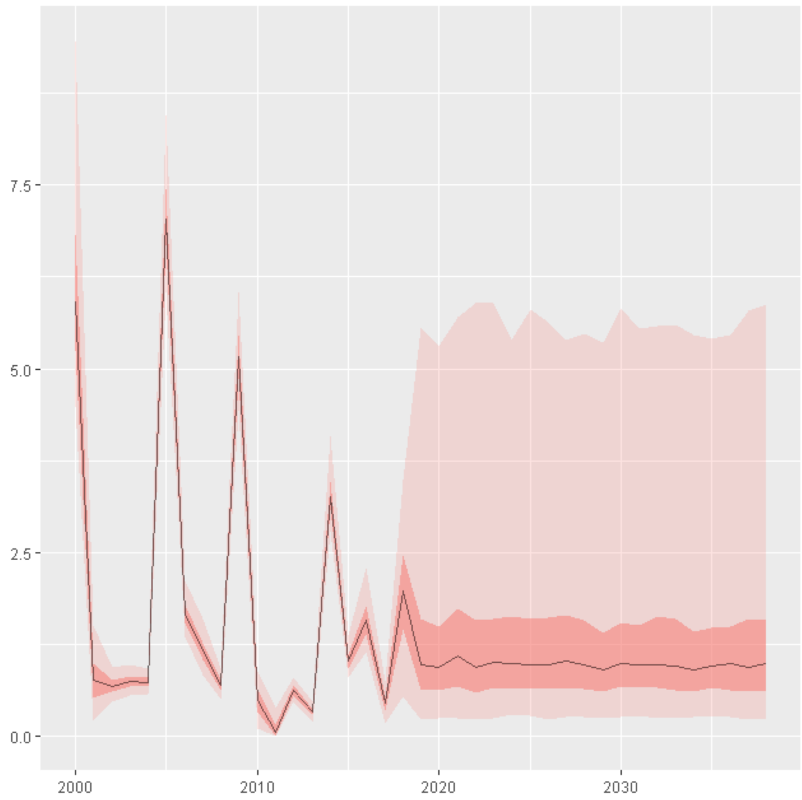


Figure 4.2.1.15. Haddock in Subarea 4, Division 6.a and Subdivision 20: Distribution of recruitment residuals for all replicates for the recent recruitment period (2000 to 2017) from which future recruitment residuals (2018–2038) are resampled.

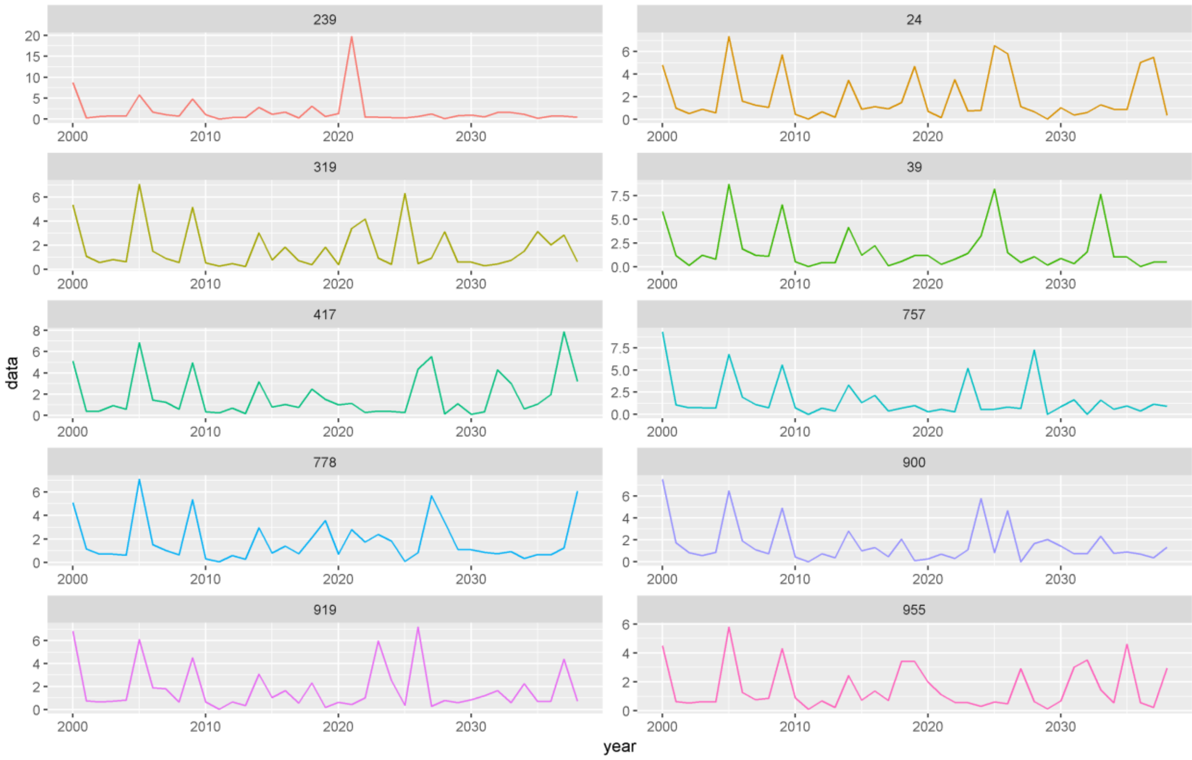


Figure 4.2.1.16. Haddock in Subarea 4, Division 6.a and Subdivision 20: Recruitment residuals for randomly selected replicates (2000-2038)

Selectivities

For this alternative OM (OM2), future selectivities were generated in a similar way to the baseline OM (OM1) though with a longer time period from which to resample. In this case, no strong trend was seen over time in the selection curves as with the baseline OM. Therefore, a 10-year period was used for the resampling (2008–2017 with replacement) which is consistent with the EqSim approach. The selection curves for 2008–2017 are shown in Figure 4.2.1.17 and are quite variable, though the 10-year, 5-year (2008–2012 and 2013–2017) and 3-year means are all quite similar and are all fairly similar to the 20-year mean.

Another check was performed to assess if variability in the selection curves might be being driven by the occurrence of the moderately large 2005, 2009 and 2014 year-classes. This comprised of a paired t-test between the selection curves for each year and the 10-year mean (2008–2017). The selection curve in 1 year (2013) was seen to be statistically different to the 10 year mean in which the 2009 year-class contributes almost 40% to the total stock biomass. However, this effect was not seen in other years where moderately large year classes dominate the stock to a similar extent.

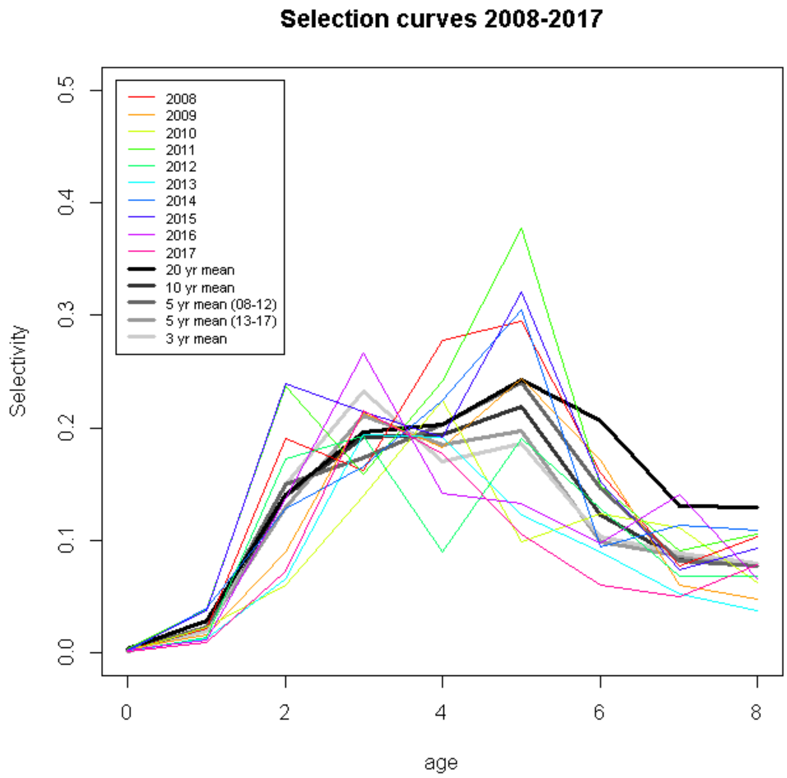


Figure 4.2.1.17. Haddock in Subarea 4, Division 6.a and Subdivision 20: Selection curves for 2008–2017. 10 year, 5 year (2008–2012 and 2013–2017) and 3 year means are also shown. The 20-year mean is also shown for comparison.

Generating data from the operating model

Catch was generated when projecting the stock with the fwd function in FLR package Flash. Catches from the operating model were multiplied by an error term $e^{\varepsilon_{a,y}}$ when being passed to the management procedure, where $\varepsilon_{a,y} \sim N(0, \sigma_a^2)$ and σ are observation standard deviations for catch as estimated by TSA.

Survey observations were generated from the operating model as follows:

$$I_{a,y,i} = q_{a,i} N_{a,y} e^{-t_i Z_{a,y}} \, e^{\varepsilon_{a,y,i}}$$

where N and Z are stock numbers and total mortalities from the operating model, the a, y and i subscripts denote age, year and survey (IBTS-Q1 or IBTS-Q3) respectively, q are survey catchabilities and $\varepsilon_{a,y,i} \sim N(0, \sigma_{a,i}^2)$ with σ standard deviations as estimated by TSA, and t is the timing of the survey (0.125 for Q1 and 0.625 for Q3).

In TSA, the standard deviation (σ) of both the catch and survey observations are multiplied by two terms, Q_a and $Q_{a,y}$. Q_a represents external cv multipliers to account for measurement error at age. These were made available for the catch data and survey indices at IBPHaddock (ICES 2016). $Q_{a,y}$ represents cv multipliers used to downweight specific data points in the catch and survey data. All cv multiplier settings are described in ICES (2018a).

Replicates of survey catchabilities and the error terms on the survey indices and catch-at-age were estimated from a variance-covariance matrix of the TSA parameters. The parameters estimated by TSA cover fishing selection and mortalities, catch variability, recruitment, discard rates and survey catchabilities and variability (see Table 4.2.1.1). Parameters can be fixed to specific values or estimated by TSA. To generate a usable variance-covariance matrix, a subset of the key

TSA parameters was used to form the matrix due to numerical difficulties with some ill-defined parameters and to reduce the computation time needed. This subset of parameters included the CV for landings and discards, the survey age selectivities and the two survey CVs (sigma and eta). All other parameters were fixed at the final estimated values from the WGNSSK 2018 assessment fit (ICES, 2018a). The parameters beta and omega were fixed for generating the variance-covariance matrix. Beta describes the persistent changes in catchability through time and is fixed at 0 in the WGNSSK assessment as it is assumed there is no trend in the catchability of the surveys. Omega is an inflation term to increase the survey CV when survey index values are low as the uncertainty in the index values is higher when stock levels are low and not as many fish are encountered during the survey. The omega term is not well defined for haddock as the survey indices have not been low enough in the past for this term to become important, and so it was decided to fix this parameter at its final estimate from the WGNSSK 2018 assessment (ICES, 2018a).

Table 4.2.1.1. Haddock in Subarea 4, Division 6.a and Subdivision 20. TSA final assessment parameter estimates from WGNSSK 2018 (ICES, 2018a).

	estimate	lower bound	upper bound	Estimated	on bound
F age 0	0.0384	0.005	0.1	TRUE	FALSE
F age 1	0.0881	0.05	0.15	TRUE	FALSE
F age 2	0.8525	0.6	1	TRUE	FALSE
F age 7	1.2893	1	1.4	TRUE	FALSE
sd F	0.1599	0.01	0.2	TRUE	FALSE
sd U	0.0721	0.01	0.15	TRUE	FALSE
sd V	0.1977	0.01	0.2	TRUE	FALSE
sd Y	0.1258	0.01	0.25	TRUE	FALSE
cv landings	0.1459	0.1	0.3	TRUE	FALSE
cv discards+bycatch+bms	0.2729	0.2	0.4	TRUE	FALSE
log mean recruitment at start	7.1087	7	9	TRUE	FALSE
sd of random walk	0.0803	0	0.25	TRUE	FALSE
recruitment cv	0.4834	0.3	0.6	TRUE	FALSE
discards sd transitory	0.0054	0	0.35	TRUE	FALSE
discards sd persistent	0.3375	0.25	0.5	TRUE	FALSE
NSQ1 selection age 1	0.2869	0.1	0.3	TRUE	FALSE
NSQ1 selection age 2	0.7025	0.4	0.8	TRUE	FALSE
NSQ1 selection age 3	0.7202	0.6	0.9	TRUE	FALSE
NSQ1 selection age 4	0.5925	0.4	0.8	TRUE	FALSE

	estimate	lower bound	upper bound	Estimated	on bound
NSQ1 selection age 5	0.4529	0.4	0.8	TRUE	FALSE
NSQ1 cv sigma	0.3728	0.1	0.4	TRUE	FALSE
NSQ1 cv eta	0.1745	0.1	0.8	TRUE	FALSE
NSQ1 cv omega	0.073	0	0.3	TRUE	FALSE
NSQ1 cv beta	0	0	0.1	FALSE	TRUE
NSQ3 selection age 0	0.2685	0.1	0.4	TRUE	FALSE
NSQ3 selection age 1	0.3919	0.2	0.6	TRUE	FALSE
NSQ3 selection age 2	0.5931	0.2	0.8	TRUE	FALSE
NSQ3 selection age 3	0.5019	0.2	0.8	TRUE	FALSE
NSQ3 selection age 4	0.3917	0.2	0.8	TRUE	FALSE
NSQ3 selection age 5	0.3492	0.2	0.8	TRUE	FALSE
NSQ3 cv sigma	0.2557	0.1	0.4	TRUE	FALSE
NSQ3 cv eta	0.0818	0	0.3	TRUE	FALSE
NSQ3 cv omega	0.105	0	0.3	TRUE	FALSE
NSQ3 cv beta	0	0	0.1	FALSE	TRUE

4.2.2 OM3 - Alternative recruitment – fixed regularity of recruitment spikes

This alternative OM for haddock (OM3) models future recruitment by fixing the timing of recruitment spikes. In the recent period of recruitment, the 2005, 2009 and 2014 year-classes are considerably larger than other years. In the Baseline OM (OM1) the residuals for these year classes are randomly resampled. OM3 samples the residuals for these year classes at a specified interval so that spikes in future recruitment happen at a certain regularity. The future residuals for recruitment for OM3 are shown in Figure 4.2.2.1 and some individual iterations are shown in Figure 4.2.2.2.

The timing of the recruitment spikes is modelled following the approach of Skagen (2012). A segmented regression was fitted to the recent period of recruitment (2000 onwards) as done for the Baseline OM (OM1). Future recruitment is initially generated from residuals that are resampled from all years except for the 2005, 2009 and 2014 year-classes. The timing of the spikes is then modelled as follows:

1. A random number (x_i) is drawn from a uniform distribution in (0,1) with mean 0.5
2. x_i is then multiplied by a variability factor, s, to generate a distribution in (0,s) with mean s/2
3. The timing of the next spike, y_i is calculated as: y_i = mean interval × ($sx_i + 1 - s^2$). y_i has a uniform distribution in (mean interval × ($1-s^2$), mean interval × ($1+s^2$)).

4. This number y_i is then rounded to the nearest integer to set the year of the next recruitment spike.

For OM3 the mean interval was set at 4.5 years (mean interval between the 2005, 2009 and 2014 year-classes) and s was set to 0.5 (intermediate regularity of spikes). Recruitment residuals for the spike years were randomly sampled from the residuals for the 2005, 2009 and 2014 year-classes. The timing of the spikes is shown in Figure 4.2.2.3.

The influence of the value of s (variability factor) was investigated. This variable controls the variability in the interval between spike years. Lower values of s result in more regular spike intervals than higher values. This is shown in Figure 4.2.2.4. A value of 0.1 for s gives spike intervals of either 4 or 5 years whereas a value of 1 for s results in intervals that vary from 3 to 6 years. Since the value of y_i is rounded to the nearest integer, a value of 0.5 or higher for s is needed to prevent the variability introduced by s being reduced by the rounding. The values of s was set at 0.5 as this was seen to be a compromise between having very regular intervals between spikes (at lower values of s), which are potentially unrealistic, and having higher variability in the spike interval (at higher values of s), which would not be consistent with the purpose of this OM3 (to have a regularity to the occurrence of spike years).

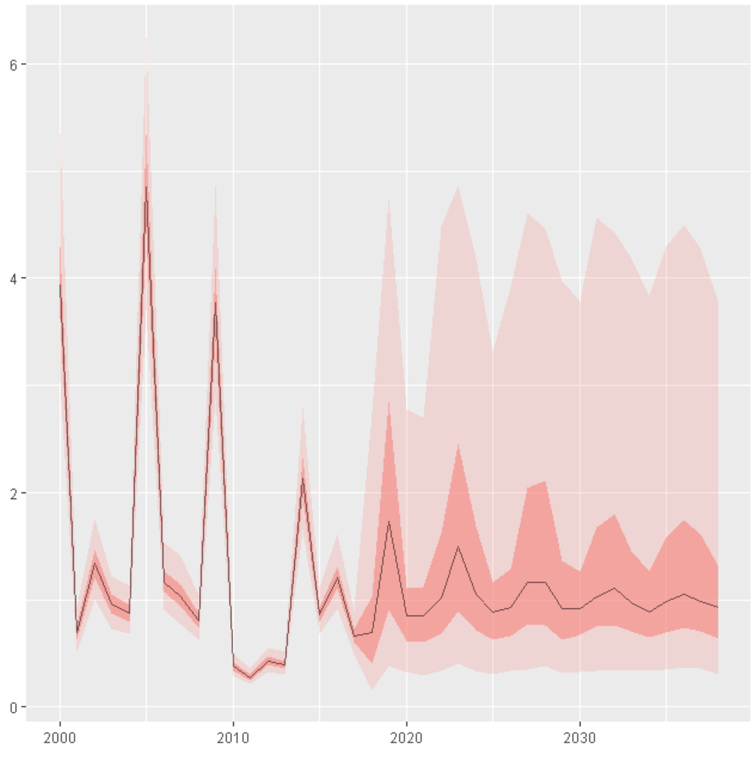


Figure 4.2.2.1. Haddock in Subarea 4, Division 6.a and Subdivision 20: residuals for OM3 future recruitment with fixed regularity of recruitment spikes.

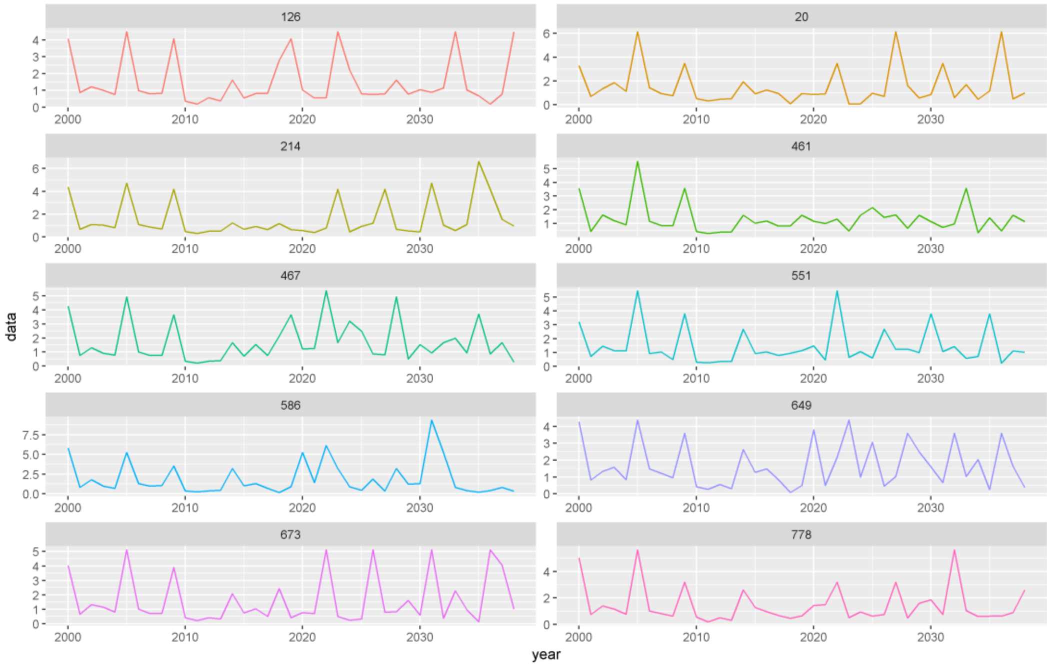


Figure 4.2.2.2. Haddock in Subarea 4, Division 6.a and Subdivision 20: recruitment residuals (2000–2038) for selected replicates.

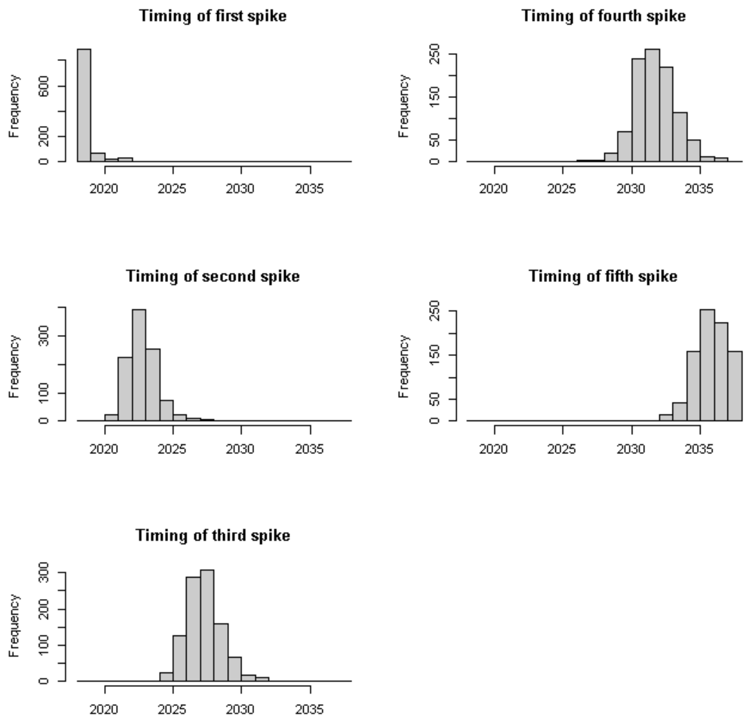


Figure 4.2.2.3. Haddock in Subarea 4, Division 6.a and Subdivision 20: timing of first, second, third and fourth recruitment spikes when s = 0.5.

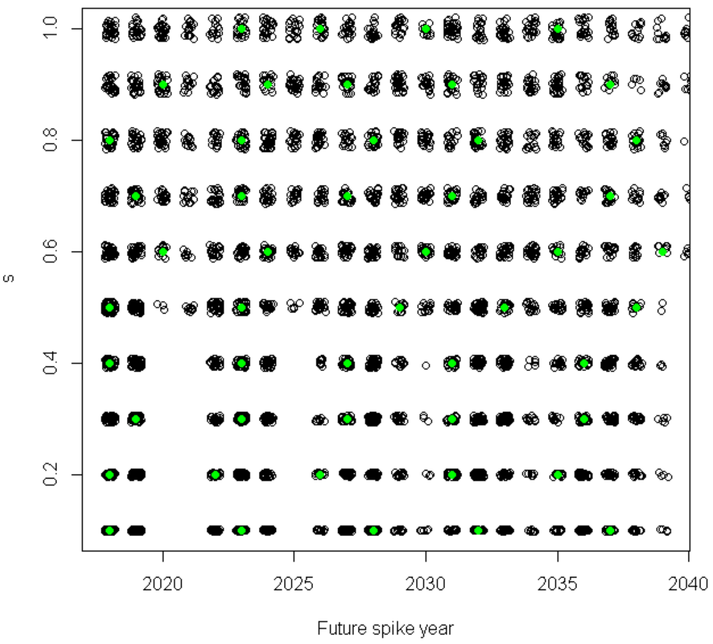


Figure 4.2.2.4. Haddock in Subarea 4, Division 6.a and Subdivision 20: influence of variability factor (s) on interval between spikes. Black circles represent the years selected as recruitment "spike" years for 1000 replicates at different values of s and green dots represent the years selected as recruitment "spike" years for 1 replicate.

4.3 Management procedure

The management procedure (MP) comprises of the estimation model and the decision model. The decision model comprises the management strategies that are being evaluated (Section 2.1), and the estimate of SSB needed by the decision model is supplied by the estimation model.

The estimation model (SAM) is the same as that which is used to condition OM1 and OM3. However, OM2 is conditioned using TSA which is the actual assessment model used in the annual stock assessment of Northern Shelf haddock. It is simply impractical to use TSA in the management procedure (MP; see Figure 2.3) due to the length of time it takes to converge (approximately 2 hours) and the *ad hoc* adjustments to settings that are needed as TSA does not have the robustness to deal with atypical situations. A solution to this problem is to use SAM in the MP instead as an approximation for using TSA. It is therefore important to demonstrate that SAM is a reasonable approximation as a working group assessment model for TSA, and the focus of this section is to demonstrate this.

4.3.1 Comparison of TSA with SAM

At the last benchmark for Northern Shelf haddock (ICES, 2014), TSA and SAM were both considered as candidate stock assessment models. TSA was first developed by Gudmundsson (1994) and was re-implemented and extended by Fryer (2002) to allow joint modelling of landings-at-age and discards-at-age. SAM (Nielsen and Berg 2014) is inherently similar to TSA since it is also a development of Gudmundsson's time-series approach. The state vectors and survival and catch equations are the same, but there are small differences between the two models (i.e. the state equations for fishing mortality, various model options). Both models are based on similar assumptions, both treat catches as observations with noise and both allow for time varying selectivity.

TSA and SAM were compared during WKHAD (ICES, 2014) and were found to be "almost equally plausible" as assessment models for Northern Shelf haddock with estimates from both models being very similar. The main differences were:

- The confidence intervals for SAM were wider for SSB and recruitment.
- Recruitment estimates differ in years with large year classes due to the use of the lambda multiplier in TSA to give a higher variance to large year classes.

The reason for the difference in confidence intervals was not clear although may arise from the *ad hoc* adjustments that can be utilised in TSA but not in SAM, such as down-weighting catch and survey outliers, and the use of measurement error/recruitment variability multipliers.

WKHAD (ICES, 2014) concluded that TSA should be used as the principal stock assessment method for the following reasons:

- TSA models landings and discards+bycatch separately which is more likely to produce more robust results given that the two components have different age compositions and error structures.
- Northern Shelf haddock recruitment has sporadic, very large year classes that are difficult to model using standard distributional approaches. The log-normal distribution used in SAM may underestimate the very large year classes. TSA allows for increasing the variance on estimates of large year classes. This *ad hoc* solution in TSA isn't elegant but is probably a closer approximation than the approached used in SAM (though this was not a strong conclusion).
- A practical consideration is that the developer of TSA (Rob Fryer) and stock assessor are both based at the Marine Laboratory in Aberdeen, Scotland. This means any issues arising from using TSA can be quickly resolved.

SAM is run alongside TSA each year during WGNSSK as an exploratory method. A comparison of the assessment results from TSA and SAM during WKNSSK 2018 show that the results for SSB, recruitment and F are reasonably similar (Figure 4.3.1.1, ICES 2018a). The SSB estimate is quite close between the two models over the majority of the time series, though TSA has given a noticeably higher estimate of SSB since approximately 2004. The overall trends in SSB are the same between the two models. The agreement between the two models in recruitment is good in recent years, though there is less agreement further back in time. The estimate of F in SAM is smoother over time compared to TSA, though the overall trend is very similar. The confidence intervals for SSB and recruitment in SAM are generally wider than in TSA, though they overlap along much of the time series.

A comparison of the assessment estimates from both models in previous working groups (ICES 2016, 2017) is shown in Figures 4.3.1.2 and 4.3.1.3. The degree of agreement between the models from WGNSSK 2017 (ICES, 2017) is similar to that of WGNSSK 2018 (ICES, 2018a). However, the SAM estimate of F appears smoother in IBPHaddock (ICES, 2016) in addition to the recent values of SSB in SAM being lower than the TSA estimate. A comparison of N-at-age between TSA and SAM for WGNSSK 2018 show good agreement between the two assessment models, though, in general, SAM tends to underestimate peaks in abundance (Figure 4.3.1.4). The agreement in the age 8+ group in recent years between the models is not as great as for other age classes. TSA is known to overestimate the abundance in the plus-group; however, this has not been a significant issue in the past as the plus-group comprises a small part of the overall stock. Nevertheless, the importance of the plus-group may increase over time as more fish survive to older ages. SAM again has generally similar trends over time to TSA for F at age though there is less agreement in ages 0 and 1 prior to the mid-1980s, and F-at-age is generally higher in SAM since the mid-1990s for ages 6–8 (Figure 4.3.1.5).

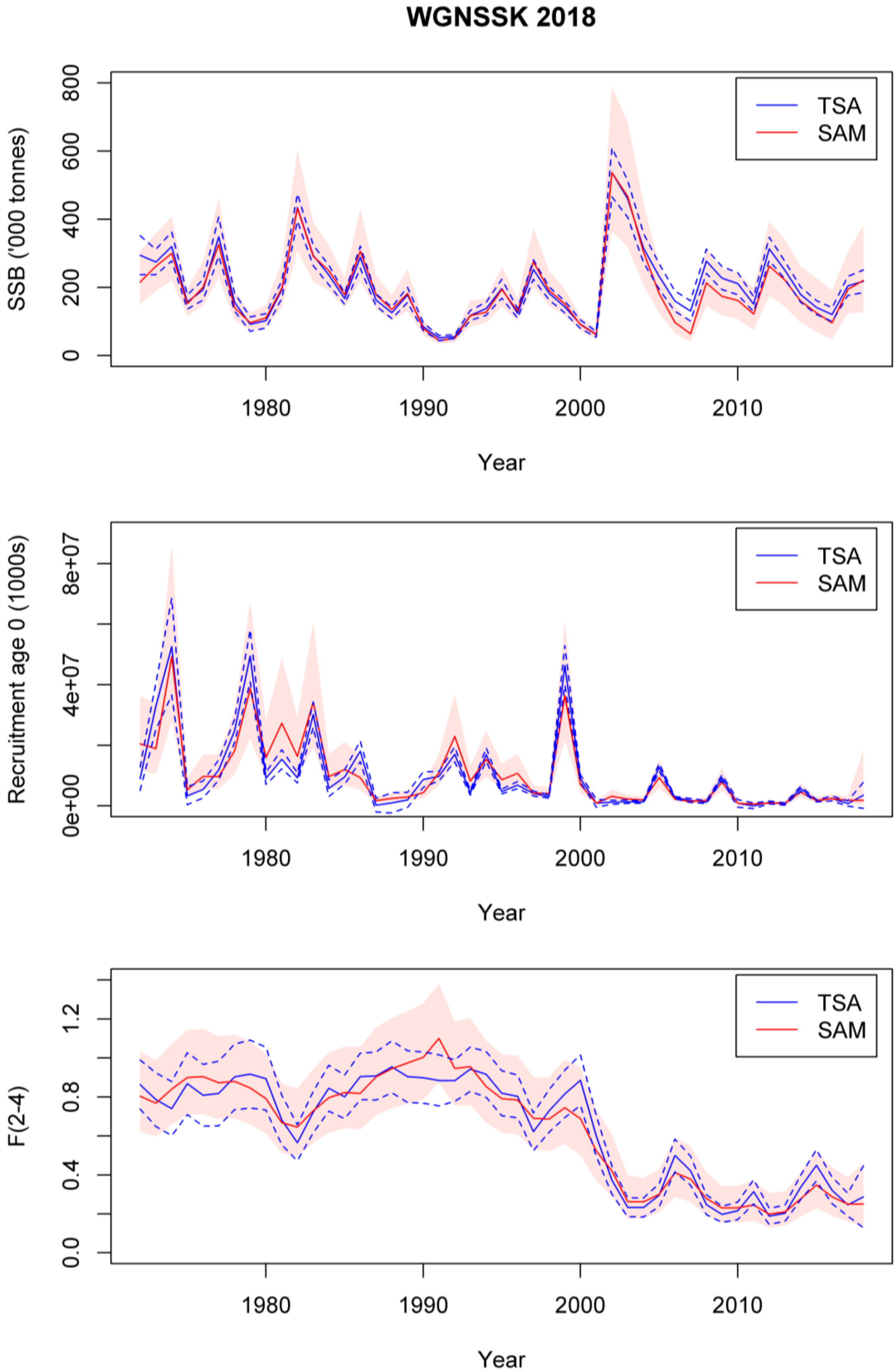


Figure 4.3.1.1. Haddock in Subarea 4, Division 6.a and Subdivision 20: Comparison of spawning stock biomass (SSB), recruitment and fishing mortality (age 2-4) (F(2-4)) estimates from TSA (blue line) and SAM (red line) from WGNSSK 2018. Dashed blue lines and the red shaded area represent the approximate point-wise 5% and 95% confidence intervals of the TSA and SAM estimates respectively.

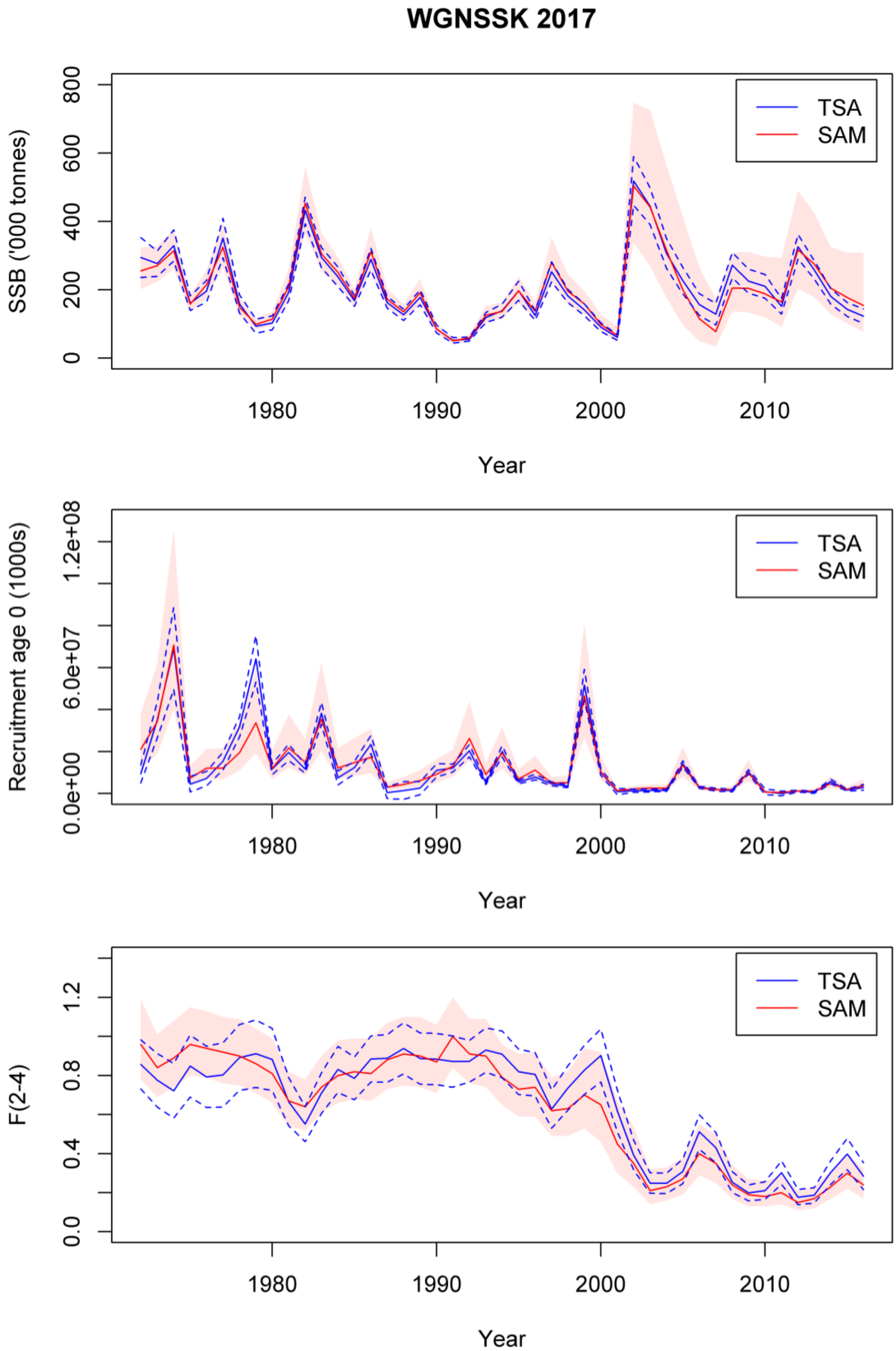


Figure 4.3.1.2. Haddock in Subarea 4, Division 6.a and Subdivision 20: Comparison of spawning stock biomass (SSB), recruitment and fishing mortality (age 2–4) (F(2–4)) estimates from TSA and SAM from WGNSSK 2017. Dashed blue lines and the red shaded area represent the approximate point-wise 5% and 95% confidence intervals of the TSA and SAM estimates respectively.

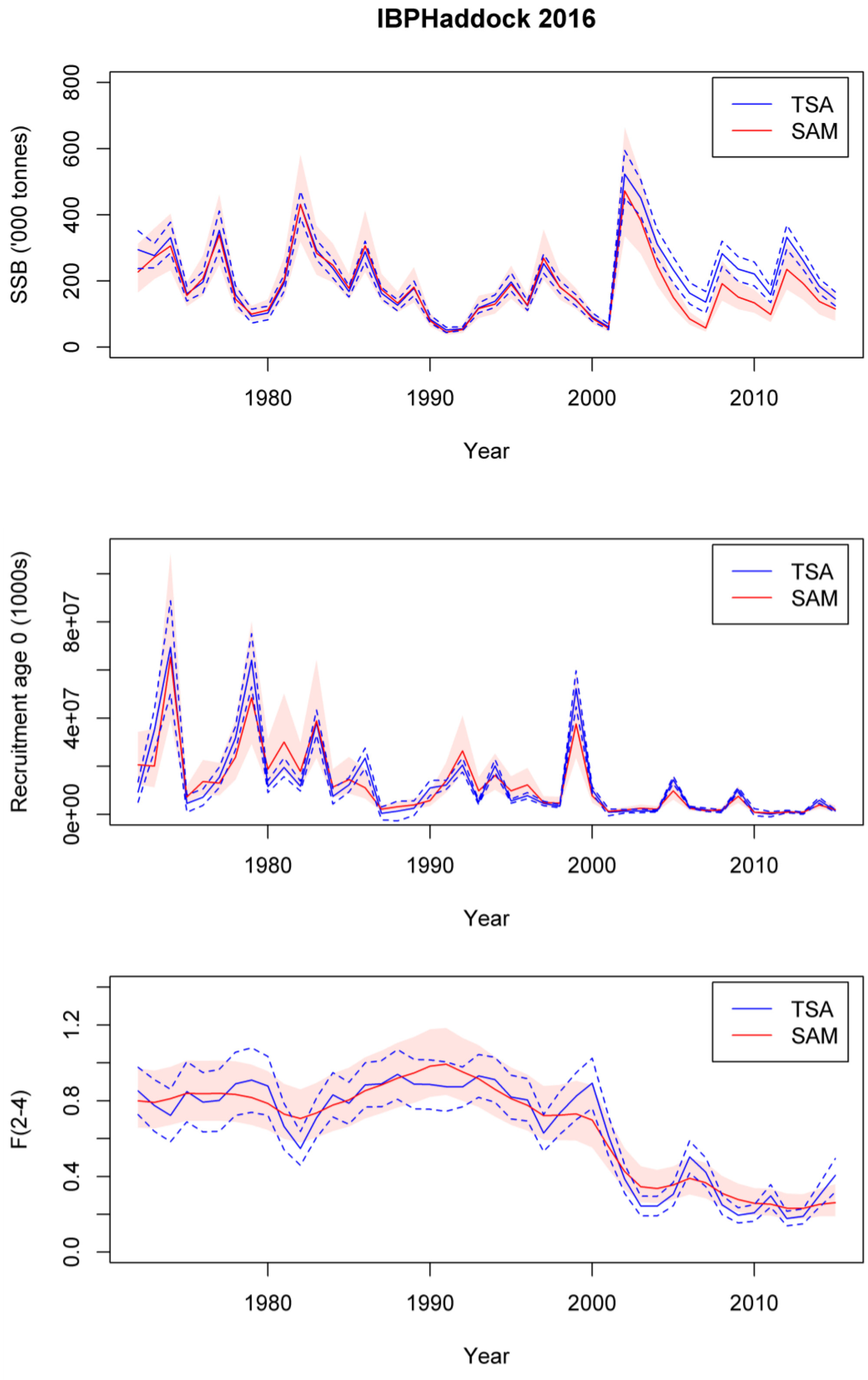


Figure 4.3.1.3. Haddock in Subarea 4, Division 6.a and Subdivision 20: Comparison of spawning stock biomass (SSB), recruitment and fishing mortality (age 2–4) (F(2–4)) estimates from TSA and SAM from IBPHaddock 2016 (ICES, 2016). Dashed blue lines and the red shaded area represent the approximate point-wise 5% and 95% confidence intervals of the TSA and SAM estimates respectively.

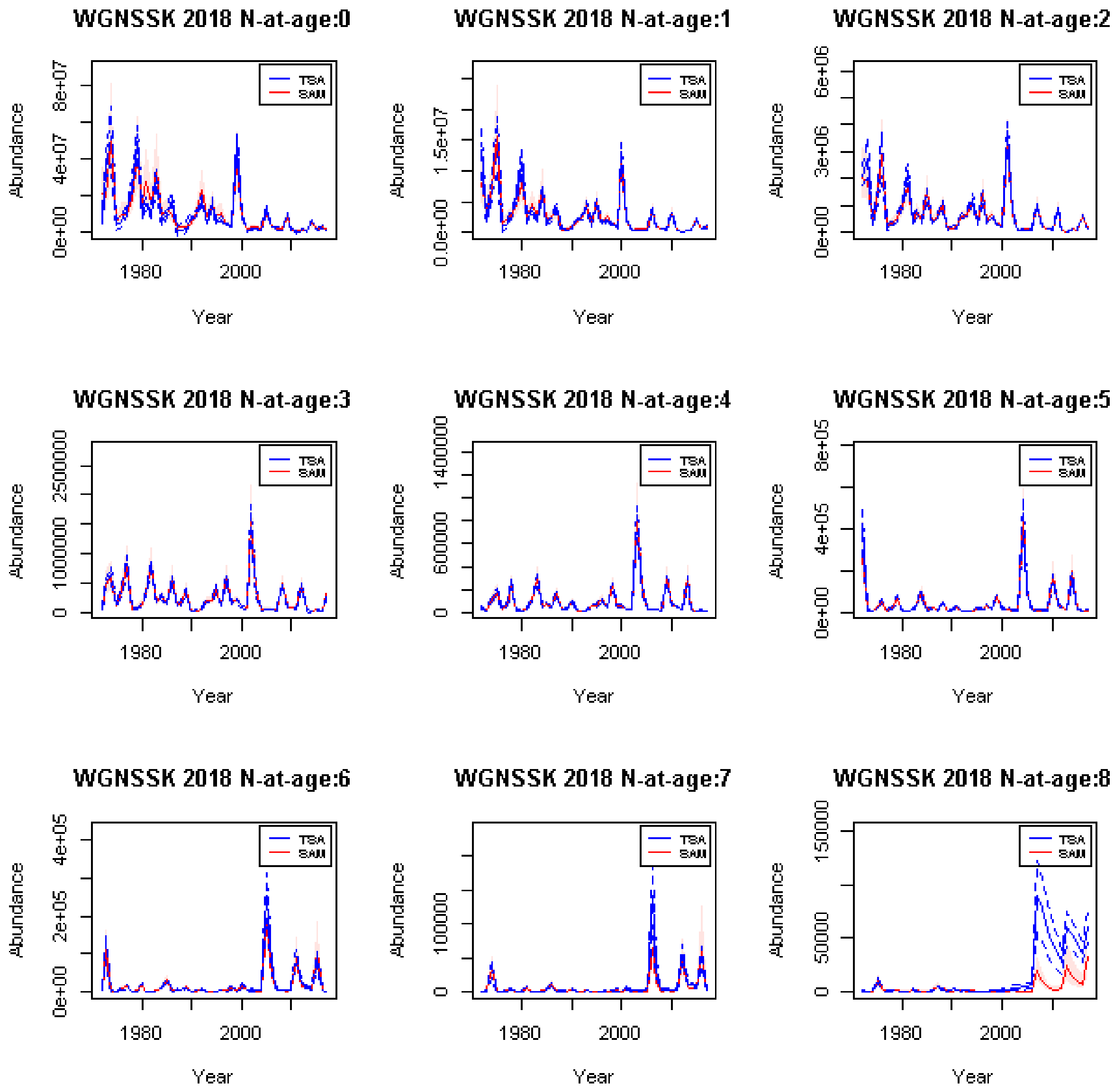


Figure 4.3.1.4. Haddock in Subarea 4, Division 6.a and Subdivision 20: Comparison of N-at-age for TSA and SAM from WGNSSK 2018. Dashed blue lines and the red shaded area represent the approximate point-wise 5% and 95% confidence intervals of the TSA and SAM estimates respectively.

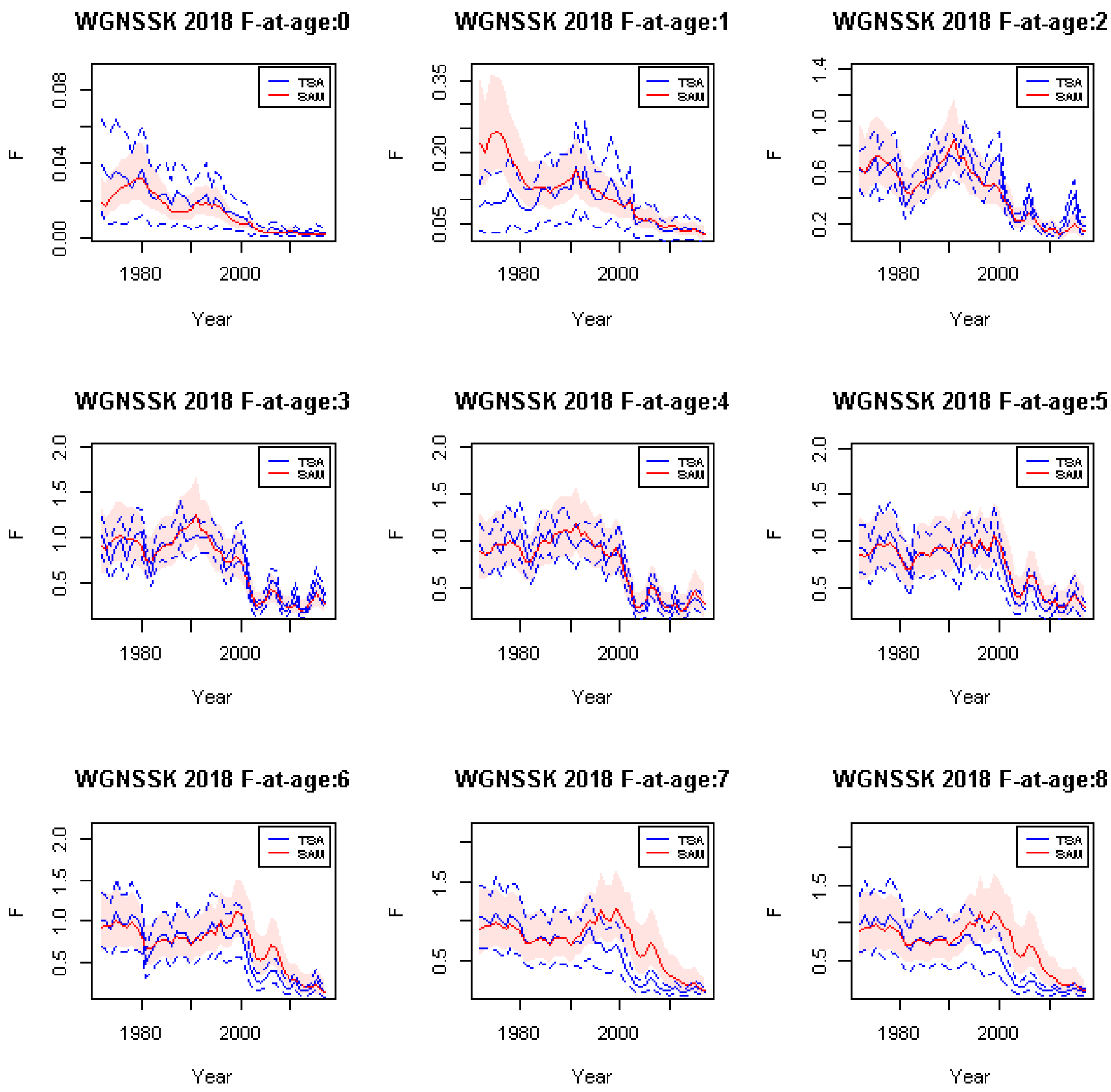


Figure 4.3.1.5. Haddock in Subarea 4, Division 6.a and Subdivision 20: Comparison of fishing mortality-at-age estimates from TSA and SAM from WGNSSK 2018. Dashed blue lines and the red shaded area represent the approximate point-wise 5% and 95% confidence intervals of the TSA and SAM estimates respectively.

4.3.2 Assessment settings

This section describes the settings used in the estimation model when conducting the stock assessment given the change in model from TSA to SAM. The input data types and characteristics used in SAM are the same as those used in TSA. The only difference is that SAM uses only catch input rather than separating landings and discards as done in TSA. The initial parameters used in SAM are set to the final parameter estimates from a SAM fit to data provided at WGNSSK 2018 (ICES, 2018a).

SAM settings used:

```
# Configuration saved: Mon Jan  7 14:02:50 2019
#
# Where a matrix is specified rows corresponds to fleets and columns to ages.
# Same number indicates same parameter used
# Numbers (integers) starts from zero and must be consecutive
#
$minAge
# The minimium age class in the assessment
 0

$maxAge
# The maximum age class in the assessment
 8

$maxAgePlusGroup
# Is last age group considered a plus group (1 yes, or 0 no).
 1

$keyLogFsta
# Coupling of the fishing mortality states (nomally only first row is used).
   0   1   2   3   4   5   6   7   7
  -1  -1  -1  -1  -1  -1  -1  -1  -1
  -1  -1  -1  -1  -1  -1  -1  -1  -1

$corFlag
# Correlation of fishing mortality across ages (0 independent, 1 compound symmetry, or 2 AR(1)
 2

$keyLogFpar
# Coupling of the survey catchability parameters (nomally first row is not used, as that is covered
by fishing mortality).
  -1  -1  -1  -1  -1  -1  -1  -1  -1
  -1   0   1   2   3   3  -1  -1  -1
   4   5   6   7   8   8  -1  -1  -1

$keyQpow
# Density dependent catchability power parameters (if any).
  -1  -1  -1  -1  -1  -1  -1  -1  -1
  -1  -1  -1  -1  -1  -1  -1  -1  -1
  -1  -1  -1  -1  -1  -1  -1  -1  -1

$keyVarF
# Coupling of process variance parameters for log(F)-process (nomally only first row is used)
   0   0   0   0   0   0   0   0   0
  -1  -1  -1  -1  -1  -1  -1  -1  -1
  -1  -1  -1  -1  -1  -1  -1  -1  -1

$keyVarLogN
# Coupling of process variance parameters for log(N)-process
 0 1 1 1 1 1 1 1 1

$keyVarObs
# Coupling of the variance parameters for the observations.
   0   0   0   0   0   0   0   0   0
  -1   1   1   1   1   1  -1  -1  -1
   2   2   2   2   2   2  -1  -1  -1

$obsCorStruct
# Covariance structure for each fleet ("ID" independent, "AR" AR(1), or "US" for unstructured). |
Possible values are: "ID" "AR" "US"
 "ID" "ID" "ID"

$keyCorObs
# Coupling of correlation parameters can only be specified if the AR(1) structure is chosen above.
# NA's indicate where correlation parameters can be specified (-1 where they cannot).
#V1 V2 V3 V4 V5 V6 V7 V8
   NA  NA  NA  NA  NA  NA  NA  NA
  -1   NA  NA  NA  NA -1  -1  -1
   NA  NA  NA  NA  NA -1  -1  -1

$stockRecruitmentModelCode
# Stock recruitment code (0 for plain random walk, 1 for Ricker, and 2 for Beverton-Holt).
 0

$noScaledYears
# Number of years where catch scaling is applied.
 0

$keyScaledYears
# A vector of the years where catch scaling is applied.


$keyParScaledYA
# A matrix specifying the couplings of scale parameters (nrow = no scaled years, ncols = no ages).
```

```
$fbarRange
# lowest and higest age included in Fbar
 2 4

$keyBiomassTreat
# To be defined only if a biomass survey is used (0 SSB index, 1 catch index, and 2 FSB index).
 -1 -1 -1

$obsLikelihoodFlag
# Option for observational likelihood | Possible values are: "LN" "ALN"
 "LN" "LN" "LN"

$fixVarToWeight
# If weight attribute is supplied for observations this option sets the treatment (0 relative weight,
1 fix variance to weight).
 0
```

4.3.3 Forecast settings

The forecast settings used in the decision model follow the settings used at WGNSSK as far as possible. Some changes were necessary due to the difference in the decision model used. The forecast conducted at WGNSSK for Northern Shelf haddock uses MFDP which allows for forecasting of multiple fleets (e.g. human consumption/directed fishery and industrial bycatch). Forecasting with SAM does not allow for fleet separation; however, in this MSE, the IBC catch component has been amalgamated with the human consumption catch because it makes up such a small part of the total catch.

Initial stock size

The initial stock size used at WGNSSK is taken as the deterministic starting populations from the TSA survivors' estimates. This is repeated for the MSE though using the SAM fit survivors' estimate rather than TSA.

Maturity

Knife edge at age 3 (0 for ages 0–2, 1 for ages 3+). This is identical to WGNSSK.

Natural mortality

An average of the final three years of assessment data is used. This is identical to WGNSSK.

Weight at age

Future weights at age for the catch are calculated using a linear cohort-based approach (Jaworski 2011) since density dependent effects may result in large year classes growing more slowly than smaller year classes. This modelling of future weights is reproduced in the decision model. The weight at age in the stock is assumed to be the same as the weight at age in the catch.

Weights at age a for cohort c are fitted with the linear model:

$$W_{a,c} = \alpha_c + \beta_c a$$

where parameters α_c and β_c are cohort-specific. For the most recent cohorts, less than three data points exist, therefore weights-at-age are taken as an average of three previous weights at the same age. Similarly, for cohorts where there is insufficient information, a three-year average is used.

Exploitation pattern

This is set to be the same as the previous year. This is identical to WGNSSK.

Intermediate year assumptions

At WGNSSK, the fishing mortality estimate for the current year is taken to be the same as the final year. Where this results in landings that overshoot the TAC, a TAC constraint should be considered. At ICES-WKBENCH (ICES, 2011), recent haddock catches had seen to be increasing and some segments of the Scottish fleet were exhausting their quota, whereas this had not been an issue in the past. The exhausting of quota was likely due to restrictions in cod catch, and so a TAC constraint was recommended for the haddock forecast. This process was not replicated in the decision model due to the additional computational and time requirements needed to conduct the TAC constraint procedure. However, a test simulation of the A* management scenario (a version of management strategy A that sets $F_{target} = F_{MSY} = 0.194$ and $B_{trigger}$ =MSY $B_{trigger}$ = 132 000 t) showed that a TAC constraint was applied in the first few years of the projection (up to approximately 2025) after which the conditions needed to apply a TAC constraint were never met.

Stock recruitment model used

At WGNSSK the recruits in the intermediate and TAC years are taken as the TSA estimate of forecasted recruits at age 0 in the intermediate year. This ensures consistency between assessment and forecast. The SAM forecast resamples recruitment from a specified period. This was limited to the recent period of lower recruitment (2000 onwards), which is congruent with the recruitment period used to determine the stock reference points in the EqSim analysis (ICES 2016).

4.4 Results

4.4.1 Search grid for "optimal" combination of F_{target} and $B_{trigger}$

Only the baseline OM1 was used to search for the "optimal" combinations of F_{target} and $B_{trigger}$ (i.e. those that maximise long-term yield while fulfilling the ICES precautionary criterion of risk3 ≤ 5%) for each of the six management strategies. The grid searches are shown in Figures 4.4.1.1-6. The grids are only partially complete because each cell in the grid takes just under 80 hours on a single core computer. The search was conducted in steps of 0.01 for F_{target}, and 10 000 t for $B_{trigger}$ and was focussed on complying with the 5% threshold in risk3 while maximising catch after an initial set of runs were completed. The runs for Northern Shelf haddock took much longer compared to other demersal stocks with a longer amount of time being taken by the estimation model to complete the stock assessment. The "optimal" combination is highlighted in each plot with a black border around the corresponding cell.

Table 4.4.1.1 summarises the result of the search for the "optimal" combinations. The mean F reached the maximum of 2.0 in 1 replicate in two of the scenarios. In this replicate, there is a run of low recruitment following a recruitment "spike". F_{max} is reached due to the slow response of the HCR to the sustained period of low recruitment, possibly as a result of recruitment being over-estimated in the forecast during that time.

Table 4.4.1.1. Haddock in Subarea 4, Division 6.a and Subdivision 20: "optimal" combinations for F_{target} and $B_{trigger}$ for the baseline OM1 and six management strategies. Also reported are the median long-term values for catch, SSB, realized mean F (ages 2-4), interannual catch variability (ICV), interannual TAC variability (ITV), risk3, risk1, the number of times the SAM assessment did not converge during the simulation and the number of times mean F reached the maximum of 2.0. The results for F = 0 and management strategy A* (i.e. with F_{target} = F_{MSY} = 0.194 and $B_{trigger}$ = MSY $B_{trigger}$ = 132 000 t) and A*+D are provided for comparison.

Management strategy	F_{target}	$B_{trigger}$	Catch	SSB	ICV	ITV	risk1	risk3	Realised F	Conv_failed	F_maxed
A	0.28	180000	51358	196587	0.275	0.273	4.5%	4.9%	0.262	0	0
B	0.29	190000	51574	194672	0.296	0.295	4.4%	4.8%	0.265	0	1
C	0.28	180000	51350	196587	0.275	0.273	4.5%	4.9%	0.262	0	0
A+D	0.28	180000	49628	196781	0.348	0.275	4.5%	5.0%	0.256	0	0
B+E	0.27	170000	49831	200267	0.393	0.274	4.2%	4.9%	0.256	0	0
C+E	0.26	160000	49398	203534	0.378	0.253	4.4%	5.0%	0.251	0	1
A*	0.194	132000	45296	252152	0.207	0.208	1.6%	1.9%	0.203	0	0
A*+D	0.194	132000	44480	251788	0.361	0.207	1.6%	2.1%	0.201	0	0
F=0	0	-	0	578988	0	0	0	0	0	-	0

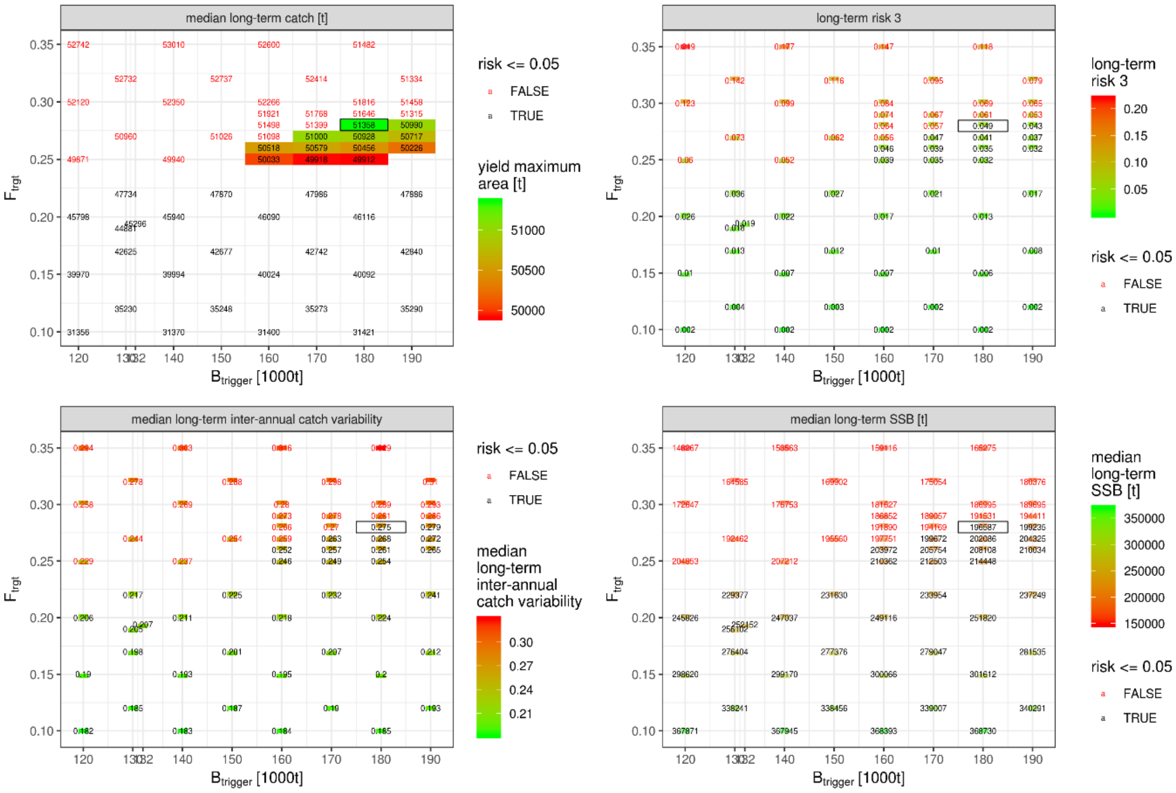


Figure 4.4.1.1. Haddock in Subarea 4, Division 6.a and Subdivision 20: Grid search for "optimal" combination of F_{target} and $B_{trigger}$ for management strategy A for the long-term (i.e. final 10 years of the 20-year projection). The top-left plot is median long-term catch, top-right the long-term risk3, bottom left the median long-term inter-annual catch variability and bottom right the median long-term SSB. The "optimal" combination is surrounded by a black box. The combinations that meet the precautionary criterion (risk3 ≤ 5%) are in black text, while those that don't are in red.

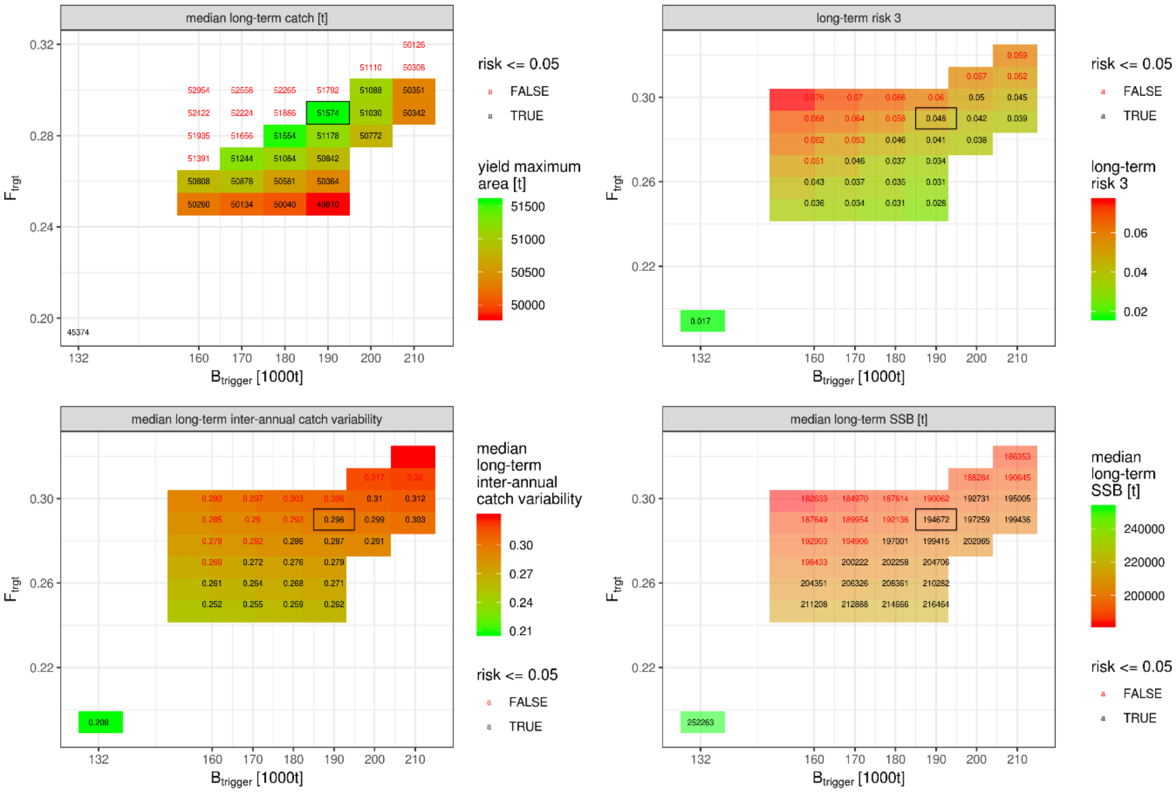


Figure 4.4.1.2. Haddock in Subarea 4, Division 6.a and Subdivision 20: Grid search for "optimal" combination of F_{target} and $B_{trigger}$ for management strategy B for the long-term (i.e. final 10 years of the 20-year projection). See caption to Figure 4.4.1.1 for further details.

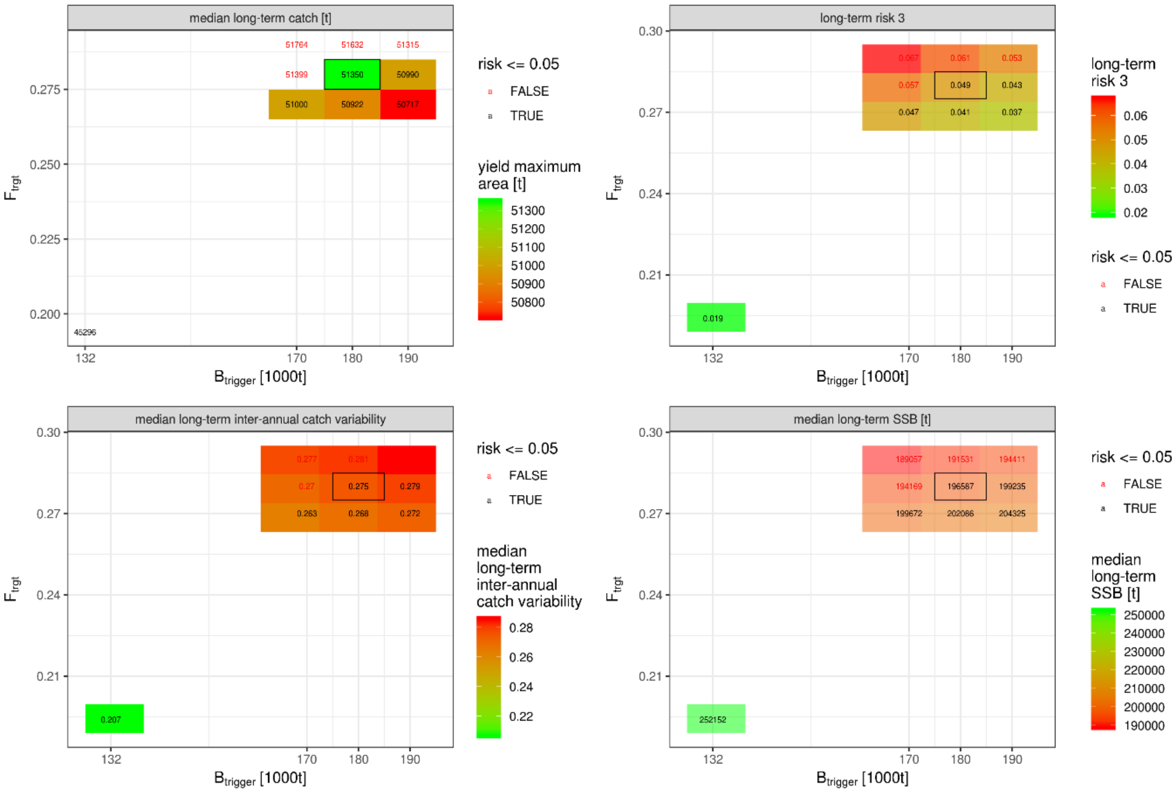


Figure 4.4.1.3. Haddock in Subarea 4, Division 6.4 and Subdivision 20: Grid search for "optimal" combination of F_{target} and $B_{trigger}$ for <u>management strategy C</u> for the long-term (i.e. final 10 years of the 20-year projection). See caption to Figure 4.4.1.1 for further details.

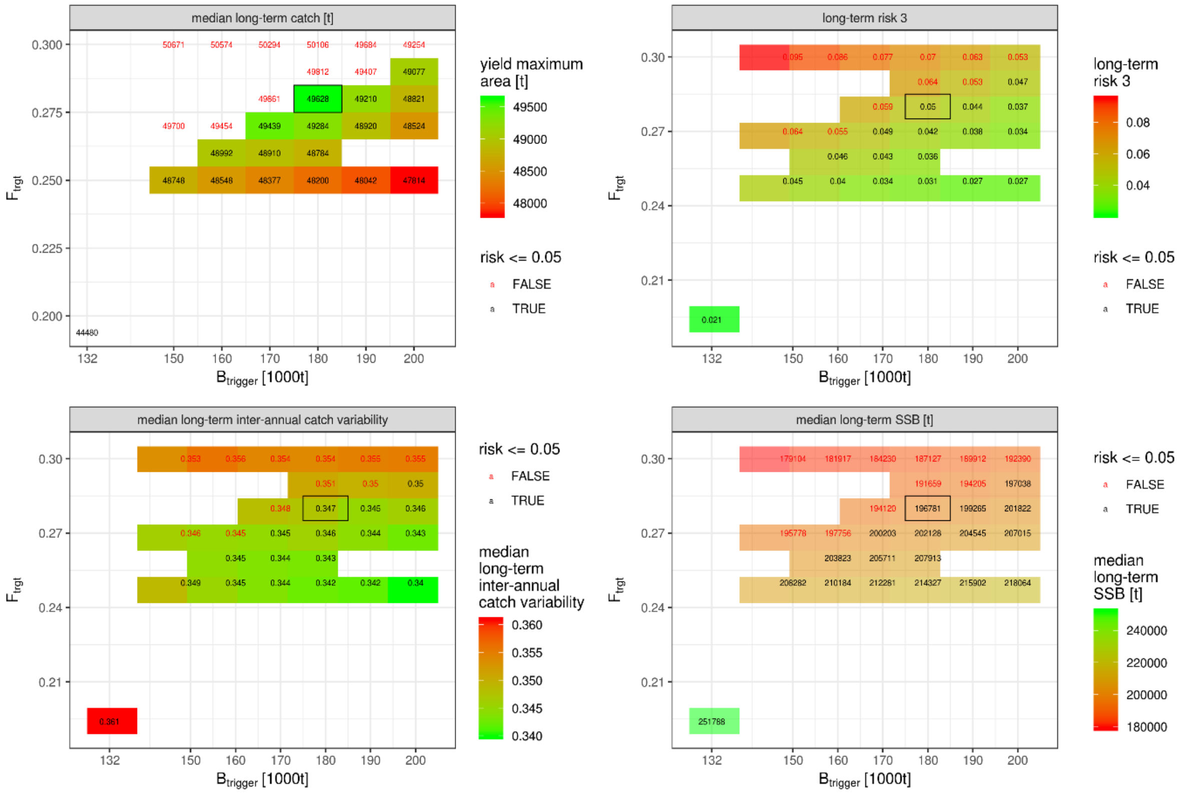


Figure 4.4.1.4. Haddock in Subarea 4, Division 6.4 and Subdivision 20: Grid search for "optimal" combination of F_{target} and $B_{trigger}$ for <u>management strategy A+D</u> for the long-term (i.e. final 10 years of the 20-year projection). See caption to Figure 4.4.1.1 for further details.

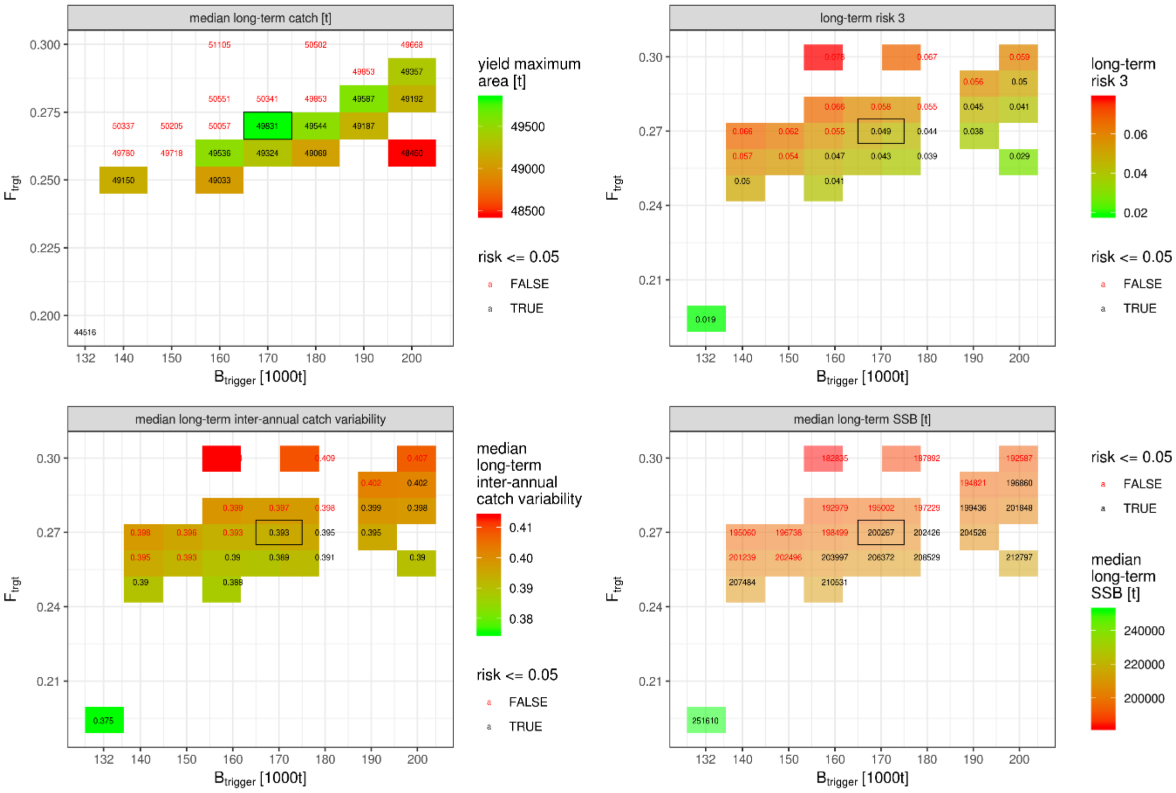


Figure 4.4.1.5. Haddock in Subarea 4, Division 6.4 and Subdivision 20: Grid search for “optimal” combination of F_{target} and $B_{trigger}$ for management strategy B+E for the long-term (i.e. final 10 years of the 20-year projection). See caption to Figure 4.4.1.1 for further details.

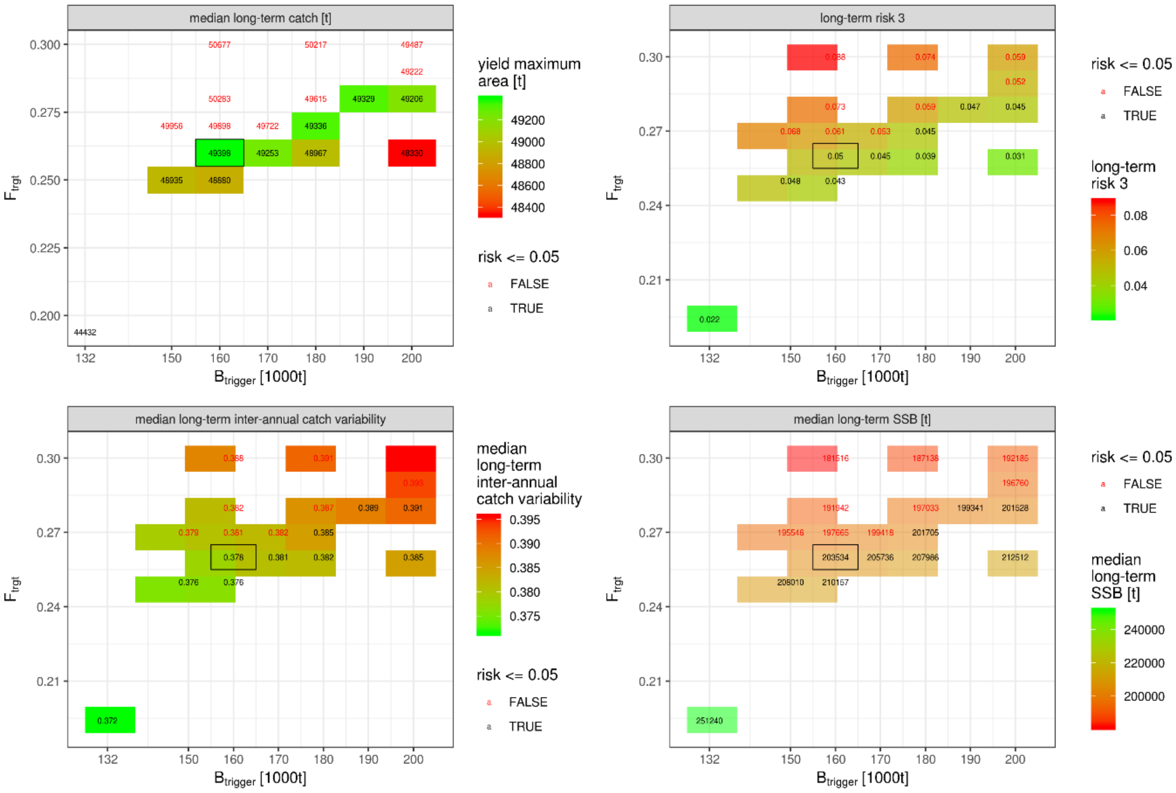


Figure 4.4.1.6. Haddock in Subarea 4, Division 6.4 and Subdivision 20: Grid search for "optimal" combination of F_{target} and $B_{trigger}$ for management strategy C+E for the long-term (i.e. final 10 years of the 20-year projection). See caption to Figure 4.4.1.1 for further details.

4.4.2 Summary projections

Summary projections for recruitment (age 0), SSB, catch and mean F (ages 2–4) for the baseline OM1 are given for F = 0 in Figure 4.4.2.1, a version of management strategy A that sets $F_{target} = F_{MSY} = 0.194$ and $B_{trigger}$ = MSY $B_{trigger}$ = 132 000 t (labelled A*) in Figure 4.4.2.2, and a version of A* that includes the stability mechanisms (labelled A*+D) in Figure 3.4.2.3. Summary projections for the six "optimised" management strategies (see Table 4.4.1.1) are given in Figures 4.4.2.4–9. Figure 4.4.2.10 plots the annual risk for "optimised" management strategy A, which indicates that annual risk stabilises from around 2033 onwards.

In all six management strategies, the projections show an initial decline in SSB towards the $B_{trigger}$ value, followed by a short-term fall in F_{bar} and catch, before SSB, F_{bar} and catch rise again and reach equilibrium. The plots of individual replicates better demonstrate the differences between the scenarios. The zig-zag nature of the banking and borrowing in management strategies A+D, B+E and C+E can be seen clearly in the projections of F_{bar}, total catch and to a lesser extent in SSB. The plots of individual replicates show that the year to year changes in total catch and F_{bar} and more dramatic in management strategies A+D, B+E and C+E than A, B and C.

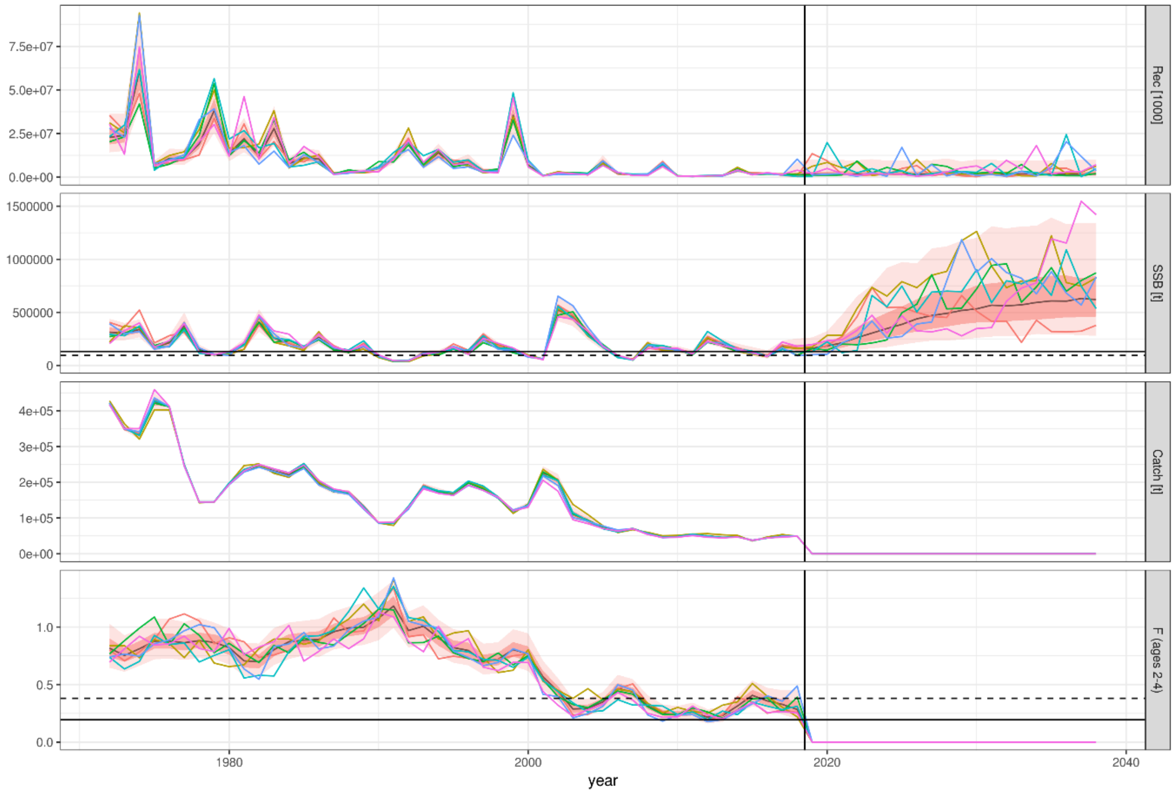


Figure 4.4.2.1. Haddock in Subarea 4, Division 6.a and Subdivision 20: Summary projections for F = 0. Top plot is recruitment (age 0), second plot SSB, third plot catch and bottom plot mean F (ages 2–4). The vertical black line separates the historical period from the projection period. The SSB plot includes B_{pa} = MSY $B_{trigger}$ (horizontal solid line) and B_{lim} (horizontal hashed line), while the mean F plot includes F_{MSY} (horizontal solid line) and F_{lim} (horizontal dashed line). The actual plots show medians (solid black line) with the darker shaded area indicating the 25th and 75th percentiles, and the light shaded area the 5th and 95th percentiles. The results for 5 individual replicates are shown in solid coloured lines.

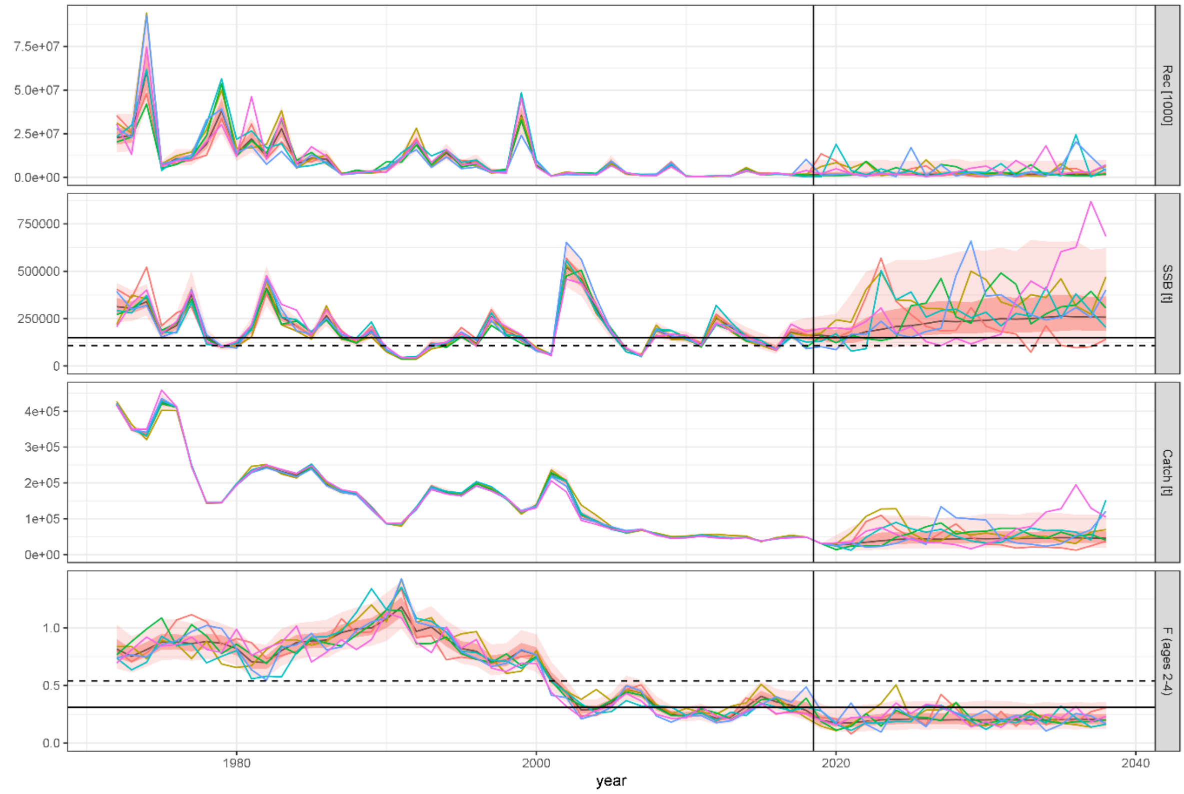


Figure 4.4.2.2. Haddock in Subarea 4, Division 6.a and Subdivision 20: Summary projections for <u>management strategy A*</u> (i.e. with F_{target} = F_{MSY} = 0.194 and $B_{trigger}$ = MSY $B_{trigger}$ = 132 000 t). See the caption to Figure 4.4.2.1 for further details.

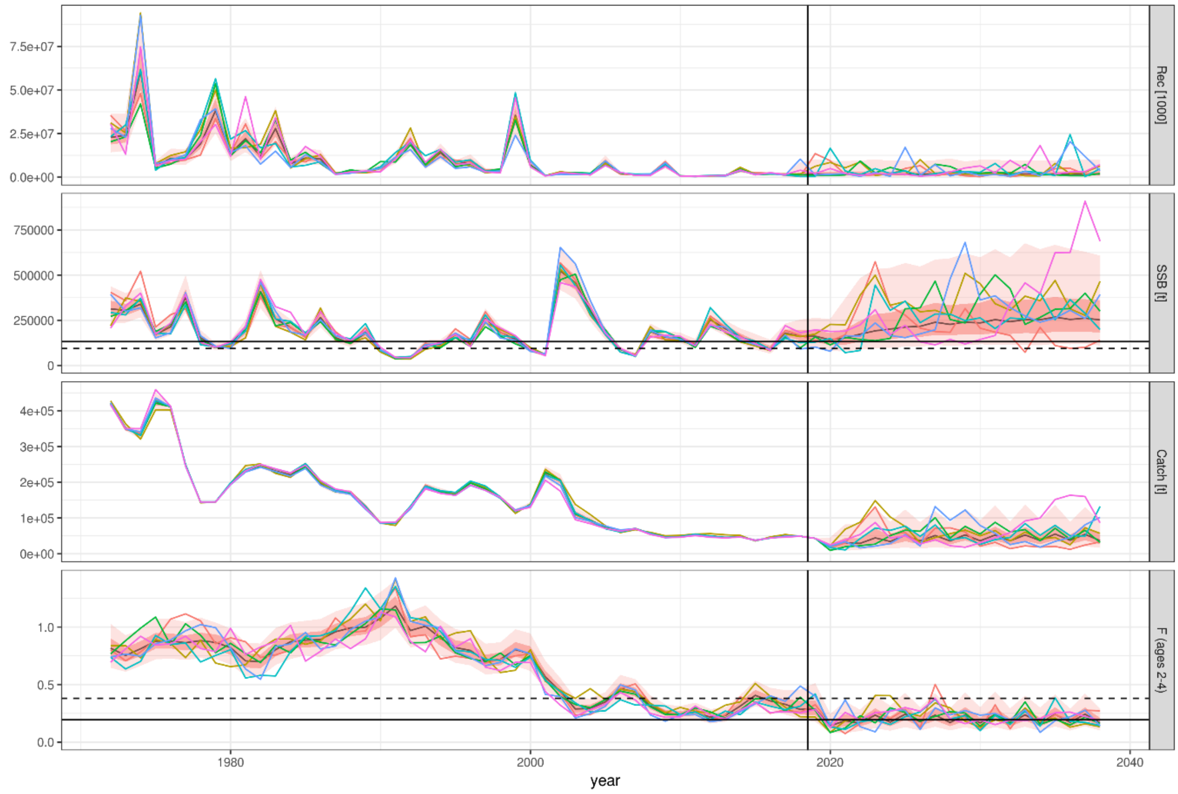


Figure 4.4.2.3. Haddock in Subarea 4, Division 6.a and Subdivision 20: Summary projections for management strategy A*+D (i.e. with F_{target} = F_{MSY} = 0.194 and $B_{trigger}$ = MSY $B_{trigger}$ = 132 000 t). See the caption to Figure 4.4.2.1 for further details.

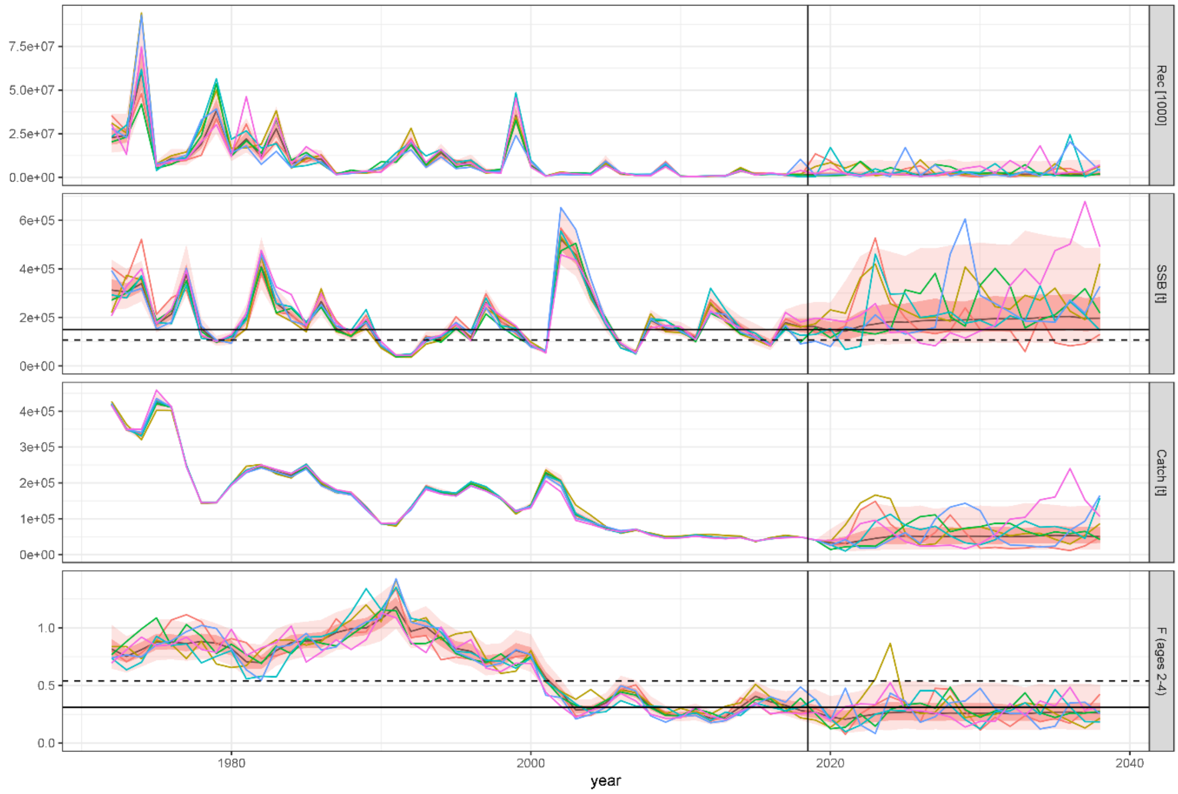


Figure 3.4.2.4. Haddock in Subarea 4, Division 6.a and Subdivision 20: Summary projections for "optimised" <u>management strategy A</u> (see Table 4.4.1.1). See the caption to Figure 4.4.2.1 for further details.

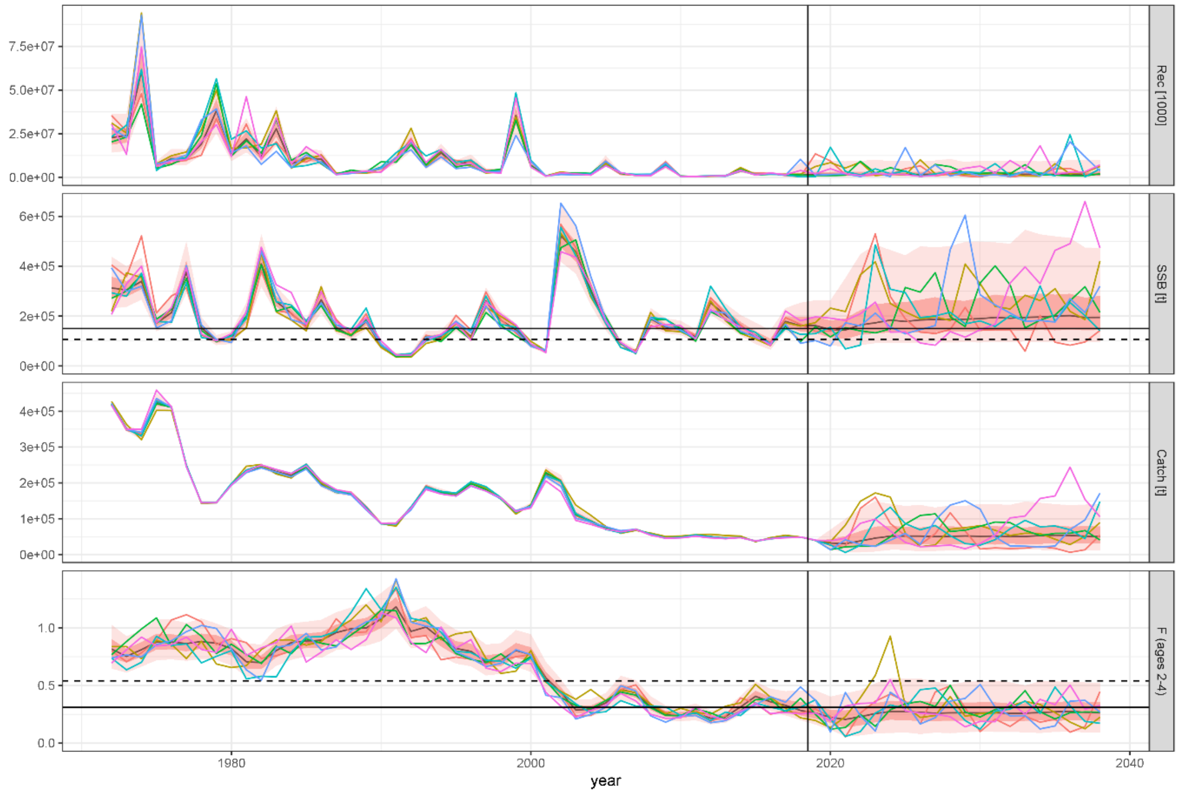


Figure 3.4.2.5. Haddock in Subarea 4, Division 6.a and Subdivision 20: Summary projections for “optimised” <u>management strategy B</u> (see Table 4.4.1.1). See the caption to Figure 4.4.2.1 for further details.

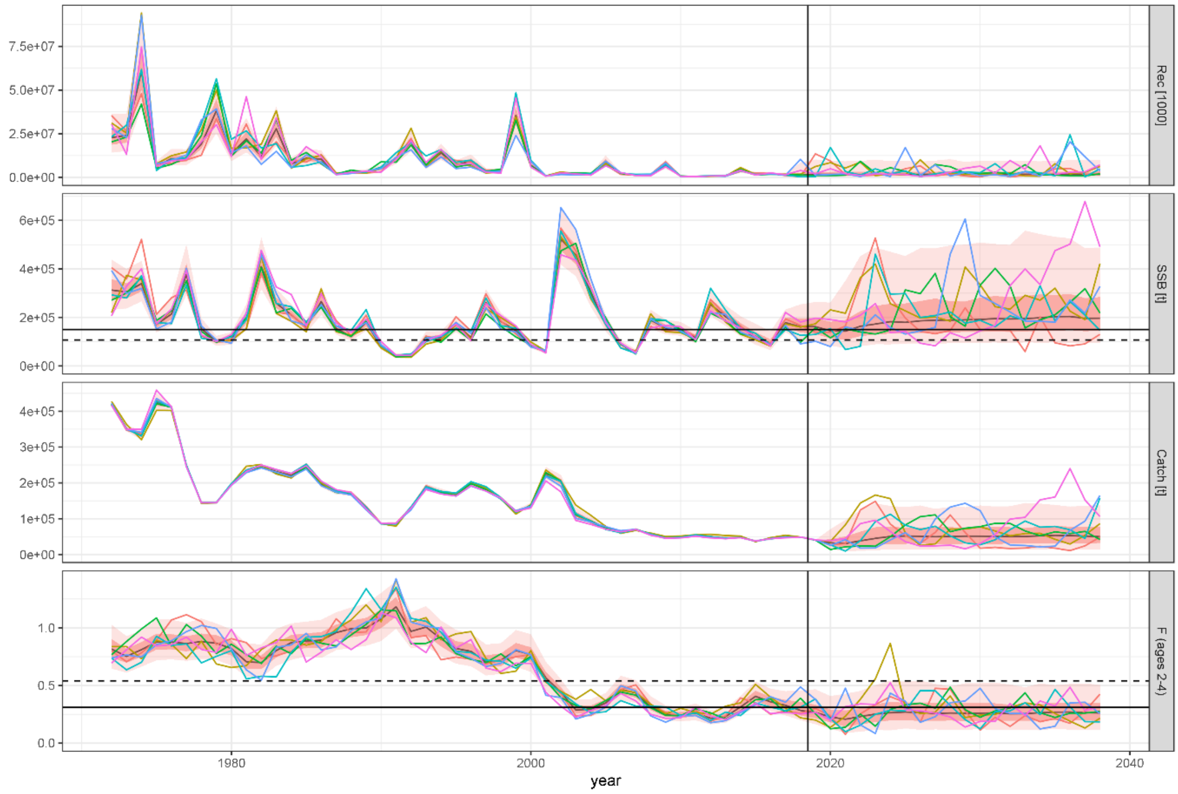


Figure 3.4.2.6. Haddock in Subarea 4, Division 6.a and Subdivision 20: Summary projections for "optimised" <u>management strategy C</u> (see Table 4.4.1.1). See the caption to Figure 4.4.2.1 for further details.

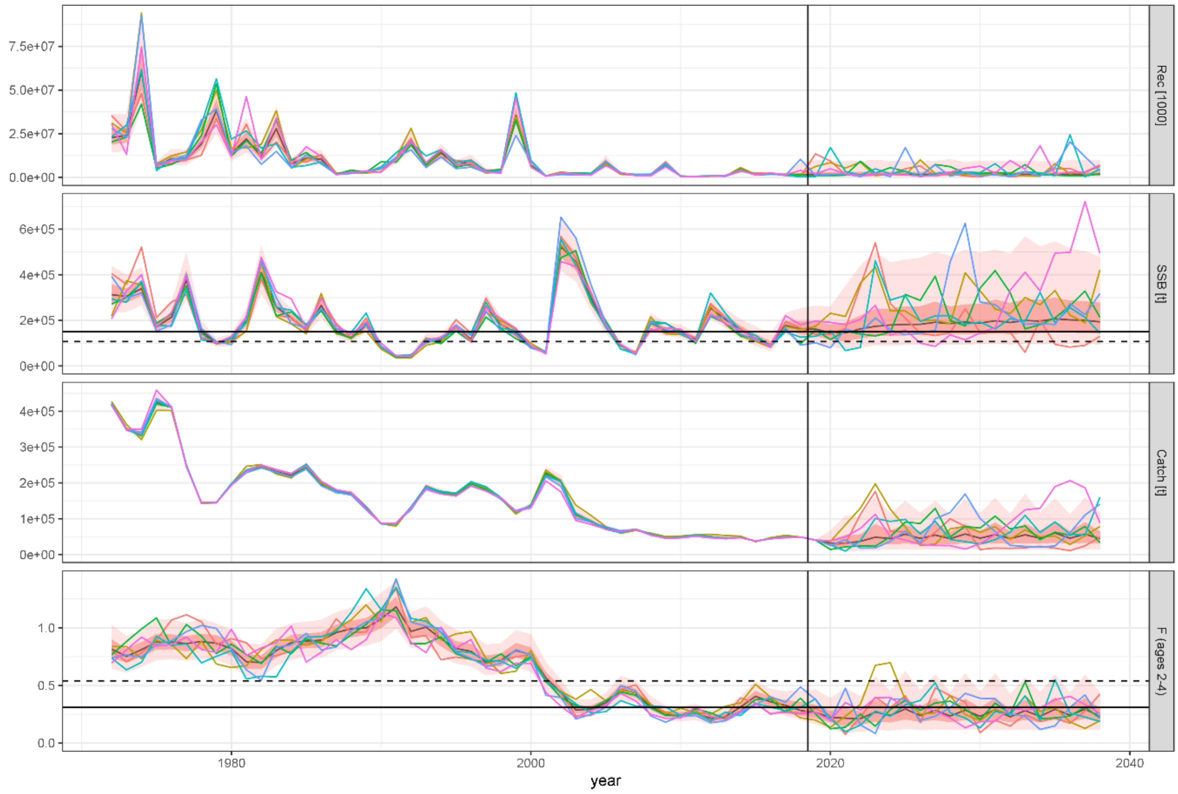


Figure 3.4.2.7. Haddock in Subarea 4, Division 6.a and Subdivision 20: Summary projections for "optimised" <u>management strategy A+D</u> (see Table 4.4.1.1). See the caption to Figure 4.4.2.1 for further details.

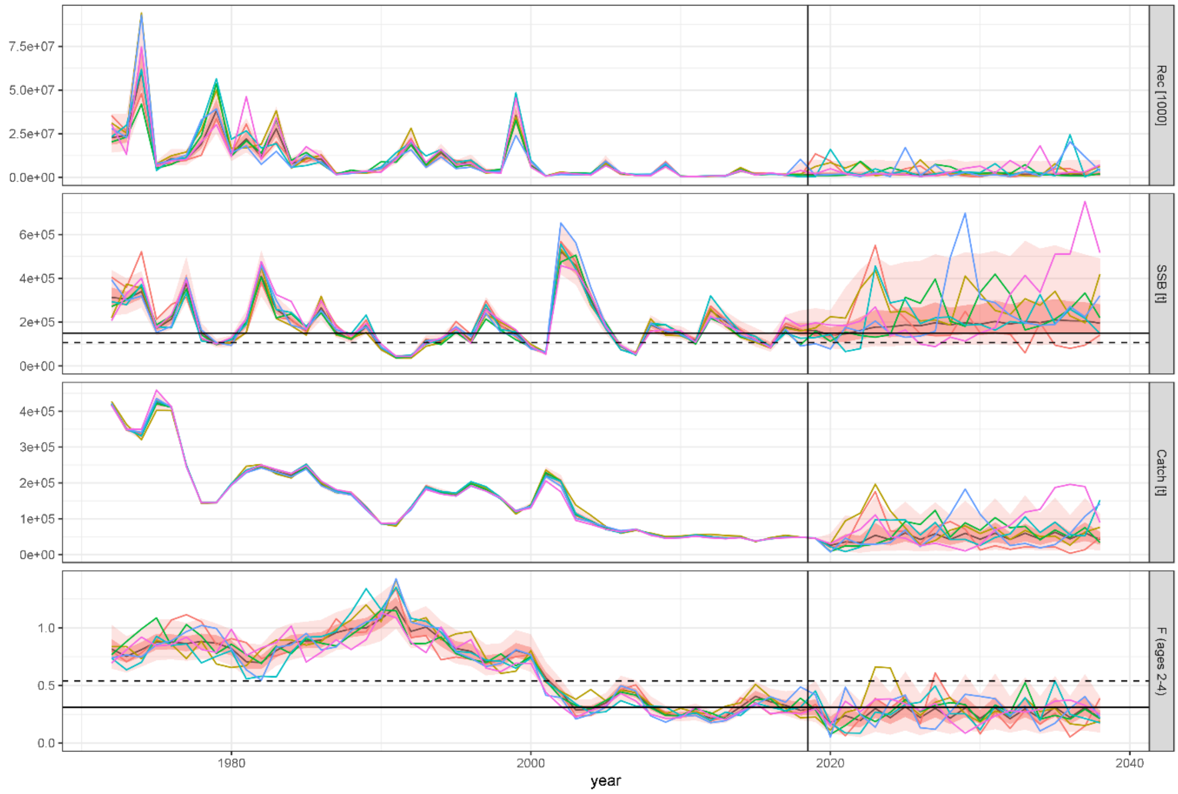


Figure 3.4.2.8. Haddock in Subarea 4, Division 6.a and Subdivision 20: Summary projections for "optimised" management strategy B+E (see Table 4.4.1.1). See the caption to Figure 4.4.2.1 for further details.

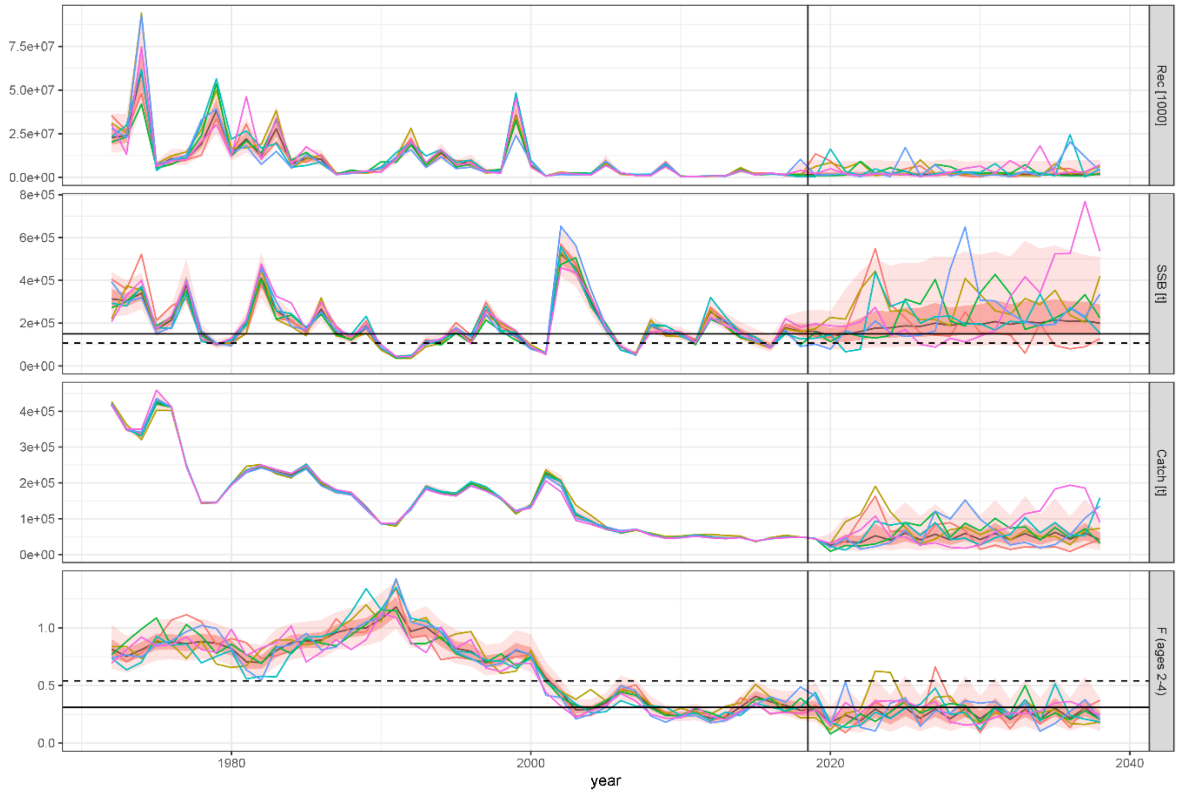


Figure 3.4.2.9. Haddock in Subarea 4, Division 6.a and Subdivision 20: Summary projections for "optimised" management strategy C+E (see Table 4.4.1.1). See the caption to Figure 4.4.2.1 for further details.

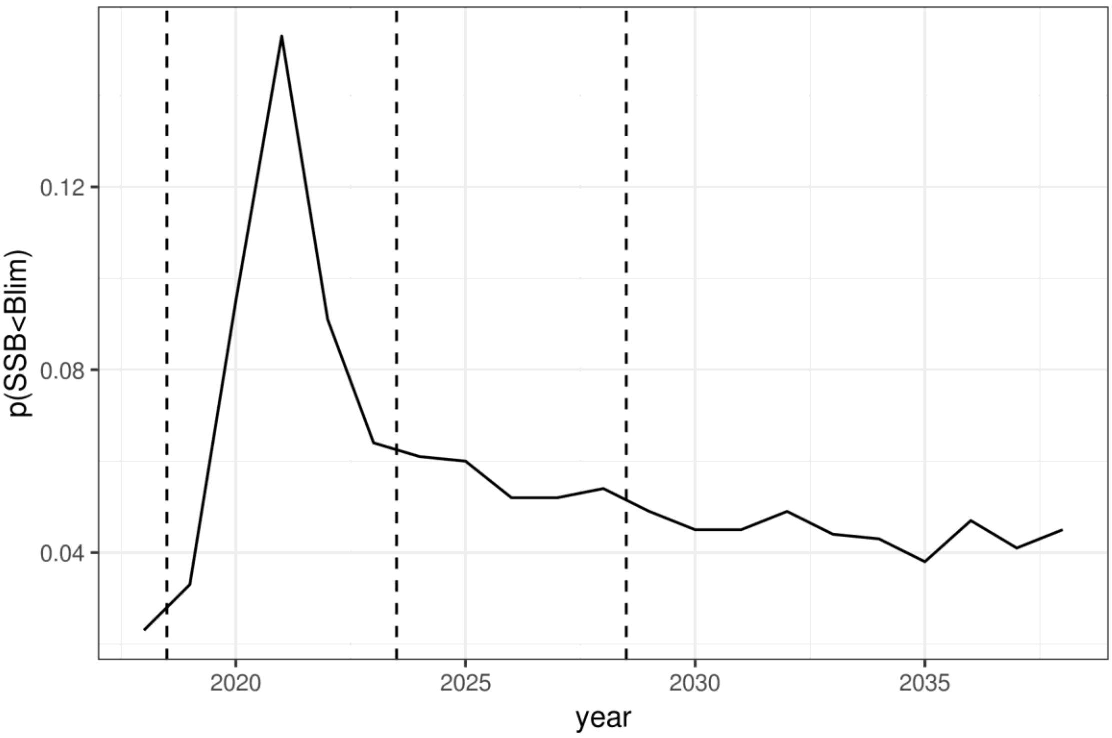


Figure 4.4.2.10. Haddock in Subarea 4, Division 6.a and Subdivision 20: Annual risk (P(SSB<Blim)) for "optimised" management strategy A. The horizontal hashed lines separate the short- medium- and long-term projection periods used for the performance statistics.

4.4.3 Comparison of management strategies for the baseline OM1

The performance of F = 0, a version of management strategy A that sets F_{target} = F_{MSY} = 0.194 and $B_{trigger}$ = MSY $B_{trigger}$ = 132 000 t (labelled A*), and the six "optimised" management strategies are compared in terms of catch, risk 1 and 3, inter-annual catch variability and SSB in the short (first five years), medium (years 6–10) and long (final 10 years) term in Figures 4.4.3.1–4.4.3.3. Two additional performance statistics were calculated: the proportion of replicates that recover past B_{pa} = MSY $B_{trigger}$ = 132 000 t within the 20-year simulation period and the number of years it takes for each replicate to recover above B_{pa} = MSY $B_{trigger}$. These results are presented for A* and the six "optimised" management strategies in Figure 4.4.3.4.

The long-term performance of the six "optimised" management strategies is summarised in Table 4.4.3.1 and Figure 4.4.3.3 is quite similar in terms of total catch and SSB with a range of approximately 2000 t and 9000 t respectively across the scenarios. The optimal combinations for each management strategy are similar, though in general, the values of F_{target} and $B_{trigger}$ for A+D, B+E and C+E (the scenarios with stability mechanisms) are lower than for management strategies A, B and C. All six management strategies lead to a long term SSB of approximately 200 000 t, which is roughly a third of the long-term SSB when the fishery is closed (F = 0).

Management strategy B has the highest F_{target} value and gives the highest long term catch, but correspondingly, has the lowest long term SSB. The lowest F_{target} and highest $B_{trigger}$ values are seen for management strategy C+E which results in the lowest catch of the 6 strategies. Management strategies A+D, B+E and C+E have slightly lower total catches, slightly higher interannual catch variability and slightly higher SSB values than their corresponding management strategies which do not include banking and borrowing and a TAC constraint (A, B and C).

The long-term performance of the six management strategies are similar to that of the A* strategy (F_{target} = F_{msy} and $B_{trigger}$ = MSY $B_{trigger}$) in terms of long-term median catch. However, the interannual variability in catch for the six optimised strategies is higher than A* with larger interquartile ranges and SSB is lower than A*. The A* strategy is found to be precautionary and has very low values for risk 1 and 3 compared to the 6 “optimised” management strategies in the long term (though these are all within the 5% threshold).

SSB increases in all the scenarios through each time period (short to medium to long term). The values of risk 1 and risk 3 exceed the 5% threshold in the short and medium term for all scenarios but are seen to fall to below 5% in the long term. The A* scenario is seen to be precautionary in the medium- and long-term. When F = 0, the risk is well below 5% throughout all time periods.

The recovery statistics show that the recovery potential in all the strategies is very high since the stock is currently well above its MSY $B_{trigger}$ (Figure 4.4.3.4).

Table 4.4.3.1. Haddock in Subarea 4, Division 6.a and Subdivision 20: performance statistics for F = 0 and the “optimised” six management strategies. Statistics are reported for three time periods, short (first five years), medium (years 6–10) and long (final 10 years) term. Other statistics reported include the interannual variability (iav) in the catch and TAC, the mean proportion of years across all replicates where the management strategy is operating “on the slope”, the number of replicates where the estimation model (SAM) failed to converge, the number of replicates where Fmax (Fmax = 2) was reached, the proportion of replicates that recover above B_{pa} = MSY $B_{trigger}$ and the number of years taken to recover above B_{pa} = MSY $B_{trigger}$ for the first time.

Performance statistic	F=0	A*	A	B	C	AD	BE	CE
Ftarget	0	0.194	0.28	0.29	0.28	0.28	0.27	0.26
Btrigger	-	132000	180000	190000	180000	180000	170000	160000
risk1 long term	0.000	0.016	0.045	0.044	0.045	0.045	0.042	0.044
risk1 short term	0.012	0.056	0.087	0.082	0.087	0.087	0.091	0.092
risk1 medium term	0.000	0.027	0.056	0.053	0.056	0.055	0.052	0.056
risk3 long term	0.000	0.019	0.049	0.048	0.049	0.050	0.049	0.050
risk3 short term	0.033	0.090	0.153	0.148	0.153	0.151	0.147	0.143
risk3 medium term	0.001	0.041	0.061	0.055	0.061	0.062	0.060	0.070
Iav catch long term	-	0.207	0.275	0.296	0.275	0.347	0.393	0.378
Iav catch short term	-	0.300	0.213	0.225	0.213	0.232	0.348	0.329
Iav catch medium term	-	0.221	0.289	0.310	0.289	0.342	0.400	0.374
Median catch long term	0	45296	51358	51574	51350	49628	49831	49398
Median catch short term	0	30699	39799	39181	39799	39715	42829	42961
Median catch medium term	0	43300	50486	50969	50486	47690	46946	46427
Median ssb long term	578988	252152	196587	194672	196587	196781	200267	203534
Median ssb short term	213913	167527	155855	156911	155855	156038	156338	156057
Median ssb medium term	427970	222095	185040	183986	185040	184419	185816	187096

Performance statistic	F=0	A*	A	B	C	AD	BE	CE
Median Fbar long term	0	0.203	0.262	0.265	0.262	0.256	0.256	0.251
Median Fbar short term	0	0.189	0.238	0.236	0.238	0.236	0.237	0.236
Median Fbar median term	0	0.205	0.263	0.268	0.263	0.254	0.248	0.243
Iav TAC long term	-	0.207	0.273	0.295	0.273	0.275	0.274	0.253
Iav TAC short term	-	0.225	0.294	0.316	0.294	0.296	0.307	0.278
Iav TAC medium term	-	0.221	0.289	0.310	0.289	0.291	0.295	0.274
Slope long term	-	0.11	0.26	0.26	0.26	0.26	0.26	0.25
Slope short term	-	0.15	0.24	0.24	0.24	0.24	0.24	0.24
Slope medium term	-	0.22	0.26	0.27	0.26	0.25	0.25	0.24
Convergence failure	-	0	0	0	0	0	0	0
Fmax reached	0	0	0	1	0	0	0	1
Recovery proportion	1	1	1	1	1	1	1	1
Recovery time	1	1	1	1	1	1	1	1

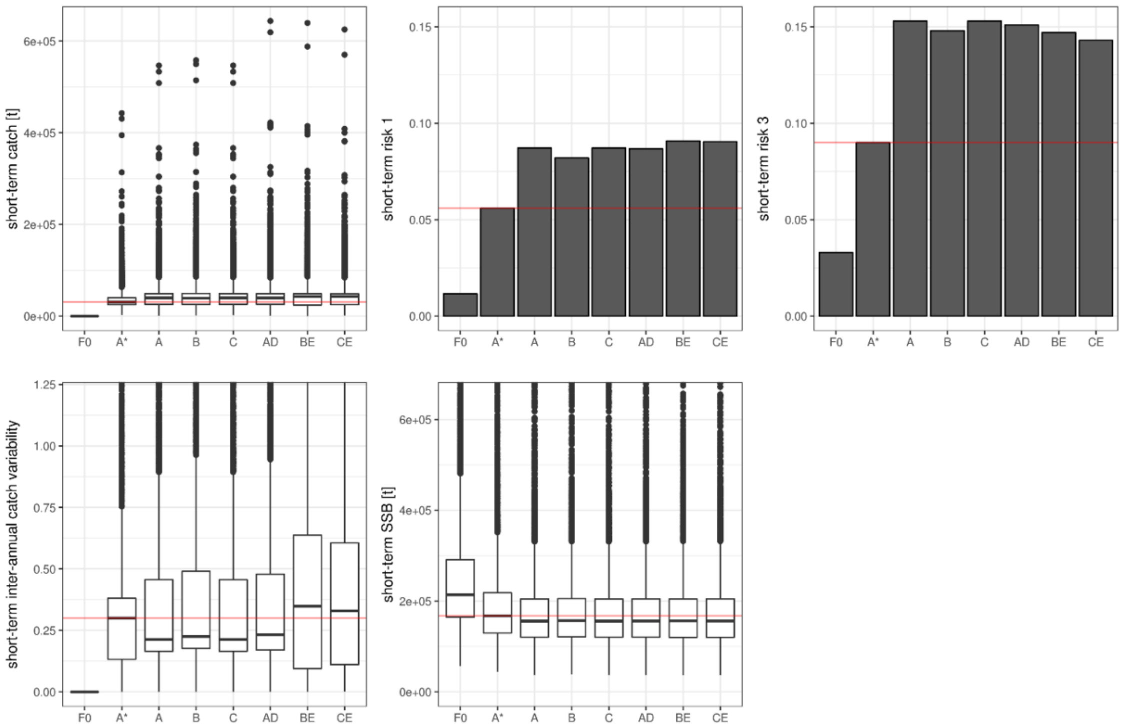


Figure 4.4.3.1. Haddock in Subarea 4, Division 6.a and Subdivision 20: Comparing the performance of management strategies in the short-term (first five years). Individual plots are as indicated by the label on the y-axis. Within each plot, the management strategies are F = 0, A* (i.e. management strategy A with $F_{target} = F_{MSY} = 0.194$ and $B_{trigger}$ = MSY $B_{trigger}$ = 132 000 t, and the six "optimised" management strategies (A, B, C, A+D, B+E and C+E). In the box and whisker plots, the heavy horizontal line within the box indicates the median, the edges of the box indicate the 25th and 75th percentiles, and the whiskers extend to the largest and smallest values within 1.5 times the inter-quartile range (IQR) from the edges, and the remaining points indicated as dots outside the whiskers are the outliers to 1.5*IQR from the edges. The red horizontal line corresponds to the median (box and whisker plots) or actual value (risk plots) for management strategy A* for comparison.

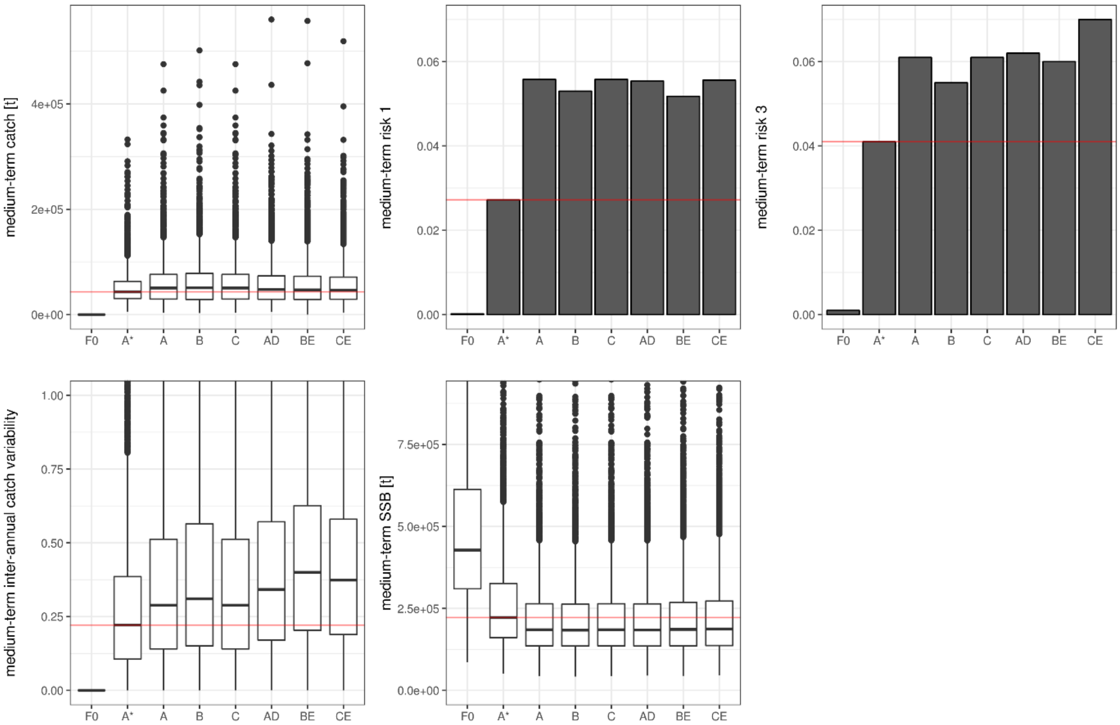


Figure 4.4.3.2. Haddock in Subarea 4, Division 6.a and Subdivision 20: Comparing the performance of management strategies in the medium-term (years 6–10). See Figure 4.4.3.1 for more details.

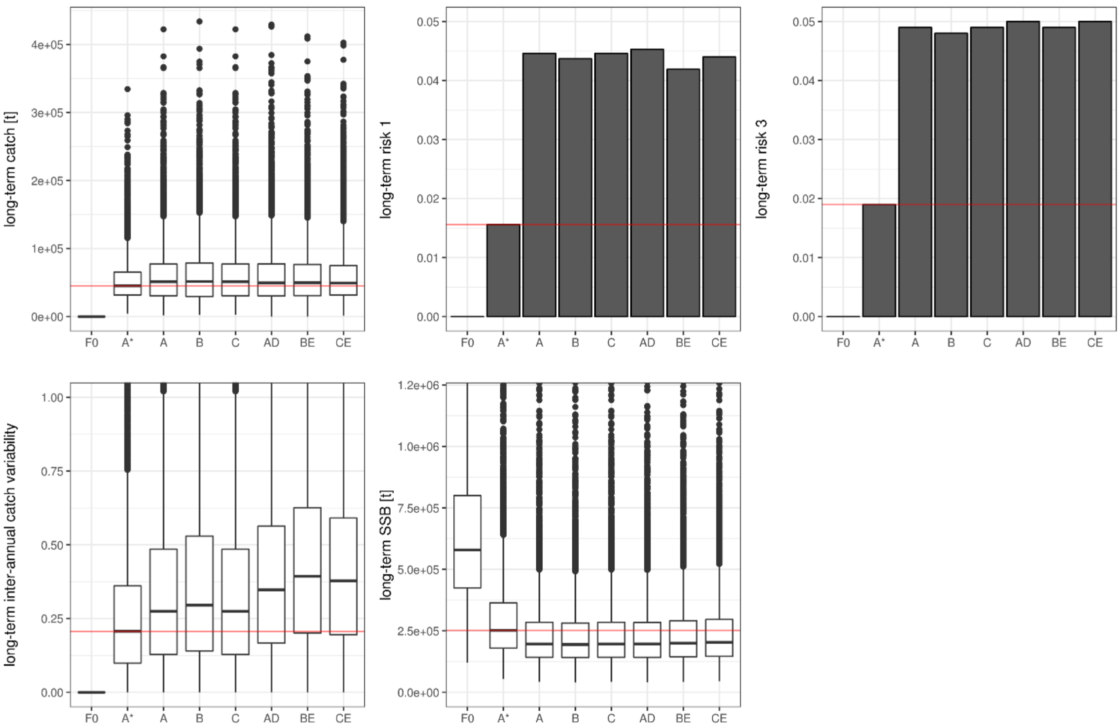


Figure 4.4.3.3. Haddock in Subarea 4, Division 6.a and Subdivision 20: Comparing the performance of management strategies in the long-term (final 10 years). See Figure 4.4.3.1 for more details.

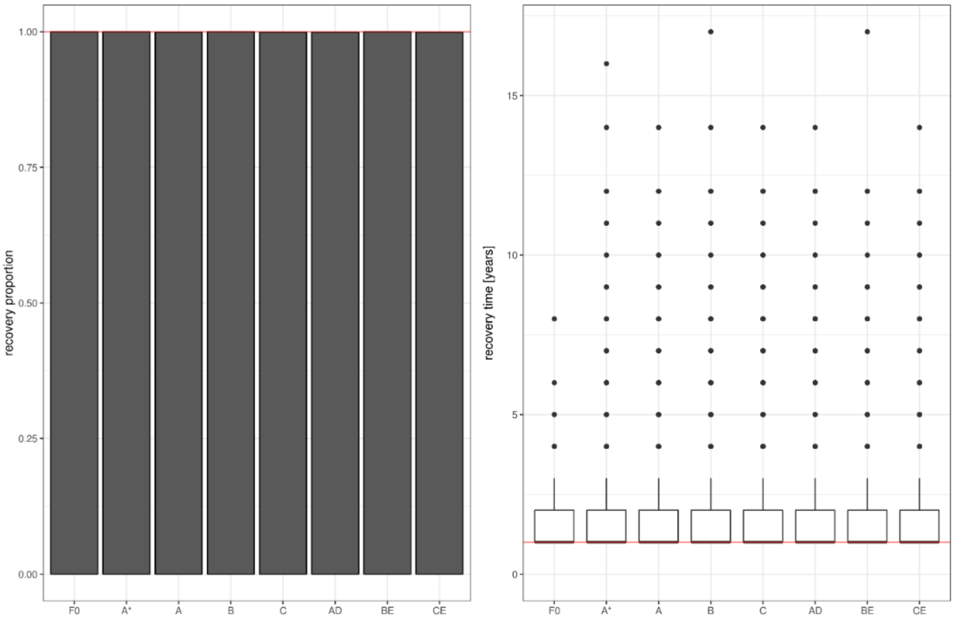


Figure 4.4.3.4. Haddock in Subarea 4, Division 6.a and Subdivision 20: recovery statistics for the various management strategies (as described in Figure 4.4.3.1). The left plot indicates the proportion of replicates that recover above B_{pa}=MSY $B_{trigger}$, while the right plot indicates the number of years taken to recover above B_{pa} =MSY $B_{trigger}$ for the first time, indicated as box and whisker plots (see Figure 4.4.3.1 for a description).

4.4.4 Sensitivity of management strategies for the baseline OM1

The sensitivity of performance statistics for the six "optimised" management strategies (A, B, C, A+D, B+E and C+E) to five fishing pressure scenarios (0.9*F_{target}, F_{target}, 1.1*F_{target}, $F_{MSY\ lower}$ = 0.167 and $F_{MSY\ upper}$ = 0.194) in the short (first five years), medium (years 6–10) and long (final 10 years) term are presented in Figures 4.4.4.1–4.4.4.3. Sensitivity of recovery statistics for the management strategies to the same fishing pressure scenarios are presented in Figure 4.4.4.4. For haddock, the sensitivity of the performance statistics for the management strategies A and A+D to two additional scenarios (1.5*$B_{trigger}$ and 2*$B_{trigger}$) are also presented.

The median total catches are similar across the 0.9*F_{target}, F_{target}, 1.1*F_{target} range in the short-, medium- and long-term. Correspondingly, interannual variation in the catch increases and SSB decreases with increasing F in the medium and long term. Both $F_{MSY\ lower}$ and $F_{MSY\ upper}$ have lower catches compared to the other scenarios because these values of F are much lower than the F_{target}.

The six "optimised" management strategies are found to be within the 5% risk threshold in the long term for all but 1 (1.1*F_{target}) of the sensitivity scenarios.

The scenarios that increase $B_{trigger}$ to 1.5 and 2*$B_{trigger}$ result in lower catches, lower risk, higher interannual variation in the catch and higher SSB in the long term. This is because the higher $B_{trigger}$ values mean the rules are operating "on the slope" and lead to more variation in the realised F.

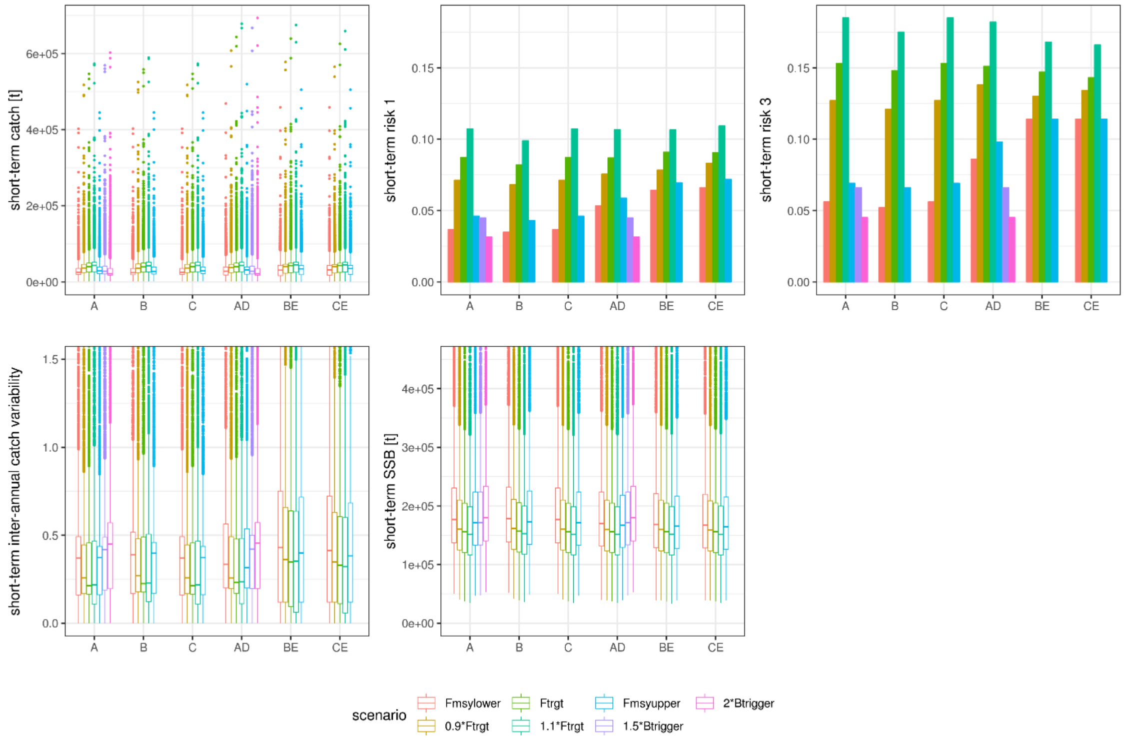


Figure 4.4.4.1. Haddock in Subarea 4, Division 6.a and Subdivision 20: Sensitivity of performance statistics for the "optimised" management strategies to changes in F in the short-term (first five years). Individual plots are as indicated by the label on the y-axis. In the box and whisker plots, the heavy horizontal line within the box indicates the median, the edges of the box indicate the 25th and 75th percentiles, and the whiskers extend to the largest and smallest values within 1.5 times the inter-quartile range (IQR) from the edges, and the remaining points indicated as dots outside the whiskers are the outliers to 1.5*IQR from the edges.

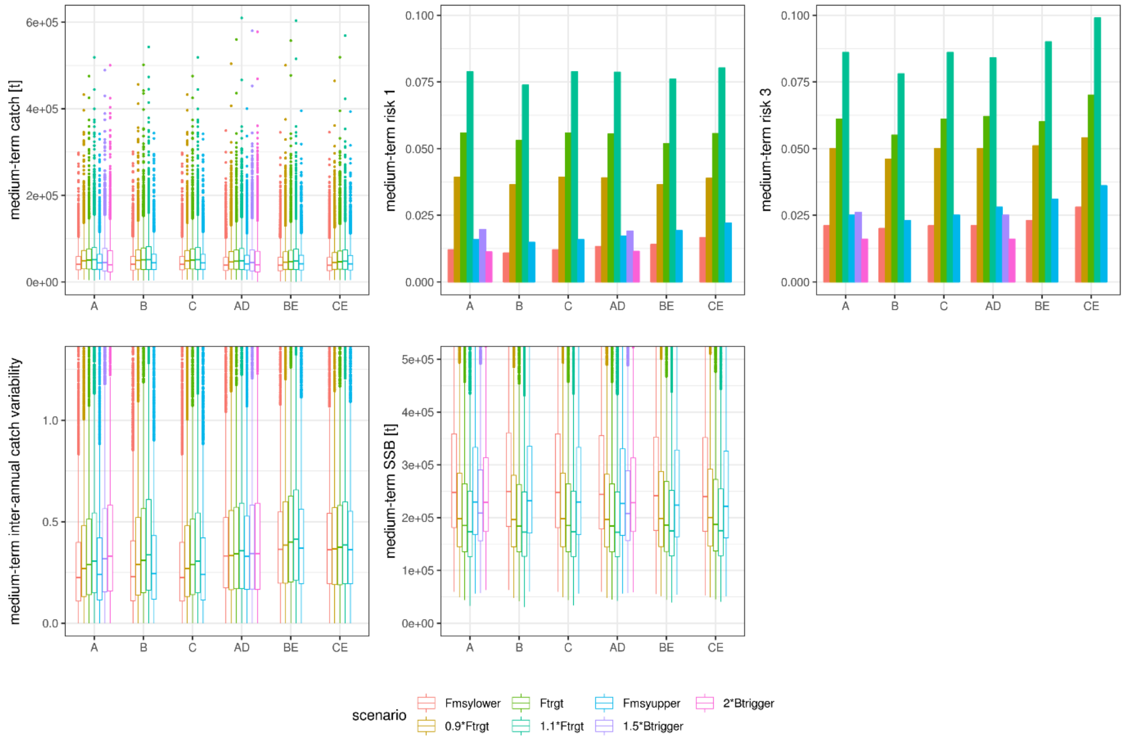


Figure 4.4.4.2. Haddock in Subarea 4, Division 6.a and Subdivision 20: Sensitivity of performance statistics for the "optimised" management strategies to changes in F in the medium-term (years 6–10). See Figure 3.4.4.1 for more details.

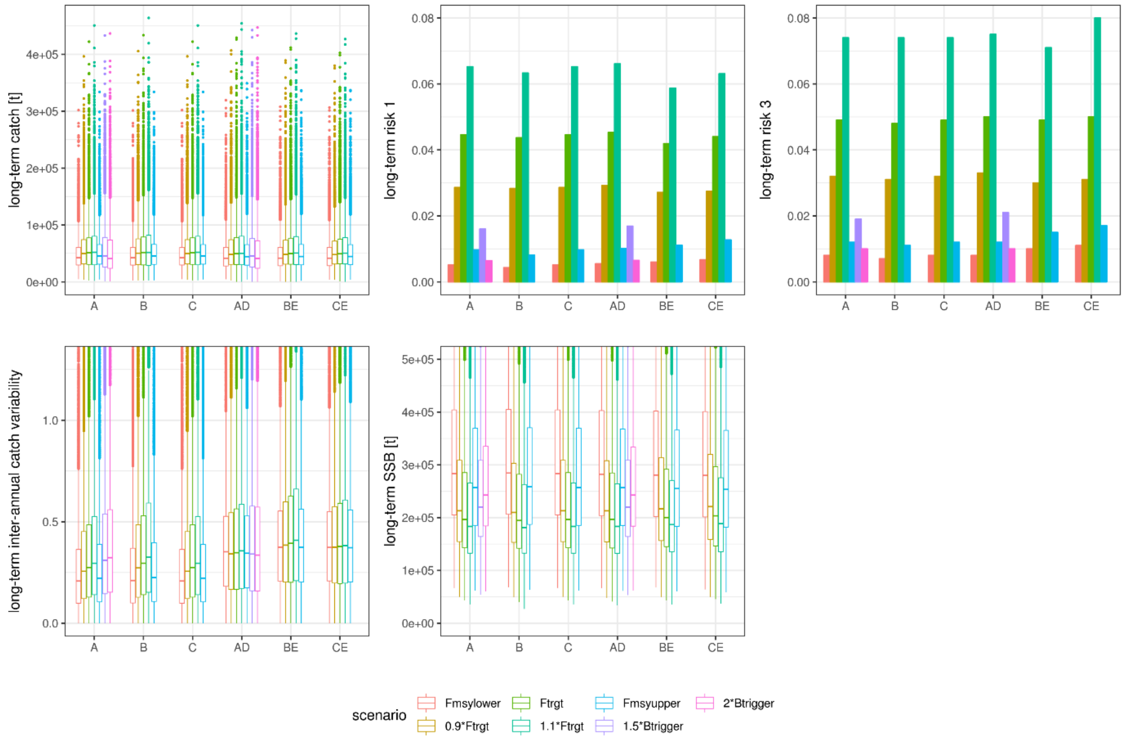


Figure 4.4.4.3. Haddock in Subarea 4, Division 6.a and Subdivision 20: Sensitivity of performance statistics for the "optimised" management strategies to changes in F in the long-term (final 10 years). See Figure 4.4.4.1 for more details.

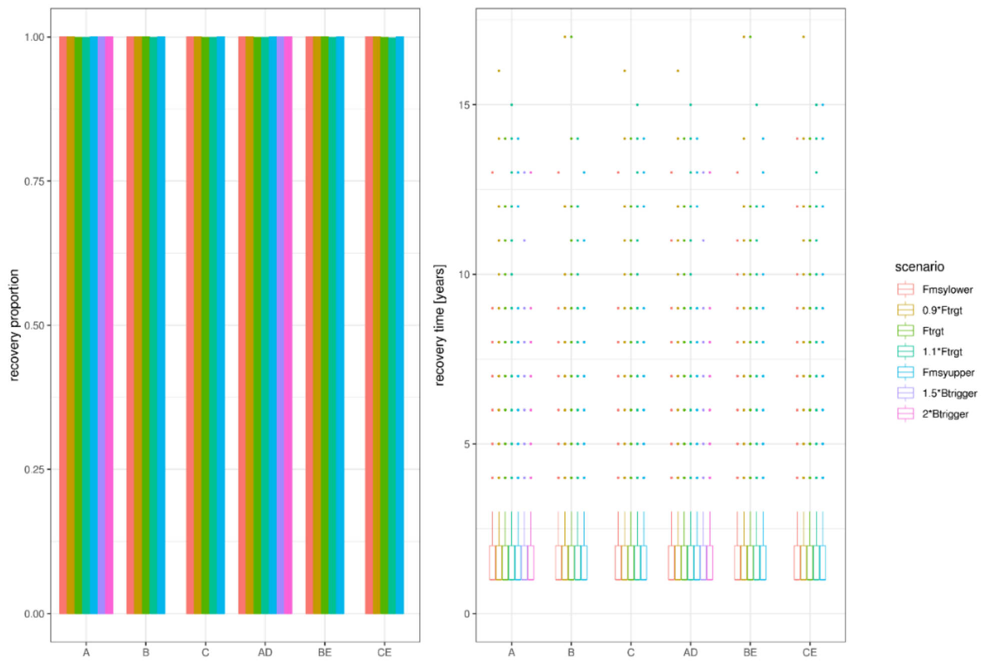


Figure 4.4.4.4. Haddock in Subarea 4, Division 6.a and Subdivision 20: Sensitivity of recovery statistics for the "optimised" management strategies (as described in Figure 4.4.4.1) to changes in F. The left plot indicates the proportion of replicates that recover above B_{pa} = MSY $B_{trigger}$, while the right plot indicates the number of years taken to recover above B_{pa} = MSY $B_{trigger}$ for the first time, indicated as box and whisker plots (see Figure 4.4.4.1 for a description).

4.4.5 Robustness of management strategies across alternative OMs

Robustness of the "optimised" management strategies (A, B, C, A+D, B+E and C+E) across alternative operating models (OMs 1–3, described in Sections 4.1–4.2) is evaluated in the short (first five years), medium (years 6–10) and long (final 10 years) term. Performance statistics for each "optimised" management strategy are compared across operating models and to performance statistics for F = 0 and a version of management strategy A that sets $F_{target} = F_{MSY} = 0.194$ and $B_{trigger}$ = MSY $B_{trigger}$ = 132 000 t (labelled A*) in Figures 4.4.5.1–4.4.5.3. Similar plots comparing recovery statistics for the various management strategies across alternate operating models are presented in Figure 4.4.5.4.

OM2 uses an operating model conditioned on a different assessment model (TSA). Compared to the baseline OM (OM1), this alternative OM results in higher catches, interannual variation in catch and SSB. Risk 1 and risk3 were both lower for OM2, most probably reflecting the fact that the management procedure (SAM) thinks there are less fish than there are in the OM (TSA) since there is a bias in the estimates of F and SSB from the management procedure compared to the underlying "truth" of the operating model (see Figure 4.4.5.5). This bias between the OM and MP means that the management decisions taken will be more precautionary than if this bias did not exist (as in OM1). This implies the converse is true, i.e. if the OM was SAM and TSA was the management procedure (as currently used by the WGNSSK), then a more precautionary management strategy would be needed to counter the bias. Additionally, for at least 1 replicate in each scenario run, the stock assessment fit in the management procedure failed to converge for this alternative OM (in one case 8 replicates failed to converge). These replicates were removed before any further analysis. The reason for the non-convergence of the stock assessment fit is thought to be related to the initial parameters used but would need further investigation.

OM3 is conditioned on the results from a SAM stock assessment fit but fixes the regularity of "spikes" in recruitment. Compared to the baseline OM (OM1), this alternative OM results in higher catches and higher SSB across the short, medium and long term and lower risk in the short and medium term. The interannual variation in catch for this OM is mostly lower or has similar values compared to the baseline (OM1). Risk 3 in the medium term has similar values for both OMs. The fixed regularity of spikes in recruitment prevents long periods of poor recruitment, which increase the risk of SSB falling below B_{lim}.

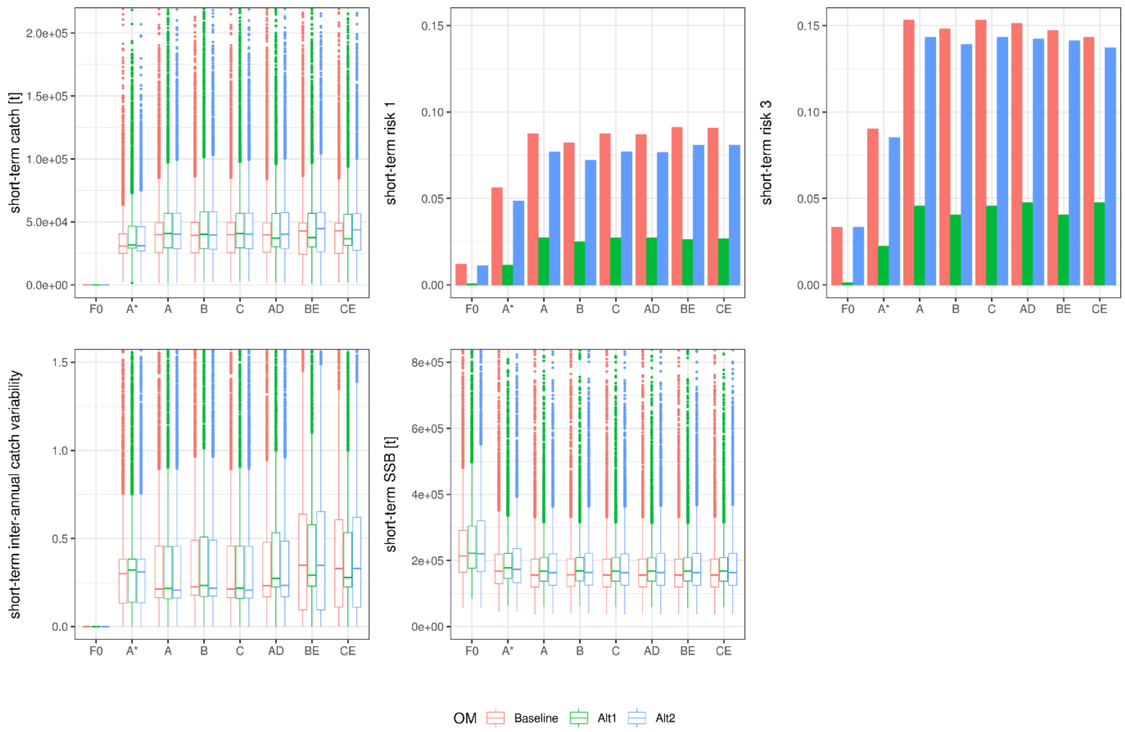


Figure 4.4.5.1. Haddock in Subarea 4, Division 6.a and Subdivision 20: Performance statistics for the various management strategies with alternate operating models in the short-term (first five years). Individual plots are as indicated by the label on the y-axis. Within each plot, the management strategies are F0 (i.e. F = 0), A* (i.e. management strategy A with F_{target} = F_{MSY} = 0.194 and $B_{trigger}$ = MSY $B_{trigger}$ = 132 000 t and the six "optimised" management strategies (A, B, C, A+D, B+E and C+E). The operating models are OM1 (Baseline), OM2 (Alt1) and OM3 (Alt2) and are described in sections 4.1–4.2. In the box and whisker plots, the heavy horizontal line within the box indicates the median, the edges of the box indicate the 25th and 75th percentiles, and the whiskers extend to the largest and smallest values within 1.5 times the inter-quartile range (IQR) from the edges, and the remaining points indicated as dots outside the whiskers are the outliers to 1.5*IQR from the edges.

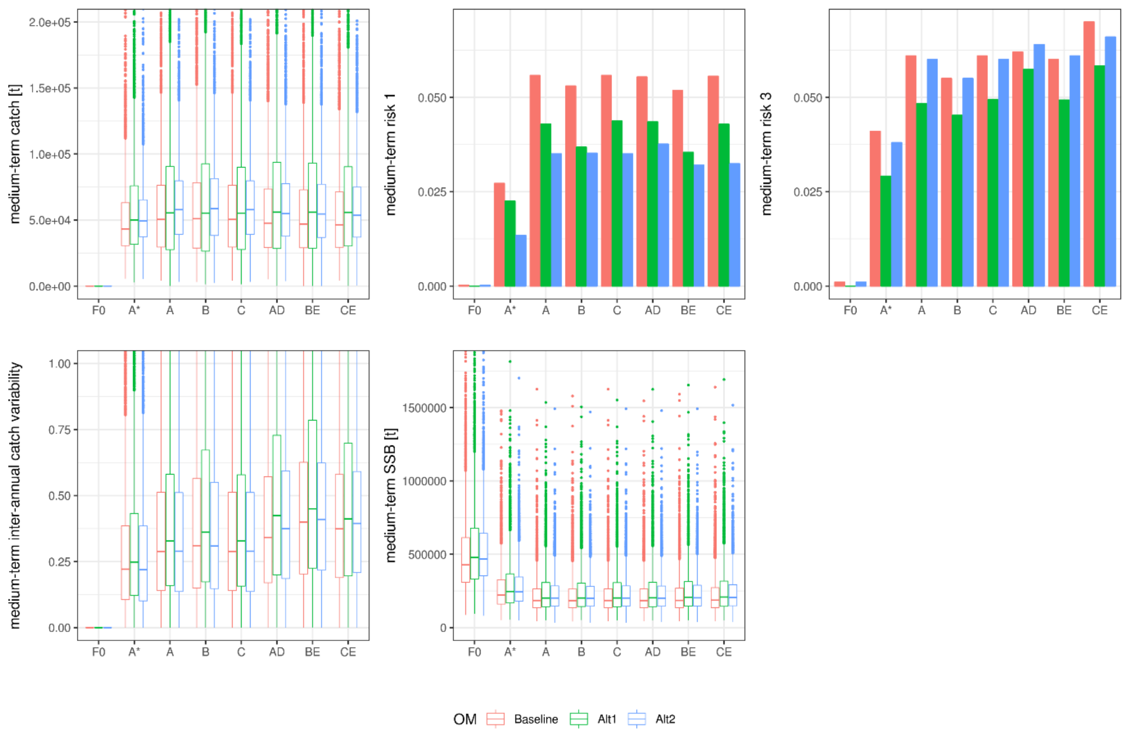


Figure 4.4.5.2. Haddock in Subarea 4, Division 6.a and Subdivision 20: Performance statistics for the various management strategies with alternate operating models in the medium-term (years 6–10). See Figure 4.4.5.1 for more details.

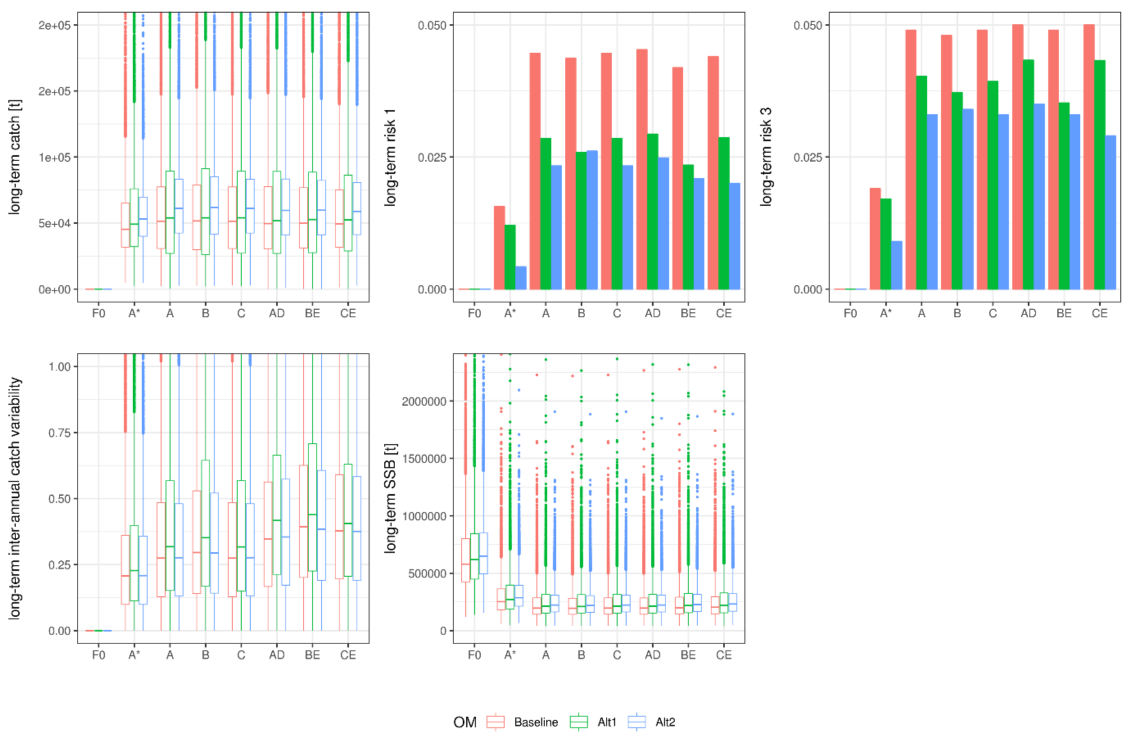


Figure 4.4.5.3. Haddock in Subarea 4, Division 6.a and Subdivision 20: Performance statistics for the various management strategies with alternate operating models in the long-term (final 10 years). See Figure 4.4.5.1 for more details.

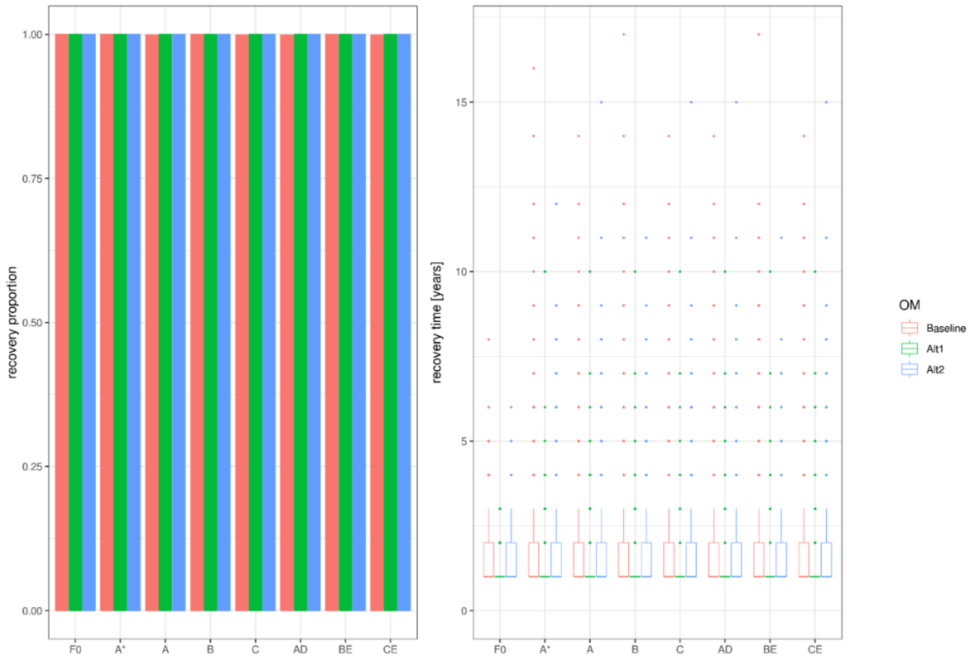


Figure 4.4.5.4. Haddock in Subarea 4, Division 6.a and Subdivision 20: Recovery statistics for the various management strategies (as described in Figure 4.4.5.1) with alternate operating models (see Figure 4.4.5.1 for definitions). The left plot indicates the proportion of replicates that recover above B_{pa} = MSY $B_{trigger}$, while the right plot indicates the number of years taken to recover above B_{pa} = MSY $B_{trigger}$ for the first time, indicated as box and whisker plots (see Figure 4.4.5.1 for a description).

Figure 4.4.5.5 plots the discrepancy between the management procedure and the underlying "truth" for each alternate operating model under "optimised" management strategy A. Because the estimation model component of the management procedure revises historical estimates of stock numbers, fishing mortality and any derived metrics with each new estimation, only the final year of the management procedure is plotted in each time step. The rise in F near the beginning of the projection period results from the slow response of the management procedure to the decline in F under "optimised" management strategy A.

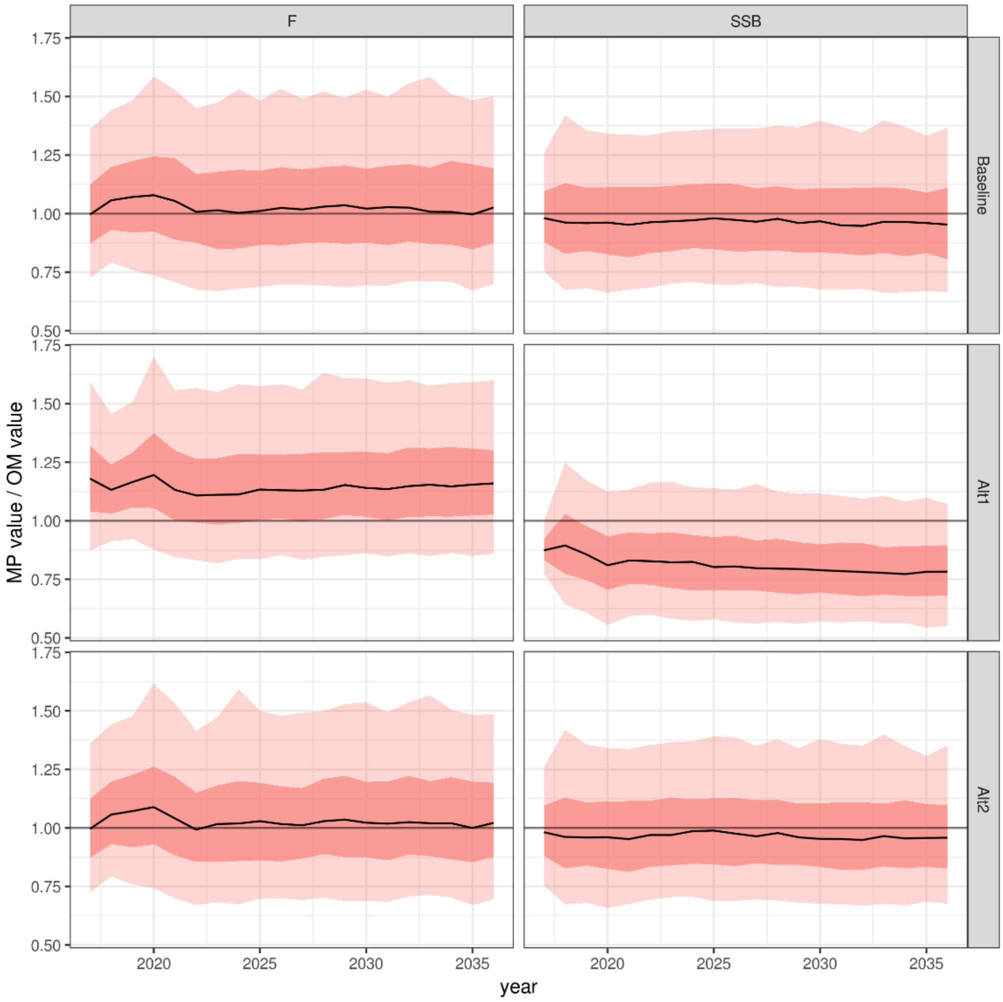


Figure 4.4.5.5. Haddock in Subarea 4, Division 6.a and Subdivision 20: Discrepancy in estimates of F and SSB from the management procedure compared to the underlying "truth" for each alternative operating model (see Figure 4.4.5.1 for definitions). Values > 1 indicate an overestimation by the management procedure while values < 1 indicate an underestimation.

4.5 Conclusions

"Optimised" combinations without stability

- The performance of management strategies A and C are very similar because SSB does not drop low enough in the majority of replicates to result in a difference. $B_{trigger}$ = 180 000 t and F_{target} = 0.28 in both cases.
- Management strategy B results in a slightly higher median long-term catch and lower SSB with higher interannual variability in the catch. $B_{trigger}$ = 190 000 t and F_{target} = 0.29.
- The short-term risk 3 is well above the 5% threshold for A, B and C. The medium-term risk 3 is just over the 5% threshold for all three management strategies.
- In all three cases, the median long-term SSB is above the $B_{trigger}$ value, indicating the rules are mostly operating "on the plateau". The high interannual variation in catch is driven by the sporadic nature of haddock recruitment.

"Optimised" combinations with stability

- The effect of including stability mechanisms is a reduction in the median long-term catch, an increase in the long-term SSB and an increase in the interannual variation in catch; the latter is a result of the extreme banking and borrowing implementation used.
- F_{target} and $B_{trigger}$ are reduced in 2 of the 3 management strategies with stability mechanisms (B+E and C+E). This is likely due to the exclusion of the stability mechanisms being used in A+D when SSB is less than $B_{trigger}$.
- The management strategy C+E results in the highest long-term SSB, though management strategy B still gives the overall highest long-term catch.
- Risk 3 is over the 5% threshold for all 3 management strategies in the short- and medium-term.

Compared to MSY advice rule approach

- The MSY approach advice rule gives lower long-term catch and higher SSB compared to the six management strategies and has a lower risk and interannual variation in catch.
- The MSY approach advice rule is precautionary in the medium and long term.
- The recovery time to above MSY $B_{trigger}$ is 1 year and the recovery proportion is 100% for all management strategies.

Sensitivity for "Optimised" Combinations

- Short-, medium- and long-term catches are similar across the F range from 0.9–1.1*F_{target}. $F_{MSY\text{-}lower}$ and $F_{MSY\text{-}upper}$ both have consistently lower catches.
- The long-term risk is above 5% for 1.1*F_{target} for all management strategies. Both $F_{MSY\text{-}lower}$ and $F_{MSY\text{-}upper}$ are found to be precautionary.
- The interannual variation in catch increases and SSB decreases with higher F in the long term.
- Increasing $B_{trigger}$ to 1.5 and 2*$B_{trigger}$ results in lower catches, lower risk, higher interannual variation in catch and higher SSB. This is because the higher $B_{trigger}$ values mean the rules are operating "on the slope" and lead to more variation in the realised F.

Robustness tests against alternative operating models

- The alternative operating model OM2 results in higher catches, interannual variation in catch and SSB and lower risk 3 in most cases across the short, medium and long term. The lower risk compared to the baseline OM (OM1) most probably reflects the bias between the estimates of F and SSB in the management procedure compared to the underlying "truth" in the OM. In this case, the MP (SAM) estimates less fish than there are in the OM (TSA). A bias in the opposite direction is likely to exist if we had tested OM=SAM and MP=TSA (currently WGNSSK uses TSA), but it was not possible to test this scenario (see Section 4.3); since it is plausible that such a bias exists, management strategies may need to be more precautionary than those optimised under the baseline OM1 to counter it.
- The alternative OM3 results in higher catches, higher SSB, lower interannual variation in catch and lower risk in most cases across the short, medium and long term. The

fixed regularity of spikes in recruitment prevents long periods of poor recruitment; such periods which would increase the risk of SSB falling below B_{lim}.

- These results indicate that good recruitment events at regular intervals reduce the risk of SSB falling below B_{lim}. However, if recruitment falls below the level tested here (i.e. the downwards trends in the size of recruitment spikes continues) then more precautionary HCRs may be needed.

Computational considerations

- The simulations required for this MSE were computationally very expensive and it was not possible to run the full grid for all management strategies. Computing facilities available in-house were used together with external resources.
- The maximum number of convergence failures seen was 8 replicates, but most runs experienced 0 convergence failures. At least 1 replicate in all simulation runs using OM2 had a convergence failure during the stock assessment fit. The choice of initial parameters is thought to be the cause. Convergence failures were almost exclusively an issue with OM2.
- Care needs to be taken when using a different assessment model within the MSE to that which is used for conditioning the OM to ensure that any bias introduced is plausible.

5 Whiting (*Merlangius merlangus*) in Subarea 4 and Division 7.d (North Sea and eastern English Channel)

5.1 Baseline operating model (OM1)

5.1.1 Model and settings

A management strategy evaluation (MSE) was conducted in FLR (a4a MSE framework) with code in R developed for WKNSMSE 2018. Simulations were conditioned based on the WGNSSK 2018 assessment data (ICES 2018a). The current stock assessment for whiting in Subarea 4 and Division 7d is classified as an update assessment. The assessment model is SAM fitted to combined catches (landings, discards, industrial bycatch). The most recent benchmark took place in WKNSEA 2018 (ICES, 2018c). The age range includes individuals aged 0 to 8+. The input data includes survey indices (Q1, Q3), catch data, stock weights at age, smoothed maturity estimates (ICES, 2018a), smoothed natural mortality estimates (WGSAM, 2017 key run; ICES, 2018b), and survey indices from NS-IBTS Q1 and Q3 (Table 5.1.1.1). The operating model was conditioned on the historical data from the SAM assessment result from spring 2018 (ICES 2018a). The baseline operating model was developed guided by the current SAM assessment model, to represent estimated autocorrelation in recruitment, assumed process and observation error structure, as well as assumptions made in the EqSim to determine reference points (ICES 2018c). The projection period covered 20 years with 1000 replicates.

Table 5.1.1.1 Whiting in Subarea 4 and Division 7.d. Assessment settings used in the current stock assessment settings WGNSSK 2018 (ICES 2018a).

Assessment setting (WGNSSK)	
First tuning year	1983
Last data year	2018
Ages	0-8+
Plus group	8+
Catch at age	1978-2017
Tuning indices	IBTS Q1 1983-2018, ages 1-5
	IBTS Q3 1991-2017, ages 0-5
Assessment model	SAM

The EqSim analysis was conducted for North Sea whiting during the benchmark in 2018 (ICES 2018c). Smoothed maturity and natural mortality, and observed weights at age, were used, including the recent 10 years of biological data and recent 3 years for selectivity. The recruitment time series was included since 1983, and the underlying recruitment model was assumed to follow a segmented regression. Due to the lack of a clear spawning stock-recruitment relationship, it was assumed that $B_{lim}=B_{loss}$. Recruitment residuals were assumed to be autocorrelated with lag 1. SSB is estimated at the beginning of the year. Current reference points and MSY ranges are listed in Table 5.1.1.2 and Table 5.1.1.3.

Table 5.1.1.2 Whiting in Subarea 4 and Division 7.d. Reference points derived at the benchmark 2018 using EqSim (ICES 2018c).

	MSY $B_{trigger}$	B_{pa}	B_{lim}	F_{pa}	F_{lim}	$F_{P.05}$	$F_{MSY\_unconstr}$	F_{MSY}
value	166708	166708	119970	0.33	0.458	0.172	0.392	0.172

Table 5.1.1.3 Whiting in Subarea 4 and Division 7.d. MSY ranges.

Reference point	Value	Technical basis (EqSim)
$F_{MSY-lower}$	0.158	$F_{P.05-lower}$
F_{MSY}	0.172	$F_{P.05}$
$F_{MSY-upper}$	0.172	$F_{P.05}$

SAM, a state-based assessment model, is described in detail by Nielsen and Berg (2014). It connects observed (log-transformed survey, catches) to unobserved states (log-transformed stock size, fishing mortality). The underlying process in the model is considered as the unobserved random variables.

Observed state process:

Logarithms of total catches were assumed to be independently distributed with observation error variance being coupled for all ages except age 0 (recruits). The logarithms of survey indices are estimated assuming observation error with correlation between age classes of order 1. Correlation parameters were coupled for all age pairs except 1-2 in IBTS Q1, and for Q3 parameters were coupled for 0-1 and 1-2 and all other pairs were coupled separately. A common observation variance was assumed for all ages, for Q1 and Q3 separately. The survey catchabilities were coupled only for the oldest two age groups in each survey separately (age 4 and 5).

Unobserved state process:

SAM allows for uncertainty in the observed states and produces estimates of the unobserved variables without the need to specify variances directly. Instead the distribution of process error can be defined. The prediction noise is assumed to be Gaussian with zero mean and three variance parameters (recruitment, other age groups, fishing mortality). The component of process error relating to stock size at age was assumed to be uncorrelated. Process variance of stock size was coupled for all ages except for age 0 (recruitment). A correlation structure for prediction noise in fishing mortalities at age was specified. The model allowed for time-varying selectivity which determines fishing mortality at age. Fishing mortality states were coupled only for two oldest age groups, age 7 and 8. Process variance for fishing mortality was coupled across all age groups.

The stock recruitment relationship was modelled as a plain random walk. The current stock assessment results are illustrated in Figure 5.1.1.1. Diagnostic including retrospectives, fits and residuals are shown in Figure 5.1.1.2-.7.

These setting of the SAM assessment were used in the MSE. The SAM variance-covariance matrix representing variances and correlation structures were used create uncertainty in the historical period and the projection period.

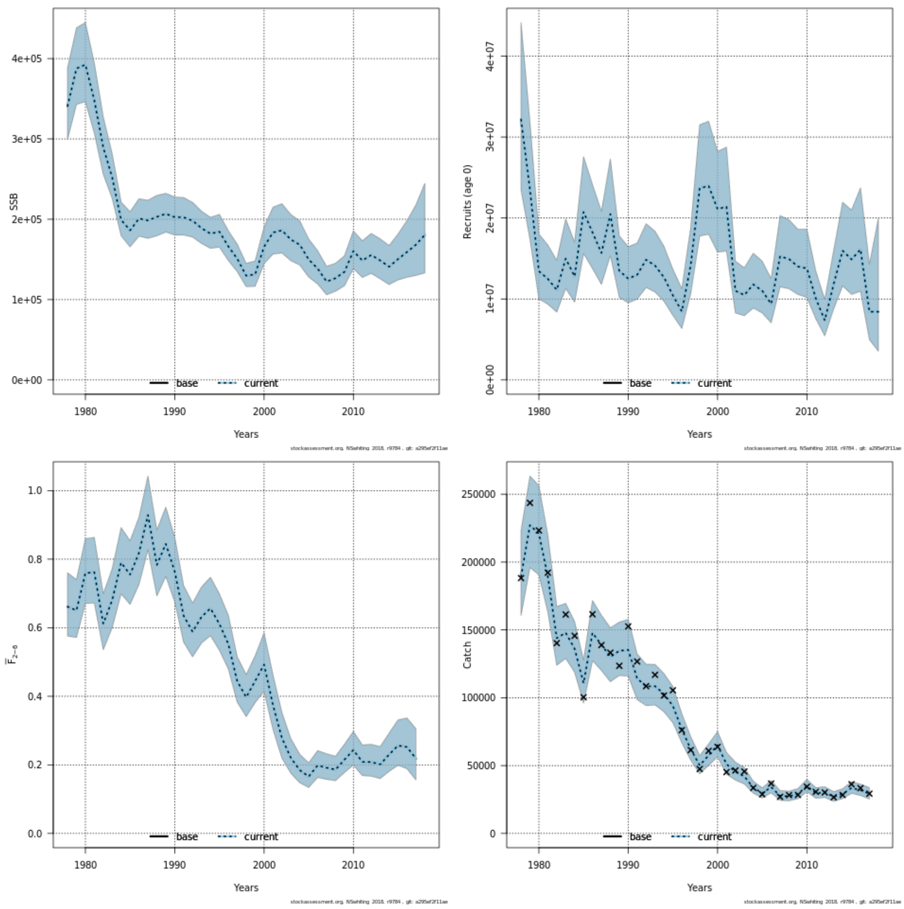


Figure 5.1.1.1 Whiting in Subarea 4 and Division 7.d. SAM assessment fit WGNSSK (ICES 2018a). SAM estimates and 95% confidence intervals of spawning stock biomass (SSB), recruitment (age 0), mean fishing mortality for ages 2–6 and catch.

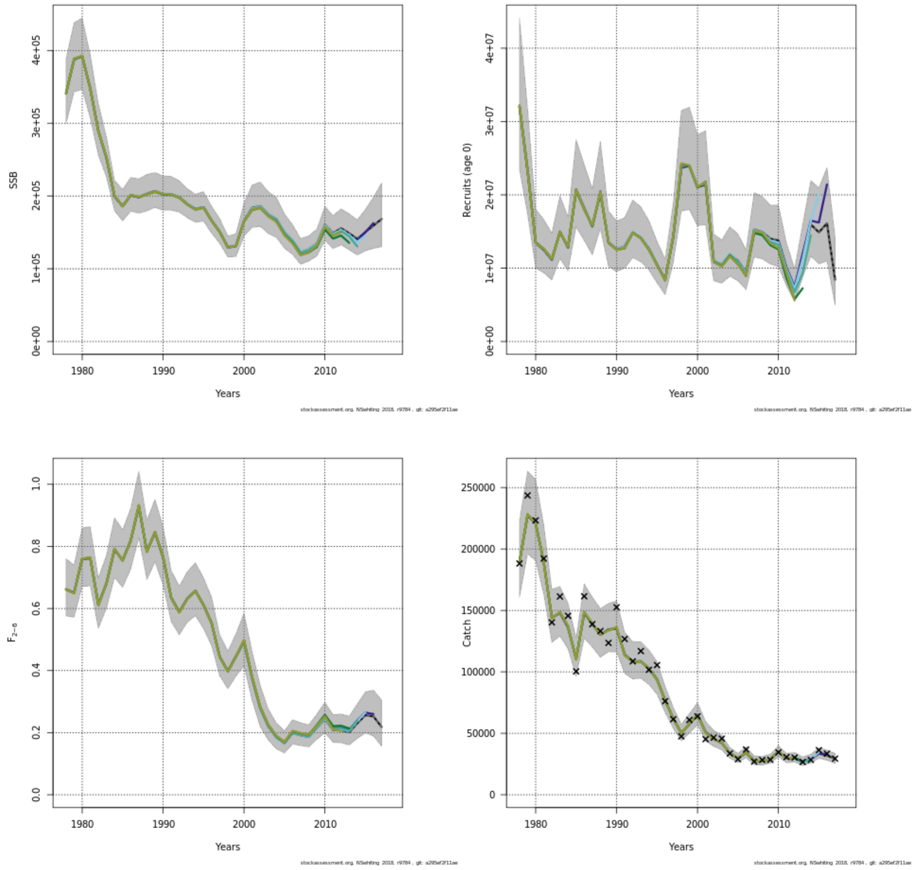


Figure 5.1.1.1. Whiting in Subarea 4 and Division 7.d. SAM retrospectives in 2018 assessment (ICES 2018a).

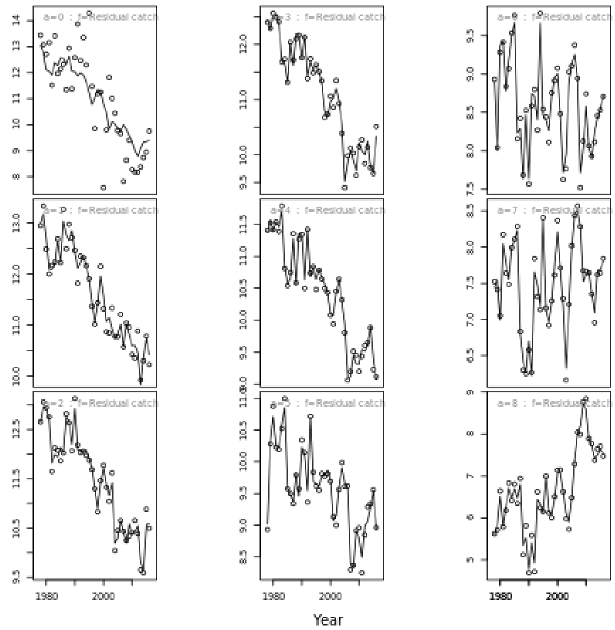


Figure 5.1.1.2 Whiting in Subarea 4 and Division 7.d. Predicted line and observed points (log scale) for the catch fleet (ICES 2018a).

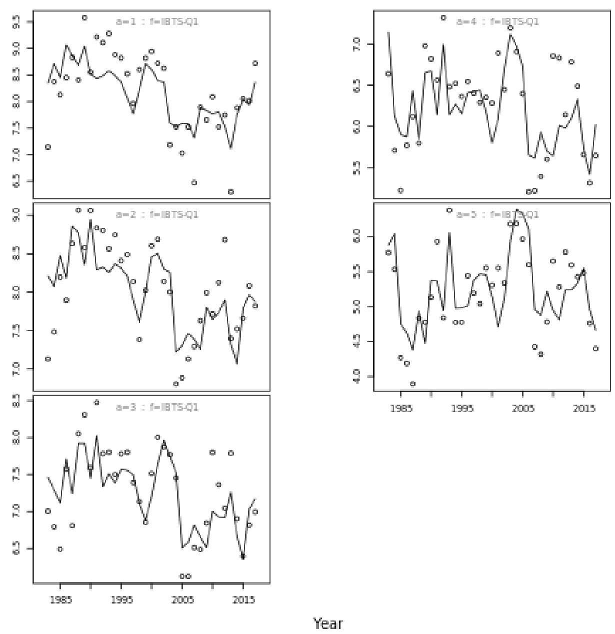


Figure 5.1.1.3 Whiting in Subarea 4 and Division 7.d. Predicted line and observed points (log scale), for survey fleet IBTS Q1 (ICES 2018a).

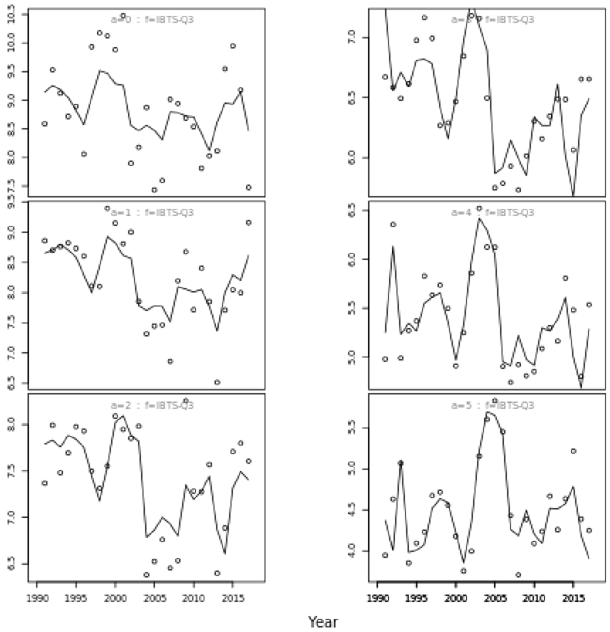


Figure 5.1.1.4 Whiting in Subarea 4 and Division 7.d. Predicted line and observed points (log scale), for survey fleet IBTS Q3 (ICES 2018a).

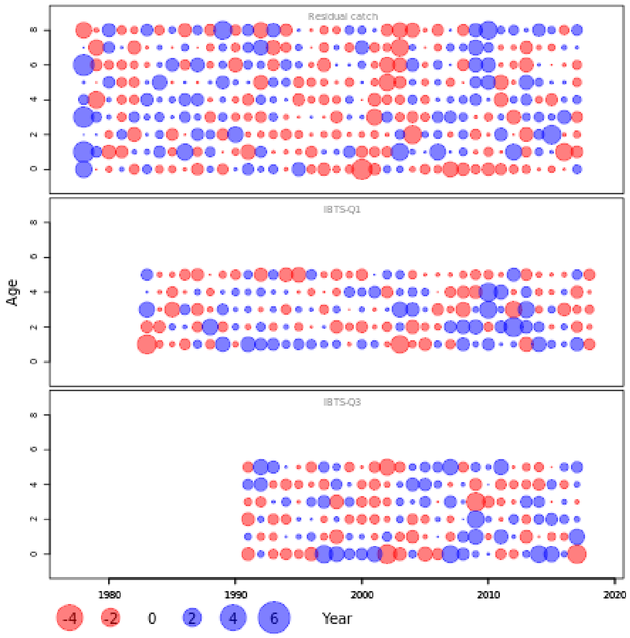


Figure 5.1.1.5 Whiting in Subarea 4 and Division 7.d. SAM standardized one-observation-ahead residuals for catches and surveys (ICES 2018a). Blue circles indicate positive residuals and red circles negative residuals.

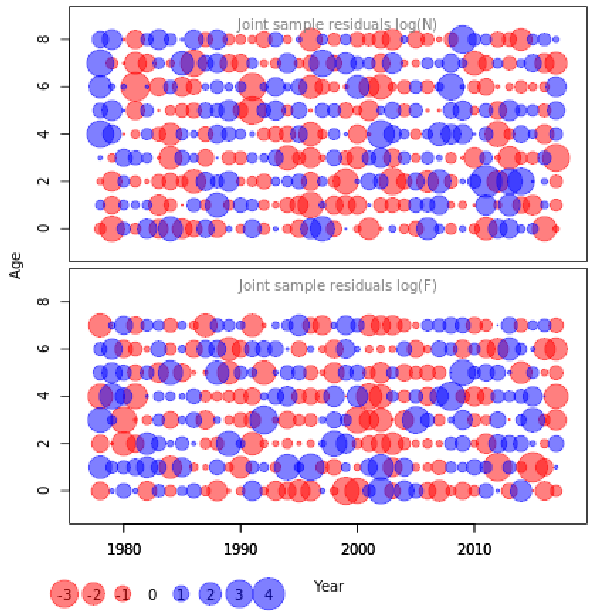


Figure 5.1.1.6 Whiting in Subarea 4 and Division 7.d. SAM standardized single-joint-sample residuals of process increments (for stock size N and fishing mortality F processes) (ICES 2018a). Blue circles indicate positive residuals and red circles negative residuals.

5.1.2 Parameter uncertainty

Uncertainty in the historical period was estimated using variance-covariance matrix of all model parameters from the recent SAM assessment. Replicate sets were produced, each set containing parameters and variables needed to run the operating model forward. In the historical time period biological parameters were assumed constant across replicates, and are assumed to be the same as in the 2018 SAM assessment.

Process error in the projection period is included. Stock numbers at age (ages 1-8) use standard deviation from the historical SAM assessment (Figure 5.1.2.1). The generation of recruitment (age 0) and residuals is detailed in the following section.

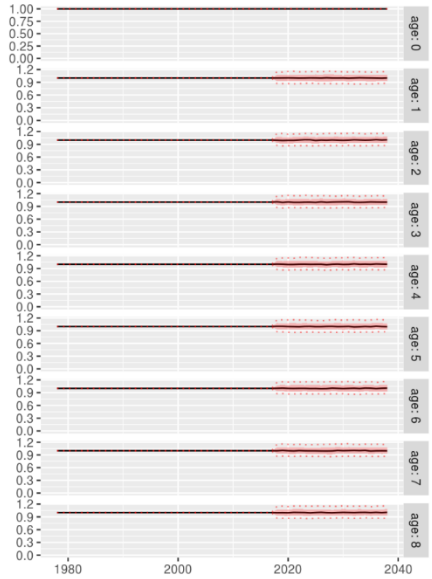


Figure 5.1.2.1 Whiting in Subarea 4 and Division 7.d. Process error on numbers at age in the projected period (value 1 for recruits coming from stock-recruit relationship). Median values and 25th, 75th, 5th and 95th percentiles in red.

5.1.3 Recruitment

The spawning stock recruitment relationship was modelled as a segmented regression and estimated based on historical data. Two data periods were compared including years a): 1983-2017 or b) 2002-2017. Segmented regressions were estimated for each historical replicate, separately (Figure 5.1.3.1).

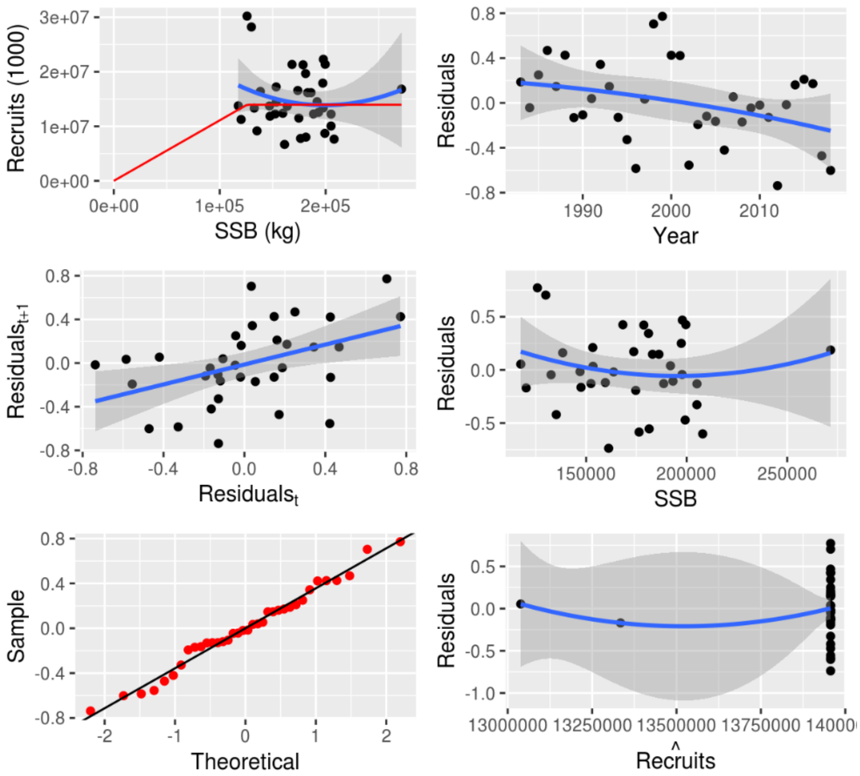


Figure 5.1.3.1 Whiting in Subarea 4 and Division 7.d. Diagnostics for estimated SSR relationship for one replicate, data since 1983.

The residuals for the stock-recruitment relationship were generated for each replicate from historical observations by resampling from the smoothed frequency distribution of residuals with mean zero. The residuals should take into account autocorrelation if the historical time series indicates it. Significant autocorrelation was found for the time series since 1983 (lag 1, Figure 5.1.3.10), but not for the time series since 2002. Residuals were generated for 1983 data series with autocorrelation in lag 1, and for 2002 data series without autocorrelation.

Autocorrelation in residuals Res_t with lag 1 were included as:

$$\text{Res}_t = \rho \text{Res}_{t-1} + \sqrt{1-\rho^2}\varepsilon_t$$

with autocorrelation coefficient of ρ (lag 1, Figure 5.1.3.2), and ε_t the sampled residuals in each replicate derived through re-sampling of the smoothed recruitment period residuals.

The autocorrelation coefficient was retrieved using the R function acf(data, lag.max=1). Residuals were then transformed from additive error (mean zero) to multiplicative error (mean 1).

In individual replicates, spawning stock recruitment pairs as well as cumulative distributions showed good agreement between simulated and observed estimates (Figures 5.1.3.3-4). Overall, simulated residuals led to occasionally higher recruitment, as expected using smoothed distributions; otherwise there is good agreement (Figures 5.1.3.5-6).

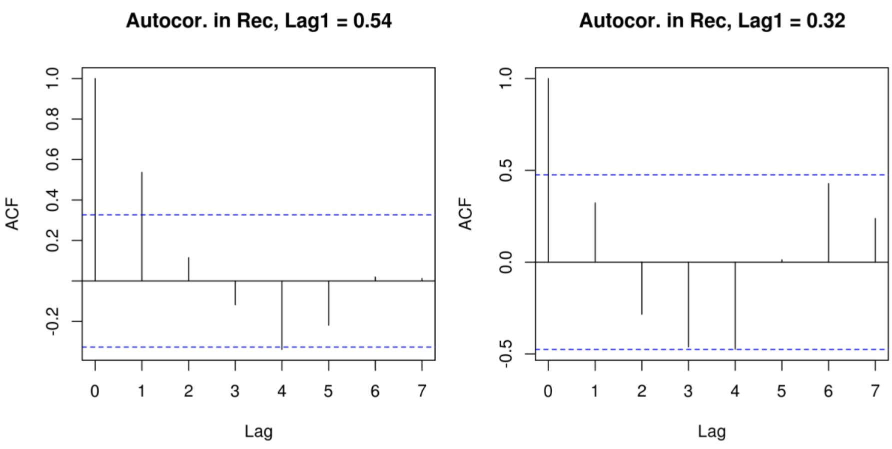


Figure 5.1.3.2 Whiting in Subarea 4 and Division 7.d. Autocorrelation in recruitment for the time series of 1983-2017 (left) and for the time series of 2002-2017 (right). Autocorrelation coefficient in lag1 in the title of plot.

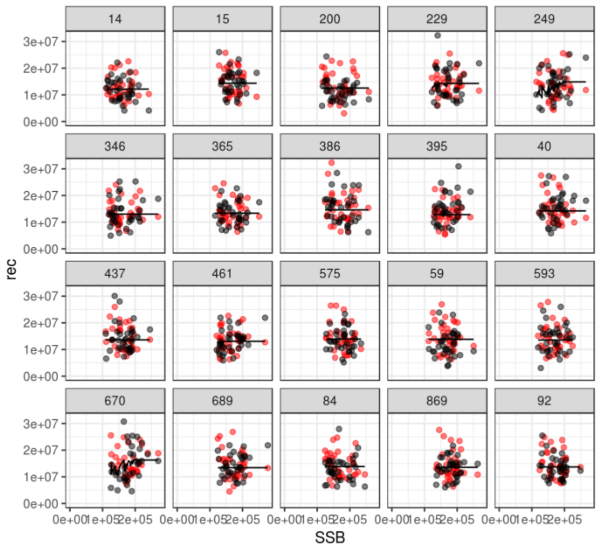


Figure 5.1.3.3 Whiting in Subarea 4 and Division 7.d. Observed vs. estimated SSR pairs for individual replicates (data since 1983, AR(1)), red observed, black simulated.

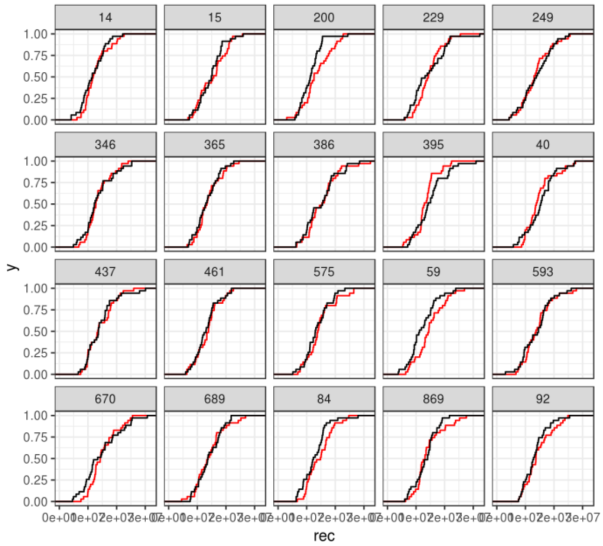


Figure 5.1.3.4 Whiting in Subarea 4 and Division 7.d. Observed vs. estimated cumulative distributions for individual replicates (data since 1983, AR(1)), red observed, black simulated.

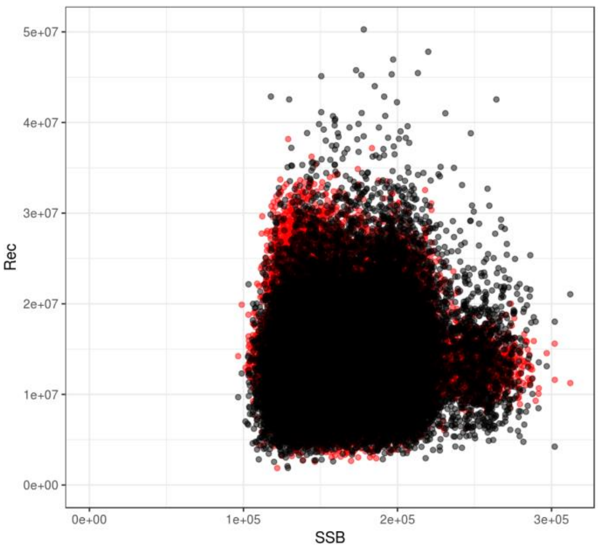


Figure 5.1.3.5 Whiting in Subarea 4 and Division 7.d. Comparison all pairs SSR using simulated residuals on historical data, observed in red, simulated in black.

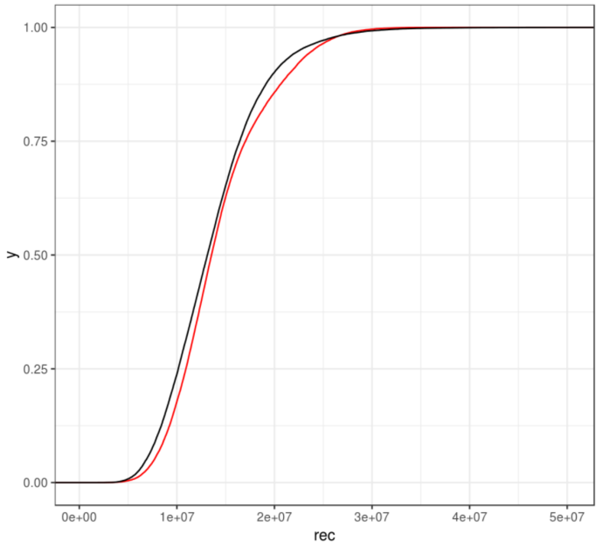


Figure 5.1.3.6 Whiting in Subarea 4 and Division 7.d. Cumulative distribution for all replicates combined (data since 1983, AR(1)), observed in red, simulated in black.

5.1.4 Mean weights, maturity, natural mortality and selection

For the projection period, variability in biological parameters and selectivity in the operating model were created by sampling from the recent 10 years and 3 years of historical data, respectively (following EqSim assumptions). This appears to be a reasonable assumption also for the MSE.

If more recent biological parameters were included (recent 3 or 5 years), the F_{MSY} estimates increased in the EqSim analysis. As biological parameters were variable and future developments were uncertain, the recent 10-year average was used, representing sufficiently-well the shift in natural mortality, maturity and stock weights at age in recent years.

Natural mortality has been relatively stable across recent years for most ages. At age 0, a steep increase around 2000 was observed (Figure 5.1.4.1). The recent 10 year period should be representative for the MSE simulation. Using maturity data in the recent 10 years from which to sample in the projection period allows some variability observed in recent years but avoids lowest values observed in the early 2000s (Figure 5.1.4.2). Similarly, catch and stock weights at age in the recent 10 years allows some variability observed in recent years but avoids lowest observed values in the early 2000s (Figures 5.1.4.3-4). Fisheries selectivity has been relatively constant across periods (Figure 5.1.4.5); the most recent 3 year period was used in MSE representing recent fishing patterns (Figure 5.1.4.6).

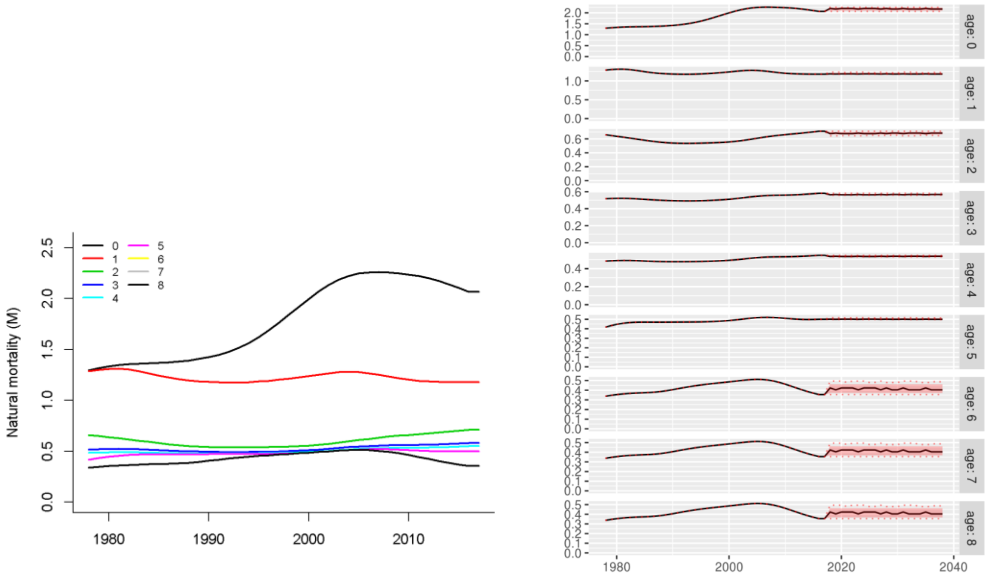


Figure 5.1.4.1 Whiting in Subarea 4 and Division 7.d. Natural mortality estimates for the historical period have been relatively stable in recent years (left panel, ages 6+ identical). Natural mortality for the projected years (right panel). Median values and 25th, 75th, 5th and 95th percentiles in red.

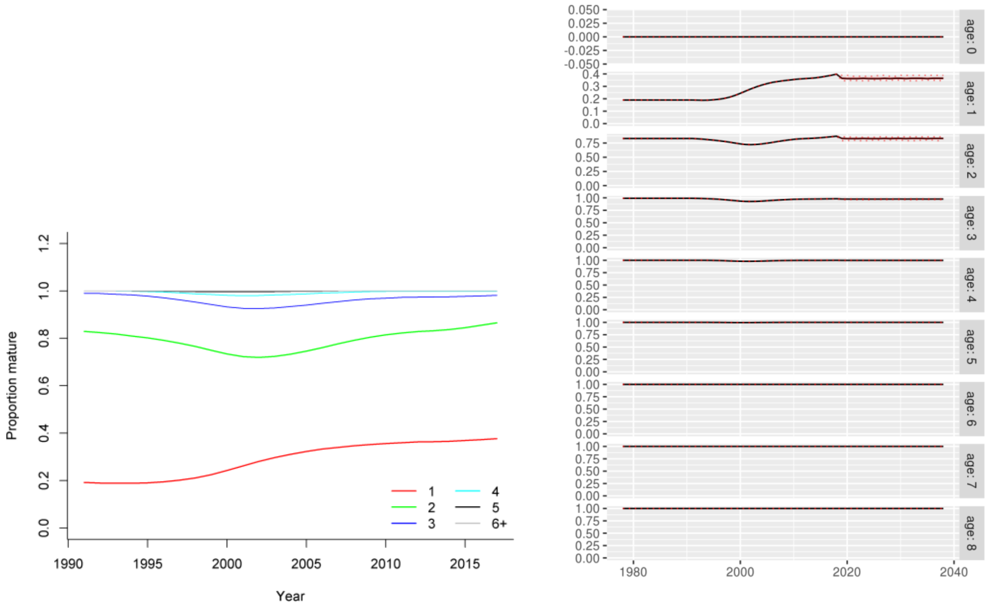
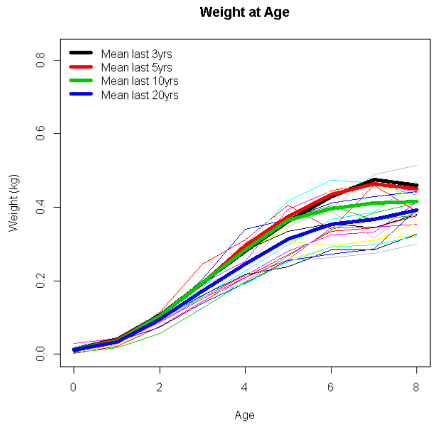


Figure 5.1.4.2 Whiting in Subarea 4 and Division 7.d. The proportion mature at age in the historical period (left, prior 1991 constant) and together with simulated residuals for the projection period (right). Median values and 25th, 75th, 5th and 95th percentiles in red.



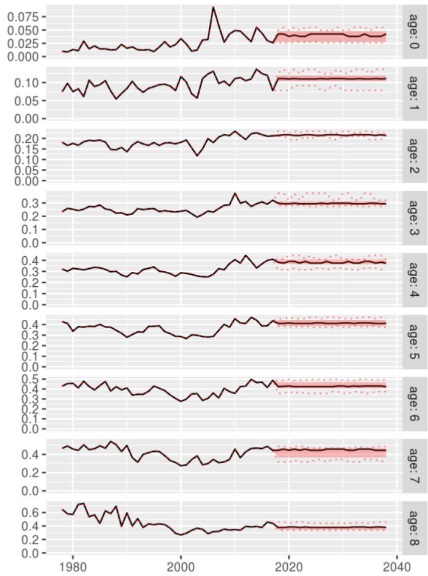


Figure 5.1.4.3 Whiting in Subarea 4 and Division 7.d. Mean catch weights at age in historical periods (left). Catch mean weights at age with residuals estimated for the projection period (right). Median values and 25th, 75th, 5th and 95th percentiles in red.

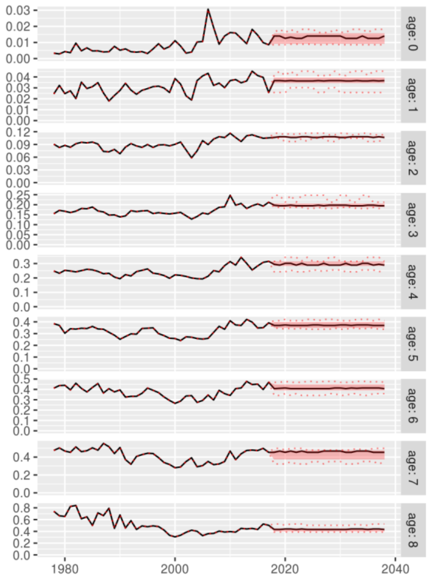


Figure 5.1.4.4 Whiting in Subarea 4 and Division 7.d. Stock weights at age with residuals estimated for the projection period. Median values and 25th, 75th, 5th and 95th percentiles in red.

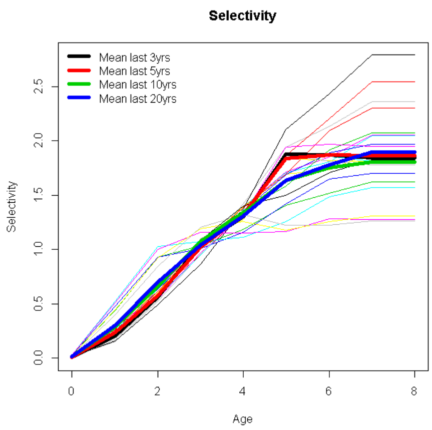
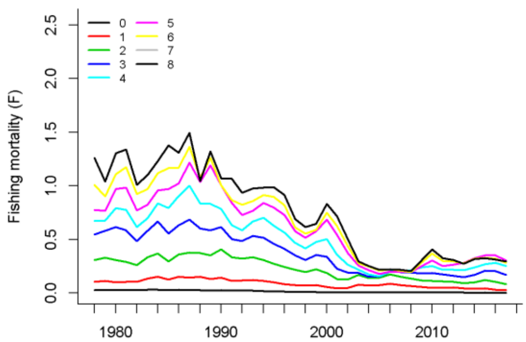


Figure 5.1.4.5 Whiting in Subarea 4 and Division 7.d. Fishing selectivity at age by year and averages for the recent 3, 5, 10, 20 years.



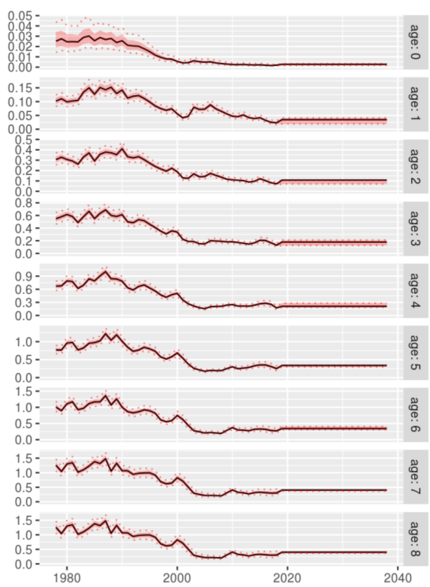


Figure 5.1.4.6 Whiting in Subarea 4 and Division 7.d. Fishing mortality at age in the historical time period (left), together with fishing mortality with estimated residuals (Fstatus quo) for the projection period (right). Median values and 25th, 75th, 5th and 95th percentiles in red.

5.1.5 Generating data from the operating model

Observation error is included on "true" survey indices and catch at age. Deviances to the observed survey indices in the projection period were simulated using the variance-covariance matrix for survey indices to account for observation error correlated between ages (Figure 5.1.5.1). Three replicates are plotted for IBTS Q1 in Figure 5.1.5.2 and for IBTS Q3 in Figure 5.1.5.3. Survey observations were generated from the operating model as follows:

$$I_{a,y,i} = q_{a,i} N_{a,y} e^{-t_i Z_{a,y}} \, e^{\varepsilon_{a,y,i}}$$

where N are stock numbers at age a and year y; Z are total mortalities at age and year from the operating model; q are survey catchabilities at age; t is the timing of the survey (0.125 for IBTS Q1 and 0.625 for IBTS Q3). The observation errors follow a multivariate normal distribution:

$$\varepsilon_{a,y,i} \sim N(0, \Sigma_i)$$

Where Σ_i are the covariance matrices between age classes within years for each survey i, as estimated in the current SAM assessment (Nielsen and Berg 2014).

Observation error is included on catches at age as multiplicative lognormal error using standard deviations from the historical estimated catches of the SAM assessment (Figure 5.1.5.4).

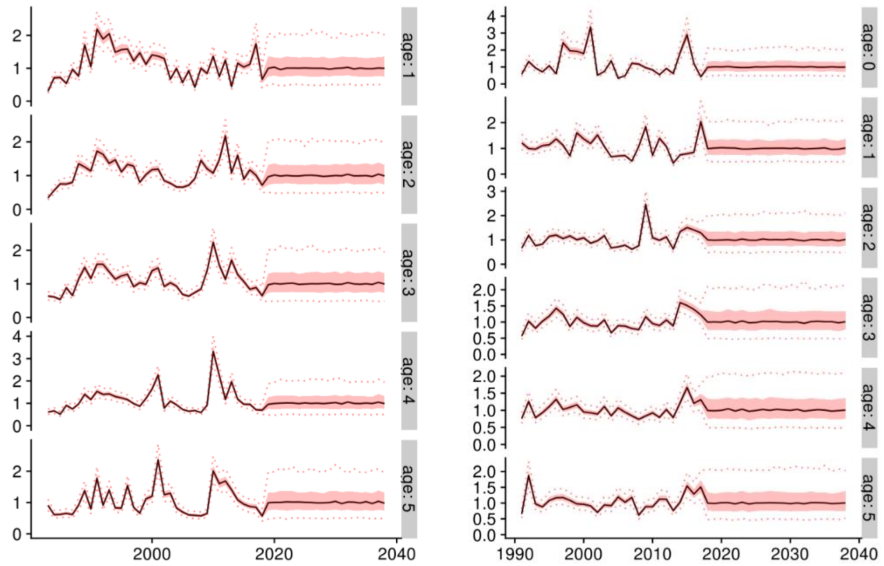


Figure 5.1.5.1 Whiting in Subarea 4 and Division 7.d. Survey deviation in the historical period (SAM estimated uncertainty) and for the projection period (including correlated error) for IBTS Q1 (left) and IBTS Q3 (right).

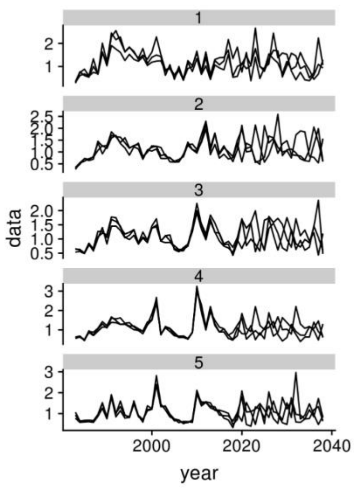


Figure 5.1.5.2 Whiting in Subarea 4 and Division 7.d. Three replicates of survey deviations, IBTS Q1 for ages 1-5.

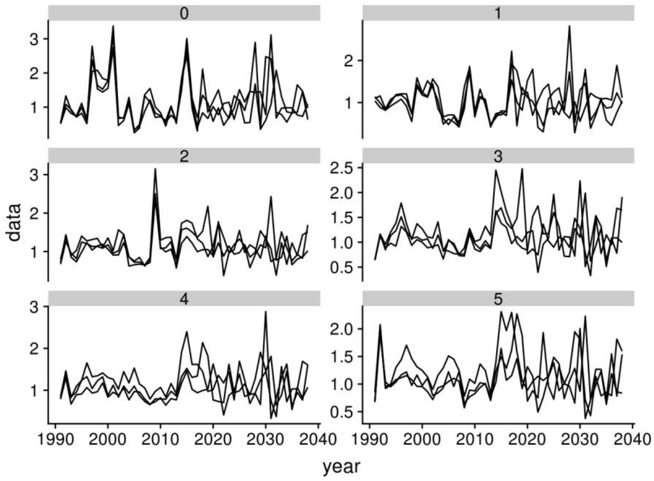


Figure 5.1.5.3 Whiting in Subarea 4 and Division 7.d. Three replicates of survey deviations for IBTS Q3 for ages 0-5.

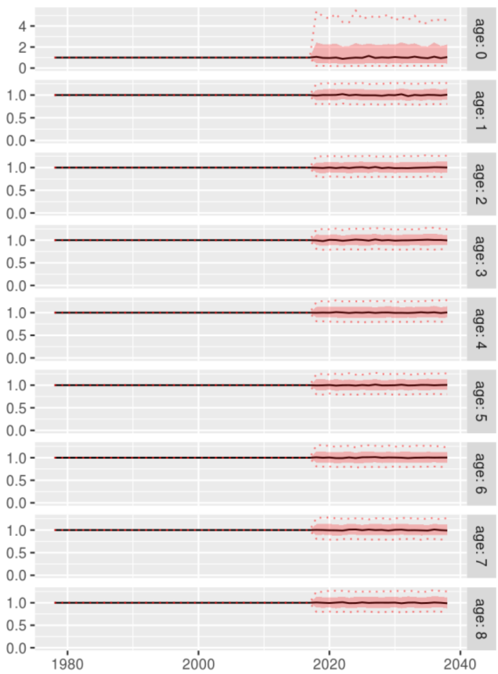


Figure 5.1.5.4 Whiting in Subarea 4 and Division 7.d. Observation noise on catch at age.

5.1.6 Implementation error

The banking and borrowing algorithm used is explained in Section 2.3.4.

In the alternative operating model OM3, an extra implementation error is included because of the uncertainty related to industrial bycatch (Section 5.2.2).

5.1.7 Number of replicates and projection years

The number of replicates was 1000, based on a simulation study performed by North Sea cod (see section 3.1.7). During webex 2 in late January, it was agreed that if stock coordinators had time to do a similar study, they should do so, but if not, to default to 1000 replicates.

Twenty years were used for the projection period. This was again based on the simulation study performed by North Sea cod (see section 3.1.7), where SSB was found to plateau after 20 years.

5.2 Alternative operating models

Alternative operating models consider a different, more pessimistic, recruitment scenario and implementation error in catches to account for uncertainty in catches due to variability industrial bycatch unrelated to the management procedure.

In Figure 5.1.1, we can see that recruitment for North Sea whiting has not exceeded 20 000 000 since 2002 and is fluctuating around a lower level since. It is not clear whether this is due to a regime shift in the North Sea and the pattern will continue in the future. Regime shifts have been discussed for cod in the North Sea (Engelhard et al. 2014). One of the major factors inducing a regime shift was climate anomalies which can affect recruitment and spatial distribution of fish (Engelhard et al. 2014, Stige et al. 2017). To ensure sustainable management, the possibility of a regime shift to lower productivity (i.e. recruitment level) since the early 2000s is accounted for in the two alternative operating models by using a more pessimistic recruitment scenario.

Two alternative operating models were constructed for 1000 replicates and 20 years of projection period. In the first alternative operating model (OM2) random recruitment level shifts to a lower level are applied. In the second operating model (OM3) random recruitment level shifts to a lower level are applied together with extra implementation error to account for variability in industrial bycatch proportion (OM3).

Operating models 2 and 3 are both more pessimistic in terms of recruitment, because in some years (randomly selected periods of 1-4 years) recruitment shifts to a lower level (by factor 0.75). The effect of industrial bycatch variability of implementation error on the catch target was applied to the pessimistic recruitment scenario (Table 5.2.1).

Table 5.2.1 Whiting in Subarea 4 and Division 7.d. Alternative operating models

Assumption	OM1 (baseline)	OM2 (alternative)	OM3 (alternative)
SSR	Since 1983, AR(1), Segmented regression	Since 1983, AR(1), Segmented regression, occasional periods (1-4 years) of low recruitment	Since 1983, AR(1), Segmented regression, occasional periods (1-4 years) of low recruitment
IBC	No extra implementation error	No extra implementation error	Extra IBC implementation error

5.2.1 OM2 – pessimistic recruitment

As an alternative operating model, a worst-case scenario for recruitment was developed to match projected recruitment to observed levels since 2002.

This was done by allowing occasional recruitment level shifts. The recruitment shift to lower level was done using a multiplier (0.75) on the prepared multiplicative autocorrelated residuals. The time periods (duration 1-4 years) and the respective recruitment level (multiplier 1 or 0.75) were both randomly selected.

When comparing the residuals for data series since 1983 (AR(1)) and 2002, it was found that the residuals for the short time series (since 2002) show narrower confidence intervals, which do not cover the lower ranges of observed recruitment (Figure 5.2.1.1). In contrast, the longer time series (since 1983) shows larger recruitment confidence intervals, with an upper bound larger than expected from the most recent time period since 2002.

Residuals calculated using either time series with recruitment level shift, decreases the lower and upper bound of the confidence interval (Figure 5.2.1.2). Therefore, the long time series (since 1983) appears to capture the lower range values and still allow peaks in recruitment at a level characteristic for the period since 2002. The short time series (since 2002) shows that the upper bound of the confidence interval is now lower than in the recent past. It is therefore recommended to use the longer time series (since 1983) with recruitment level shift to capture the characteristics of the recruitment time series since 2002 (Figure 5.2.1.2, left panel). In Figure 5.2.1.3 it is shown that including the recruitment-level shift maintained variability but shifts individual data point downwards by factor 0.75.

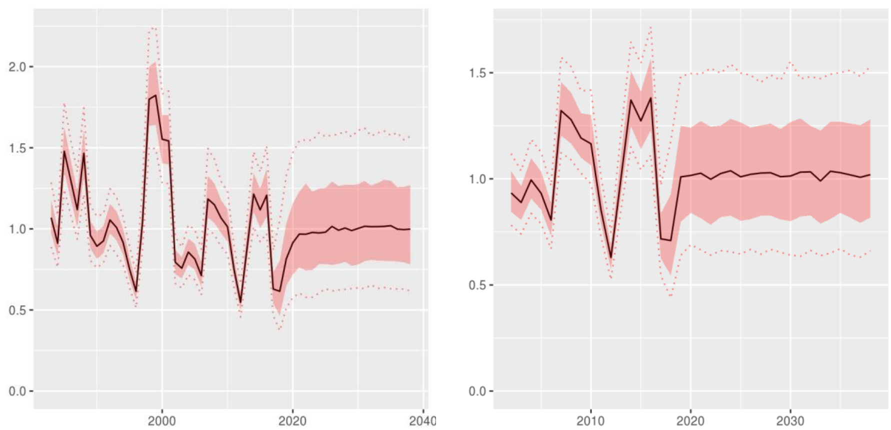


Figure 5.2.1.1 Whiting in Subarea 4 and Division 7.d. Recruitment residuals data since 1983 (AR(1)) (left) and since 2002 (right).

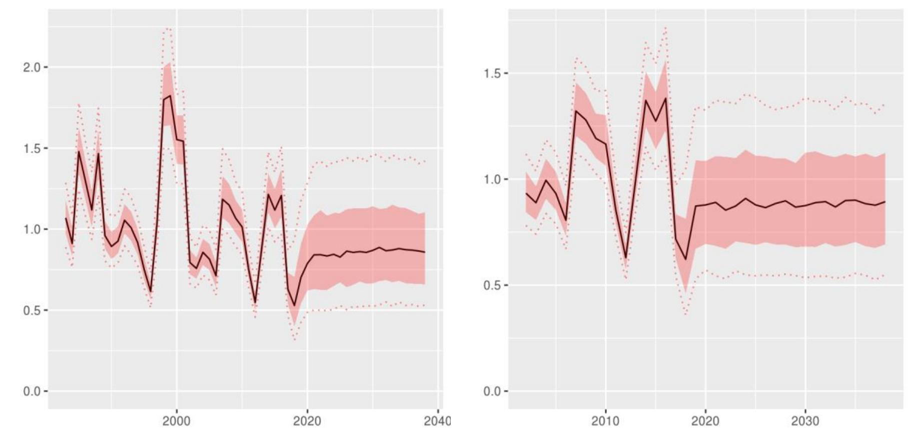


Figure 5.2.1.2 Whiting in Subarea 4 and Division 7.d. Recruitment residuals data since 1983 (AR(1)) (left) and since 2002 (right), with recruitment level shift.

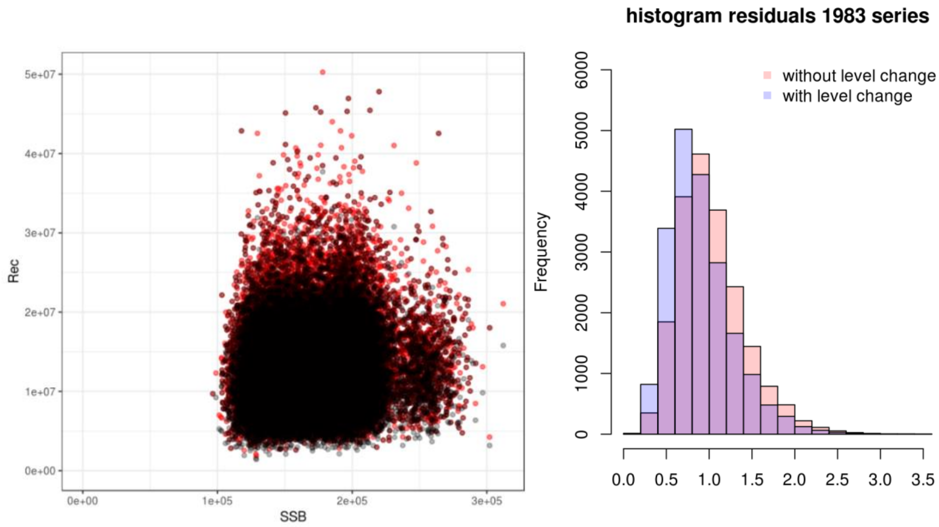


Figure 5.2.1.3 Whiting in Subarea 4 and Division 7.d. Left Panel: Spawning stock recruitment pairs using the 1983 data series (AR(1)) original (red) compared to the data series 1983 (AR(1)) with recruitment level shifts (black). Right panel: frequency distribution of residuals.

5.2.2 OM3 – pessimistic recruitment and variability in industrial by-catch

The IBC decreased over time, and has been relatively stable since 1996 (Figure 5.2.2.1). The percentage of IBC of total catch is relatively noisy and there is no trend over time (Figure 5.2.2.2). The proportion of IBC in the catch cannot be explained by the SSB of the stock. The variability in catch proportion of IBC should be considered by applying additional implementation error on total catches (Figure 5.2.2.3). The implementation error is added to an alternative operating model as a robustness test.

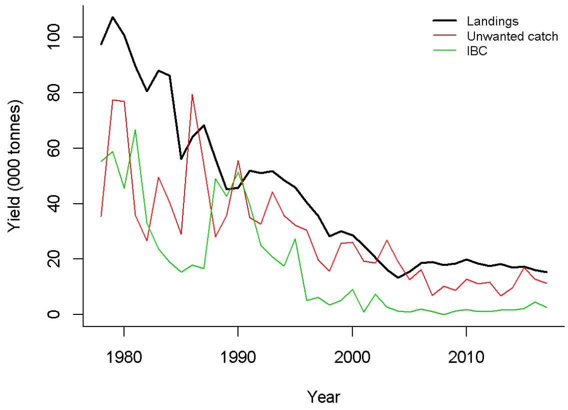


Figure 5.2.2.1 Whiting in Subarea 4 and Division 7.d. Catch components since 1978. In the years since 1996 IBC has been on a lower level.

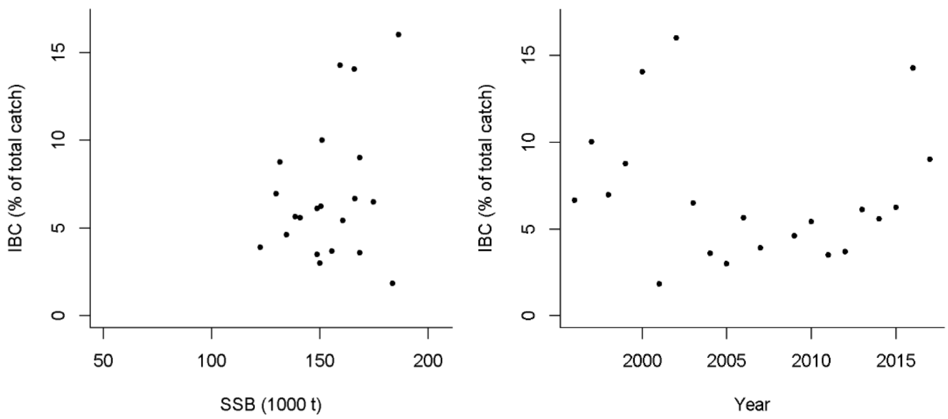


Figure 5.2.2.2 Whiting in Subarea 4 and Division 7.d. Left SSB vs percentage of IBC since 1996. Right: Percentage of IBC since 1996 by year.

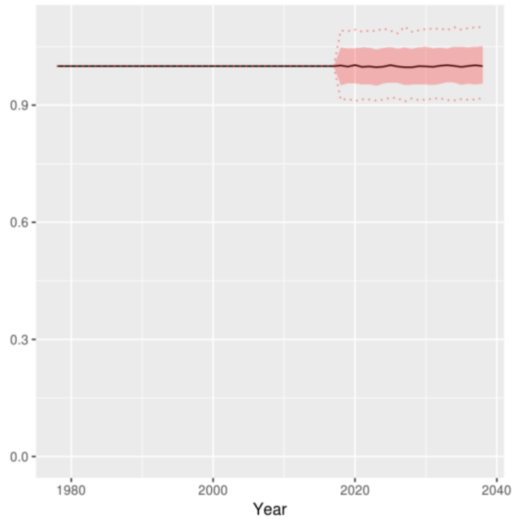


Figure 5.2.2.3 Whiting in Subarea 4 and Division 7.d. Implementation error in total catches to account for variability in IBC.

5.3 Management procedure

The MSE uses a "full approach" in the management procedure by using SAM as the assessment model to estimate stock status. The SAM settings are the same as in the current routine assessment (described in stock annex for this stock).

In the management procedure, the assessment results are used to forecast catches following the respective HCR to give catch advice. Assessment and forecast in the MSE are done using SAM. For this stock, the HCRs deliver a target catch given as total catches (for the total assessment area, including unwanted, wanted catch and industrial bycatch).

For North Sea whiting, catch advice is given as total catches at annual WGNSSK ICES expert group. In the ICES advice, total catches are split per area 4 and 7d and catch components (IBC, human consumption catches). The TAC is then set for human consumption catches in area 4 and 7d separately. The TAC for the Eastern Channel (7d) is given together with the rest of area 7 (except 7a), which is assessed separately. Due to the mismatch of assessment and management units for the North Sea whiting stock, it is difficult to use TAC directly in the MSE. Furthermore, the amount of catch due to IBC does not depend directly on the TAC for whiting but is a result of fishing regulations and fisheries dynamics of industrial fisheries fleet for sprat, Norway pout and sandeel.

Therefore, in the MSE, the catch target is given as the total catch advice, which implicitly includes the human consumption TAC of area 4 and 7d as well as IBC, to be used as removals in the operating model during the projection period.

The forecast performed in the MSE with SAM uses similar assumptions as used during WGNSSK (Table 5.3.1). A simulated population is fished, surveyed and assessed using SAM assessment model with the settings from the current routine assessment. The TAC was set following a two-year forecast.

WGNSSK: MFDP short term forecast

In the forecast for the assessment in WGNSSK, the MFDP software is used for a deterministic short term-forecast. This allows for fleet separation of human consumption and industrial bycatch fleet. The initial stock size is taken from the current SAM assessment. In the intermediate year, numbers at age (ages 1-8+) are assumed to be the survivors of the final year of the current SAM assessment. The recruitment (age 0) is set as the geometric mean of recruitment since 2002 in the intermediate and advice year. In the autumn update, the RCT3 estimate, calculated using most recent survey information, is used as the recruitment for the intermediate year if the difference between assumption and estimate is significant. Biological parameters (maturity at age, weights at age, natural mortality) and exploitation pattern follow the recent three-year average in the intermediate and TAC year. In the intermediate year, generally no TAC constraint is applied, and fishing mortality is set to $F_{status\text{-}quo}$. In the advice year fishing mortality is set to the respective target F (F_{HCR}).

MSE: SAM short-term forecast

In the MSE, the operating model and management procedure operates on total catch. Industrial bycatch is not explicitly modelled, but included in the total catch. Uncertainty in the proportion of industrial bycatch relative to total catch was considered in alternative operating model OM3 as a simple implementation error on the total catch target. The forecast covers the intermediate and advice year. The forecast uses the SAM assessment results, including survivors of the numbers at age in the final year of the current assessment. The recent three-year average of biological parameters and exploitation pattern are used in the intermediate and TAC year. In the intermediate year, generally no TAC constraint is applied, and fishing mortality is set to $F_{status\text{-}quo}$. Recruitment is estimated by sampling from the historical recruitments (since 2002). In the advice year, fishing mortality is set to the respective target F (F_{HCR}).

Differences in settings between forecast in WGNSSK and MSE are summarized in Table 5.3.1. Harvest control rules are used to adjust catch targets in the projection years. They aim to reduce F_{target} when SSB falls below thresholds. The reduction of fishing mortality below B_{lim} varies in rule A, B and C (Figure 2.1). In addition, stability mechanisms such as TAC constraint and banking and borrowing are implemented by combining the three HCRs with stability rules D and E. The following HCRs were evaluated A, B, C, A+D, B+E, C+E (see Section 2.1). Banking and borrowing was implemented in option D and E, assuming that banking and borrowing alternates between years. In the alternative operating model OM3, an implementation error on the final catch target is applied (after TAC constraint and banking and borrowing,), representing the variability in proportion of industrial bycatch.

Table 5.3.1 Whiting in Subarea 4 and Division 7.d. Summary comparison forecast settings at WGNSSK 2018 and for MSE

Forecast settings in assessment (WGNSSK)	
Biological parameters	Recent 3 year average
Selectivity	Recent 3 year average by catch-component scaled to final historical year
Intermediate year TAC constraint	none
Recruitment (year+1)	RCT3 estimate in autumn update or geometric mean of historical assessment (since 2002)
Recruitment (year+2)	Geometric mean of historical assessment (since 2002)
Software	MFDP
Forecast settings in MSE projection	
Biological parameters	Recent 3 year average
Selectivity	Recent 3 year average scaled to final historical year
Intermediate year TAC constraint	none
Recruitment (year+1, year+2)	Sampled from historical assessment (since 2002)
Software	SAM

Comparison shorterm-forecast SAM and MFDP

The short-term forecast was compared between SAM and MFDP. For both the SAM survivors in 2018 and SAM median recruitment 2018 was used. In the following years SAM uses the sampled recruitment since 2002, MFDP the geometric mean since 2002. Results for the $F_{statusquo}$, F_{msy} and F_{lim} scenarios are shown (Table 5.3.2-4). Results are reasonable similar. There are ongoing efforts to implement the forecast in SAM to allow for fleet separation in the forecast.

Table 5.3.2. Whiting in Subarea 4 and Division 7.d. Forecast SAM vs. MFDP, Fstatus quo for all years (note: here the SAM median recruitments and SAM survivors for 2018 are used, such that results differ from spring advice). For SAM, median values are given.

Year	F	Rec (SAM)	SSB (SAM)	Catch (SAM)	Rec (MFDP)	SSB (MFDP)	Catch (MFDP)
2018	0.218	8593208	182080	31094	8593208	178083	32400
2019	0.218	11793614	168054	31787	11964329	165862	31563
2020	0.218	11793614	157767		11964329	154781	

Table 5.3.3. Whiting in Subarea 4 and Division 7.d. Forecast SAM vs. MFDP, Fstatus quo, F_{msy}, F_{msy} (note: here the SAM median recruitments and SAM survivors for 2018 are used, such that results differ from spring advice). For SAM, median values given.

Year	F	Rec (SAM)	SSB (SAM)	Catch (SAM)	Rec (MFDP)	SSB (MFDP)	Catch (MFDP)
2018	0.218	8593208	182080	31094	8593208	178083	32400
2019	0.172	11793614	168054	25502	11964329	165862	24637
2020	0.172	11793614	162379		11964329	159712	

Table 5.3.4. Whiting in Subarea 4 and Division 7.d. Forecast SAM vs. MFDP, Fstatus quo, F_{lim}, F_{lim} (note: here the SAM median recruitments and SAM survivors for 2018 are used, such that results differ from spring advice). For SAM, median values given.

Year	F	Rec (SAM)	SSB (SAM)	Catch (SAM)	Rec (MFDP)	SSB (MFDP)	Catch (MFDP)
2018	0.218	8593208	182080	31094	8593208	178083	32400
2019	0.458	11793614	168054	61986	11964329	165862	62762
2020	0.458	11793614	137619		11964329	133066	

5.4 Results

5.4.1 Search grid for "optimal" combination of F_{target} and $B_{trigger}$

A grid search was performed to determine the "optimal" combination of F_{target} and $B_{trigger}$ for each of the six management strategies under the baseline operating model. The "optimal" pairs were selected to produce maximum yield while risk3≤5% in the long-term. risk1 is calculated as the average of the annual probability of SSB being below B_{lim} and risk3 is the maximum of the annual probability of SSB being below B_{lim}, both over a specified period. Due to limited time and computational capabilities, first only a coarse grid followed by a finer grid of F_{target} and $B_{trigger}$ combinations were run.

First, a range of $B_{trigger}$ values up to the maximum observed SSB since 1983 (in steps of 10000) were used in the grid search. To find the "optimal" pair, the grid search was extended for higher $B_{trigger}$ values, which led to "optimal" $B_{trigger}$ values larger than the observed SSB since 1983. Grid search results are plotted in Figures 5.4.1.1-6.

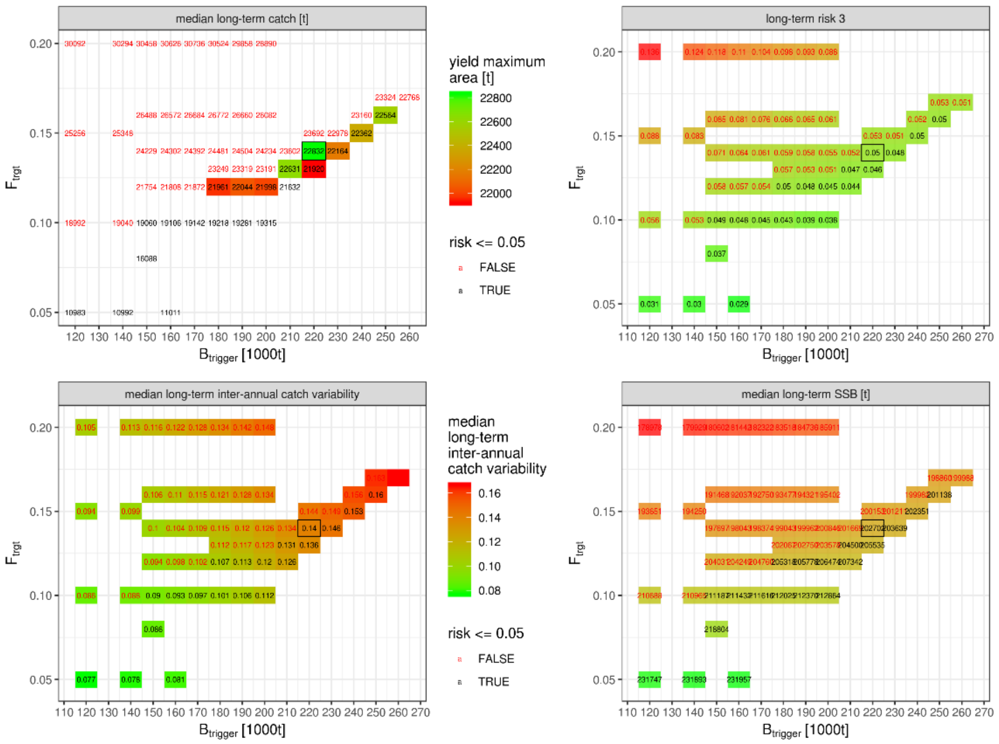


Figure 5.4.1.1 Whiting in Subarea 4 and Division 7.d. Grid search for optimal combination for <u>management strategy A</u>. Long-term results (final 10 years of the 20-year projection) median catch, risk3, median inter-annual catch variability and median SSB. The "optimal" combination delivers maximum long-term catch while meeting the precautionary criterion (risk3 ≤ 5%), F_{target}=0.14, $B_{trigger}$=220 000t. The combinations with risk3 ≤ 5% values are in black, otherwise in red.

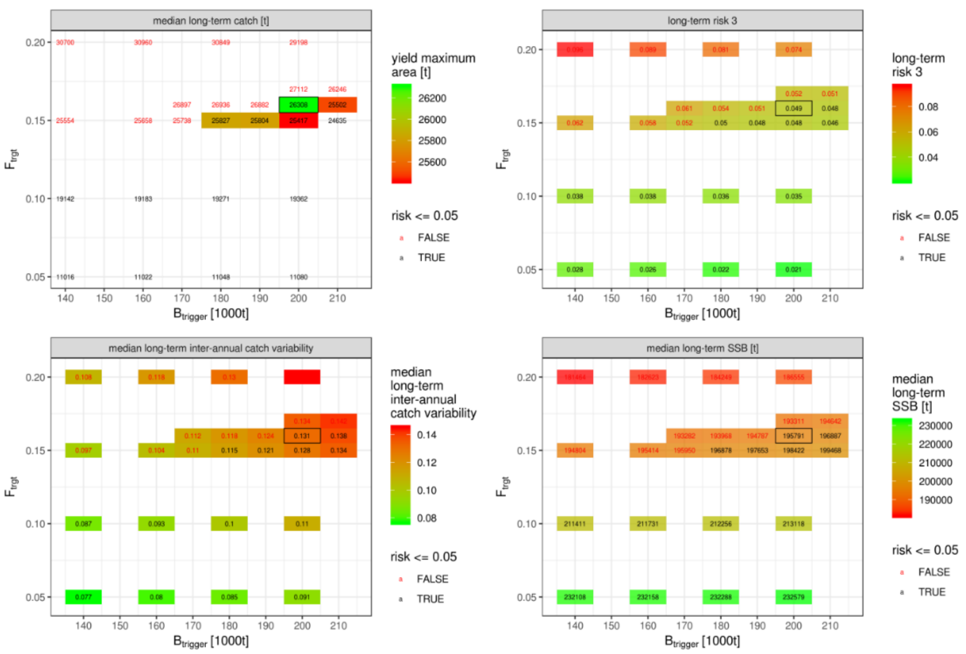


Figure 5.4.1.2 Whiting in Subarea 4 and Division 7.d. Grid search for optimal combination for <u>management strategy B</u>. Long-term results (final 10 years of the 20-year projection) median catch, risk3, median inter-annual catch variability and median SSB. The "optimal" combination delivers maximum long-term catch while meeting the precautionary criterion (risk3 ≤ 5%), F_{target}=0.16, $B_{trigger}$=200 000t. The combinations with risk3 ≤ 5% values are in black, otherwise in red.

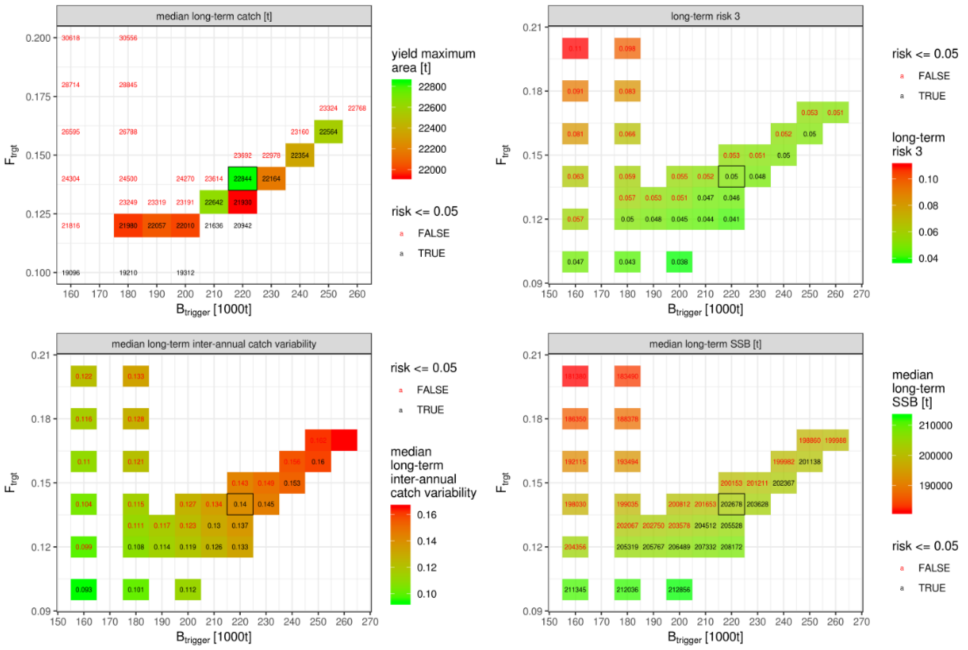


Figure 5.4.1.3 Whiting in Subarea 4 and Division 7.d. Grid search for optimal combination for <u>management strategy C</u>. Long-term results (final 10 years of the 20-year projection) median catch, risk3, median inter-annual catch variability and median SSB. The "optimal" combination delivers maximum long-term catch while meeting the precautionary criterion (risk3 ≤ 5%), F_{target}=0.14, $B_{trigger}$=220 000t. The combinations with risk3 ≤ 5% values are in black, otherwise in red.

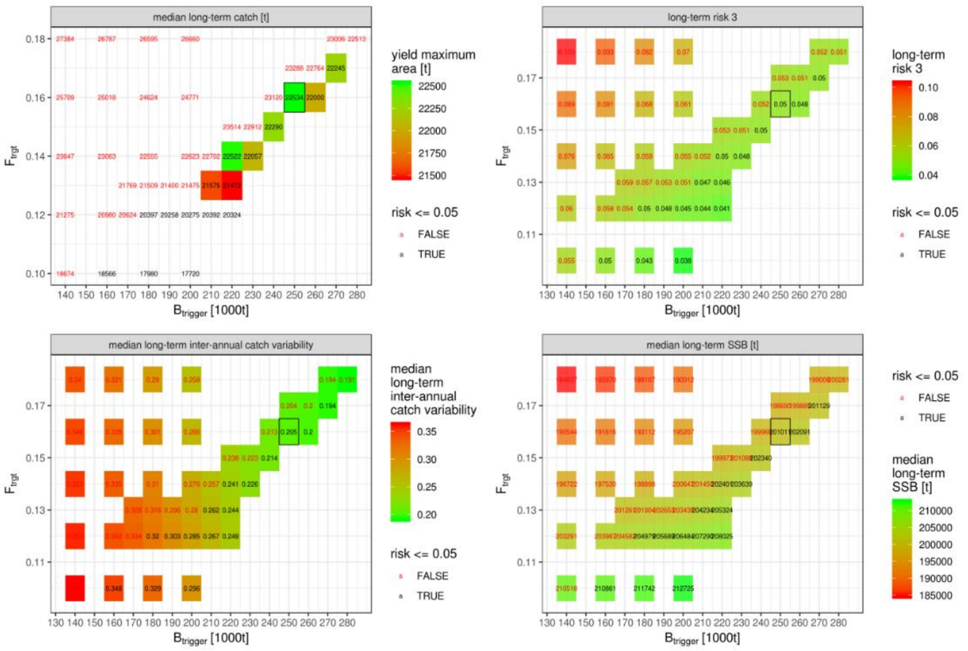


Figure 5.4.1.4 Whiting in Subarea 4 and Division 7.d. Grid search for optimal combination for <u>management strategy A+D</u>. Long-term results (final 10 years of the 20-year projection) median catch, risk3, median inter-annual catch variability and median SSB. The "optimal" combination delivers maximum long-term catch while meeting the precautionary criterion (risk3 ≤ 5%), F_{target}=0.16, $B_{trigger}$=250 000. The combinations with risk3 ≤ 5% values are in black, otherwise in red.

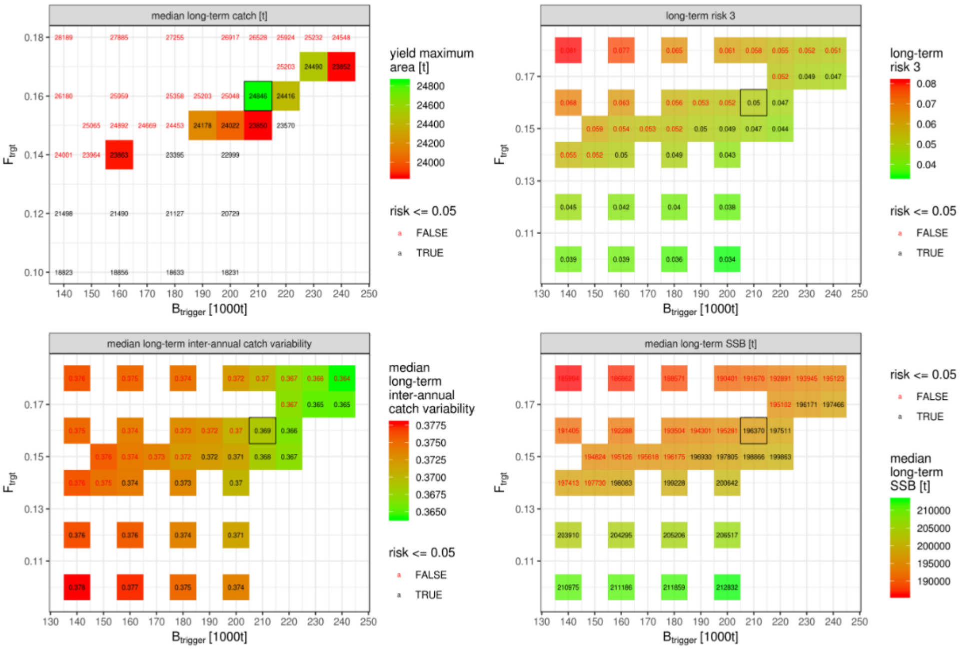


Figure 5.4.1.5 Whiting in Subarea 4 and Division 7.d. Grid search for optimal combination for management strategy B+E. Long-term results (final 10 years of the 20-year projection) median catch, risk3, median inter-annual catch variability and median SSB. The "optimal" combination delivers maximum long-term catch while meeting the precautionary criterion (risk3 ≤ 5%), F_{target}=0.16, $B_{trigger}$=210 000. The combinations with risk3 ≤ 5% values are in black, otherwise in red.

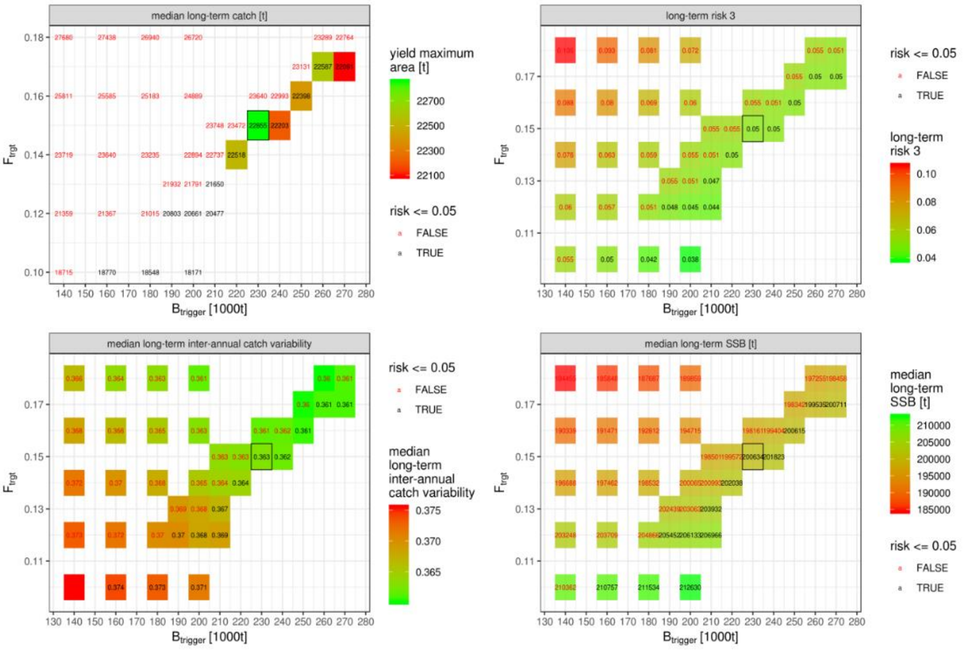


Figure 5.4.1.6 Whiting in Subarea 4 and Division 7.d. Grid search for optimal combination for management strategy C+E. Long-term results (final 10 years of the 20-year projection) median catch, risk3, median inter-annual catch variability and median SSB. The "optimal" combination delivers maximum long-term catch while meeting the precautionary criterion (risk3 ≤ 5%), F_{target}=0.15, $B_{trigger}$=230 000. The combinations with risk3 ≤ 5% values are in black, otherwise in red.

5.4.2 Summary projections

Projections are summarized for the "optimal" pairs for each management strategy using the baseline operating model in terms of recruitment (age 0), SSB, catch and mean F (age 2-6) (Figure 5.4.2.3-8). For comparison, projection results for a fishing moratorium with F_{target}=0 is plotted in Figure 5.4.2.1. Results for HCR A* that sets F_{target}=F_{MSY}=0.172 and $B_{trigger}$=MSY $B_{trigger}$=166 708t while using HCR A are summarized in Figure 5.4.2.2. Individual replicates are plotted alongside percentiles.

Management strategies A+D, B+E and C+E show the typical zigzag patterns in percentiles of catch and mean F expected from the extreme banking and borrowing scheme modelled (Figures 5.4.2.6-8).

Figure 5.4.2.9 plots the annual risk for "optimised" management strategy A, which indicates that there is a trend in annual risk. This is similar to herring, and is likely to be caused by the inclusion of auto-correlation in recruitment (these two stocks were the only ones that included this feature).

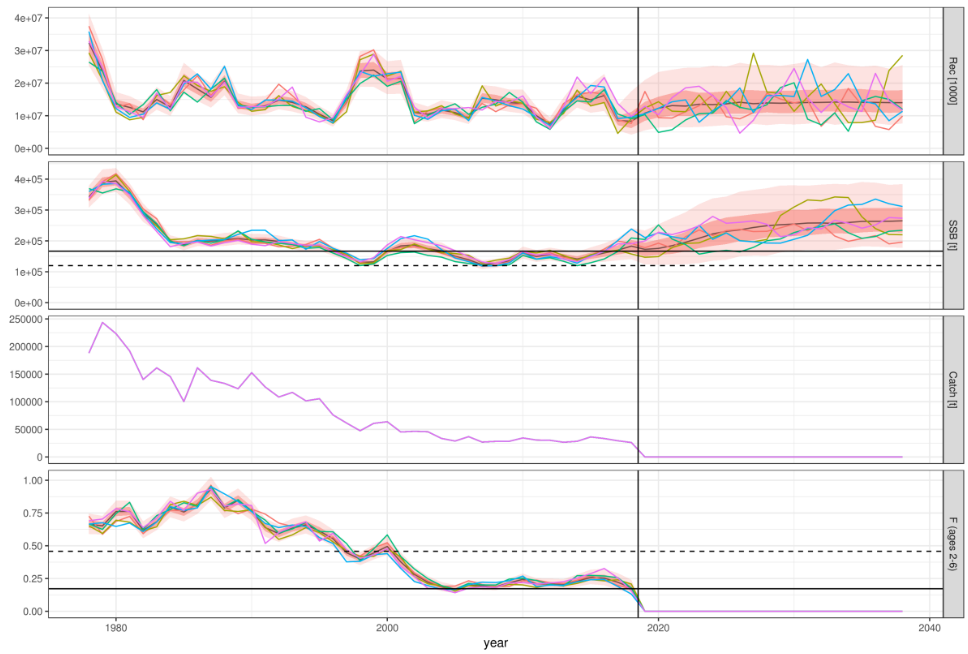


Figure 5.4.2.1 Whiting in Subarea 4 and Division 7.d. Summary projections F_{target}=0 (F0). MSY $B_{trigger}$ (SSB, black horizontal line), B_{lim} (SSB, black dashed horizontal line), F_{lim} (dashed black), F_{MSY} (solid black). Median values (black) and 25th, 75th, 5th and 95th percentiles in red. Coloured lines: 5 replicate worm plots.

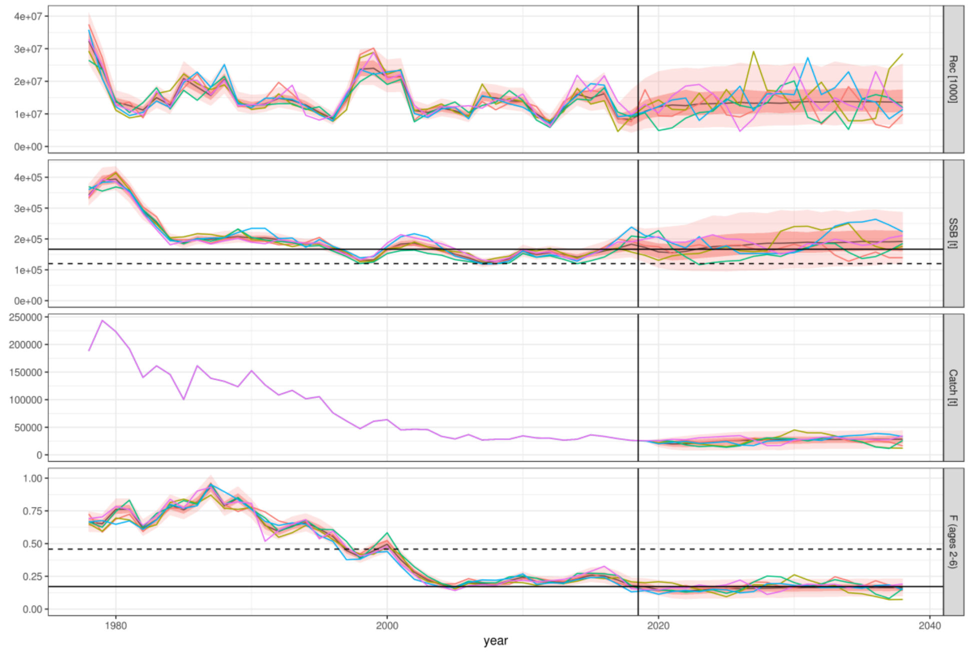


Figure 5.4.2.2 Whiting in Subarea 4 and Division 7.d. Summary projections for HCR A* (F_{target}=F_{MSY}=0.172 and $B_{trigger}$=166 708t). MSY $B_{trigger}$ (SSB, black horizontal line), B_{lim} (SSB, black dashed horizontal line), F_{lim} (dashed black), F_{MSY} (solid black). Median values and 25th, 75th, 5th and 95th percentiles in red. Coloured lines: 5 replicate worm plots.

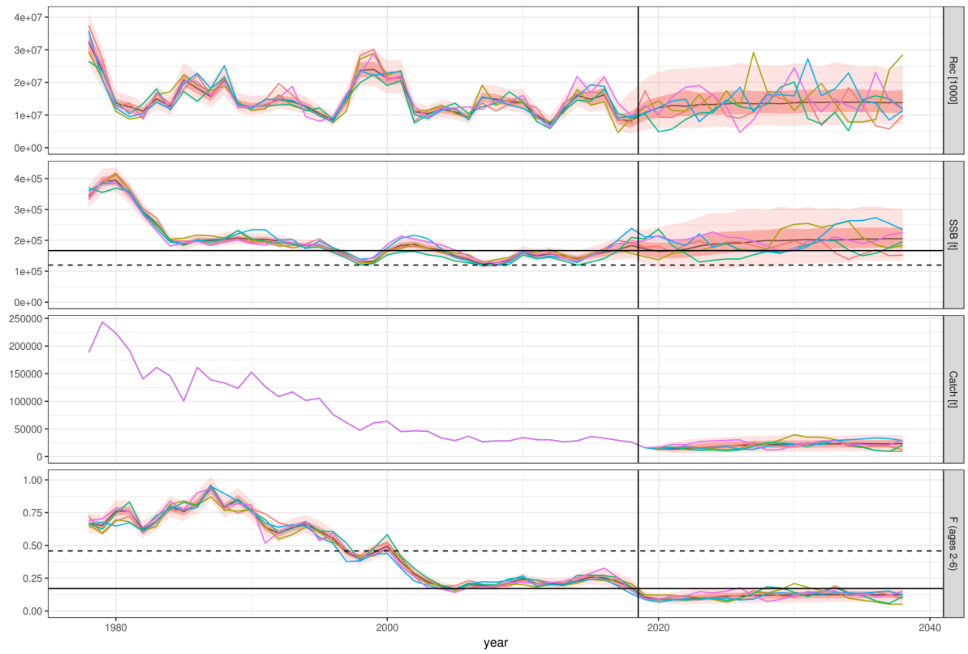


Figure 5.4.2.3 Whiting in Subarea 4 and Division 7.d. Summary projections for HCR A (F_{target}=0.14 and $B_{trigger}$=220 000 t). MSY $B_{trigger}$ (SSB, black horizontal line), B_{lim} (SSB, black dashed horizontal line), F_{lim} (dashed black), F_{MSY} (solid black). Median values (black) and 25th, 75th, 5th and 95th percentiles in red. Coloured lines: 5 replicate worm plots.

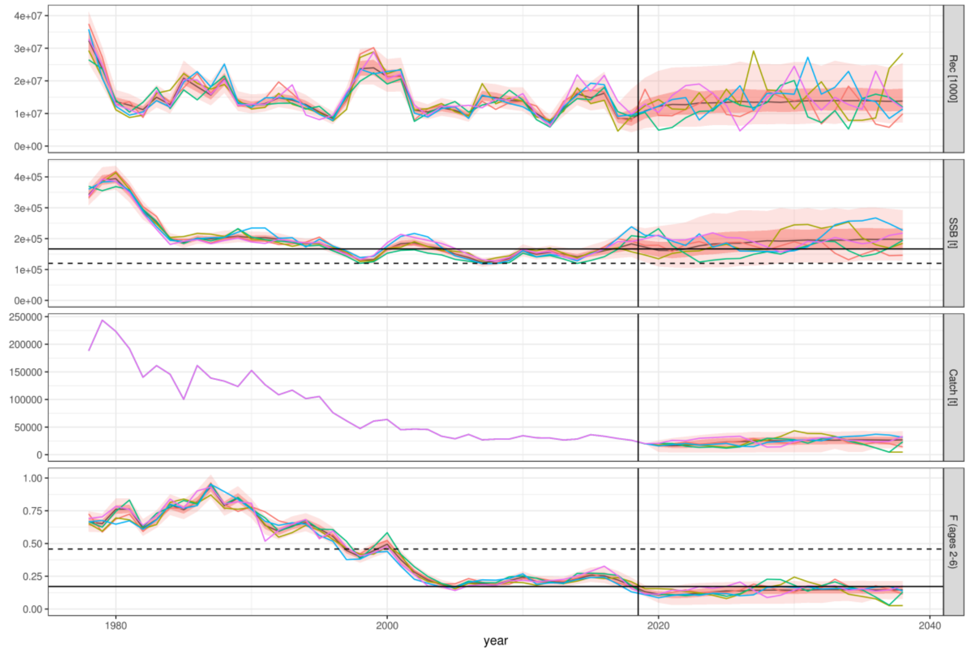


Figure 5.4.2.4 Whiting in Subarea 4 and Division 7.d. Summary projections for HCR B (F_{target}=0.16 and $B_{trigger}$=200 000 t). MSY $B_{trigger}$ (SSB, black horizontal line), B_{lim} (SSB, black dashed horizontal line), F_{lim} (dashed black), F_{MSY} (solid black). Median values and 25th, 75th, 5th and 95th percentiles in red. Coloured lines: 5 replicate worm plots.

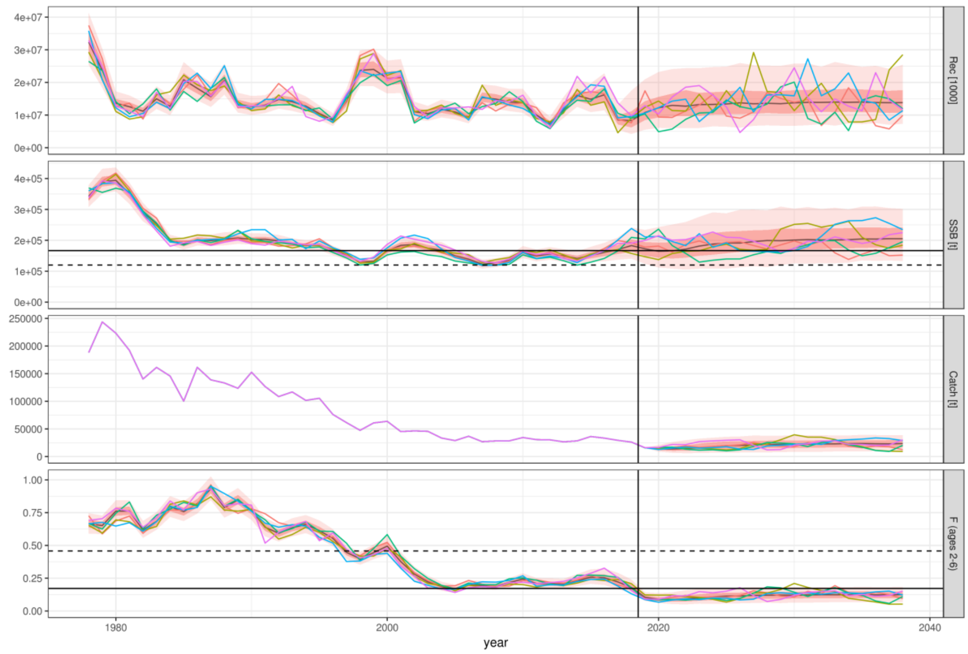


Figure 5.4.2.5 Whiting in Subarea 4 and Division 7.d. Summary projections for HCR C (F_{target}=0.14 and $B_{trigger}$=220 000 t). MSY $B_{trigger}$ (SSB, black horizontal line), B_{lim} (SSB, black dashed horizontal line), F_{lim} (dashed black), F_{MSY} (solid black). Median values and 25th, 75th, 5th and 95th percentiles in red. Coloured lines: 5 replicate worm plots.

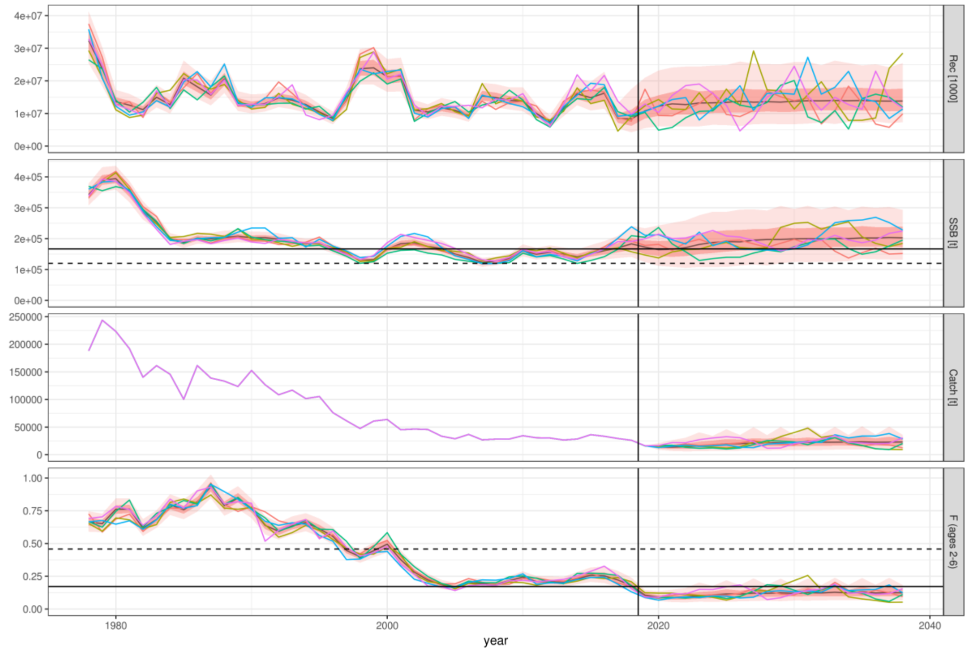


Figure 5.4.2.6 Whiting in Subarea 4 and Division 7.d. Summary projections for HCR A+D (F_{target}=0.16 and $B_{trigger}$=250 000 t). MSY $B_{trigger}$ (SSB, black horizontal line), B_{lim} (SSB, black dashed horizontal line), F_{lim} (dashed black), F_{MSY} (solid black). Median values and 25th, 75th, 5th and 95th percentiles in red. Coloured lines: 5 replicate worm plots.

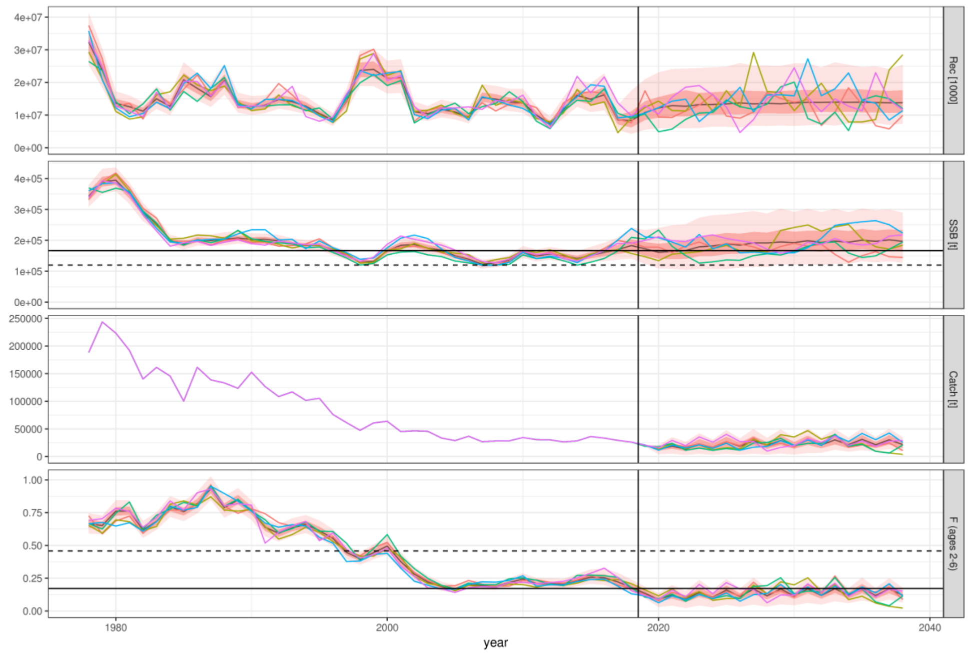


Figure 5.4.2.7 Whiting in Subarea 4 and Division 7.d. Summary projections for HCR B+E (F_{target}=0.16 and $B_{trigger}$=210 000 t). MSY $B_{trigger}$ (SSB, black horizontal line), B_{lim} (SSB, black dashed horizontal line), $B_{trigger}$ (SSB, grey horizontal line), F_{lim} (dashed black), F_{MSY} (solid black). Median values and 25th, 75th, 5th and 95th percentiles in red. Coloured lines: 5 replicate worm plots.

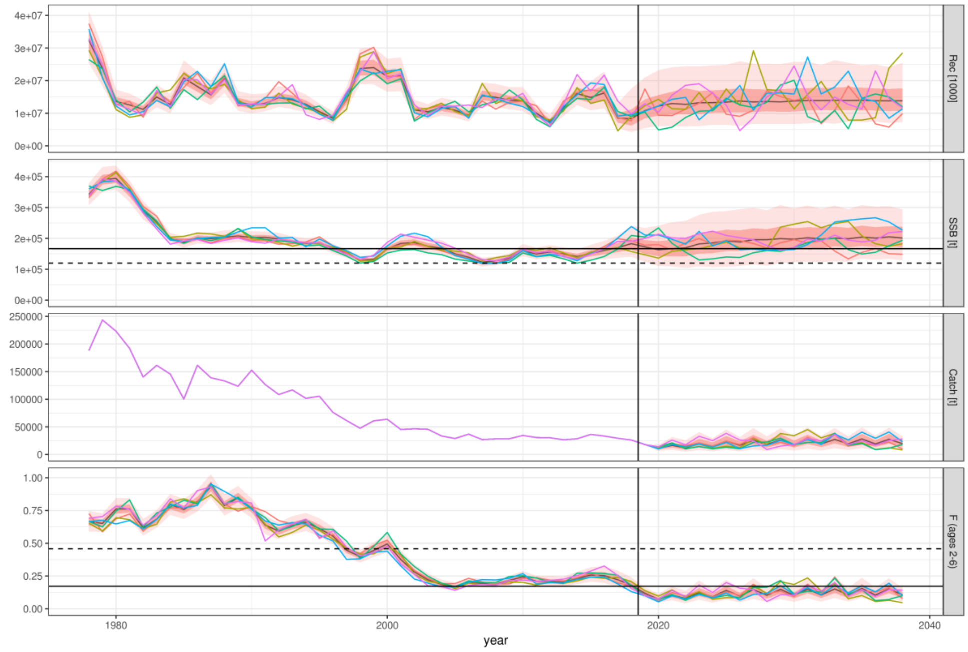


Figure 5.4.2.8 Whiting in Subarea 4 and Division 7.d. Summary projections for HCR C+E (F_{target}=0.15 and $B_{trigger}$=230 000 t). MSY $B_{trigger}$ (SSB, black horizontal line), B_{lim} (SSB, black dashed horizontal line), F_{lim} (dashed black), F_{MSY} (solid black). Median values and 25th, 75th, 5th and 95th percentiles in red. Coloured lines: 5 replicate worm plots.

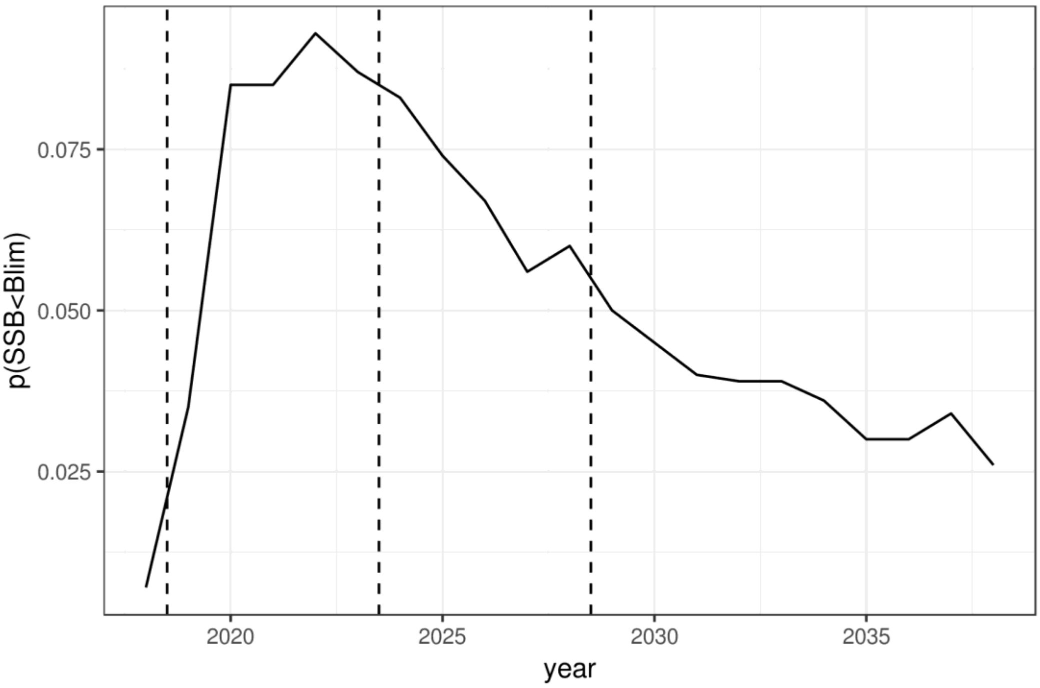


Figure 5.4.2.9. Whiting in Subarea 4 and Division 7.d. Annual risk (P(SSB<B_{lim})) for “optimised” management strategy A. The horizontal hashed lines separate the short- medium- and long-term projection periods used for the performance statistics.

5.4.3 Comparison of management strategies for the baseline OM1

The performance of F=0, a version of management strategy A that sets F_{target}=F_{MSY}=0.172 and $B_{trigger}$=MSY $B_{trigger}$=166 708 t (labelled A*), and the six “optimised” management strategies are compared in terms of catch, risk1 and risk3, inter-annual catch variability, SSB and realized F in the short (first five years), medium (years 6–10) and long (final 10 years) term in Figures 5.4.3.1–3.

Figure 5.4.3.3 and Table 5.4.3.1a illustrate long-term characteristics and illustrates that management strategies A and C perform similarly in terms of catch and SSB. In comparison, the “optimised” pair for B has higher F_{target} and lower $B_{trigger}$ leading to catches that are slightly higher while SSB is slightly lower (Table 5.4.3.1a). This indicates that for SSB below B_{lim} the SSB/$B_{trigger}$ ratio drives the fishing mortality in C (in a similar way to A). If SSB falls below B_{lim}, B leads to stronger reduction in fishing mortality (0.25*F_{target}) allowing for a higher “optimal” F_{target} value.

Due to higher catches for management strategies B and B+E, risk3 and risk1 in the short and medium term are slightly higher than for the other management strategies (Figure 5.4.3.1-2). Short-term results are listed in Table 5.2.1b. All management strategies were found to be non-precautionary in the short-term, apart from F=0. The MSY rule, F_{target}=F_{msy} together with MSY $B_{trigger}$ using HCR A (HCR A*) was found to be non-precautionary, even in the long-term.

All management strategies lead to a stock with SSB around 200 000t in the long-term. AD, BE and CE lead to higher interannual catch variability compared to the other management strategies. For all management strategies, median SSB is below “optimal” $B_{trigger}$ and realized F is below “optimal” F_{target}. In all simulations, the SAM estimation converged and the maximum value of F=2 was never reached (Table 5.4.3.1a-b). As the stock is currently very close to MSY $B_{trigger}$, the recovery potential is very high among all tested HCRs (Figure 5.4.3.4).

Table 5.4.3.1a Whiting in Subarea 4 and Division 7.d. MSE results for F=0, MSY rule (A*), and for “optimised” pairs of F_{target} and $B_{trigger}$ from grid search to ensure risk3 not below 5% and maximum yield <u>in the long-term (last 10 years)</u>. Median catch, SSB, interannual catch variability (icv), interannual TAC variability (itv), risk3, risk1, realized F in the long-term, as well as number of replicates with convergence failure, times to hit Fmax=2.

HCR	F_{trgt}	$B_{trigger}$	catch	SSB	icv	itv	risk3	risk1	Realized F	conv_failed	F_maxed
F0	0	-	0	259460	1	NA	0.01	0.007	0	0	0
A*	0.172	166708	27974	189125	0.118	0.118	0.084	0.068	0.163	0	0
A	0.14	220000	22832	202702	0.140	0.139	0.050	0.037	0.123	0	0
B	0.16	200000	26308	195791	0.131	0.131	0.049	0.042	0.146	0	0
C	0.14	220000	22844	202678	0.140	0.139	0.050	0.037	0.123	0	0
A+D	0.16	250000	22534	201011	0.205	0.16	0.050	0.038	0.124	0	0
B+E	0.16	210000	24846	196370	0.369	0.142	0.050	0.041	0.139	0	0
C+E	0.15	230000	22855	200634	0.363	0.15	0.050	0.040	0.124	0	0

Table 5.4.3.1b Whiting in Subarea 4 and Division 7.d. MSE results for F=0, MSY rule (A*), and for "optimised" pairs of F_{target} and $B_{trigger}$ from grid search to ensure risk3 not below 5% and maximum yield in the short-term (first 5 years). Median catch, SSB, interannual catch variability (icv), interannual TAC variability (itv), risk3, risk1, realized F in the short-term, as well as number of replicates with convergence failure, times to hit Fmax=2.

HCR	F_{trgt}	$B_{trigger}$	catch	SSB	icv	itv	risk3	risk1	Real-ized F	conv_failed	F_maxed
F0	0	-	0	185794	1	NA	0.036	0.034	0	0	0
A*	0.172	166708	23784	162835	0.11	0.159	0.149	0.118	0.149	0	0
A	0.14	220000	15813	170586	0.236	0.179	0.093	0.077	0.095	0	0
B	0.16	200000	19410	167463	0.226	0.175	0.104	0.087	0.118	0	0
C	0.14	220000	15728	170630	0.234	0.178	0.092	0.077	0.095	0	0
A+D	0.16	250000	15898	170506	0.245	0.181	0.093	0.077	0.096	0	0
B+E	0.16	210000	18505	168266	0.345	0.178	0.099	0.081	0.114	0	0
C+E	0.15	230000	16292	170233	0.341	0.182	0.098	0.078	0.099	0	0

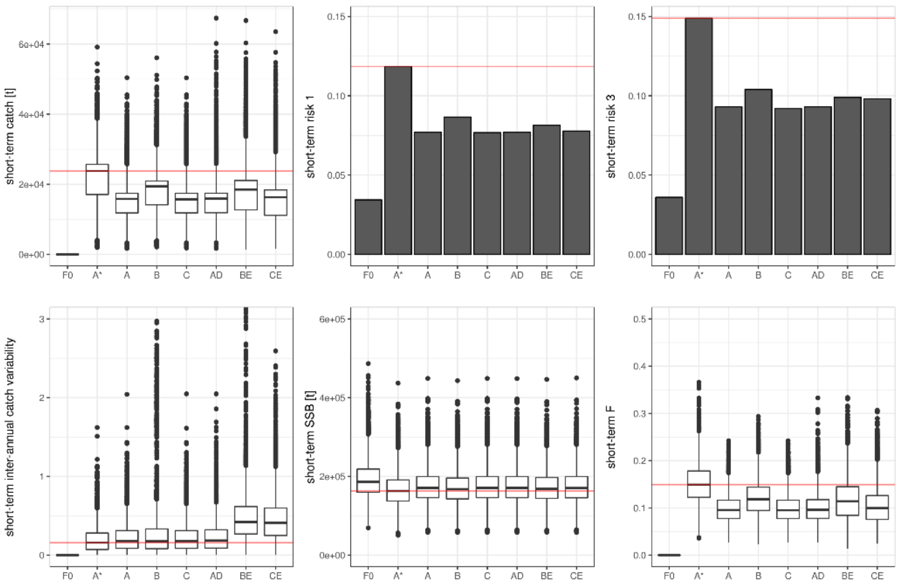


Figure 5.4.3.1 Whiting in Subarea 4 and Division 7.d. HCR comparison (short-term: years 1-5) for baseline OM. Boxplots for catches, risk1, risk3, inter-annual catch variability, SSB, realized F (mean age 2-6). Where HCR F0 represents a fishing moratorium (F_{target}=0), HCR A* represents HCR A with F_{target}=F_{MSY} and $B_{trigger}$=MSY $B_{trigger}$. For comparison, the red horizontal line corresponds to the value for HCR A*.

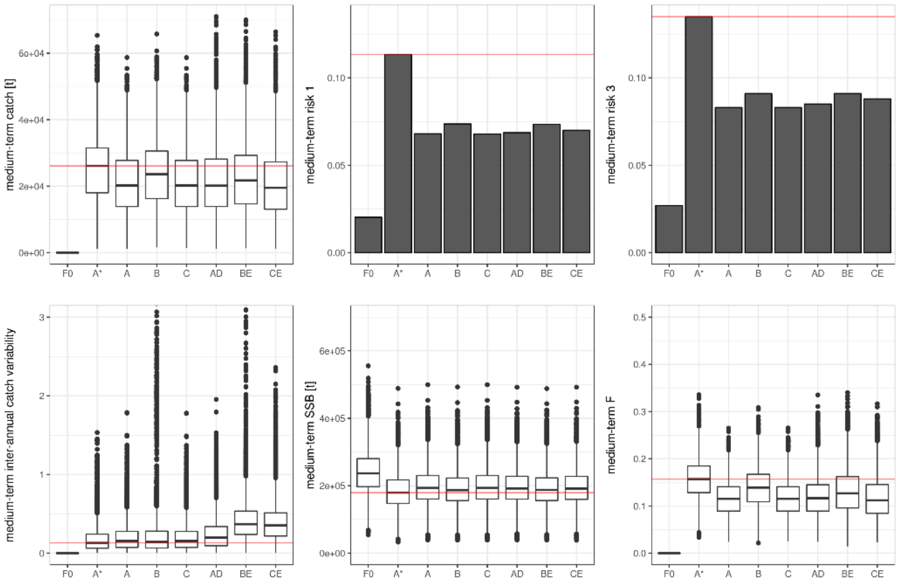


Figure 5.4.3.2 Whiting in Subarea 4 and Division 7.d. HCR comparison (medium-term: years 6-10) for baseline OM. Boxplots for catches, risk1, risk3, inter-annual catch variability, SSB, realized F (mean age 2-6). Where HCR F0 represents a fishing moratorium (F_{target}=0), HCR A* represents HCR A with F_{target}=F_{MSY} and $B_{trigger}$=MSY $B_{trigger}$. For comparison, the red horizontal line corresponds to the value for HCR A*.

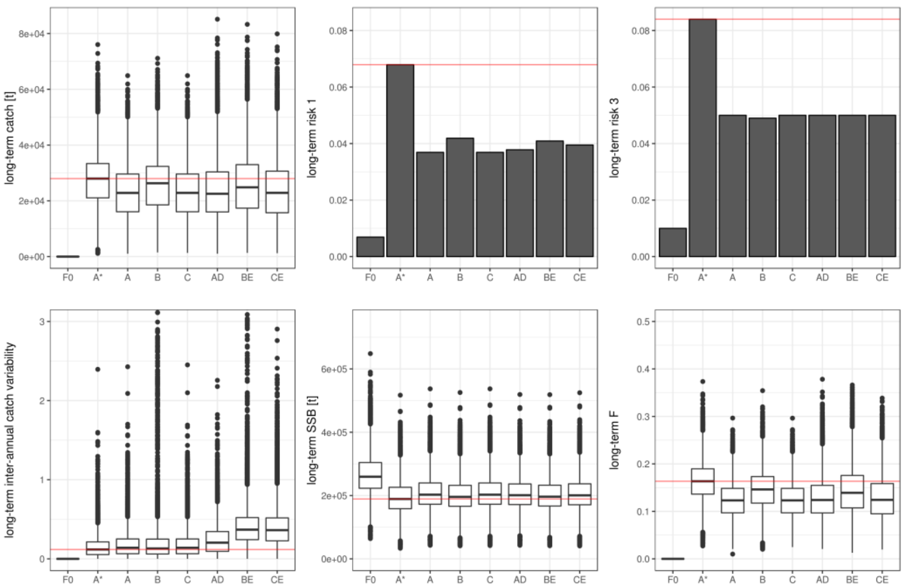


Figure 5.4.3.3 Whiting in Subarea 4 and Division 7.d. HCR comparison (long-term: last 10 years) for baseline OM. Boxplots for catches, risk1, risk3, inter-annual catch variability, SSB, realized F (mean age 2-6). Where HCR F0 represents a fishing moratorium (F_{target}=0), HCR A* represents HCR A with F_{target}=F_{MSY} and $B_{trigger}$=MSY $B_{trigger}$. For comparison, the red horizontal line corresponds to the value for HCR A*.

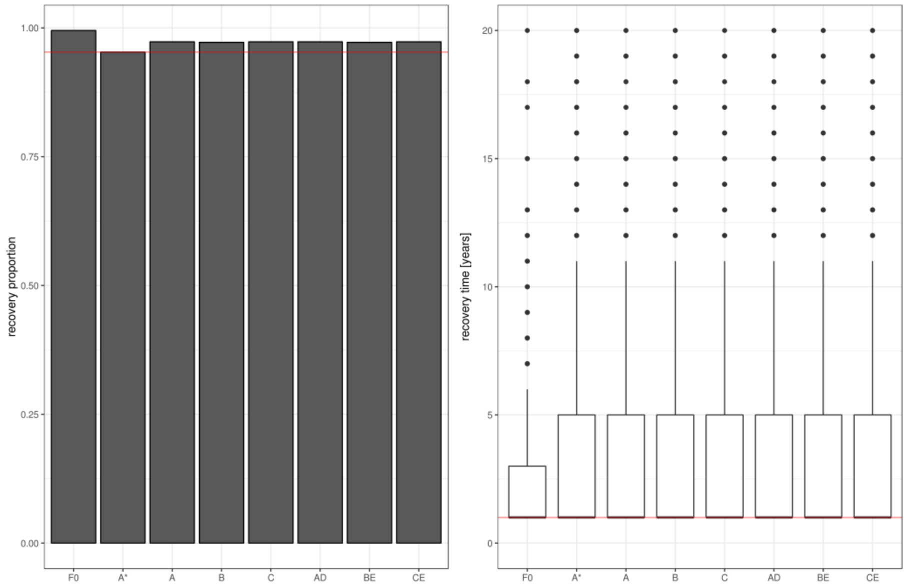


Figure 5.4.3.4 Whiting in Subarea 4 and Division 7.d. Recovery statistics for the HCRs, proportion of replicates that recover above B_{pa}=MSY $B_{trigger}$ until the end of the projection period (left). The number of years taken to recover above B_{pa}=MSY $B_{trigger}$ for the first time (right).

5.4.4 Sensitivity of management strategies for the baseline OM1

The sensitivity of performance statistics for the six "optimised" HCRs (A, B, C, A+D, B+E and C+E) to five fishing scenarios (0.9*F_{target}, F_{target}, 1.1*F_{target}, $F_{MSY-lower}$=0.158 and $F_{MSY-upper}$=0.172) in the short (first five years), medium (years 6–10) and long (final 10 years) term are presented in Figures 5.4.4.19-21.

The different F_{target} values are listed in Table 5.4.4.1. Three of the fishing scenarios, 1.1*F_{target}, F_{msy} and $F_{msy-upper}$, are not precautionary in the long-term (Figure 5.4.4.21). For management strategies A, C and C+E, $F_{msy-lower}$ is larger than F_{target}, and $F_{msy-lower}$ was found to be non-precautionary in the long term.

Table 5.4.4.1 Whiting in Subarea 4 and Division 7.d. Sensitivity runs.

	0.9F_{target}	**F_{target}**	**1.1F_{target}**	**$B_{trigger}$**
A	0.126	0.14	0.154	220 000
B	0.144	0.16	0.176	200 000
C	0.126	0.14	0.154	220 000
A+D	0.144	0.16	0.176	250 000
B+E	0.144	0.16	0.176	210 000
C+E	0.135	0.15	0.165	230 000

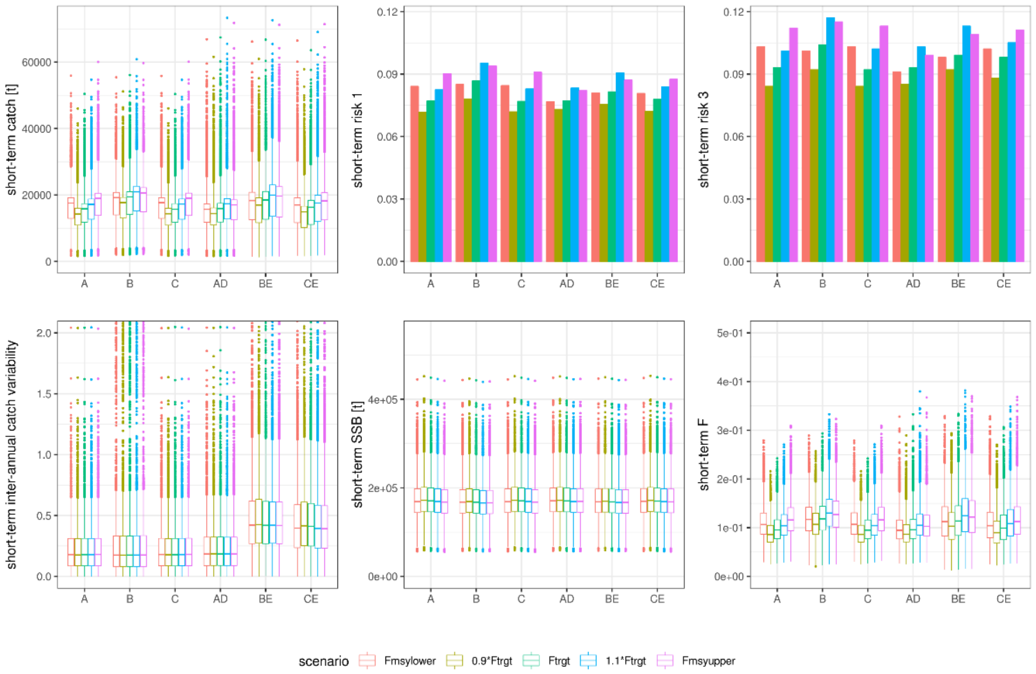


Figure 5.4.4.1 Whiting in Subarea 4 and Division 7.d. HCR comparison (short-term: first 5 years) to a range of F values $0.9F_{target}$, $1.1F_{target}$, $F_{MSY\text{-}lower}$, $F_{MSY\text{-}upper}$. Boxplots for catches, risk1, risk3, inter-annual catch variability, SSB, realized F (mean age 2-6).

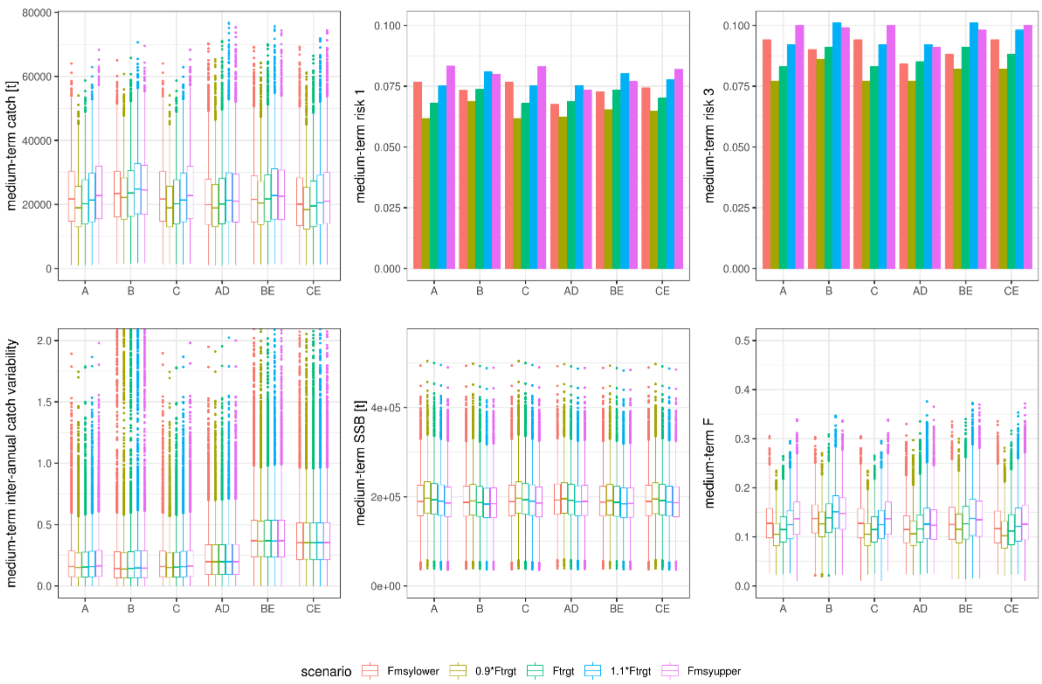


Figure 5.4.4.2 Whiting in Subarea 4 and Division 7.d. HCR comparison (medium-term: years 6-10) to a range of F values $0.9F_{target}$, $1.1F_{target}$, $F_{MSY\text{-}lower}$, $F_{MSY\text{-}upper}$. Boxplots for catches, risk1, risk3, inter-annual catch variability, SSB, realized F (mean age 2-6).

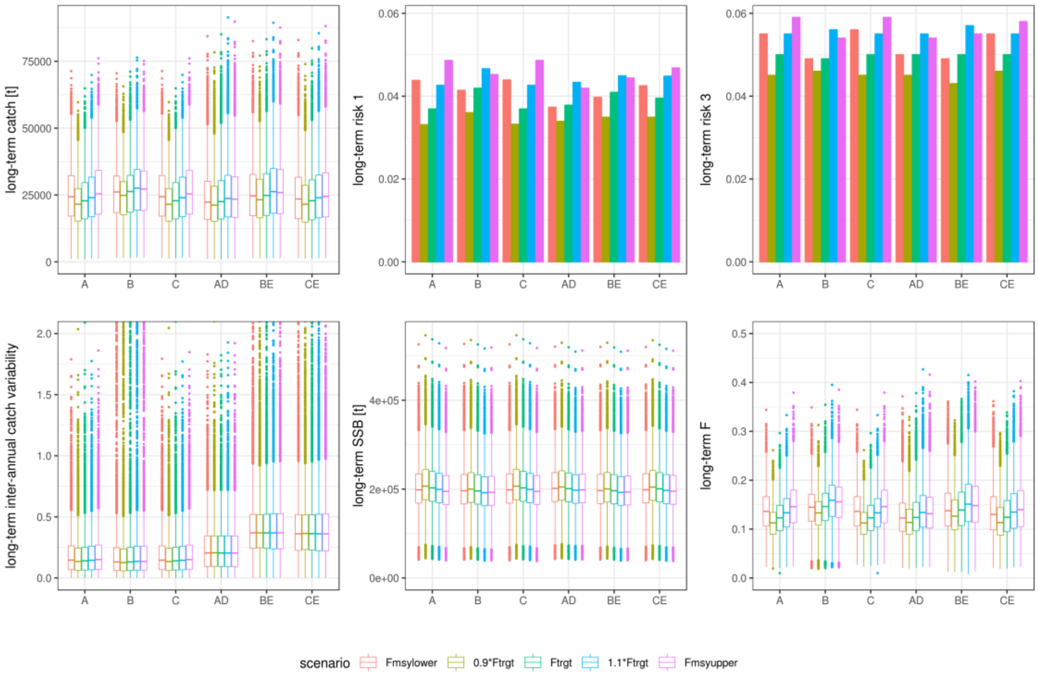


Figure 5.4.4.3 Whiting in Subarea 4 and Division 7.d. HCR comparison (long-term: last 10 years) to a range of F values 0.9F_{target}, 1.1F_{target}, $F_{MSY-lower}$, $F_{MSY-upper}$. Boxplots for catches, risk1, risk3, inter-annual catch variability, SSB, realized F (mean age 2-6).

5.4.5 Robustness of management strategies across alternative OMs

Robustness of the "optimised" management strategies (A, B, C, A+D, B+E, C+E) across alternative operating models (OM2 and OM3, described in Sections 5.2) is evaluated in the short, medium and long term. Performance statistics for each management strategy are compared across operating models and to performance statistics for F=0 and HCR A* (for which F_{target}=F_{MSY}=0.172 and $B_{trigger}$=MSY $B_{trigger}$=166 708t) (Tables 5.4.5.1a-b and 5.4.5.12-b; Figures 5.4.5.1-4). The risk increases with OM2 and OM3 due to the lower recruitment level simulated for the projection period. Both SSB and catches are lower using the alternative operating models. Including extra implementation error on catch leads to only minor differences under lower recruitment option (OM3). For OM3 in comparison to OM2, risk3 increases only slightly for the HCRs, and inter-annual catch variability is slightly larger as would be expected. The extra implementation error did not affect median SSB, realized F and median catches.

In Figure 5.4.5.5, the ratios of SSB and F between the management procedure and the underlying operating are shown for "optimised" management strategy A. This illustrates how well perception reflects the "true" status. The peak in F near the beginning of the projection period indicates overestimation of F and underestimation of SSB, which is likely due to a period of adjustment for SAM due to a change in management strategy at the start of the projection period (Figure 5.4.2.3). However, in the long term, as F and SSB stabilize, the difference disappears and median F and median SSB in the management procedure and operating model are similar.

Table 5.4.5.1a Whiting in Subarea 4 and Division 7.d. Short-term MSE results for alternative operating model OM 2 using optimized pairs of F_{target} and $B_{trigger}$. Median catch, SSB, interannual catch variability (icv), risk3, risk1, realized F in the short-term (first 5 years), as well as number of replicates with convergence failure, times to hit Fmax=2.

HCR	F_{trgt}	$B_{trigger}$	catch	SSB	icv	risk3	risk1	Real-ized F	conv_failed	F_maxed
F0	0	166708	0	178126	1	0.057	0.049	0	0	0
A*	0.172	166708	21984	155431	0.12	0.236	0.165	0.147	0	0
A	0.14	220000	14972	163183	0.232	0.154	0.108	0.093	0	0
B	0.16	200000	17922	160197	0.225	0.163	0.121	0.115	0	0
C	0.14	220000	14972	163183	0.232	0.154	0.108	0.093	0	0
A+D	0.16	250000	15036	163123	0.237	0.155	0.108	0.093	0	0
B+E	0.16	210000	17062	160898	0.352	0.157	0.117	0.11	0	0
C+E	0.15	230000	14978	162899	0.338	0.151	0.11	0.096	0	0

Table 5.4.5.1b Whiting in Subarea 4 and Division 7.d. Long-term MSE results for alternative operating model OM 2 using optimized pairs of F_{target} and $B_{trigger}$. Median catch, SSB, interannual catch variability (icv), risk3, risk1, realized F in the long-term (last 10 years), as well as number of replicates with convergence failure, times to hit Fmax=2.

HCR	F_{trgt}	$B_{trigger}$	catch	SSB	icv	risk3	risk1	Real-ized F	conv_failed	F_maxed
F0	0	166708	0	224171	1	0.037	0.026	0	0	0
A*	0.172	166708	22673	161703	0.141	0.195	0.182	0.152	0	0
A	0.14	220000	17118	175545	0.16	0.124	0.109	0.108	0	0
B	0.16	200000	19918	169603	0.15	0.133	0.12	0.131	0	0
C	0.14	220000	17118	175545	0.159	0.124	0.109	0.108	0	0
A+D	0.16	250000	17072	174824	0.193	0.125	0.11	0.108	0	0
B+E	0.16	210000	19163	170321	0.386	0.134	0.117	0.124	0	0
C+E	0.15	230000	17179	174024	0.365	0.126	0.113	0.109	0	0

Table 5.4.5.2a Whiting in Subarea 4 and Division 7.d. Short-term MSE results for alternative operating model OM 3 using optimized pairs of F_{target} and $B_{trigger}$. Median catch, SSB, interannual catch variability (icv), risk3, risk1, realized F in the short-term (first 5 years), as well as number of replicates with convergence failure, times to hit Fmax=2.

HCR	F_{trgt}	$B_{trigger}$	catch	SSB	icv	risk3	risk1	Real-ized F	conv_failed	F_maxed
F0	0	166708	0	178126	1	0.057	0.049	0	0	0
A*	0.172	166708	21895	155339	0.137	0.235	0.165	0.145	0	0
A	0.14	220000	14606	163175	0.247	0.156	0.108	0.092	0	0
B	0.16	200000	17815	160138	0.215	0.166	0.121	0.115	0	0
C	0.14	220000	14658	163094	0.248	0.156	0.108	0.092	0	0
A+D	0.16	250000	14735	163041	0.253	0.156	0.108	0.093	0	0
B+E	0.16	210000	17071	160995	0.352	0.157	0.116	0.109	0	0
C+E	0.15	230000	15055	163066	0.358	0.152	0.11	0.095	0	0

Table 5.4.5.2b Whiting in Subarea 4 and Division 7.d. Long-term MSE results for alternative operating model OM 3 using optimized pairs of F_{target} and $B_{trigger}$. Median catch, SSB, interannual catch variability (icv), risk3, risk1, realized F in the long-term (last 10 years), as well as number of replicates with convergence failure, times to hit Fmax=2.

HCR	F_{trgt}	$B_{trigger}$	catch	SSB	icv	risk3	risk1	Real-ized F	conv_failed	F_maxed
F0	0	166708	0	224171	1	0.037	0.026	0	0	0
A*	0.172	166708	22532	161506	0.157	0.198	0.183	0.151	0	0
A	0.14	220000	17098	175421	0.173	0.126	0.109	0.108	0	0
B	0.16	200000	19910	169582	0.171	0.133	0.12	0.131	0	0
C	0.14	220000	17088	175430	0.172	0.126	0.109	0.108	0	0
A+D	0.16	250000	17053	174641	0.203	0.128	0.111	0.108	0	0
B+E	0.16	210000	19089	170284	0.386	0.133	0.117	0.123	0	0
C+E	0.15	230000	17171	173681	0.369	0.128	0.114	0.108	0	0

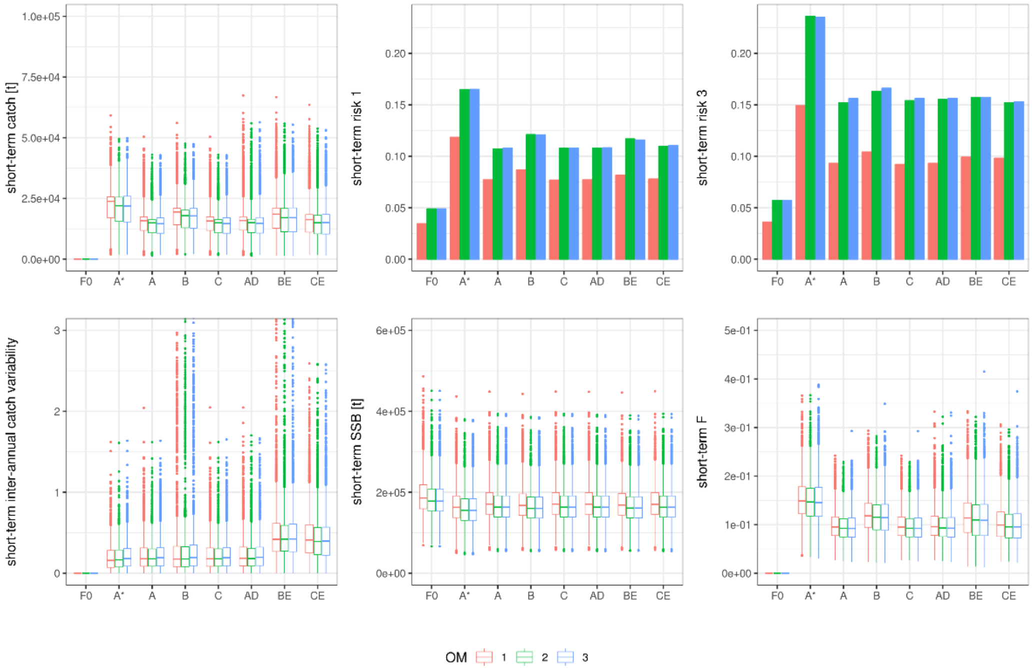


Figure 5.4.5.1 Whiting in Subarea 4 and Division 7.d. HCR comparison (short-term: first 5 years) to alternative operating models. Boxplots for catches, risk1, risk3, inter-annual catch variability, SSB, realized F (mean age 2-6). Where HCR F0 represents a fishing moratorium (F_{target}=0), HCR A* represents HCR A with F_{target}=F_{MSY} and $B_{trigger}$=MSY $B_{trigger}$.

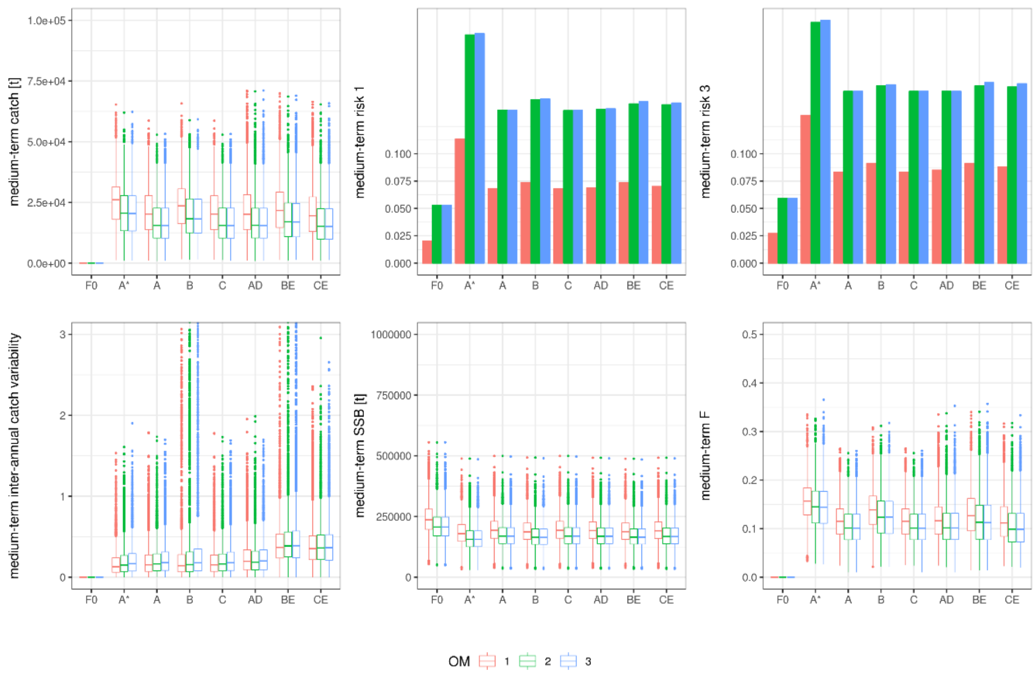


Figure 5.4.5.2 Whiting in Subarea 4 and Division 7.d. HCR comparison (medium-term: years 6-10) to alternative operating models. Boxplots for catches, risk1, risk3, inter-annual catch variability, SSB, realized F (mean age 2-6). Where HCR F0 represents a fishing moratorium (F_{target}=0), HCR A* represents HCR A with F_{target}=F_{MSY} and $B_{trigger}$=MSY $B_{trigger}$.

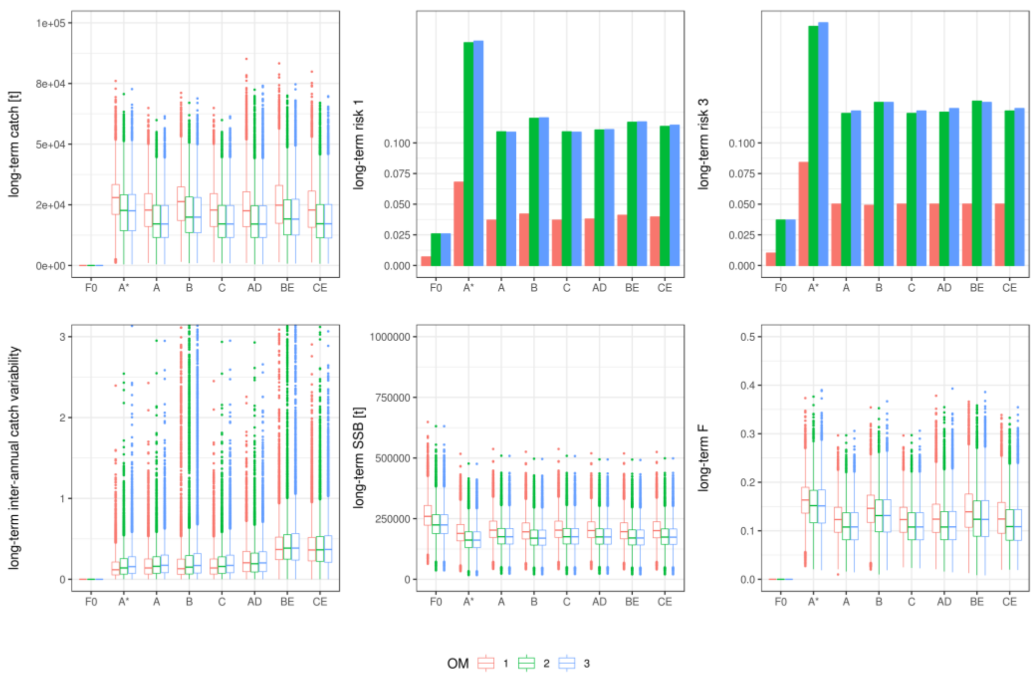


Figure 5.4.5.3 Whiting in Subarea 4 and Division 7.d. HCR comparison (log-term: last 10 years) to alternative operating models. Boxplots for catches, risk1, risk3, inter-annual catch variability, SSB, realized F (mean age 2-6). Where HCR F0 represents a fishing moratorium (F_{target}=0), HCR A* represents HCR A with F_{target}=F_{MSY} and $B_{trigger}$=MSY $B_{trigger}$.

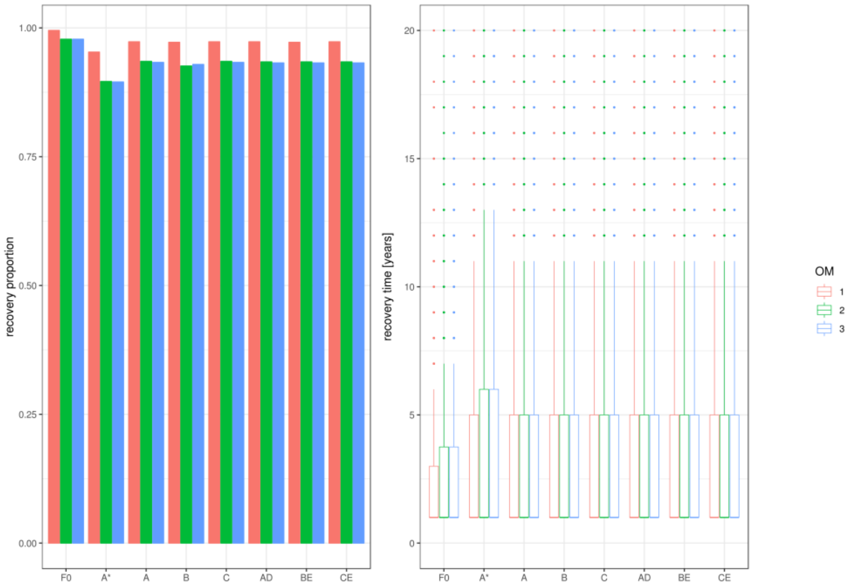


Figure 5.4.5.4 Whiting in Subarea 4 and Division 7.d. HCR comparison (log-term: last 10 years) to alternative operating models. Boxplots for catches, risk1, risk3, inter-annual catch variability, SSB, realized F (mean age 2-6). Where HCR F0 represents a fishing moratorium (F_{target}=0), HCR A* represents HCR A with F_{target}=F_{MSY} and $B_{trigger}$=MSY $B_{trigger}$.

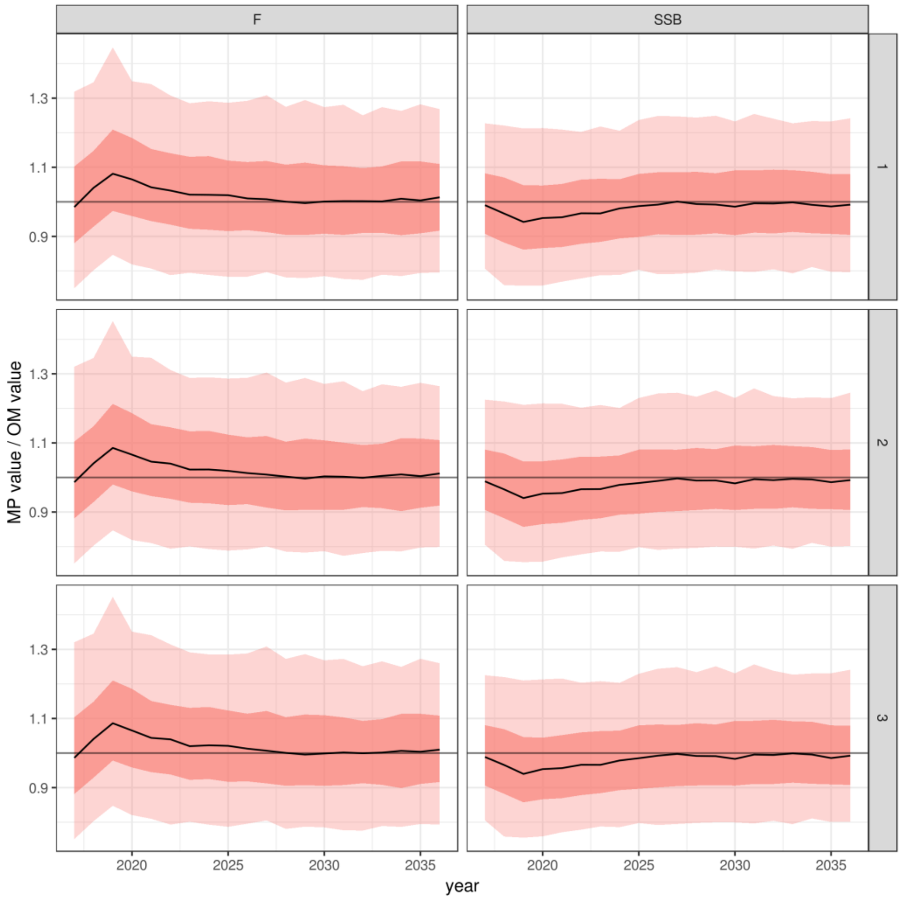


Figure 5.4.5.5 Whiting in Subarea 4 and Division 7.d. Comparison of projection results for HCR A across different operating models (1, 2, 3) between estimated F and SSB (MP) and "true" F and SSB (OM). Shown are median ratios and 25th, 75th, 5th and 95th percentiles.

5.5 Conclusions

"Optimised" combinations without stability

- A and C perform similarly because the optimal F_{target} and $B_{trigger}$ are the same and because these HCRs would result in the same catch target unless SSB is at very low level.
- B results in a slightly higher long-term catch and slightly lower SSB. While long-term risk3 is around 0.05 for all HCRs (optimised to the long-term), in the short term, B produces slightly higher risk3 than the other management strategies. In the short term, risk3 was lowest for A, C, A+D.
- For all management strategies, the short term risk3 is above 5%.
- In all management strategies, median SSB in the long-term is below the respective $B_{trigger}$ and realized F is below F_{target}, indicating the HCRs are operating "on the slope".

"Optimised" combinations with stability

- When stability mechanisms are included, median long-term catch is slightly reduced, and ICV increased for all management strategies (but to a lesser degree for A+D) due to the extreme banking and borrowing scheme implemented.

- $B_{trigger}$ are higher for the management strategies that include stability mechanisms, particularly A+D. This is likely due to the differences in the application of the banking and borrowing scheme (only when SSB≥$B_{trigger}$ for A+D, but throughout for B+E and C+E as long as certain safeguarding conditions are met).
- F_{target} and catches are highest for B+E, but catches are still lower compared to B.
- For all management strategies, the short term risk3 is above 5%.

Compared to MSY advice rule approach and F=0

- The MSY approach advice rule (A*) produces a slightly higher long-term catch than the six "optimised" management strategies, but with a much higher risk and ICV, and lower SSB.
- The MSY approach advice rule (A*) is not precautionary in the long-term and short-term.
- Short-term risk is lower than 5% only if F=0.
- Recovery to above MSY $B_{trigger}$ is 1 year in all cases, and recovery proportion approaches 100% for F=0.

Sensitivity for "Optimised" Combinations

- Short-, medium- and long-term catches are similar across the F ranges for the sensitivity tests, but lowest for 0.9F_{target}, which has a consistently lower value.
- For A, C and C+E, $F_{MSY\text{-}lower}$ is larger than the respective F_{target}, and therefore leads to long-term risk above 5%.
- Long-term risk is always above 5% for 1.1F_{target} and $F_{MSY\text{-}upper}$.

Robustness tests against alternative operating models

- All "optimised" management strategies fail the precautionary check [risk3≤5%] under the alternative operating models that includes recruitment level shifts (pessimistic recruitment scenarios).
- The effect of catch variability due to industrial bycatch can lead to very slight increases in risk3, but are less concerning than the recruitment effects
- This result indicates that if future recruitment remains at a relatively low level compared to the data series since 1983, more precautionary management strategies are needed.

Computational considerations

- The simulations required for this MSE were computationally very expensive and it was not possible to run the full grid for all management strategies. Computing facilities available in-house were used together with external resources.

6 Saithe (*Pollachius virens*) in subareas 4 and 6, and in Division 3.a (North Sea, Rockall and West of Scotland, Skagerrak and Kattegat)

6.1 Baseline operating model (OM1)

6.1.1 Model and settings

The baseline operating model was conditioned on the IBP SAM assessment for North Sea saithe (ICES 2019b). The assessment includes the year effects in the IBTS Q3 survey by introducing unstructured correlated errors between age classes (Berg and Nielsen 2016). Figures 6.1.1-6 show the assessment summaries and fits to data.

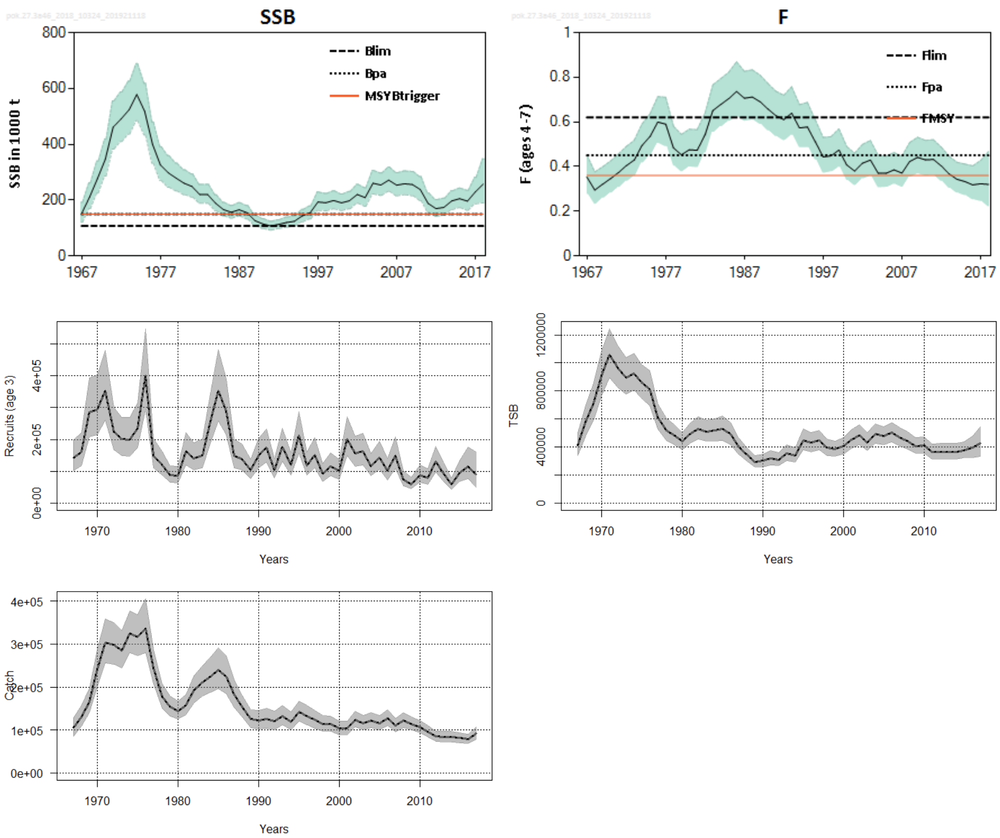


Figure 6.1.1. Saithe in Subareas 4 and 6 and Division 3a: Clockwise from top left, estimates and 95% confidence intervals of spawning stock biomass (SSB), mean fishing mortality for ages 4–7, total stock biomass (TSB), catch, and recruitment (R(age 3)) from the final SAM assessment. The heavy lines represent the point-wise estimate, and the shaded areas the confidence intervals. The horizontal broken lines in the SSB plot indicate B_{lim}=107 297 t and B_{pa}=149 098 t, and in the mean F plot F_{lim}=0.62, F_{pa}=0.45 and F_{MSY}=0.36. Catch, SSB and TSB are in tonnes, and R in thousands.

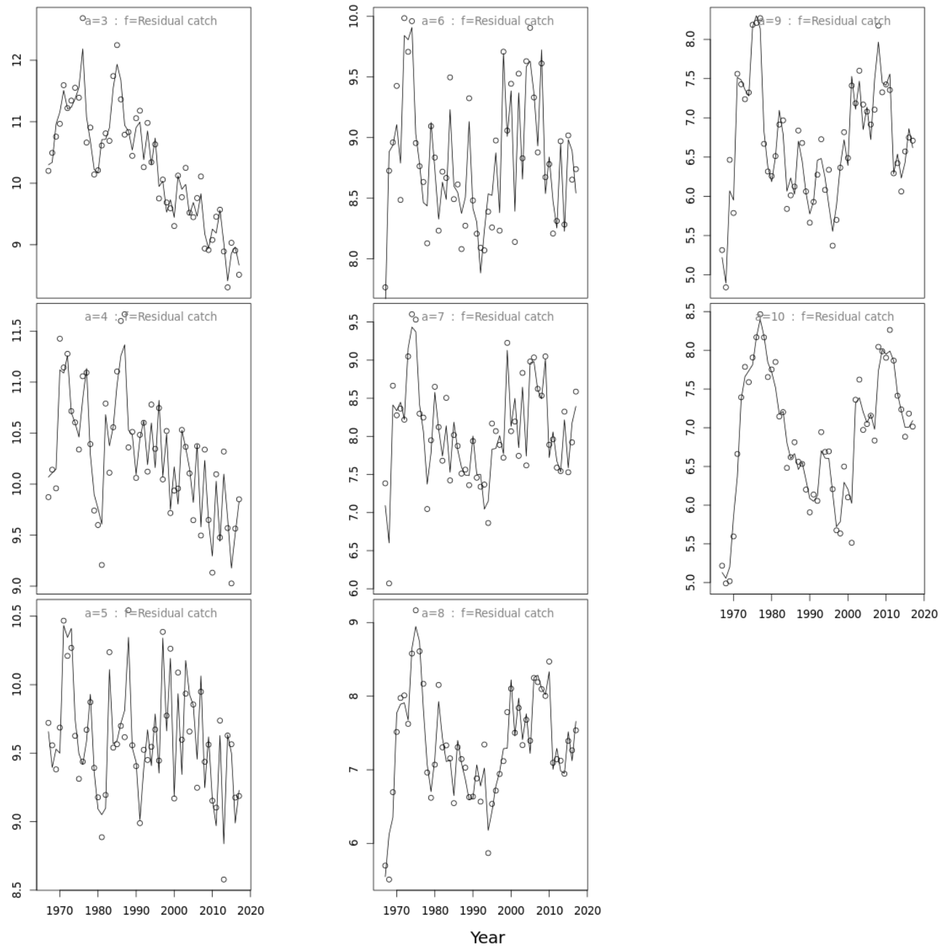


Figure 6.1.2. Saithe in Subareas 4 and 6 and Division 3a: Fits to catch-at-age data.

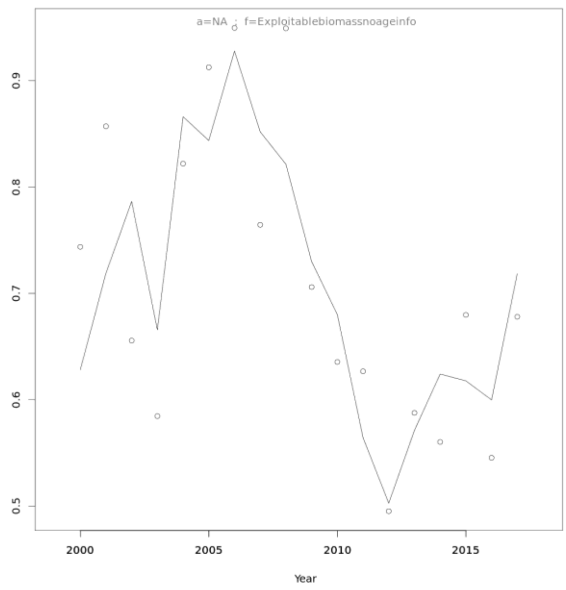


Figure 6.1.3. Saithe in Subareas 4 and 6 and Division 3a: Fits to exploitable biomass index data.

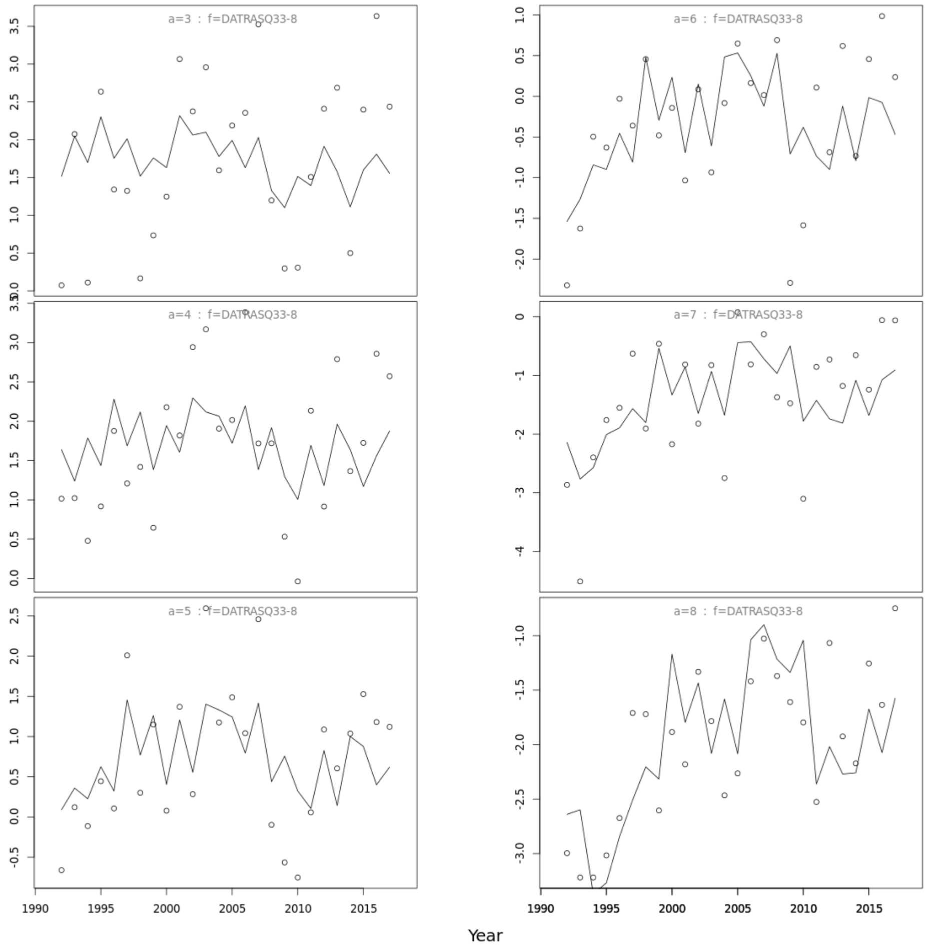


Figure 6.1.4. Saithe in Subareas 4 and 6 and Division 3a: Fits to IBTS Q3 survey data.

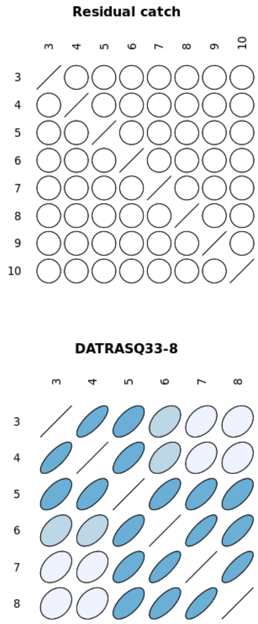


Figure 6.1.5. Saithe in Subareas 4 and 6 and Division 3a: Estimated correlations between age groups for catch-at-age (top; no correlations modelled) and IBTS Q3 index-at-age (bottom).

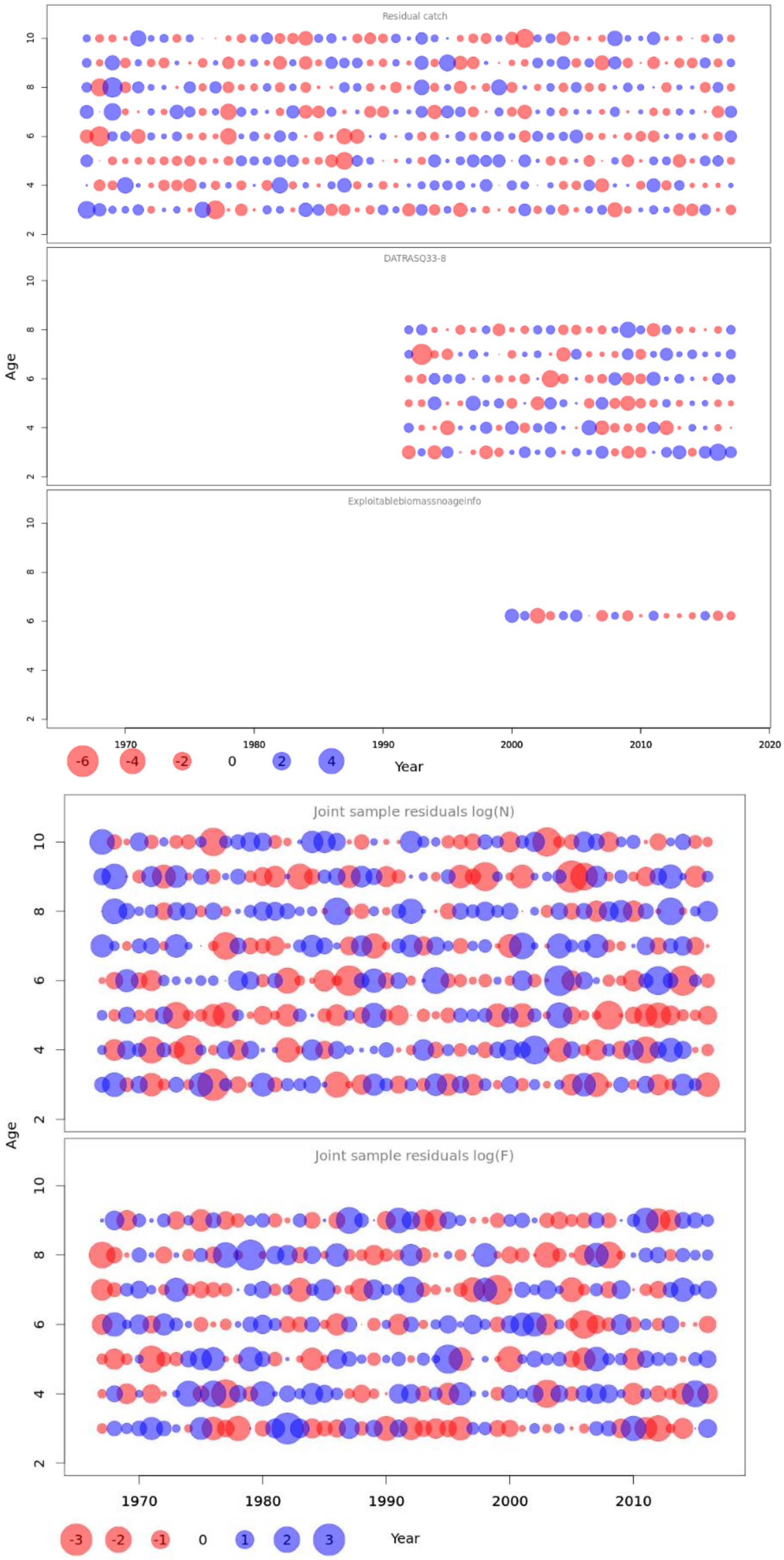


Figure 6.1.6. Saithe in Subareas 4 and 6 and Division 3a: Standardized one-step ahead residuals for the SAM assessment, for total catch, IBTS–Q3, and the exploitable biomass index, and the normalized residuals for the recruitment and survival process error and the fishing mortality process error. Blue circles indicate a positive residual and red circles a negative residual.

6.1.2 Parameter uncertainty

Parameter uncertainty, including survival process error, was derived from the variance-covariance matrix of the estimable parameters from the SAM assessment. The variance-covariance matrix was used to derive 1000 parameter sets resulting in 1000 North Sea saithe populations reflecting the historical and current status of the stock and associated uncertainty.

6.1.3 Recruitment

Recruitment was generated based on a segmented regression curve from 1998 onwards, where the inflection point was forced to be the lowest observed spawning stock biomass from the entire, untruncated, time period (from 1967). This followed the procedure used for the estimation of reference points (ICES 2019b).

A segmented regression curve was fit to each of the 1000 replicates individually, and residuals for future recruitments were drawn from smoothed distributions of the residuals for each replicate. Autocorrelation was not included because it was not significant (Figure 6.1.8).

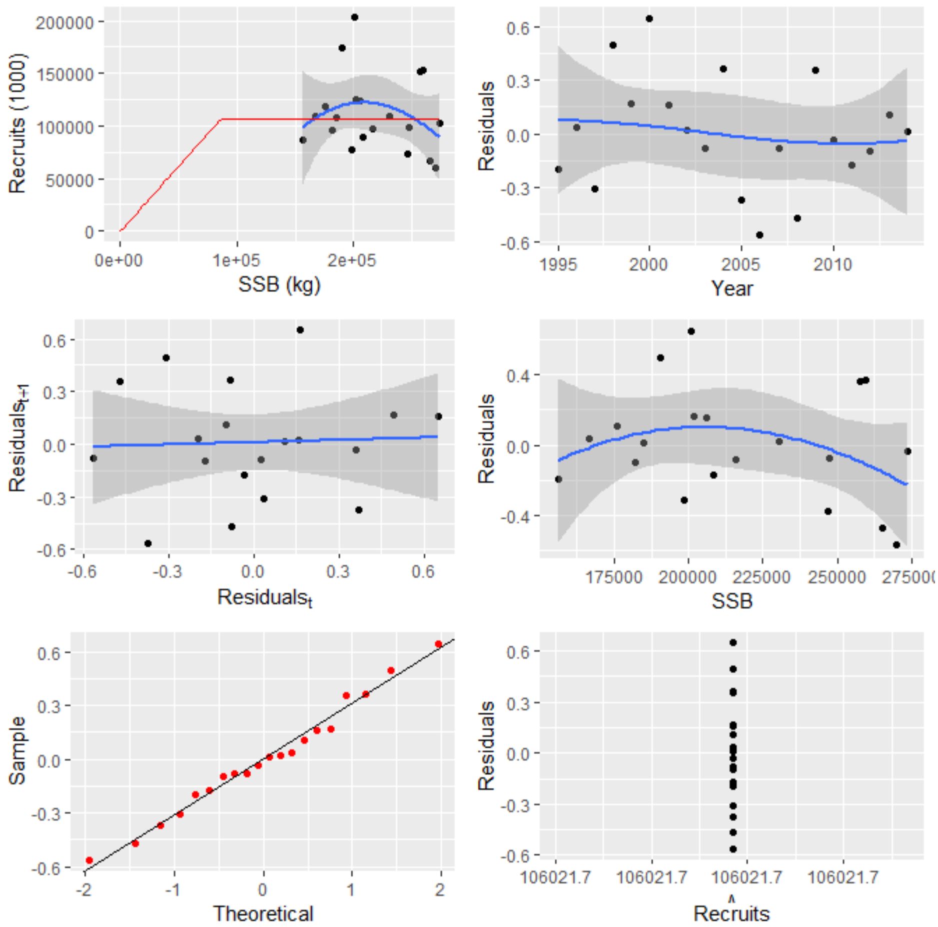


Figure 6.1.7. Saithe in Subareas 4 and 6 and Division 3a: Fit of the segmented regression stock-recruit relationship to the original assessment point estimates for the recruitment period 1998+.

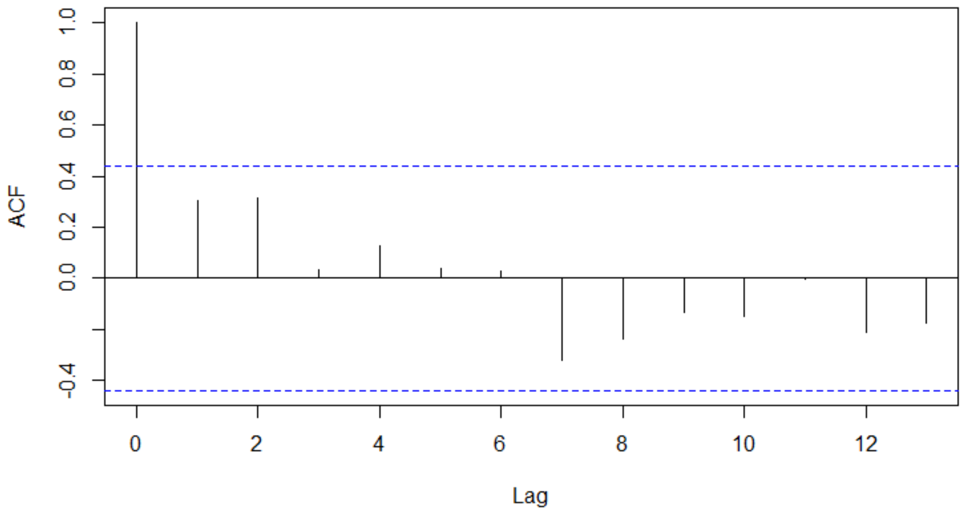


Figure 6.1.8. Saithe in Subareas 4 and 6 and Division 3a: Autocorrelation function applied to the assessment estimates of recruitment for the period 1998+.

Figures 6.1.9-10 compare generated recruitments with corresponding (i.e. based on the same SSB) historical recruitments for all 1000 replicates and indicate that the approach followed provides an appropriate basis for generating recruitment.

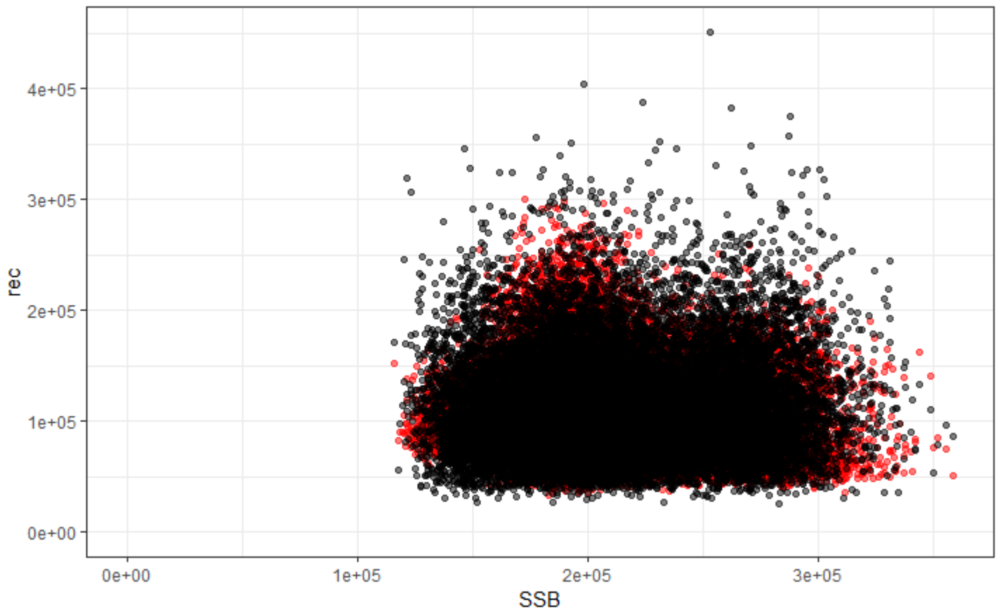


Figure 6.1.9. Saithe in Subareas 4 and 6 and Division 3a: Historical stock-recruit pairs (red dots), with recruitment generated from the fitted stock-recruit relationship (black dots) for 1000 replicates.

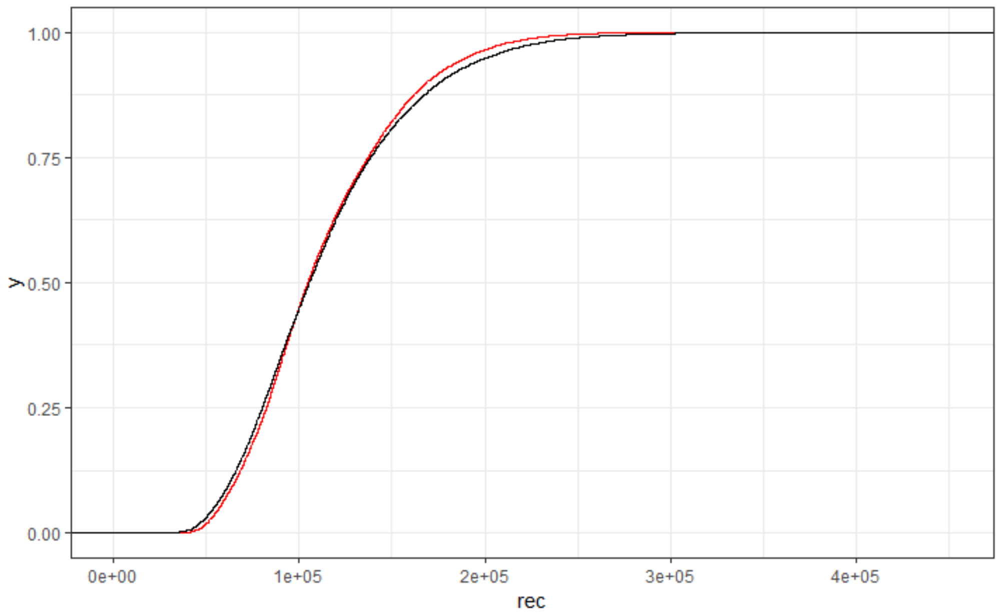


Figure 6.1.10. Saithe in Subareas 4 and 6 and Division 3a: A comparison of historical (red line) and simulated recruitments (black line) using empirical cumulative distribution function (ecdf in R) for the stock recruit pairs shown in Figure 6.1.9.

6.1.4 Mean weights, maturity, natural mortality and selection

Simulation of biological parameters followed the same assumptions as in the estimation of reference points. Reference points for North Sea saithe were last updated during the IBP in 2019 (ICES 2019b). Future mean weights were modelled by selecting a year at random with replacement from the period 2008–2017 and allocating the biological parameters for all ages in that year to the given future year. This process was done independently for each replicate and is consistent with the EqSim approach for estimating reference points, where the default ten-year time period was chosen for North Sea saithe due to the absence of notable trends (ICES 2019b).

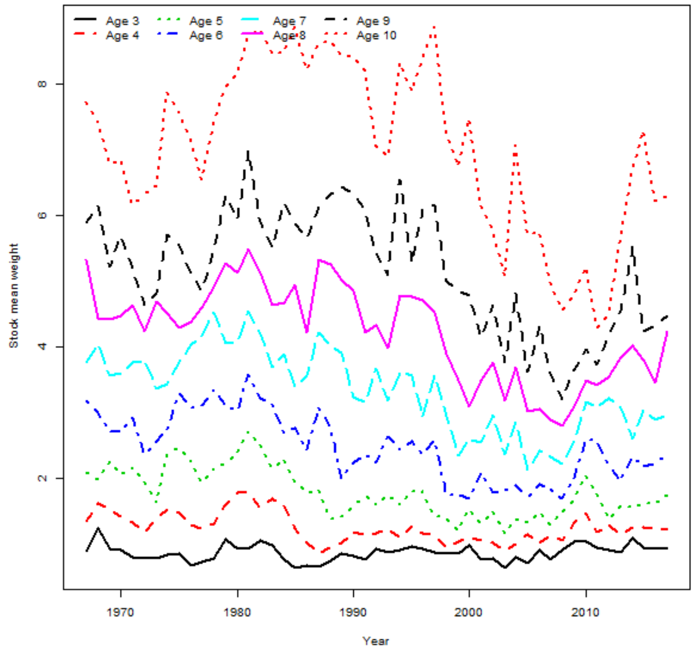


Figure 6.1.11. Saithe in Subareas 4 and 6 and Division 3a: Trends in stock weights for ages 3-10+.

Maturity (Table 6.1.1) and natural mortality (M = 0.2) were constants.

Table 6.1.1. Saithe in Subareas 4 and 6 and Division 3a: Maturity ogive.

	1	2	3	4	5	6	7	8+
Proportion mature	0.0	0.0	0.0	0.20	0.65	0.84	0.97	1.00

Selection was also resampled with replacement from the period 2013–2017 but separately to the biological parameters, following the EqSim approach for estimating reference points (ICES 2019b). The 5-year average was used because clear declines in selectivity for age 4 were present in the last 5 years (Figure 6.1.12).

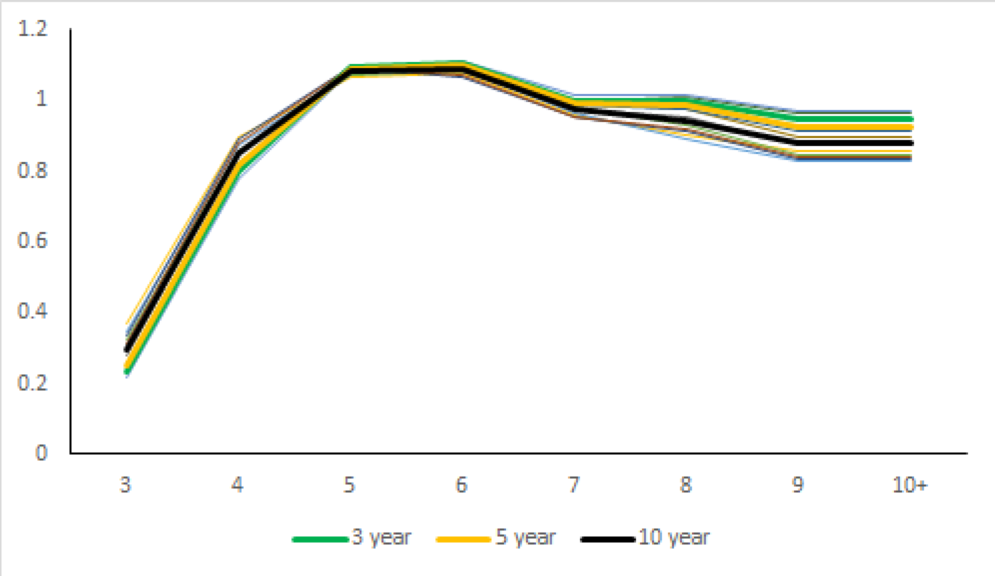


Figure 6.1.12. Saithe in Subareas 4 and 6 and Division 3a: Trends in F over the last 10 years, with emphasis on the last 3, 5, and 10 years; values were standardized to mean F.

6.1.5 Generating data from the operating model

Observation error is included on "true" survey indices and catch at age. Deviances to the observed survey index (IBTS Q3) in the projection period were simulated using the variance-covariance matrix for the survey index to account for observation error correlated between ages. Survey observations were generated from the operating model as follows:

$$I_{a,y,i} = q_{a,i} N_{a,y} e^{-t_i Z_{a,y}} \, e^{\varepsilon_{a,y,i}}$$

where N are stock numbers at age a and year y; Z are total mortalities at age and year from the operating model; q are survey catchabilities at age for survey i (IBTS-Q3); t is the timing of the survey (0.575 for IBTS Q3). The observation errors follow a multivariate normal distribution:

$$\varepsilon_{a,y,i} \sim N(0, \Sigma_i)$$

where Σ_i is the covariance matrix between age classes within years for survey i (IBTS-Q3), as estimated in the current SAM assessment (Nielsen and Berg 2014).

Observation error is included on catches at age as multiplicative lognormal error using standard deviations from the historical estimated catches of the SAM assessment.

The saithe assessment includes a commercial CPUE index, which is treated as an exploitable biomass index and generated from the operating model as follows:

$$I_y = q \left[\sum_a S_{a,y} w_{a,y}^c N_{a,y} e^{-0.5\, Z_{a,y}} \right] e^{\varepsilon_y}$$

where N and Z are as before; q is the catchability of the commercial CPUE index; w^c are the catch weights at age a and year y; 0.5 indicates projection to mid-year; S is the relative fishing mortality, F, for age a and year y, calculated as follows:

$$S_{a,y} = F_{a,y} \Big/ \sum\nolimits_a F_{a,y}$$

and $\varepsilon_y \sim N(0, \sigma^2)$, with σ from the SAM assessment.

6.1.6 Implementation error

Banking and borrowing were introduced as implementation error. Once the management strategy produces a TAC, this TAC was adjusted by the effects of the banking and borrowing scheme (see Annex 3).

6.1.7 Number of replicates and projection years

The number of replicates was 1000, based on a simulation study performed by North Sea cod (see section 3.1.7). During webex 2 in late January, it was agreed that if stock coordinators had time to do a similar study, they should do so, but if not, to default to 1000 replicates.

Twenty years were used for the projection period. This was again based on the simulation study performed by North Sea cod (see section 3.1.7), where SSB was found to plateau after 20 years. Time constraints did not allow for investigating the projection period for saithe.

6.2 Alternative operating models

6.2.1 OM2 - Natural mortality of 0.1

The first alternate model investigated the possibility that natural mortality is over-estimated and that the M is lower in the real population. Natural mortality was set to 0.1 in the OM but was 0.2 in the MP. All other parameters were as described in Section 6.1, and SAM refitted under the alternative M=0.1 assumption. B_{lim} for this OM was 90 094 t.

6.2.2 OM3 - Natural mortality of 0.3

The second alternate model investigated the possibility that natural mortality is under-estimated and that the M is higher in the real population. Natural mortality was set to 0.3 in the OM but was 0.2 in the MP. All other parameters were as described in Section 6.1, and SAM refitted under the alternative M=0.3 assumption. B_{lim} for this OM was 133 650 t.

6.3 Management procedure

The management procedure (MP) comprises of the estimation model and the decision model. The decision model comprises the management strategies that are being evaluated (Section 6.1), and the estimate of SSB needed by the decision model is supplied by the estimation model. For saithe, the estimation model is identical to the SAM model used on an annual basis for the May advice and includes the forecasting procedure needed to derive the annual advice. The model settings and forecast assumptions are therefore the same and are as described in the IBP (ICES 2019b) and stock annex for this stock.

6.4 Results

6.4.1 Search grid for "optimal" combination of F_{target} and $B_{trigger}$

The searches for "optimal" combinations of F_{target} and $B_{trigger}$ (i.e. those that maximise long-term yield while fulfilling the ICES precautionary criterion of risk3≤5%), were conducted only for the baseline OM for each of the seven management strategies. Note that North Sea saithe was asked to evaluate scenario A+D with a TAC constraint of -15% and +15% (called A_1+D below).

Time constraints meant that first a coarse grid was run to find the optimal search area, and then a finer grid was run. The grid search was conducted in steps of 0.01 for F_{target} and 10000 t for $B_{trigger}$. The same number of blocks (90) were used during parallelization to ensure that the random number generated at each year step during the forecast was the same for all runs. Despite this, non-smooth behaviour exists, e.g. Figure 6.4.1.1, long-term risk3 at F_{target} = 0.36, which indicates that SAM is responding to small changes and that behaviour is not controllable, particularly because the convergence tolerance was re-set to speed up the run time. Each run comes close to an optimum solution, but the criteria for optimization is slightly less strict. The differences in the grid were not due to SAM failing and the random number sequence among cells in the grid was inspected and was the same.

Table 6.4.1.1 summarises optimal combinations and diagnostics for each of the seven scenarios. HCR options B, B+E, and A+D are **not** precautionary in the short-term. F_{target} and $B_{trigger}$ combinations that would make these scenarios precautionary in the short-term are in Table 6.4.1.2.

The grid searches are shown in Figures 6.4.1.1-7. The optimal combination is highlighted in each plot by surrounding the cell with a black border. Figures 6.4.1.8-10 shows the grid searches for those management strategies that were not precautionary in the short-term in Table 6.4.1.2.

Table 6.4.1.1. Saithe in Subareas 4 and 6 and Division 3a: "optimal" combinations of F_{target} and $B_{trigger}$ for the baseline OM for the seven management scenarios, F=0 and A* (F_{target} = F_{MSY} and $B_{trigger}$ = MSY $B_{trigger}$); A_1+D is the +/- 15% TAC constraint scenario requested for saithe. Also reported are the median values for catch, SSB, realized mean F (ages 4-7), interannual catch variability (ICV), interannual TAC variability (ITV), risk3, and risk1. Statistics are reported for three time periods, short (first five years), medium (years 6-10) and long (final 10 years) term. Scenarios in red are not precautionary in the short-term.

Scenario	F=0	A*	A	B	C	A+D	B+E	C+E	A_1+D
F_{target}	–	0.363	0.35	0.39	0.35	0.41	0.39	0.36	0.36
$B_{trigger}$	–	149098	250000	200000	250000	210000	220000	230000	230000
Median catch long term	0	115270	116700	116835	116700	112250	112562	112351	112377
Median SSB long term	1493002	265531	292067	254513	292013	249213	263268	285057	284997
Realized mean F long term	0	0.36	0.34	0.38	0.34	0.38	0.36	0.34	0.34
ICV long term	–	0.151	0.177	0.186	0.177	0.335	0.364	0.360	0.360
ITV long term	–	0.151	0.177	0.186	0.177	0.206	0.205	0.185	0.185
risk3 long term	0	0.019	0.015	0.034	0.015	0.043	0.032	0.015	0.015
risk1 long term	0	0.014	0.010	0.027	0.010	0.033	0.020	0.010	0.010
Median catch medium term	0	116577	123747	118752	123747	117009	120358	122037	122050
Median SSB medium term	1088600	268913	302726	263398	302726	262907	275878	295801	295801
Realized mean F medium term	0	0.36	0.35	0.38	0.35	0.39	0.38	0.36	0.36
ICV medium term	–	0.158	0.185	0.197	0.185	0.361	0.429	0.414	0.414
ITV medium term	–	0.153	0.179	0.192	0.179	0.209	0.206	0.184	0.185
risk3 medium term	0	0.018	0.015	0.032	0.015	0.037	0.027	0.012	0.012
risk1 medium term	0	0.014	0.010	0.026	0.010	0.028	0.019	0.009	0.009
Median catch short term	0	107192	92464	113492	92464	106994	101448	91833	91833
Median SSB short term	441818	228781	251973	219954	251973	211176	220310	238535	238535
Realized mean F short term	0	0.37	0.31	0.40	0.31	0.42	0.38	0.34	0.34
ICV short term	–	0.102	0.204	0.114	0.204	0.255	0.305	0.309	0.309
ITV short term	–	0.142	0.186	0.167	0.186	0.178	0.178	0.177	0.177
risk3 short term	0.004	0.044	0.020	**0.064**	0.020	**0.092**	**0.075**	0.037	0.037
risk1 short term	0.001	0.028	0.010	0.040	0.010	0.048	0.037	0.017	0.017
Convergence failure	0	0	0	0	0	0	0	0	0
Fmax reached	0	3	2	11	2	15	8	2	2
Recovery proportion	1	1	1	1	1	1	1	1	1
Recovery time	1	1	1	1	1	1	1	1	1

Table 6.4.1.2. Saithe in Subareas 4 and 6 and Division 3a: combinations of F_{target} and $B_{trigger}$ for the baseline OM for the three management scenarios B, A+D and B+E comparing the "optimised" F_{target}-$B_{trigger}$ combinations (Table 6.4.1.1) with those combinations that make these management strategies precautionary in the short-term. A*+D (A* with stability mechanism D) is included for comparison. See caption to Table 6.4.1.1 for further details.

Scenario	B	B precautionary	A+D	A+D precautionary	B+E	B+E precautionary	A*+D
F_{target}	0.39	0.38	0.41	0.37	0.39	0.36	0.363
$B_{trigger}$	200000	210000	210000	230000	220000	210000	149098
Median catch long term	116835	116649	112250	111538	112562	112300	111330
Median SSB long term	254513	262704	249213	271506	263268	273801	263568
Realized mean F long term	0.38	0.37	0.38	0.34	0.36	0.34	0.35
ICV long term	0.186	0.183	0.335	0.333	0.364	0.357	0.345
ITV long term	0.186	0.183	0.206	0.193	0.205	0.187	0.165
risk3 long term	0.034	0.029	0.043	0.027	0.032	0.021	0.019
risk1 long term	0.027	0.022	0.033	0.017	0.020	0.013	0.014
Median catch medium term	118752	119621	117009	121133	120358	121736	118374
Median SSB medium term	263398	272078	262907	282148	275878	286395	269537
Realized mean F medium term	0.38	0.37	0.39	0.36	0.38	0.36	0.37
ICV medium term	0.197	0.194	0.361	0.353	0.429	0.418	0.391
ITV medium term	0.192	0.189	0.209	0.188	0.206	0.181	0.159
risk3 medium term	0.032	0.026	0.037	0.017	0.027	0.015	0.018
risk1 medium term	0.026	0.021	0.028	0.015	0.019	0.012	0.0136
Median catch short term	113492	111121	106994	103307	101448	96453	97372
Median SSB short term	219954	224138	211176	232668	220310	231951	227642
Realized mean F short term	0.40	0.38	0.42	0.35	0.38	0.34	0.36
ICV short term	0.114	0.115	0.255	0.196	0.305	0.302	0.29
ITV short term	0.167	0.168	0.178	0.178	0.178	0.166	0.147
risk3 short term	**0.064**	0.050	**0.092**	0.037	**0.075**	0.049	**0.052**
risk1 short term	0.040	0.033	0.048	0.022	0.037	0.023	0.027
Convergence failure	0	0	0	0	0	0	0
Fmax reached	11	10	15	4	8	2	2
Recovery proportion	1	1	1	1	1	1	1
Recovery time	1	1	1	_	1	1	1

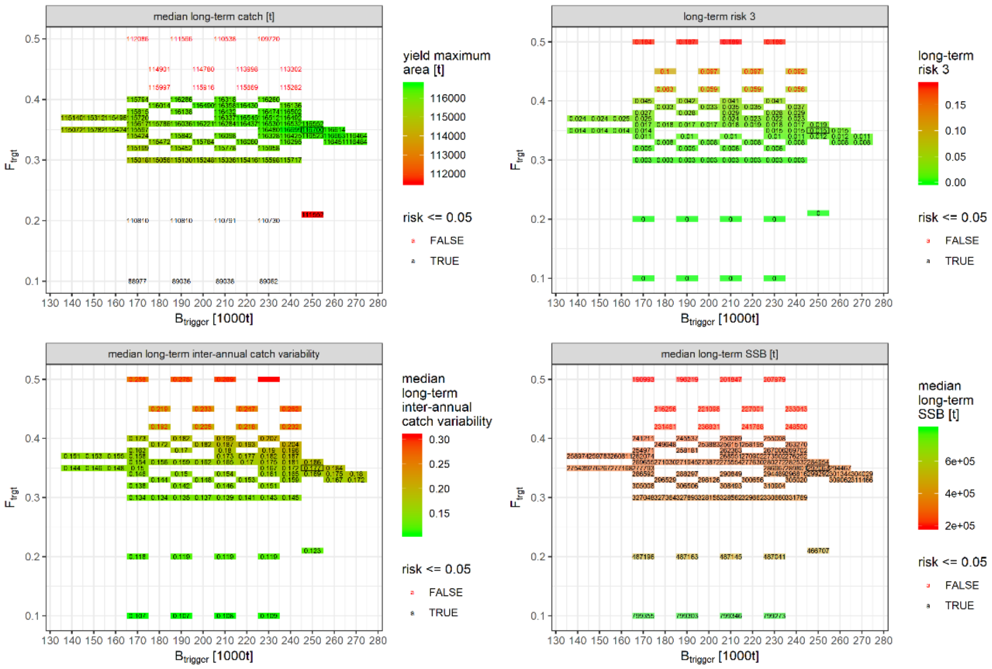


Figure 6.4.1.1. Saithe in Subareas 4 and 6 and Division 3a: Grid search for "optimal" combination of F_{target} and $B_{trigger}$ for <u>management strategy A for the long-term</u> (i.e. final 10 years of the 20-year projection). The top-left plot is median long-term catch, top-right the long-term risk3, bottom left the median long-term inter-annual catch variability and bottom right the median long-term SSB. The "optimal" combination is surrounded by a black box. The combinations that meet the precautionary criterion (risk3 ≤ 5%) are in black text, while those that do not are in red.

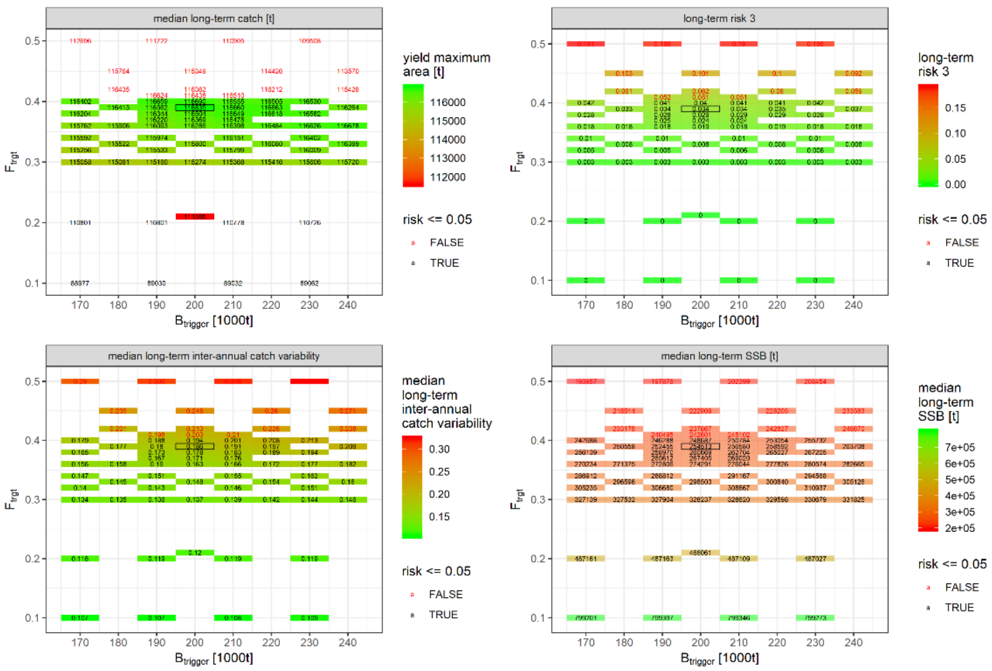


Figure 6.4.1.2. Saithe in Subareas 4 and 6 and Division 3a: Grid search for "optimal" combination of F_{target} and $B_{trigger}$ for <u>management strategy B for the long-term</u> (i.e. final 10 years of the 20-year projection). See caption to Figure 6.4.1.1. for further details.

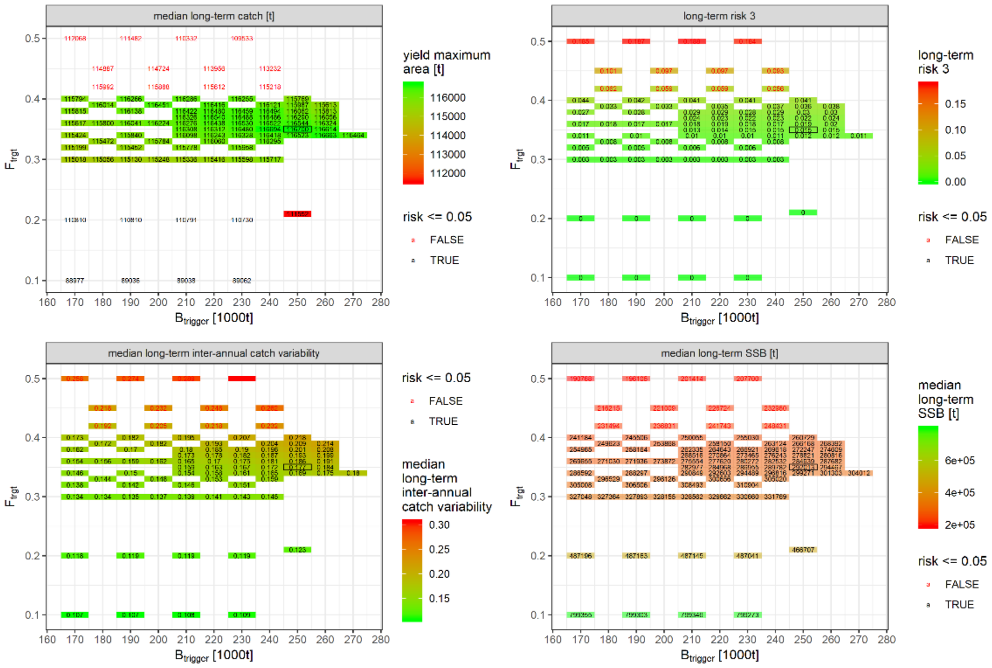


Figure 6.4.1.3. Saithe in Subareas 4 and 6 and Division 3a: Grid search for "optimal" combination of F_{target} and $B_{trigger}$ for management strategy C for the long-term (i.e. final 10 years of the 20-year projection). See caption to Figure 6.4.1.1. for further details.

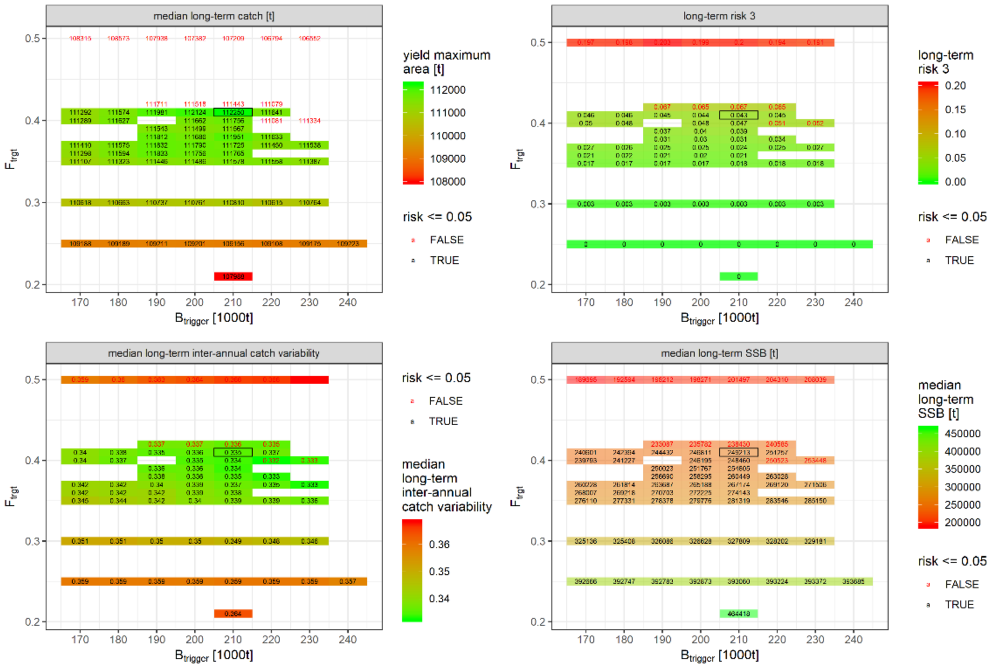


Figure 6.4.1.4. Saithe in Subareas 4 and 6 and Division 3a: Grid search for "optimal" combination of F_{target} and $B_{trigger}$ for management strategy A+D for the long-term (i.e. final 10 years of the 20-year projection). See caption to Figure 6.4.1.1. for further details.

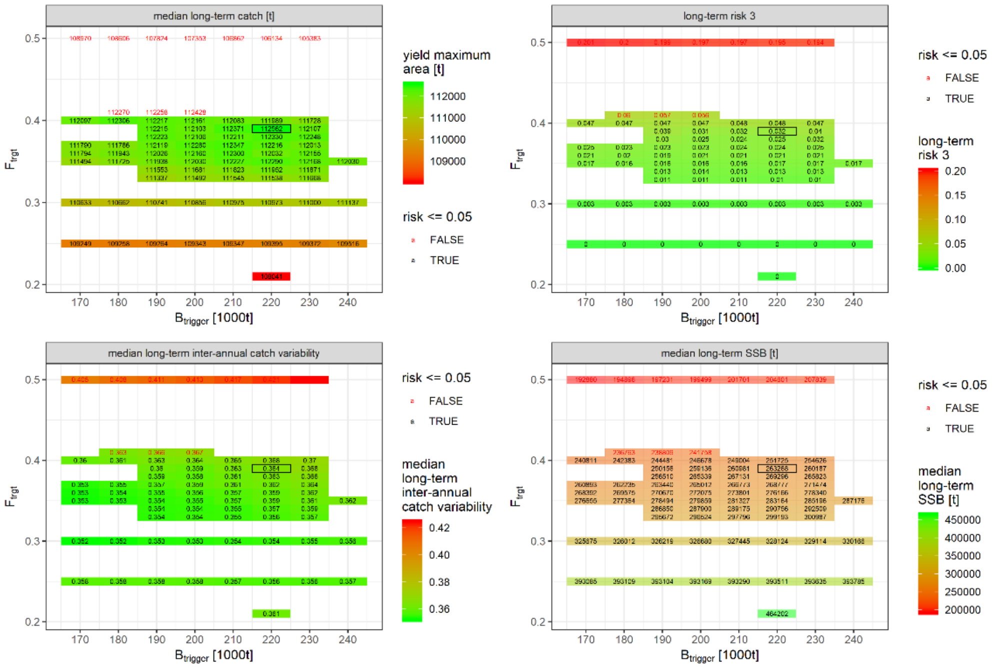


Figure 6.4.1.5. Saithe in Subareas 4 and 6 and Division 3a: Grid search for "optimal" combination of F_{target} and $B_{trigger}$ for management strategy B+E for the long-term (i.e. final 10 years of the 20-year projection). See caption to Figure 6.4.1.1. for further details.

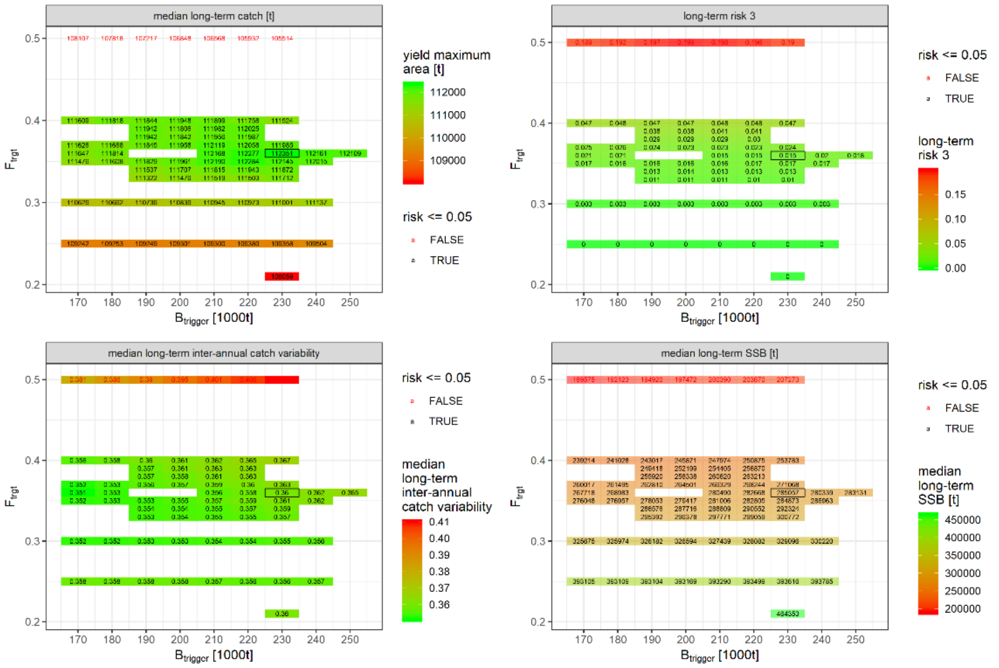


Figure 6.4.1.6. Saithe in Subareas 4 and 6 and Division 3a: Grid search for "optimal" combination of F_{target} and $B_{trigger}$ for management strategy C+E for the long-term (i.e. final 10 years of the 20-year projection). See caption to Figure 6.4.1.1. for further details.

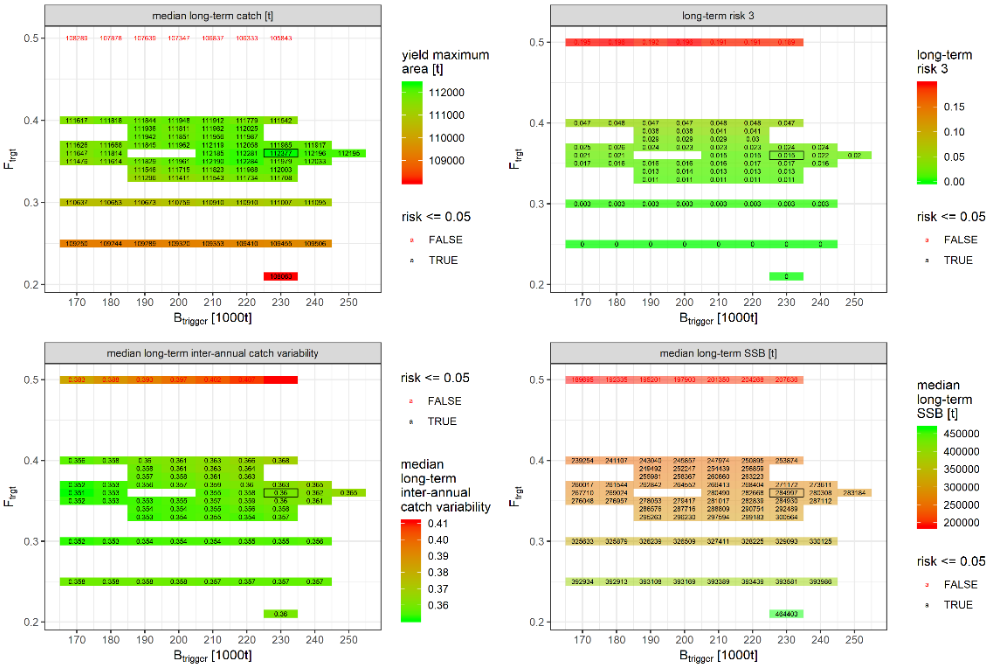


Figure 6.4.1.7. Saithe in Subareas 4 and 6 and Division 3a: Grid search for “optimal” combination of F_{target} and $B_{trigger}$ for management strategy A$_1$+D for the long-term (i.e. final 10 years of the 20-year projection). See caption to Figure 6.4.1.1. for further details.

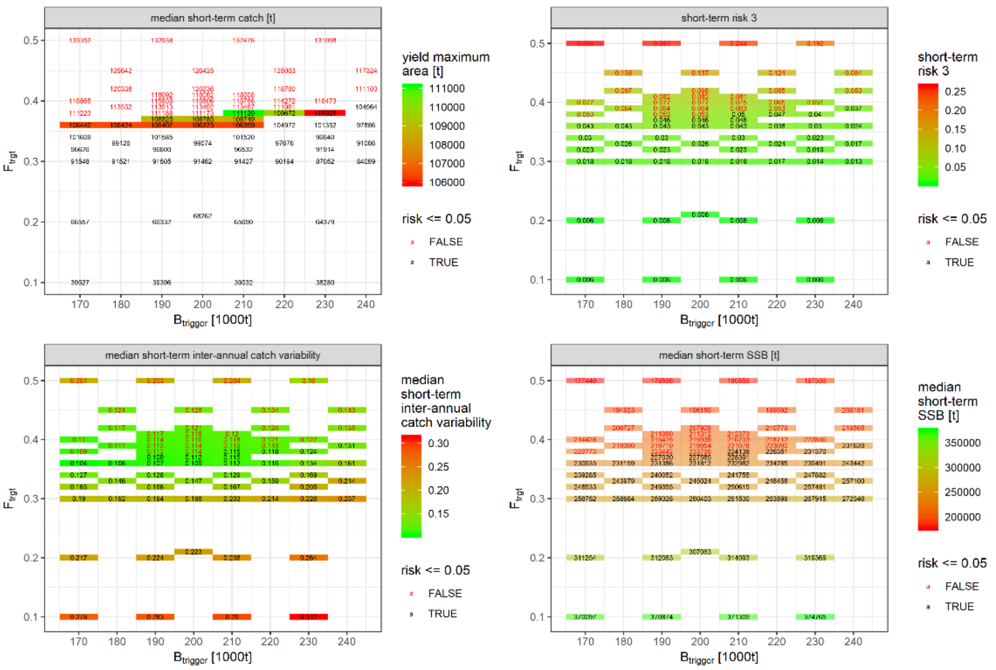


Figure 6.4.1.8. Saithe in Subareas 4 and 6 and Division 3a: Grid search for “optimal” combination of F_{target} and $B_{trigger}$ for management strategy B for the short-term (i.e. first 5 years of the 20-year projection). See caption to Figure 6.4.1.1. for further details.

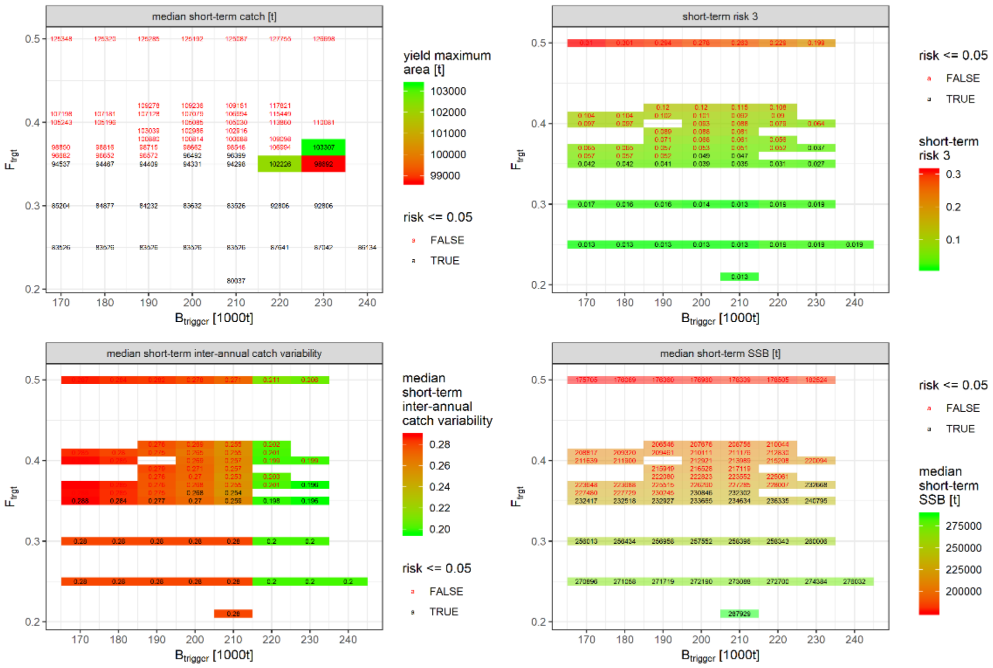


Figure 6.4.1.9. Saithe in Subareas 4 and 6 and Division 3a: Grid search for “optimal” combination of F_{target} and $B_{trigger}$ for <u>management strategy A+D for the short-term</u> (i.e. first 5 years of the 20-year projection). See caption to Figure 6.4.1.1. for further details.

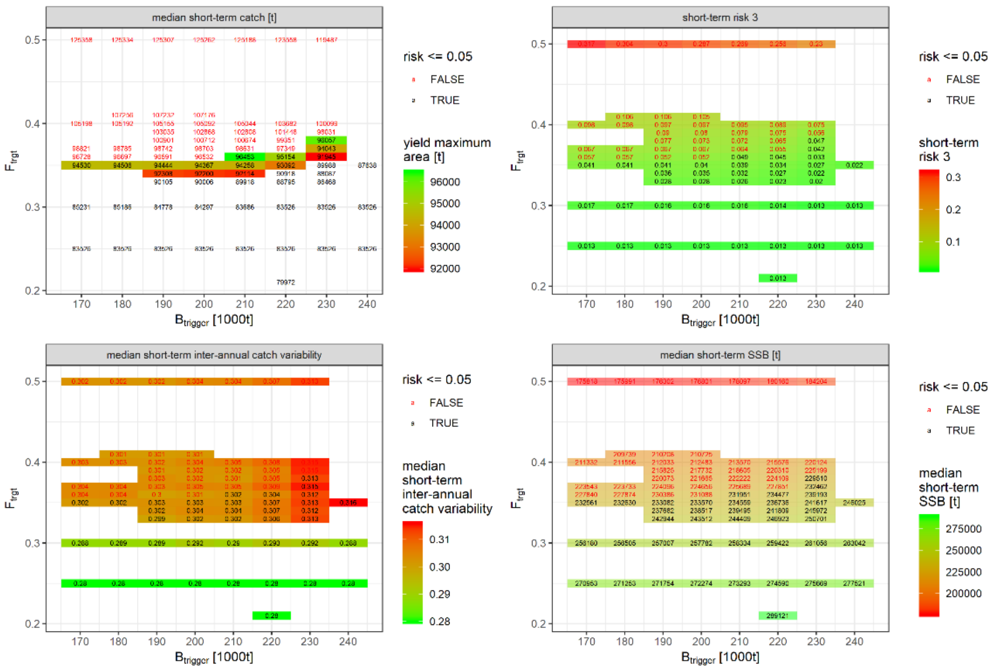


Figure 6.4.1.10. Saithe in Subareas 4 and 6 and Division 3a: Grid search for “optimal” combination of F_{target} and $B_{trigger}$ for <u>management strategy B+E for the short-term</u> (i.e. first 5 years of the 20-year projection). See caption to Figure 6.4.1.1. for further details.

6.4.2 Summary projections

Summary projections for recruitment (age 3), SSB, catch, and mean F (ages 4-7) for the baseline OM1 are given for F=0 (Figure 6.4.2.1) and management strategy A, where $F_{target} = F_{MSY} = 0.363$ and $B_{trigger}$ = MSY $B_{trigger}$ = 149098 t (A*) (Figure 6.4.2.2). Summary projects for the seven optimized management strategies (see Table 6.4.1.1) are given in Figures 6.4.2.3-9. Because HCR options B, B+E, and A+D were not precautionary in the short-term, the optimized strategies that were precautionary in the short-term are included in Figures 6.4.2.10-12. Figure 6.4.2.13 plots the annual risk for "optimised" management strategy A, which indicates that annual risk fluctuates without trend (note the risk values are low).

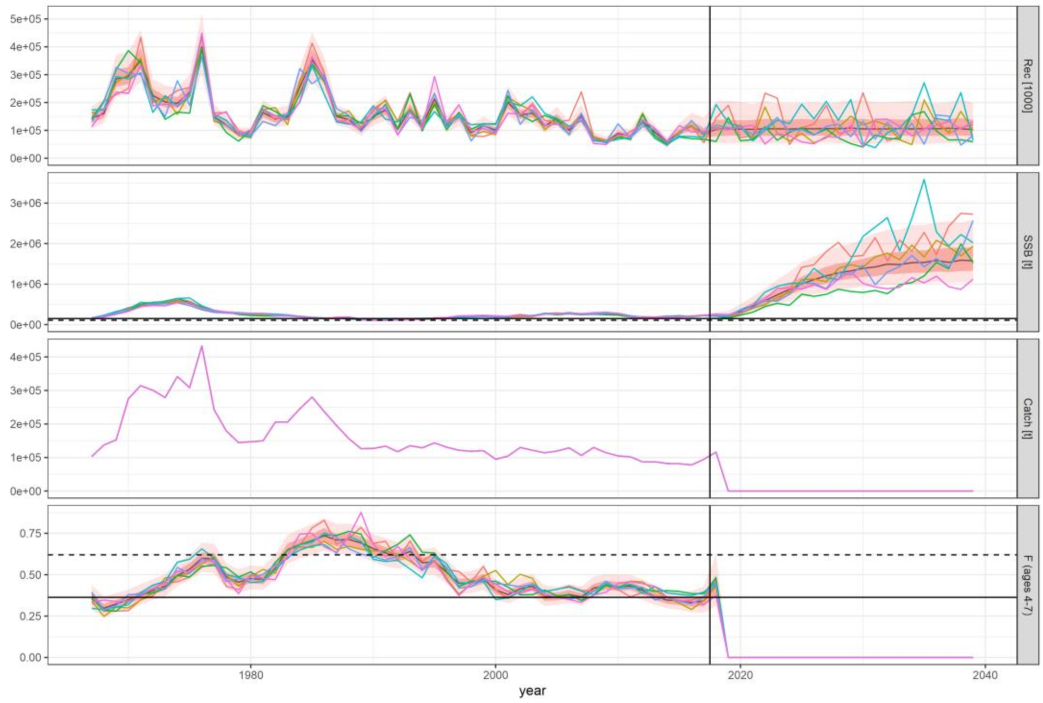


Figure 6.4.2.1. Saithe in Subareas 4 and 6 and Division 3a: Summary projections for F=0. Top plot is recruitment (age 3), second plot SSB, third plot catch, and bottom plot mean F (ages 4-7). The vertical black line separates the historical period from the projection period. The SSB plot includes B_{pa}=MSY $B_{trigger}$ (horizontal solid line) and B_{lim} (horizontal hashed line), while the mean F plot includes F_{MSY} (horizontal solid line) and F_{lim} (horizontal dashed line). The plots show medians (solid black line) with the darker shaded area indicating the 25th and 75th percentiles, and the light shaded area the 5th and 95th percentiles. The coloured lines represent the values from five replicates (replicates 100-105).

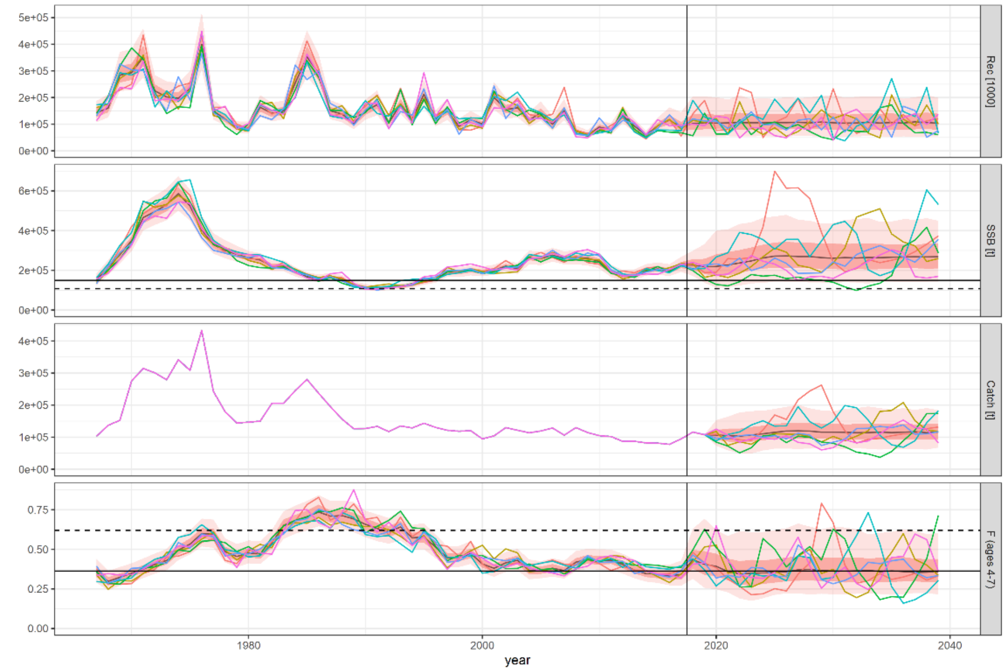


Figure 6.4.2.2. Saithe in Subareas 4 and 6 and Division 3a: Summary projections for <u>management strategy A*</u> ($F_{target} = F_{MSY} = 0.363$ and $B_{trigger}$ = MSY $B_{trigger}$ = 149098 t). For further details, refer to the caption to Figure 6.4.2.1.

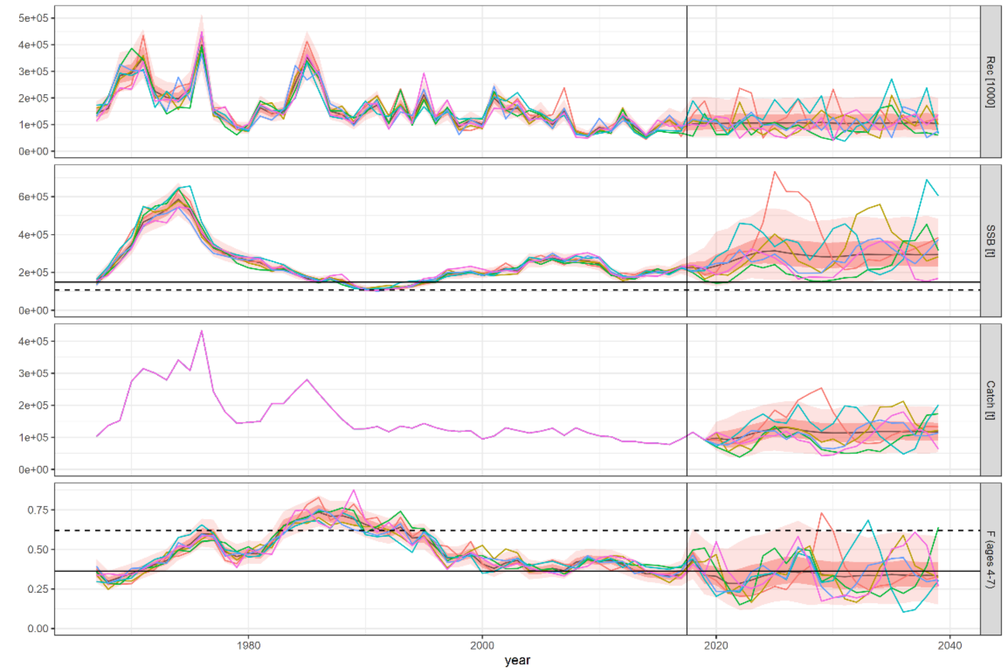


Figure 6.4.2.3. Saithe in Subareas 4 and 6 and Division 3a: Summary projections for <u>management strategy A</u> (see Table 6.4.1.1). For further details, refer to the caption to Figure 6.4.2.1.

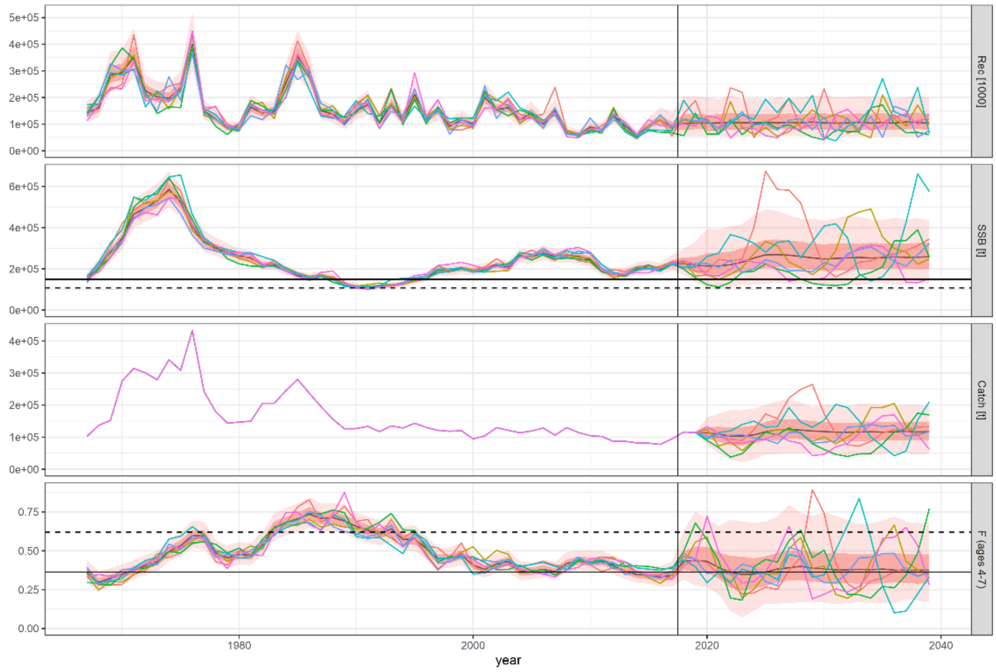


Figure 6.4.2.4. Saithe in Subareas 4 and 6 and Division 3a: Summary projections for <u>management strategy B</u>, which is not precautionary in the short-term (see Table 6.4.1.1). For further details, refer to the caption to Figure 6.4.2.1.

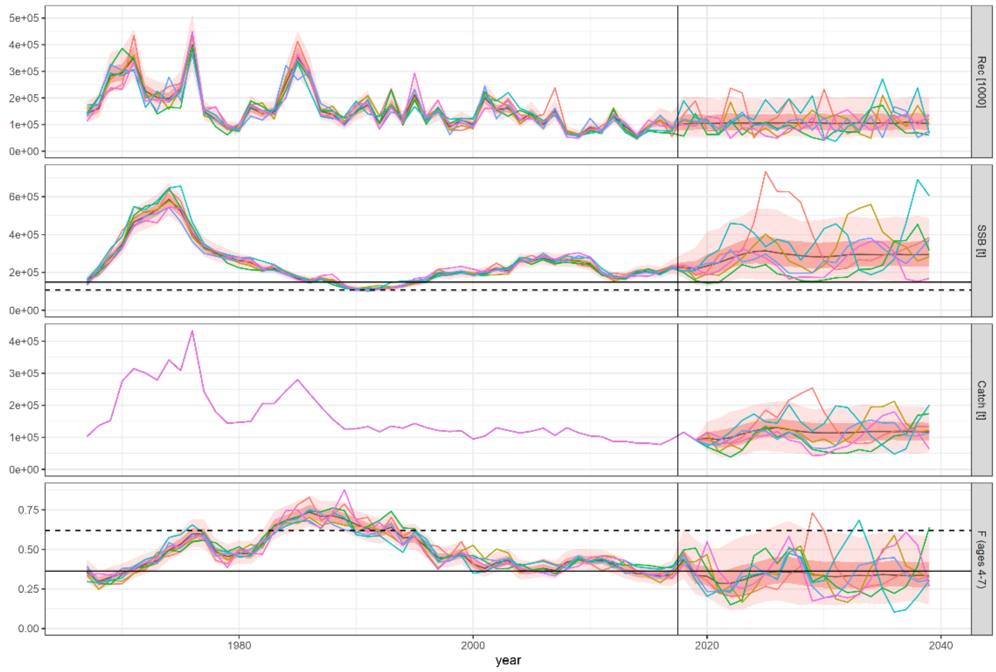


Figure 6.4.2.5. Saithe in Subareas 4 and 6 and Division 3a: Summary projections for <u>management strategy C</u> (see Table 6.4.1.1). For further details, refer to the caption to Figure 6.4.2.1.

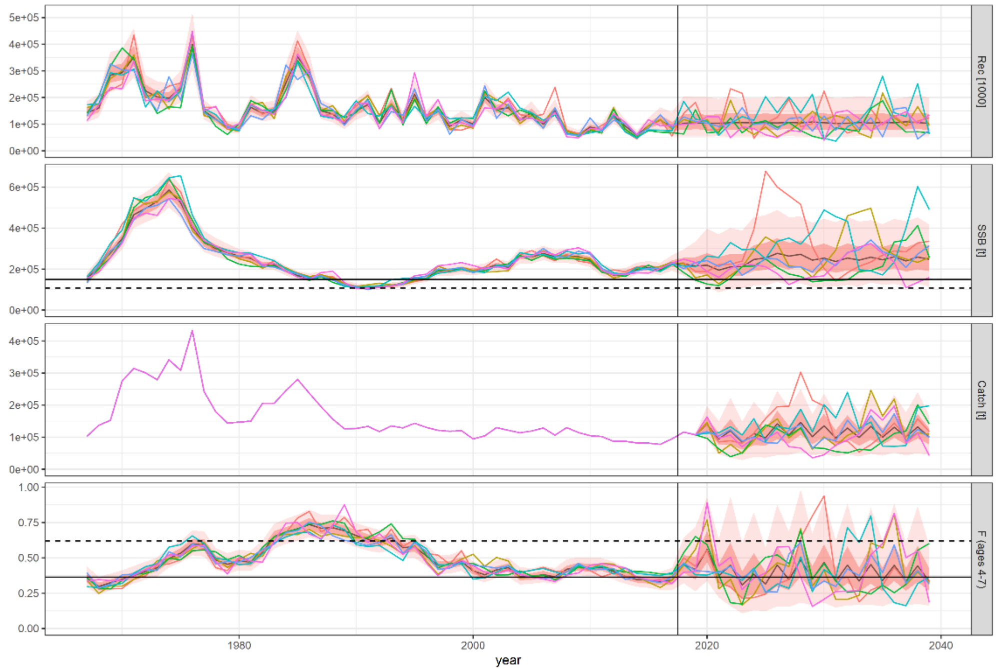


Figure 6.4.2.6. Saithe in Subareas 4 and 6 and Division 3a: Summary projections for <u>management strategy A+D</u>, which is not precautionary in the short-term (see Table 6.4.1.1). For further details, refer to the caption to Figure 6.4.2.1.

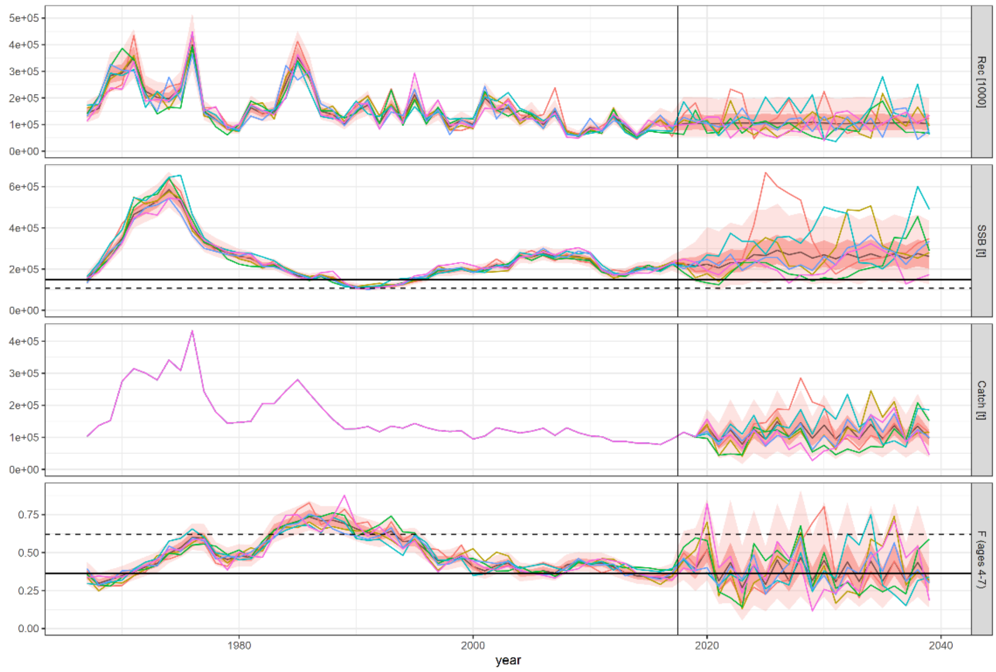


Figure 6.4.2.7. Saithe in Subareas 4 and 6 and Division 3a: Summary projections for <u>management strategy B+E</u> (see Table 6.4.1.1). For further details, refer to the caption to Figure 6.4.2.1.

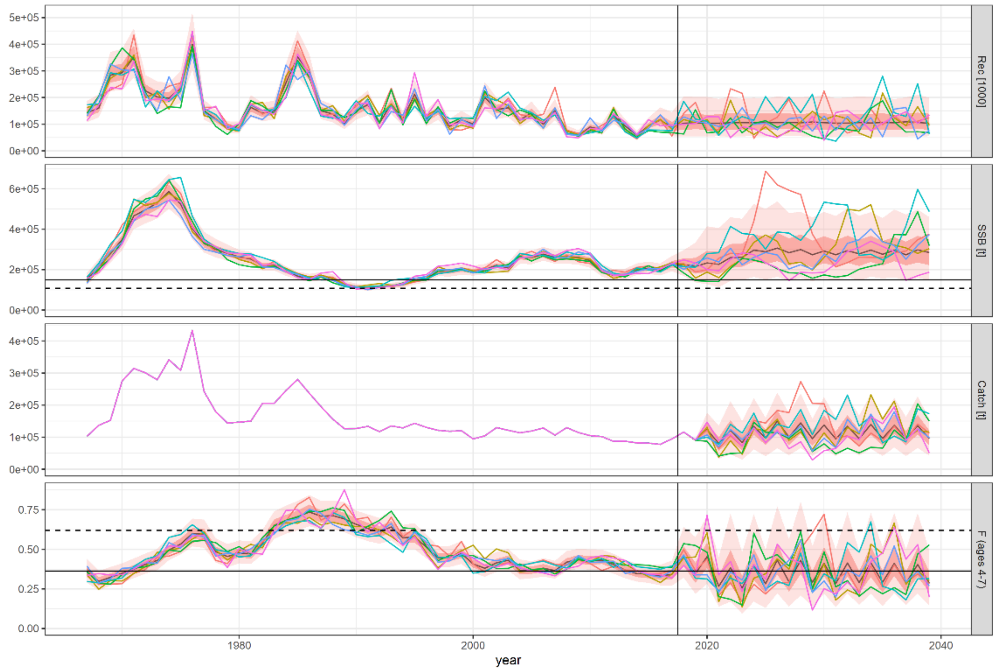


Figure 6.4.2.8. Saithe in Subareas 4 and 6 and Division 3a: Summary projections for <u>management strategy C+E</u>, which is not precautionary in the short-term (see Table 6.4.1.1). For further details, refer to the caption to Figure 6.4.2.1.

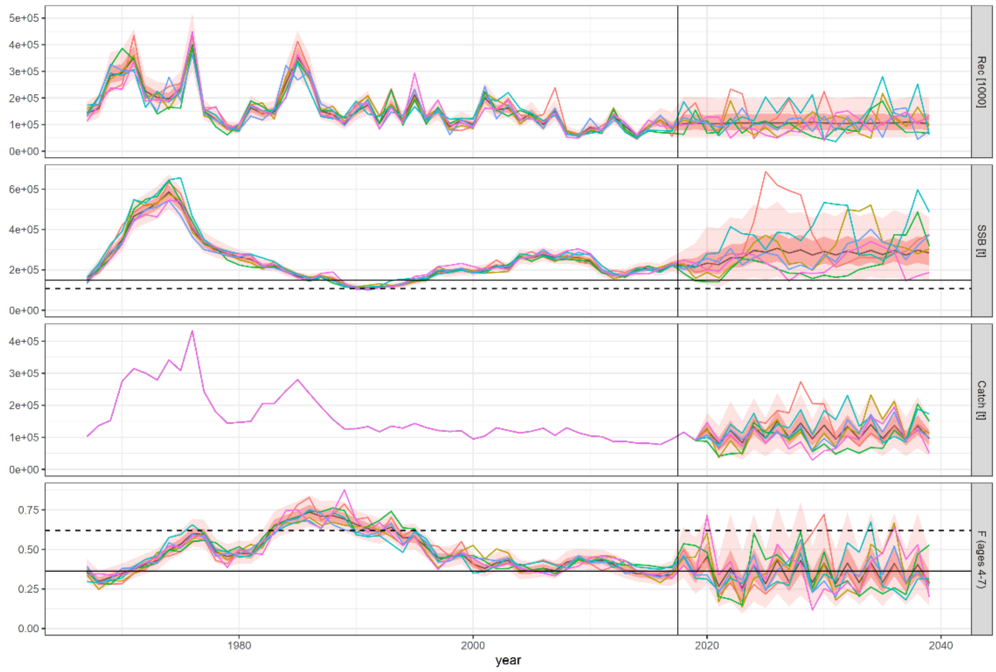


Figure 6.4.2.9. Saithe in Subareas 4 and 6 and Division 3a: Summary projections for <u>management strategy A_1+D</u> (see Table 6.4.1.1). For further details, refer to the caption to Figure 6.4.2.1.

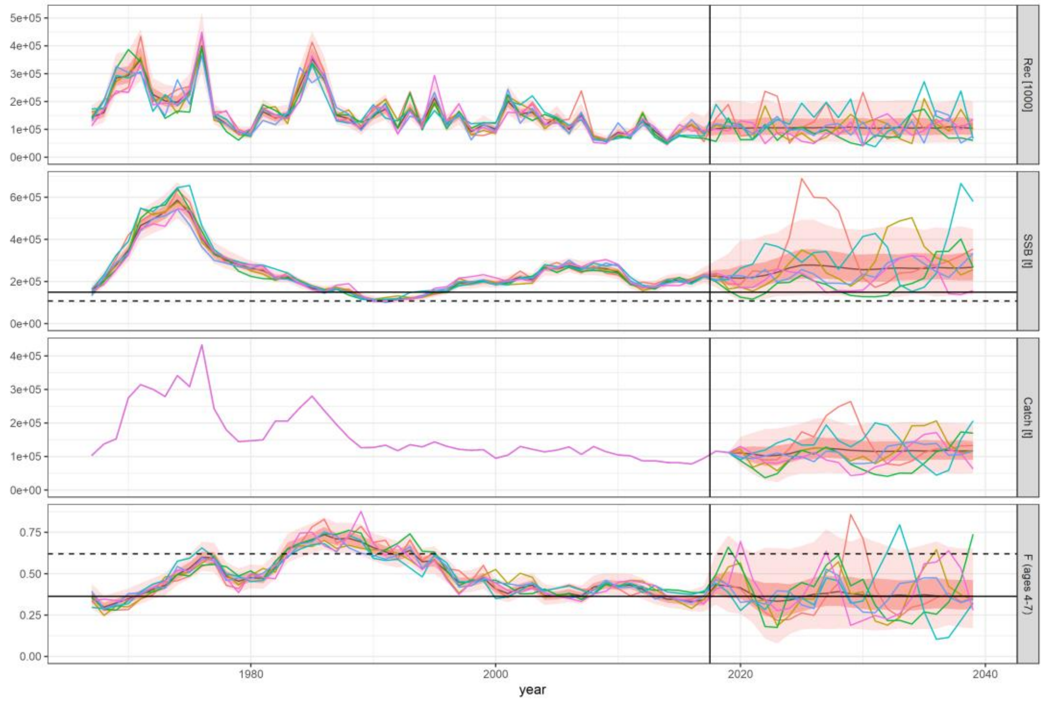


Figure 6.4.2.10. Saithe in Subareas 4 and 6 and Division 3a: Summary projections for management strategy B, which was precautionary in the short-term (see Table 6.4.1.1). For further details, refer to the caption to Figure 6.4.2.1.

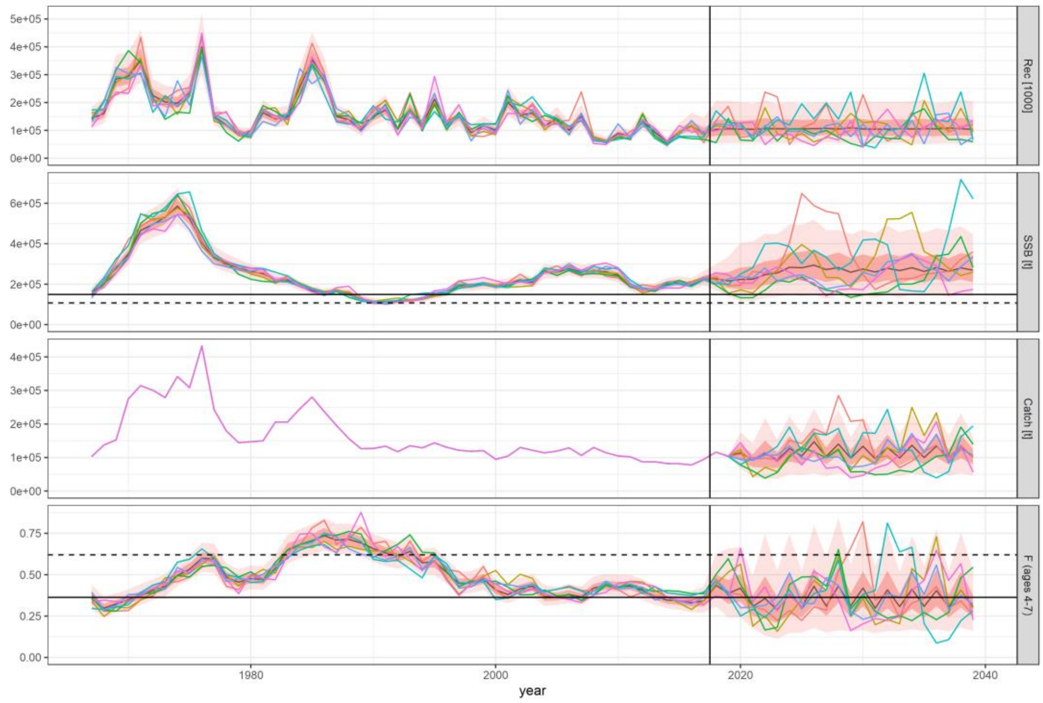


Figure 6.4.2.11. Saithe in Subareas 4 and 6 and Division 3a: Summary projections for management strategy A+D, which was precautionary in the short-term (see Table 6.4.1.1). For further details, refer to the caption to Figure 6.4.2.1.

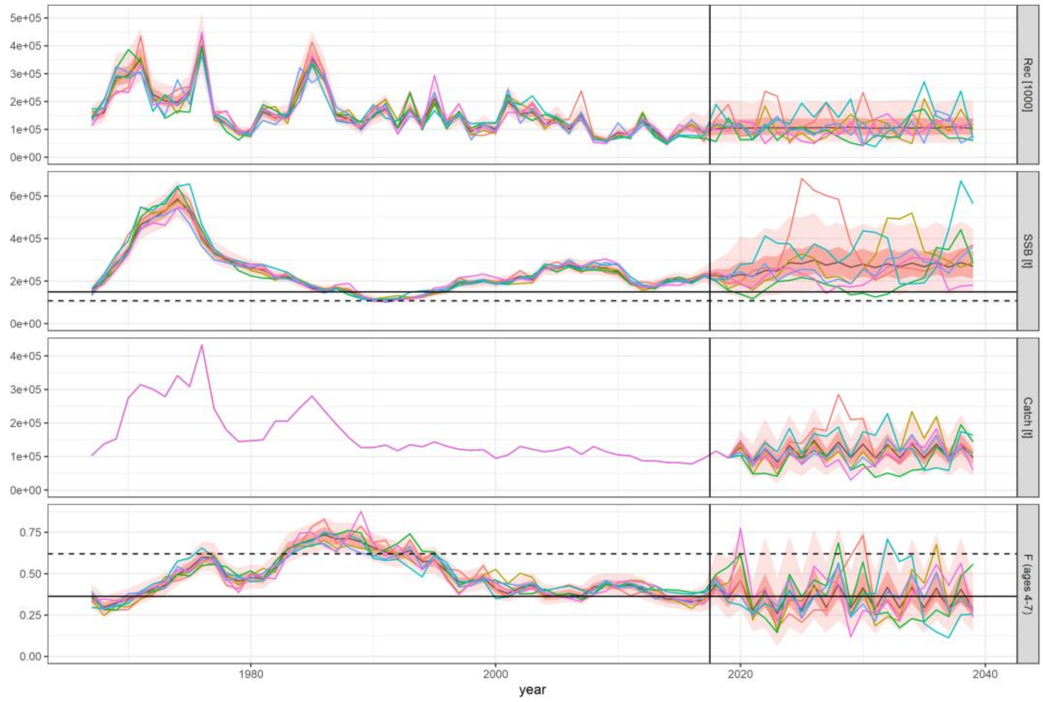


Figure 6.4.2.12. Saithe in Subareas 4 and 6 and Division 3a: Summary projections for <u>management strategy B+E</u>, which was precautionary in the short-term (see Table 6.4.1.1). For further details, refer to the caption to Figure 6.4.2.1.

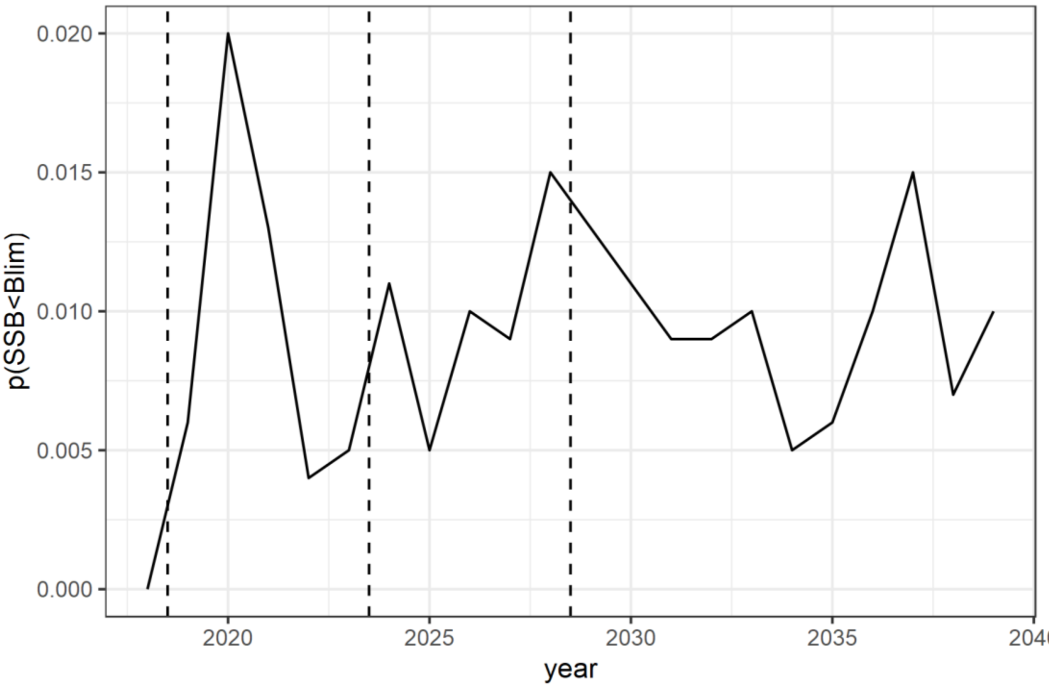


Figure 6.4.2.13. Saithe in Subareas 4 and 6 and Division 3a: Annual risk ($P(SSB<B_{lim})$) for "optimised" management strategy A. The horizontal hashed lines separate the short- medium- and long-term projection periods used for the performance statistics.

6.4.3 Comparison of management strategies for the baseline OM1

The performance of management strategy A, where $F_{target} = F_{MSY} = 0.363$ and $B_{trigger}$ = MSY $B_{trigger}$= 149 098 t (labelled A*), and the seven optimised management strategies are compared in terms of catch, risk1 and risk3, inter-annual catch variability and SSB in the short- (first five years), medium- (years 6–10) and long-term (final 10 years) in Figures 6.4.3.1-4. HCR options B, B+E, and A+D are not precautionary in the short-term (risk3>0.05).

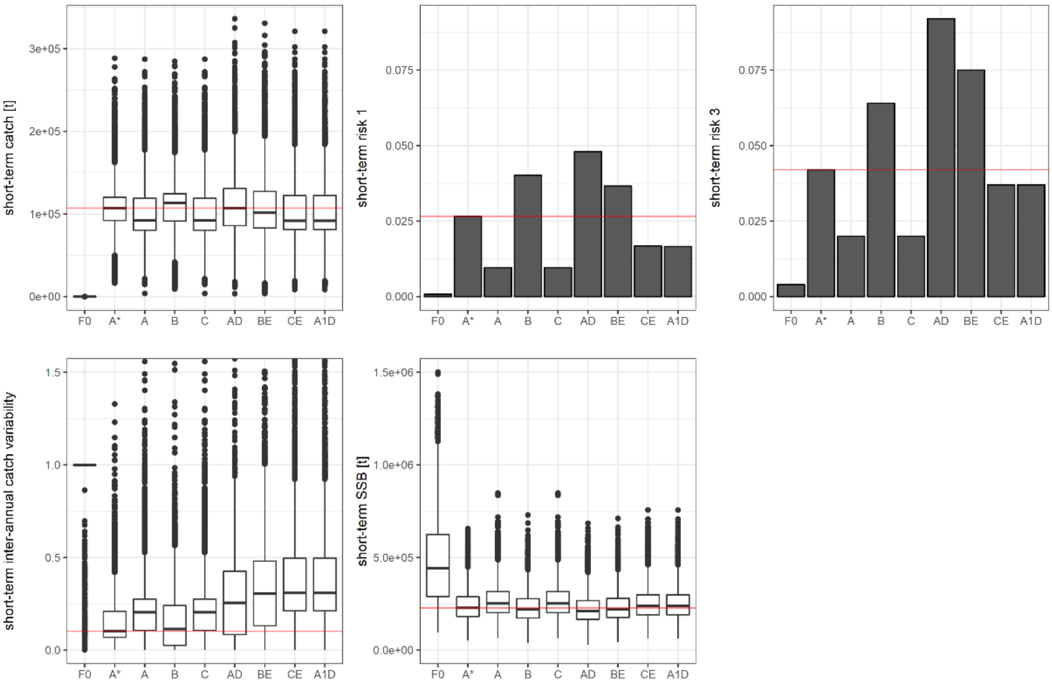


Figure 6.4.3.1. Saithe in Subareas 4 and 6 and Division 3a: Comparing the performance of management strategies <u>in the short-term</u> (first five years). Individual plots are as indicated by the label on the y-axis. Within each plot, the management strategies are F=0 (F0), A* (i.e. management strategy A with $F_{target} = F_{MSY} = 0.363$ and $B_{trigger}$ = MSY $B_{trigger}$ = 149 098 t, and the seven optimised management strategies (A, B, C, A+D, B+E, C+E, and A_1+D). In the box and whisker plots, the heavy horizontal line within the box indicates the median, the edges of the box indicate the 25th and 75th percentiles, the whiskers extend to the largest and smallest values within 1.5 times the inter-quartile range (IQR) from the edges, and the remaining points, indicated as dots outside the whiskers, are the outliers to 1.5*IQR from the edges. For comparison, the red horizontal line corresponds to the median (box and whisker plots) or actual value (risk plots) for the management strategy A*.

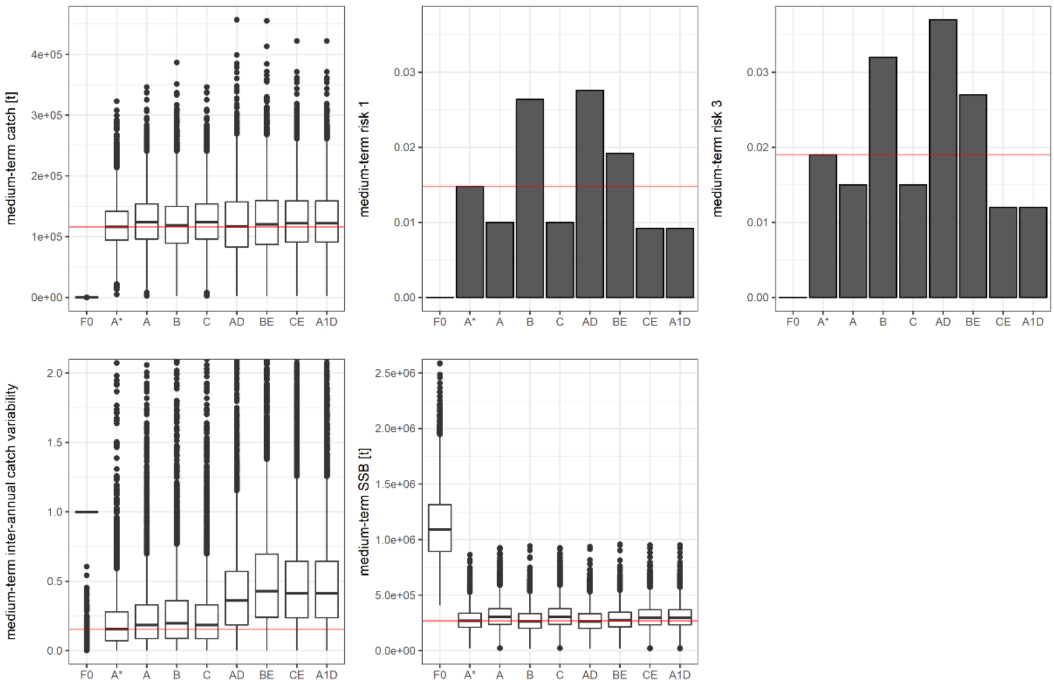


Figure 6.4.3.2. Saithe in Subareas 4 and 6 and Division 3a: Comparing the performance of management strategies <u>in the medium-term</u> (years 6-10). See Figure 6.4.3.1 for more details.

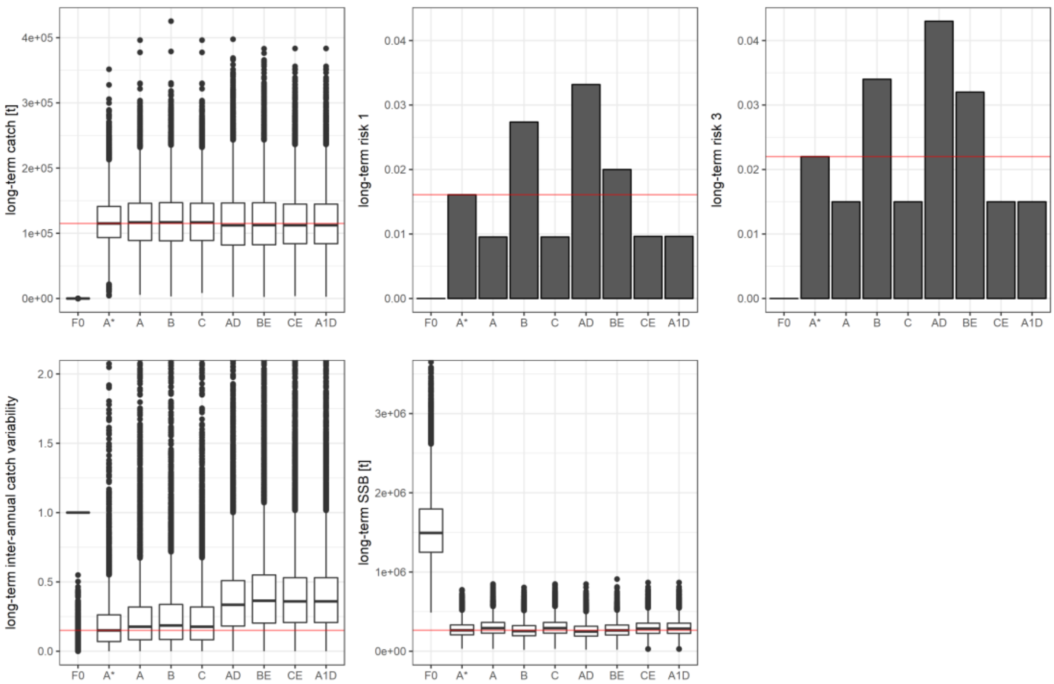


Figure 6.4.3.3. Saithe in Subareas 4 and 6 and Division 3a: Comparing the performance of management strategies <u>in the long-term</u> (final 10 years). See Figure 6.4.3.1 for more details.

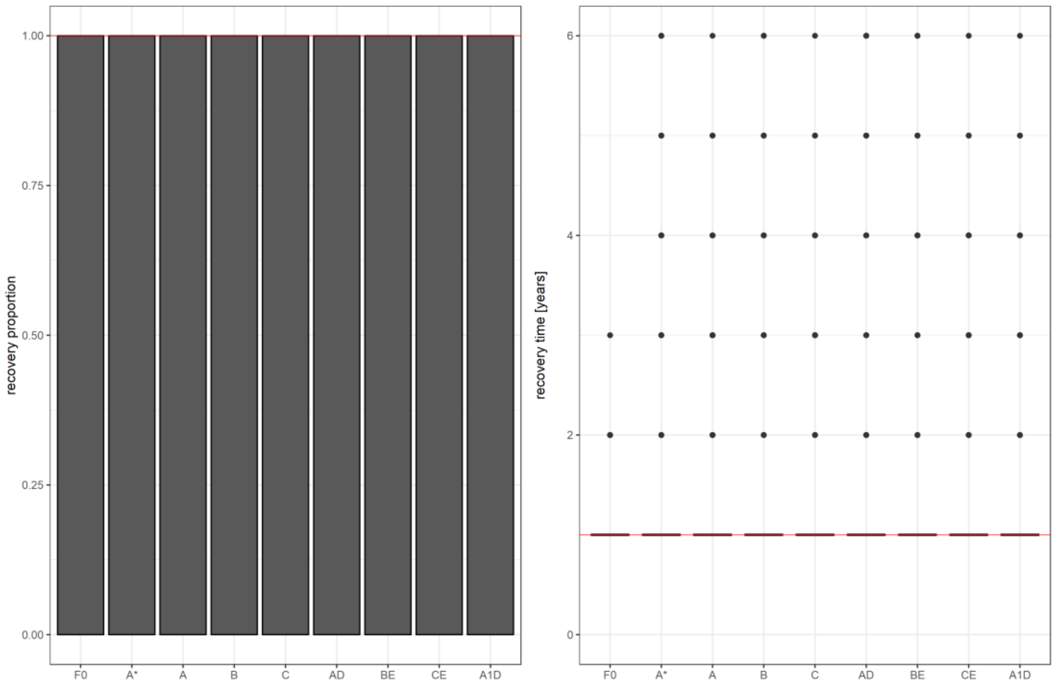


Figure 6.4.3.4. Saithe in Subareas 4 and 6 and Division 3a: Recovery statistics for the management strategies as described in Figure 6.4.3.1. The left plot indicates the proportion of replicates that recover above B_{pa} = MSY $B_{trigger}$, while the right plot indicates the number of years taken to recover above B_{pa} = MSY $B_{trigger}$ for the first time, indicated as box and whisker plots (see Figure 6.4.3.1 for a description).

6.4.4 Sensitivity of management strategies for the baseline OM

The sensitivity of performance statistics for the seven optimised management strategies (A, B, C, A+D, B+E, C+E, and A_1+D) to five fishing pressure scenarios (0.9*F_{target}, F_{target}, 1.1*F_{target}, $F_{MSY\ lower}$=0.210 and $F_{MSY\ upper}$=0.563) in the short- (first five years), medium- (years 6–10) and long-term (final 10 years) are presented in Figures 6.4.4.1-3. Sensitivity of recovery statistics for the management strategies to the same fishing pressure scenarios are presented in Figure 6.4.4.4.

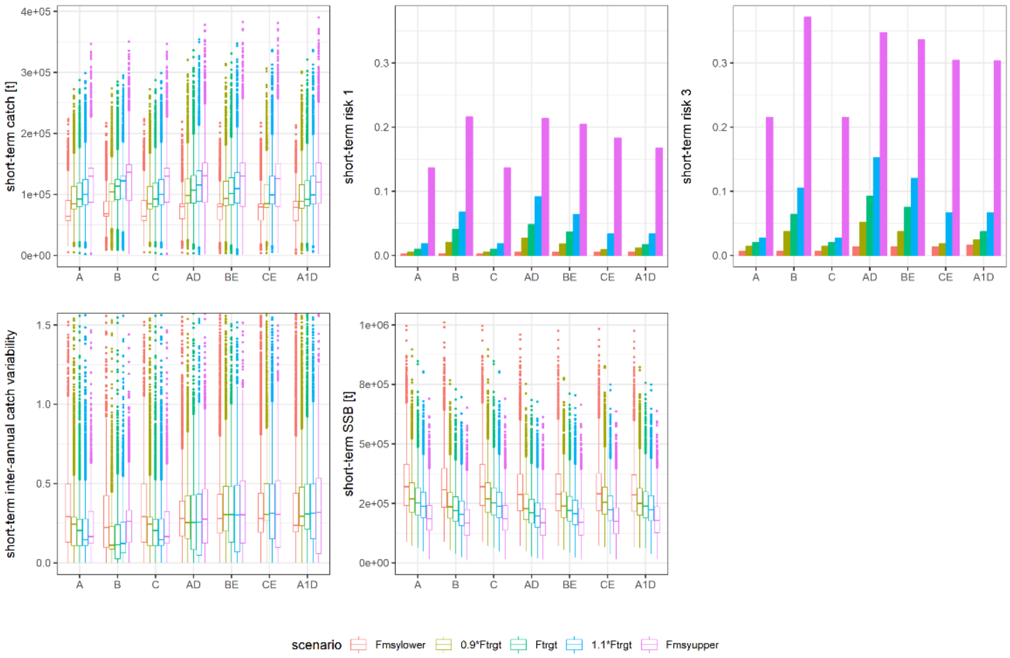


Figure 6.4.4.1. Saithe in Subareas 4 and 6 and Division 3a: Sensitivity of performance statistics for the optimised management strategies to changes in F in the short-term (first five years). Plots include median catch, risk1, risk3, inter-annual catch variability, and SSB, as indicated by the label on the y-axis. In the box and whisker plots, the heavy horizontal line within the box indicates the median, the edges of the box indicate the 25th and 75th percentiles, and the whiskers extend to the largest and smallest values within 1.5 times the inter-quartile range (IQR) from the edges, and the remaining points indicated as dots outside the whiskers are the outliers to 1.5*IQR from the edges.

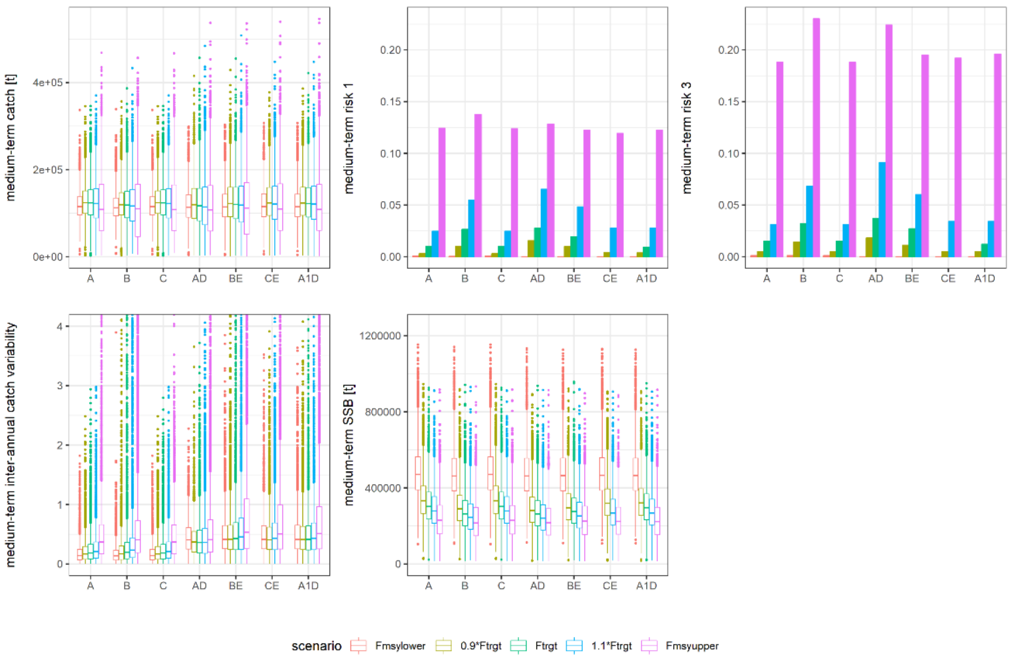


Figure 6.4.4.2. Saithe in Subareas 4 and 6 and Division 3a: Sensitivity of performance statistics for the optimised management strategies to changes in F in the medium-term (years 6-10). See Figure 6.4.4.1 for more details.

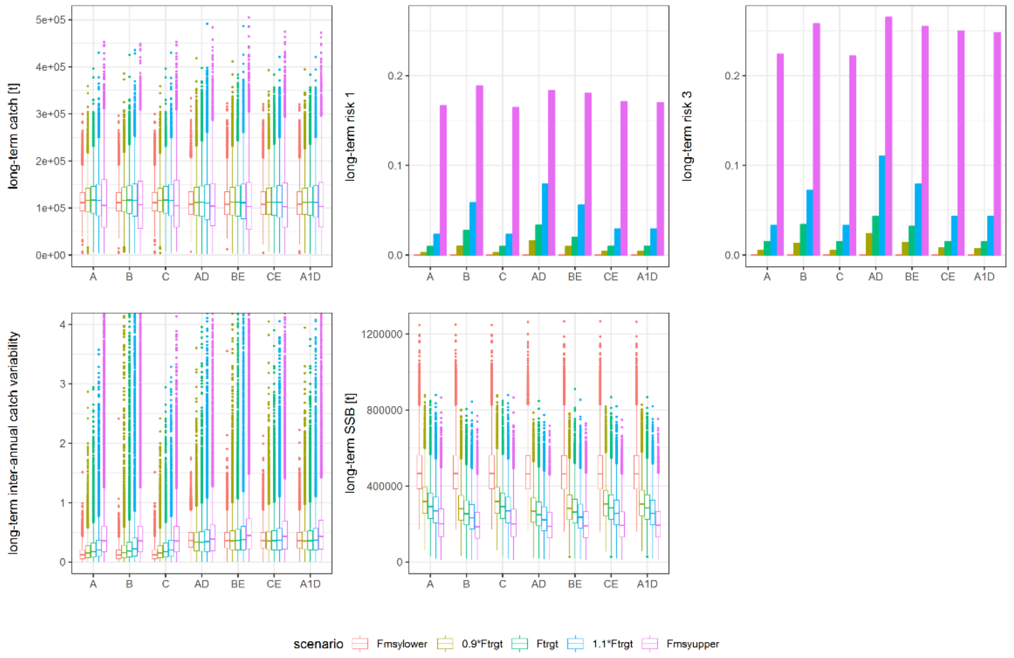


Figure 6.4.4.3. Saithe in Subareas 4 and 6 and Division 3a: Sensitivity of performance statistics for the optimised management strategies to changes in F in the long-term (final 10 years). See Figure 6.4.4.1 for more details.

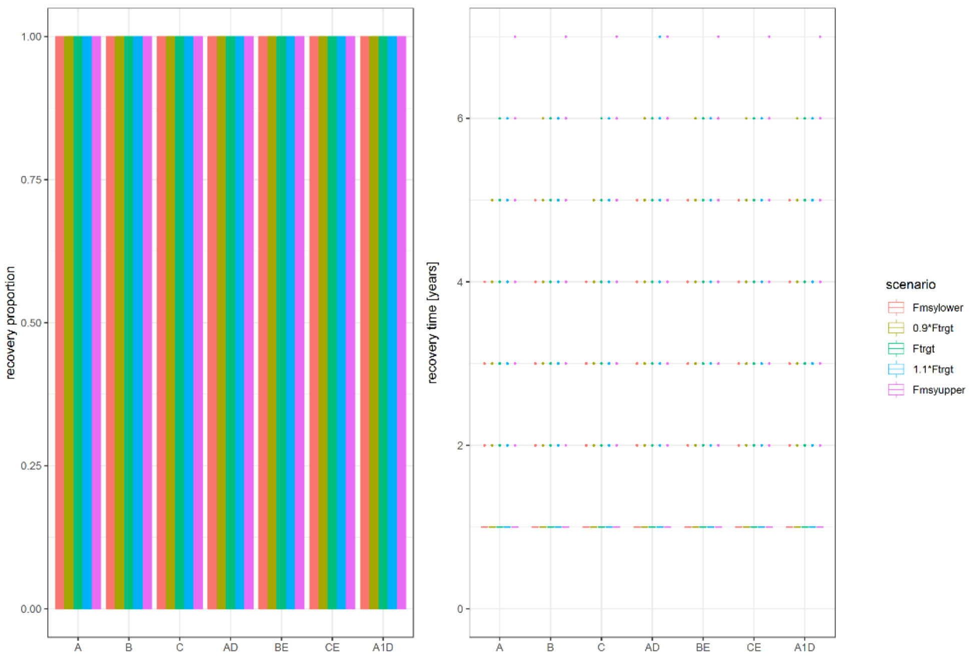


Figure 6.4.4.4. Saithe in Subareas 4 and 6 and Division 3a: Sensitivity of performance statistics for the optimised management strategies to changes in F. The left plot indicates the proportion of replicates that recover above B_{pa}=MSY $B_{trigger}$, while the right plot indicates the number of years taken to recover above B_{pa}=MSY $B_{trigger}$ for the first time, indicated as box and whisker plots. See Figure 6.4.4.1 for more details.

6.4.5 Robustness of management strategies across alternative OMs

Robustness of the "optimised" management strategies (A, B, C, A+D, B+E, C+E, and A_1+D) across alternative operating models (described in Sections 6.2.1–6.2.2) were evaluated in the short- (first five years), medium- (years 6–10) and long-term (final 10 years). Performance statistics for each "optimised" management strategy were compared across operating models and to a version of management strategy A that sets $F_{target}=F_{MSY}=0.363$ and $B_{trigger}$=MSY $B_{trigger}$=149 098 t (labelled A*) in Figures 6.4.5.1–3.

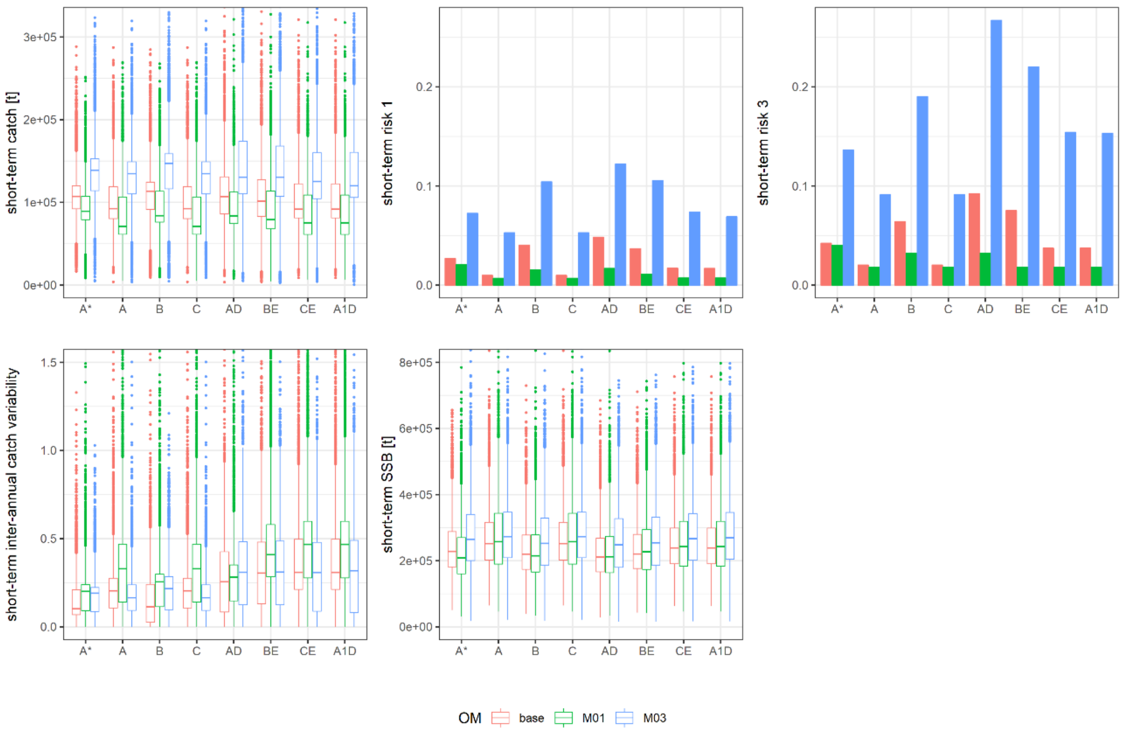


Figure 6.4.5.1. Saithe in Subareas 4 and 6 and Division 3a: Performance statistics for the various management strategies with alternate operating models in the short-term (first five years). Plots include median catch, risk1, risk3, inter-annual catch variability, and SSB, as indicated by the label on the y-axis. Within each plot, the management strategies are A* (i.e. management strategy A with $F_{target}=F_{msy}$= 0.363 and $B_{trigger}$=MSY $B_{trigger}$= 149 098 t, and the seven optimised management strategies (A, B, C, A+D, B+E, C+E, and A_1D). The operating models are the base OM (base), M = 0.1 (M01), and M = 0.3 (M03), as described in Sections 6.2.1 and 6.2.2. In the box and whisker plots, the heavy horizontal line within the box indicates the median, the edges of the box indicate the 25th and 75th percentiles, and the whiskers extend to the largest and smallest values within 1.5 times the inter-quartile range (IQR) from the edges, and the remaining points indicated as dots outside the whiskers are the outliers to 1.5*IQR from the edges.

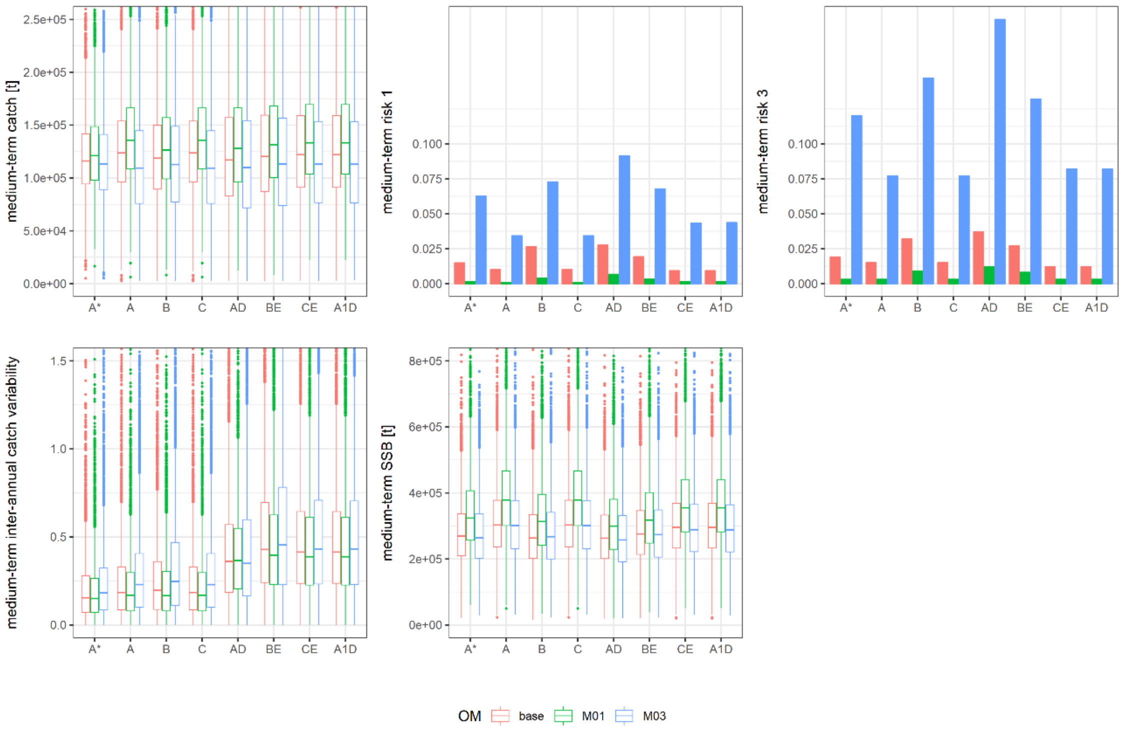


Figure 6.4.5.2. Saithe in Subareas 4 and 6 and Division 3a: Performance statistics for the various management strategies with alternate operating models in the medium-term (years 6-10). See Figure 6.4.5.1 for more details.

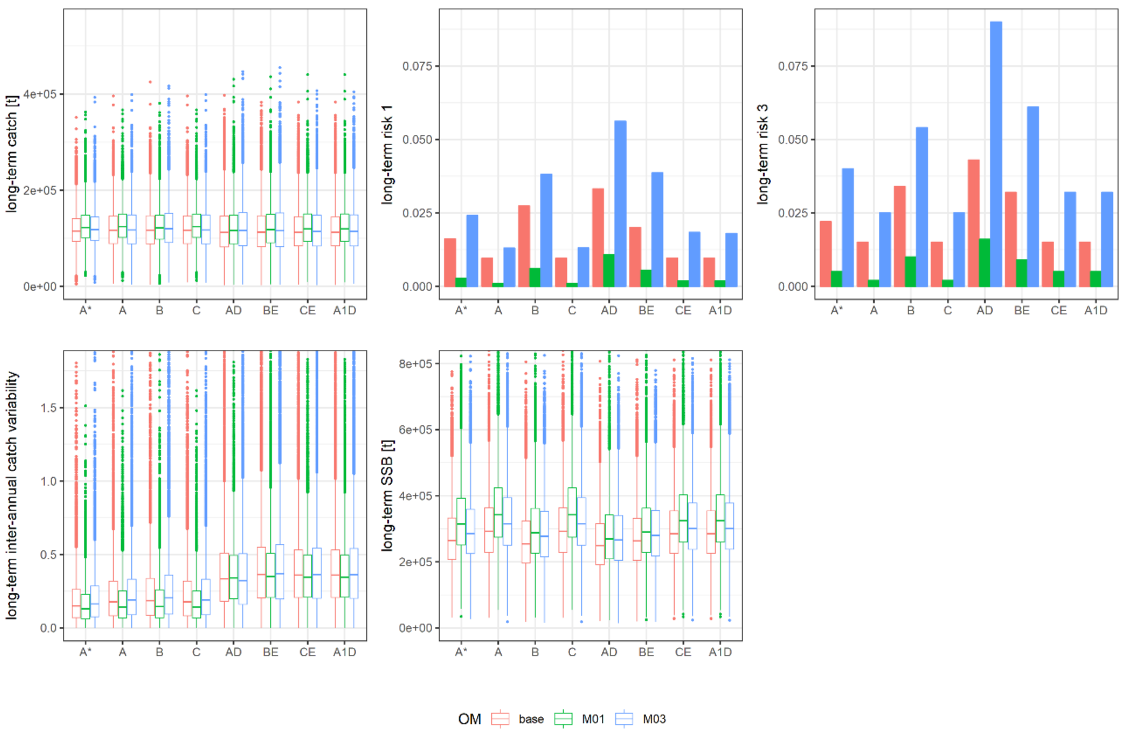


Figure 6.4.5.3. Saithe in Subareas 4 and 6 and Division 3a: Performance statistics for the various management strategies with alternate operating models in the long-term (final 10 years). See Figure 6.4.5.1 for more details.

The discrepancies between the management procedure and the underlying "truth" for the HCR A for the three operating models, base, M = 0.1, M = 0.3, are in Figure 6.4.5.4. The plot should not be considered as a continuous time series plot but is instead a discrete plot of the final year of the management procedure for each time step. The estimation model component of the management procedure revises historical estimates of stock numbers, fishing mortality and any derived metrics with each new estimation, so only the final year in each time step is shown. The dip and then peak in F near the beginning of the projection period indicates first an under- and then over-estimation of F with the start of HCR A; SAM can take time to adjust to changes in F under some model configurations (e.g. this happens for cod also). In the long-term, F stabilizes and the median for F and SSB for the baseline OM1 in the management procedure and the operating model are the same. For the alternate OMs, the deviation in F and SSB are expected. In the M = 0.1 OM, the "true" natural mortality is lower than the perception, so F is underestimated and SSB is overestimated in the management procedure in the long-term. With M = 0.3, the opposite occurs.

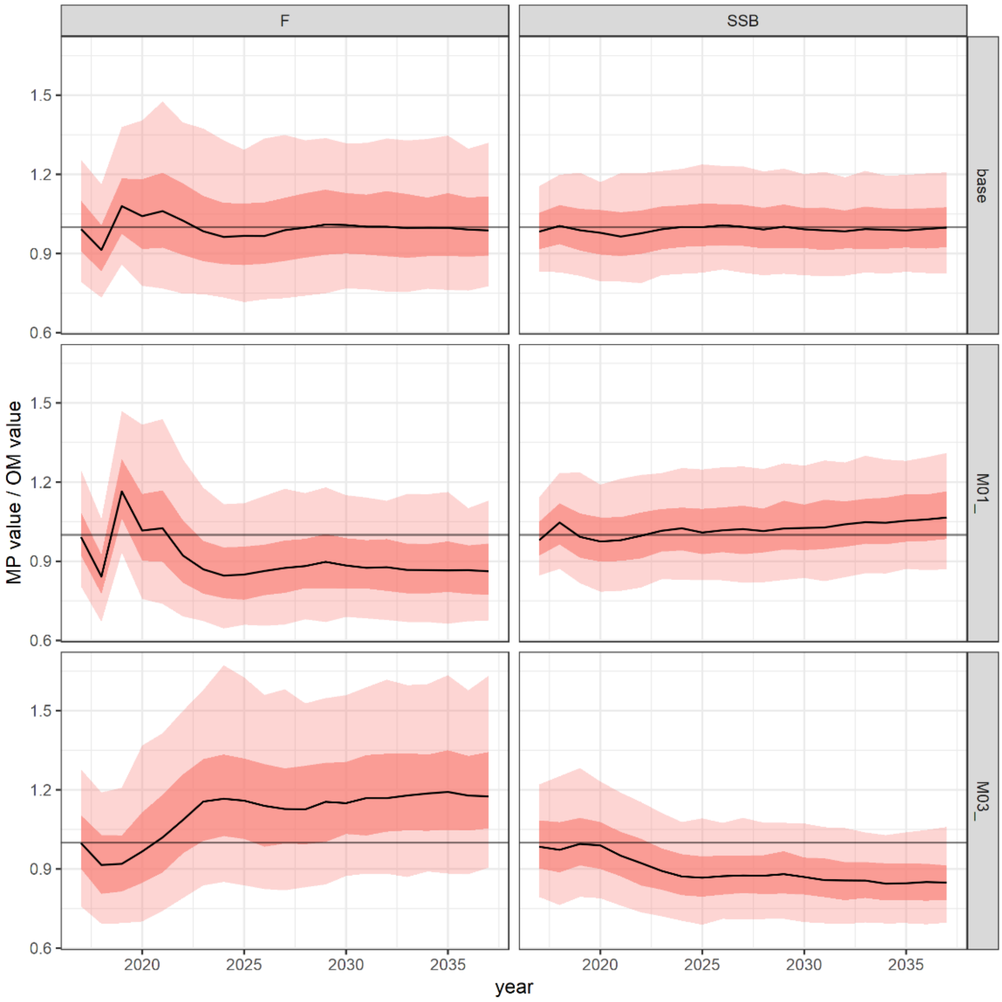


Figure 6.4.5.4. Saithe in Subareas 4 and 6 and Division 3a: Discrepancy in estimates of F and SSB from the management procedure compared to the underlying "truth" for each alternative operating model (see Figure 6.4.5.1 for definitions). Values > 1 indicate an overestimation by the management procedure while values < 1 indicate an underestimation. The plot should not be considered as a continuous time series plot but is instead a discrete plot of the final year of the management procedure for each time step.

6.5 Conclusions

In general, saithe is in a reasonably healthy state at the start of the management procedure. This stock has a relatively flat yield curve, where there is not much change in yield over a range of Fs for a given $B_{trigger}$.

"Optimised" combinations without stability

- The median long-term SSB is above $B_{trigger}$ for all optimised management strategies without stability, indicating that the rules are operating mostly on the plateau.
- The ICV is relatively low for all options.
- The performance of A and C are very similar because SSB does not drop low in the majority of the replicates to trigger a change in F. $B_{trigger}$ = 250 000 t and F_{trgt} = 0.35 for both options.
- The performance of B indicated that some replicates were in a region of low SSB. B results in a marginally higher median catch but lower SSB. $B_{trigger}$ = 200 000 t and F_{trgt} = 0.39.
- While the stock avoids extremely low stock sizes (well below B_{lim}), the functional form of B is inherently more conservative than A because it reduces F more rapidly below $B_{trigger}$. As a result, the MSE analysis presented here indicated that a higher F_{target} and lower $B_{trigger}$ is sustainable and precautionary in the long-term for B compared to A. However, there is greater variability in the short-term stock development than in the long-term (partly as a result of moving to a different management strategy).
- For A and C, the short-term risk (risk3) level remains under the 5% level, and the quoted $B_{trigger}$ and F_{target} levels are precautionary in both the short- and long-term. However, for B, the short-term risk goes over 5%, and reaches 6.4%. Although B is precautionary in the long- and medium-term, at the quoted F_{target} levels, **it is not precautionary the short-term**.

"Optimised" Combinations with stability

- Optimised management strategies including stability resulted in decreased median catch, greater ICV for all options. The increase in the ICV resulted from the extreme banking and borrowing implementation used.
- SSB was lower for A+D, A_1+D, and C+E than the corresponding management strategies without stability.
- F_{target} was higher and $B_{trigger}$ was lower for all management strategies expect B+E, when comparing to corresponding management strategies without stability.
- For optimised B+E, $B_{trigger}$ was higher but F_{target} was the same as B without stability. This resulted in a lower median catch, but higher SSB and higher ICV than B without stability.
- The short-term risk (risk3) is over the 5% threshold for A+D and B+E. For A+D, it reaches 9.2%, and for B+E, 7.5%. Although these management strategies are precautionary in the long- and medium-term, at the quoted F_{target} levels, they are **not precautionary the short-term**.

Compared to MSY advice rule approach

- The MSY approach advice rule produces a similar long-term yield as the seven management strategies but with a lower ICV. Risk is higher and long-term SSB lower for the MSY approach rule (A*) than for A, C, C+E, and A_1+D. For B, A+D, and B+E (i.e., those that are not precautionary in the short-term), A* has a lower long-term risk and slightly higher long-term SSB.
- Short-term risk is more than 5% for B, A+D, and B+E.
- Recovery to above B_{pa} is 1 year (i.e. the stock is above B_{pa} from the first year of the projection) and the recovery proportion is 100% for all management strategies

Sensitivity for "Optimised" Combinations

- Short- and long-term catches are broadly similar across the F ranges for the sensitivity tests; $F_{MSY\text{-lower}}$ and $F_{MSY\text{-upper}}$ have slightly lower values.
- Medium-term catches show a gradient across the F ranges, from low with $F_{MSY\text{-lower}}$ to a high with $F_{MSY\text{-upper}}$.
- Long-term risk3 is above 5% for $F_{MSY\text{-upper}}$ for all HCR options, and for 1.1*F_{trgt} for B, A+D, and B+E. **$F_{MSY\text{-upper}}$ is not precautionary for any of these management strategies.**
- These analyses have been conducted to analyse the yields and risk of fishing at the F_{target} level. They have **not** been conducted to ensure that F above F_{target} (for example within F_{MSY} ranges) is precautionary. The analysis suggests that **for some HCRs, F levels even 10% above F_{target} are not precautionary**. For B, A+D, and B+E, any fishing above the F_{target} calculated here **is considered non-precautionary**. Consequently, if management strategies B, A+D, or B+E are selected, the upper end of any F-range should be set to the F-target level presented here.
- ICES is encouraged to consider, for future MSE exercises conducted within Common Fisheries Policy areas (or other cases where an F-range may be advised), that the HCR should be selected based on a requirement that the upper value of a target F-range (e.g., $F_{MSY\text{-upper}}$) is precautionary.

Robustness tests against alternative operating models

- All management strategies tested were precautionary under the alternate operating model M=0.1 in the long-, medium- and short-term.
- Management strategies B, A+D, or B+E were not precautionary under the alternate operating model M=0.3 in the long-term. Furthermore, none of the management strategies were precautionary under this alternative operating model in the medium- or short-term.
- If the assumption that M=0.2 is incorrect and natural mortality is actually higher in the population, the management strategies investigated here are not precautionary. More work should be completed to ensure that M is not under-estimated for North Sea saithe.

Computational considerations

- The simulations required for this MSE were computationally very expensive and it was not possible to run the full grid for all management strategies. Computing facilities available in-house were used together with external resources, some of which were not free.

7 Herring (Clupea harengus) in Subarea 4 and divisions 3.a and 7.d, autumn spawners (North Sea, Skagerrak and Kattegat, eastern English Channel)

7.1 Baseline operating model

7.1.1 Model and settings

The assessment for autumn-spawning herring in the North Sea is performed using the SAM model (Nielsen and Berg 2014). This is run during the herring assessment working group (HAWG) and extensive results can be seen in corresponding reports. The assessment also recently went into benchmark (ICES, WKPELA, 2018). The management for autumn spawning herring in the North Sea involves four different fleets operating on the stock:

- A-fleet: human consumption in the North Sea and Eastern Channel
- B-fleet: bycatch of herring (catches of herring taken as by-catch in fisheries using nets with mesh sizes smaller than 32 mm) in the North Sea
- C-fleet: human consumption in Division 3.a
- D-fleet: bycatch of herring (catches of herring taken as by-catch in fisheries using nets with mesh sizes smaller than 32 mm) in Division 3.a

For both the B- and the D-fleet the main by-catch of herring is taken in the sprat fishery, and only smaller quantities in the Norway pout and Sandeel fishery, which are the two other fisheries where nets with mesh sizes smaller than 32 mm are used. While the main assessment carried out during the working group is single fleet, a multi-fleet assessment is also run in order to determine the fishing selectivity for the different fleets. These selection patterns are used for short term projections. Overall, the input to the assessment consists of catch data and data from five survey indices.

Catch data span from 1947 to 2017 for a single fleet and 1997 to 2017 for multiple fleets. These data consist of:

- Weight at age in the catch
- Total catch (discards considered negligible)
- Catch at age

Five different surveys are conducted yearly and provide the following indices:

- IHLS survey (early larvae index) providing the LAI index (spawning component index)
- IBTS-Q1 survey (trawl survey) providing the IBTS0 index (late larvae index) and the IBTS-Q1 index (age 1)
- IBTSQ3 survey (trawl survey) providing the IBTS-Q3 index (age 1 to 5)
- HERAS survey (acoustic survey) providing the HERAS index (age 1 to 8) and mean weight in the stock.

Results from the latest assessment are shown for: (1) the residuals for the different input sources (Figure 7.1.1.1); (2) the observation error (Figure 7.1.1.2), i.e. the contribution of the different input data to the assessment outputs; (3) the stock trajectory (Figure 7.1.1.3).

For this management strategy evaluation (MSE), the conditioning of the baseline operating model is based on the latest assessment (ICES HAWG, 2018) but excluding the LAI index. The LAI index consists of four components and is treated differently from conventional survey indices in the SAM model. In order to simplify the implementation of the current MSE, the exclusion of the LAI index was explored. The results are shown in Figure 7.1.1.4 and show that this index has marginal influence on the results of the assessment. As a result, it was decided to carry out the MSE without the LAI index.

The Management Strategy Evaluation (MSE) considers four components. The biological stock unit of herring in the North Sea [1], the four fisheries targeting the stock unit [2], the fisheries-independent surveys [3], the stock assessment procedure to obtain a perceived status of the stock unit and is used to set management targets [4]. The framework includes feedback loops, where over time, the result of set-ting management targets affects the stock unit the year after, and thereby also affects the fisheries and management. In order to reflect the uncertainties related to stock dynamics, fisheries dynamics and management implementation, the simulations are run with 1000 replicates, each representing a different but likely version of the true dynamics of the stock unit and fisheries. The combination of all replicates together indicates the range in outcomes and risk for a given stock and management structure assumption. ICES assessment result from the North Sea Autumn-Spawners (NSAS) is used to condition the model for the years 1947-2017. Simulations were run until 2037 (i.e. 20 years into the future).

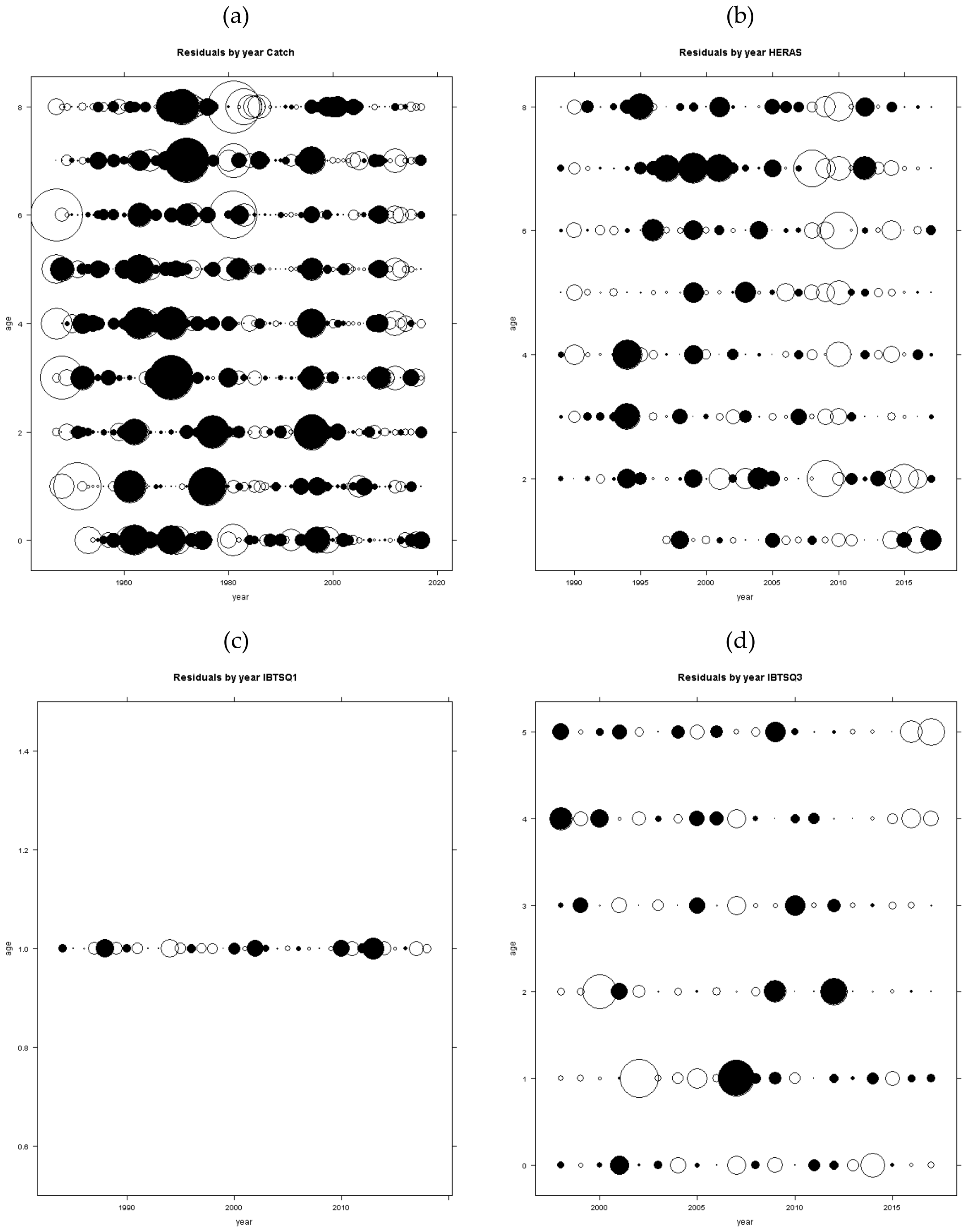


Figure 7.1.1.1: North Sea herring. Standardized residuals for the various input sources. (a) Catches. (b) HERAS. (c) IBTS-Q1. (d) IBTS-Q3. Extracted from the 2018 HAWG report (ICES, HAWG, 2018).

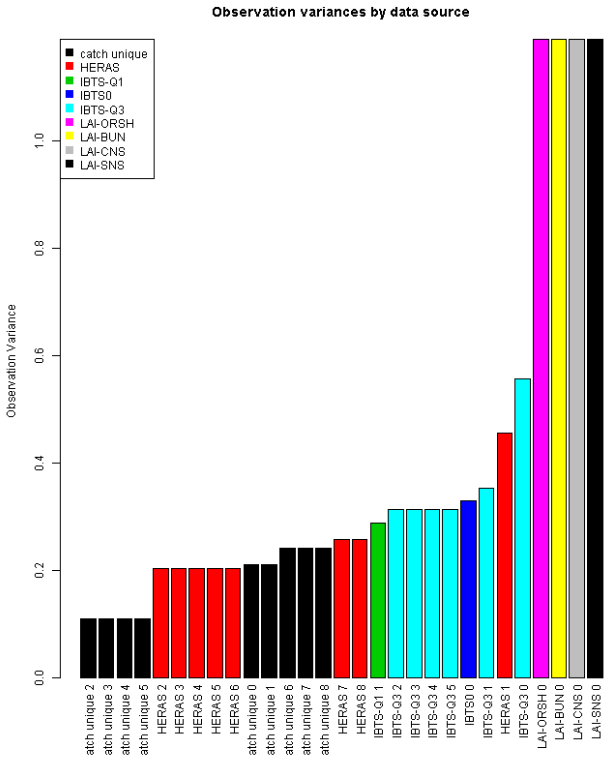


Figure 7.1.1.2: North Sea herring. Observation variance by data source as estimated by the assessment model. Observation variance is ordered from least (left) to most (right). Colours indicate the different data sources. Observation variance is not individually estimated for each data source thereby reducing the parameters needed to be estimated in the assessment model; in such cases, observation variances have equal values. Extracted from the 2018 HAWG report (ICES, HAWG, 2018).

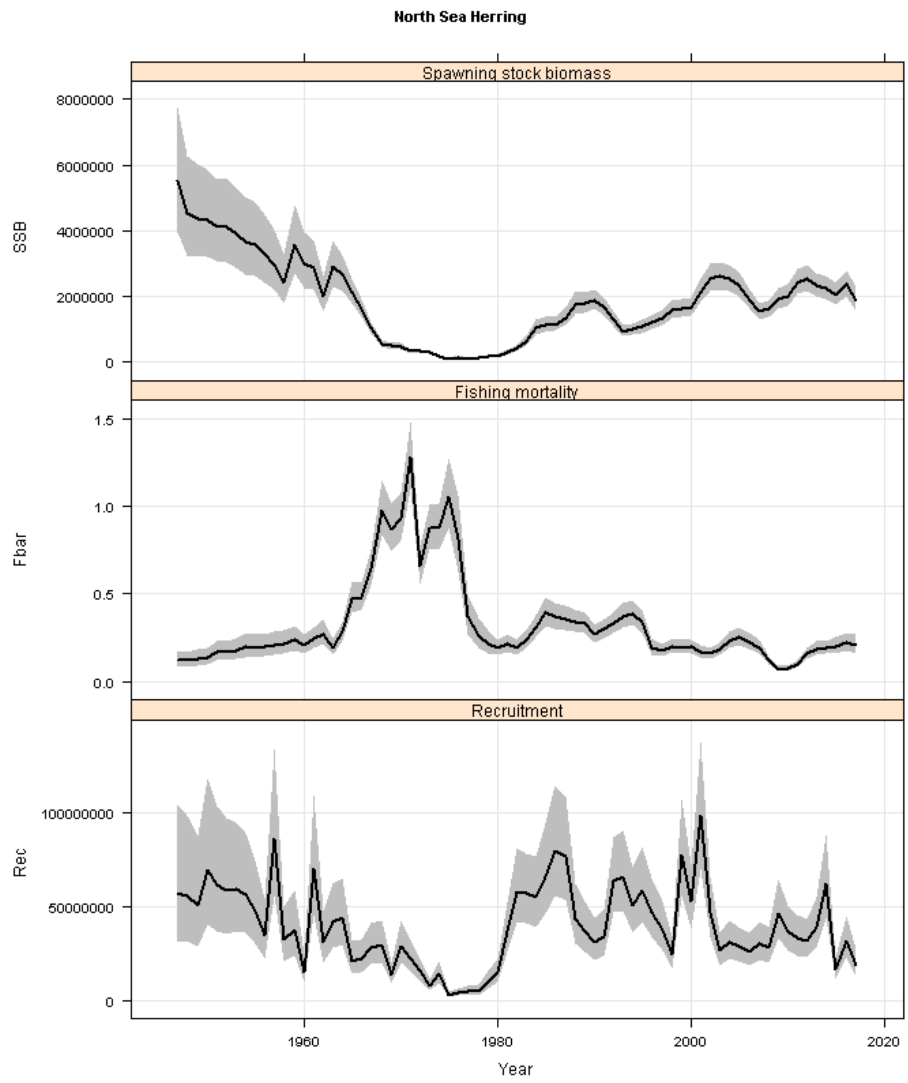


Figure 7.1.1.3: North Sea herring. Stock summary plot of North Sea herring with associated uncertainty for SSB (top panel), F ages 2–6 (middle panel) and recruitment (bottom panel). Extracted from the 2018 HAWG report (ICES, HAWG, 2018).

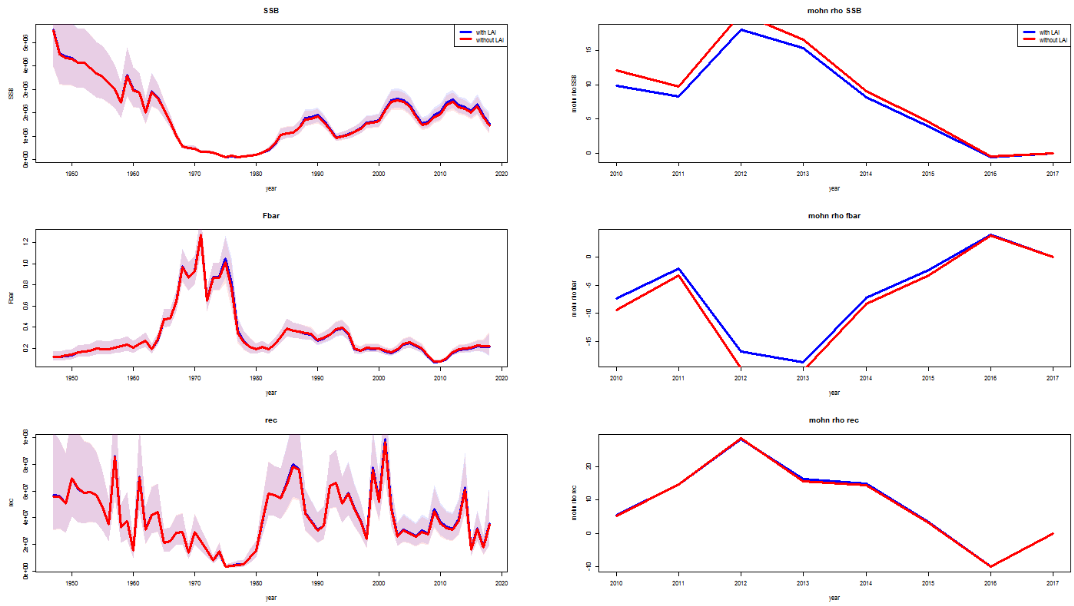


Figure 7.1.1.4: North Sea herring. Impact of the exclusion of the LAI index. Left column: Comparison of stock trajectories between assessment including and excluding the LAI index. Right column: Assessment retrospective pattern performances (Mohn's rho) for the assessment including and excluding the LAI index.

7.1.2 Parameter uncertainty

The output of the stock assessment model, carried out at ICES (ICES, HAWG, 2018), was used to populate the age-structured (ages 0–8) population model for North Sea Herring. Different replicates for the historical stock numbers at age and fishing mortality-at-age were drawn from a multivariate normal distribution using the variance/covariance matrix estimated using the SAM model with the data available at HAWG 2018 (excluding LAI index). For this study, 200 and 1000 replicates were generated for further input to the operating model. The 200 set of replicates was used for the $F_{target}/B_{trigger}$ grid search, while the 1000 set of replicates was used for fine tuning of $F_{target}/B_{trigger}$ optima and evaluation runs of the operating model.

7.1.3 Recruitment

Recruits are being added to the future population assuming two types of stock-recruitment relationships: Ricker and Segmented regression. These are fitted to stock-recruit pairs from 2002-2016 (corresponding to a low productivity phase for the stock). The models are weighted in the 1000 and 200 replicate sets according to a 85-15% split (respectively, ricker-segmented regression). This is in agreement with the EqSim analyses that was used to define reference points at the ICES 2018 benchmark of North Sea herring (ICES, WKPELA, 2018). Residuals of the fit for each replicate was used to generate future deviations from the stock-recruitment curve. This was modelled using an ARIMA process (stats package in R) to account for auto-correlation in recruitment, following:

$$X[t] = a[1]X[t-1] + \ldots + a[p]X[t-p] + e[t] + b[1]e[t-1] + \ldots + b[q]e[t-q]$$

where X are recruitment residuals, t is time, a and b are the parameters of the autoregressive model, p is number of autoregressive terms, q is the number of lagged errors and e is the error term. In the future period, median residuals are expected to be around 0 but do cover the total variation of recruitment residuals observed.

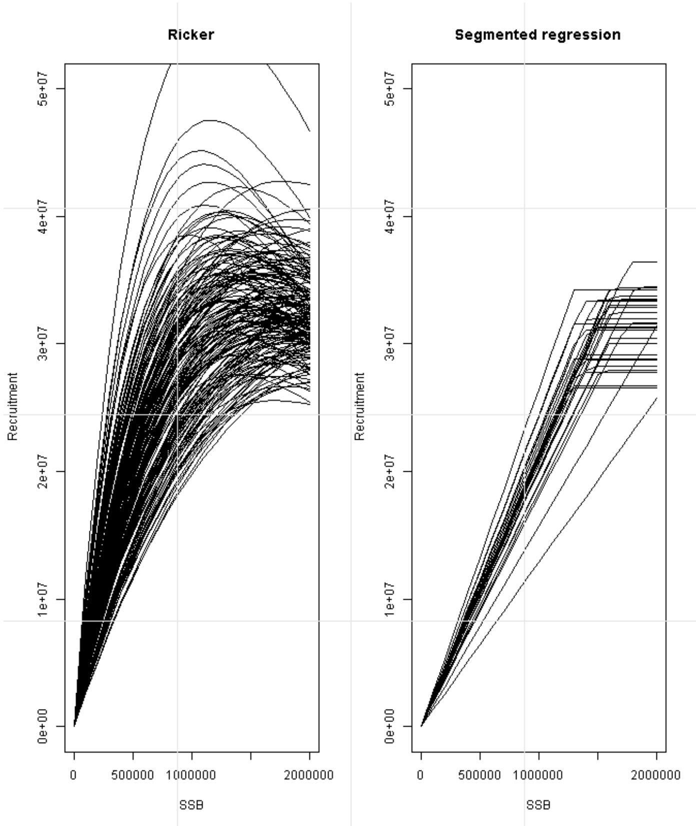


Figure 7.1.3.1: North Sea herring. Fitted stock-recruitment relationships for the ricker curve (left) and the segmented regression curve (right)

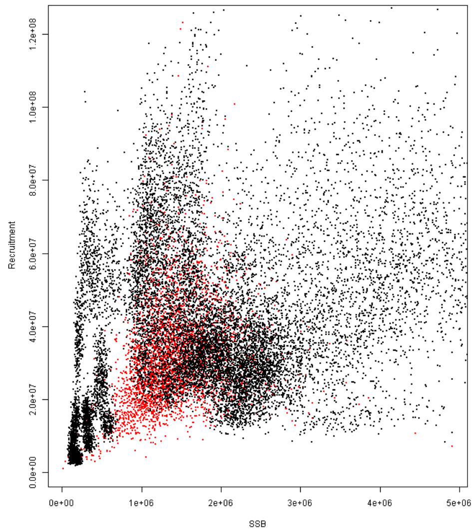


Figure 7.1.3.2: North Sea herring. Predicted recruitments from the model from the ricker curve (in black) and the segmented regression (in red)

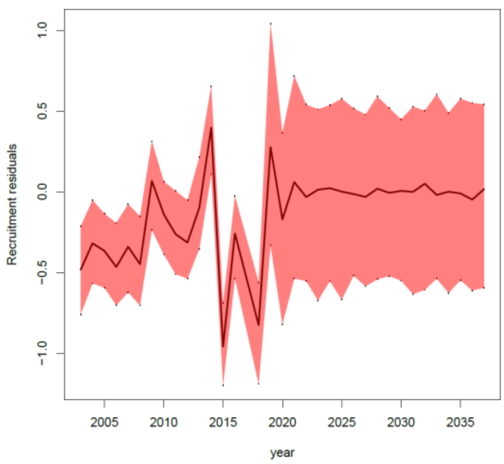


Figure 7.1.3.3: North Sea herring. Spread in recruitment residuals over time as simulated from the fitted SR-curves

7.1.4 Mean weights, maturity, natural mortality and selection

To maintain a certain level of autocorrelation, previously observed natural mortality vectors (all ages at once) are sampled in blocks up to ten years (2007–2017), similar to the low productivity phase for the stock, and glued together until the entire projection period is filled. Additionally, to maintain a degree of correlation between maturity-at-age and weight-at-age (both in the stock and in the fishery), year ranges are shared among these processes. These block of years for natural mortality, weight at age and maturity at age are randomized (length of blocks, years in block of years) for each replicate. There is no evidence that M and weight-at-age or maturity-at-age are correlated and hence M-at-age vectors are drawn separate from the other biological parameters. Catches and survivors in the forecasted years of the stocks are calculated using the (natural and fishing) mortality rates. Pre-smoothed natural mortality estimates from the 2017 SMS keyrun (WGSAM 2018) are used in the OM.

Fishing mortality may be caused by a variety of fisheries, each associated with different selection patterns and catch targets. The fishing mortality encountered by a stock unit therefore depends on the sum of the fishing mortalities from each fishery.

The four fleets targeting the herring stock units consist of:

- A: North Sea human consumption (targeting Herring in area 4 and 7d)
- B: North Sea industrial (catches of herring taken as by-catch in fisheries using nets with mesh sizes smaller than 32 mm)
- C: Division 3.a human consumption (targeting Herring)
- D: Division 3.a industrial (catches of herring taken as by-catch in fisheries using nets with mesh sizes smaller than 32 mm)

Each of these fleets catch fish at different ages following a certain selection-at-age pattern. The selection pattern that is obtained from the multi-fleet assessment is used for this purpose. The sum of multi-fleet selection is identical to the single-fleet estimated selection. The future selection patterns are assumed to follow an age-correlated random walk (similar to the design in the assessment). Starting from the 2017 estimated selection pattern, each following years' selection is obtained by modelling a change in selection-at-age to the next year. All steps from one year to the next for the entire time-series follows a normal distribution with mean 0 and variance estimated based on the covariance of log-transformed F-at-age change (from year y to year y+1) over the years 2007–2017 for NSAS. To prevent extreme changes, steps outside the 95% CI of the distribution were excluded.

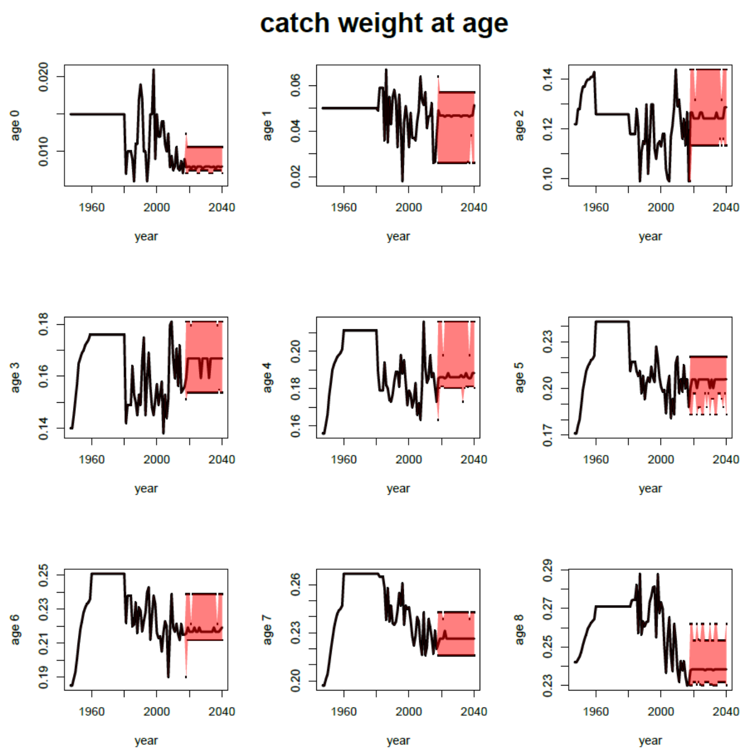


Figure 7.1.4.1: North Sea herring. Simulated catch-weight-at-age

Figure 7.1.4.2: North Sea herring. Simulated stock-weight-at-age

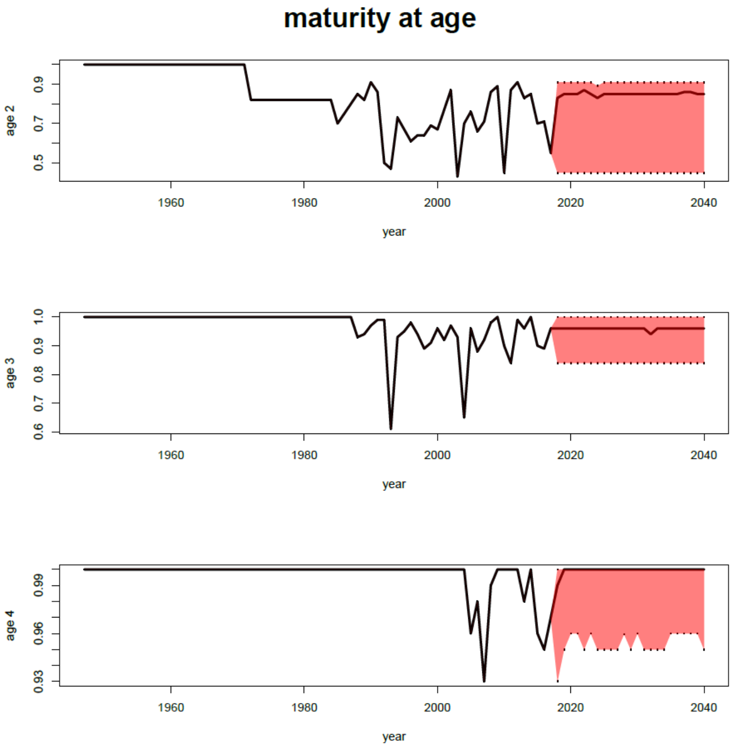


Figure 7.1.4.3: North Sea herring. Simulated maturity-at-age

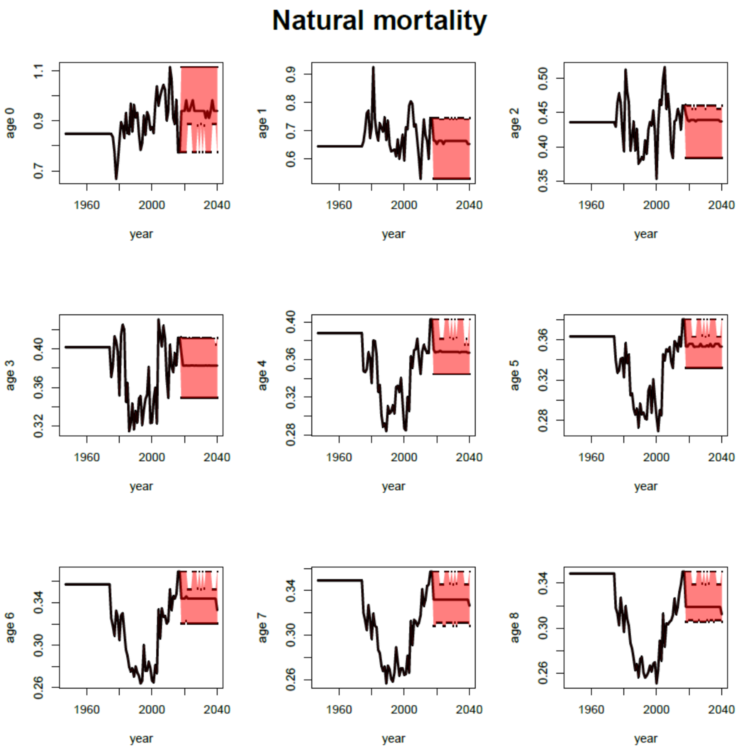


Figure 7.1.4.4: North Sea herring. Simulated natural mortality-at-age

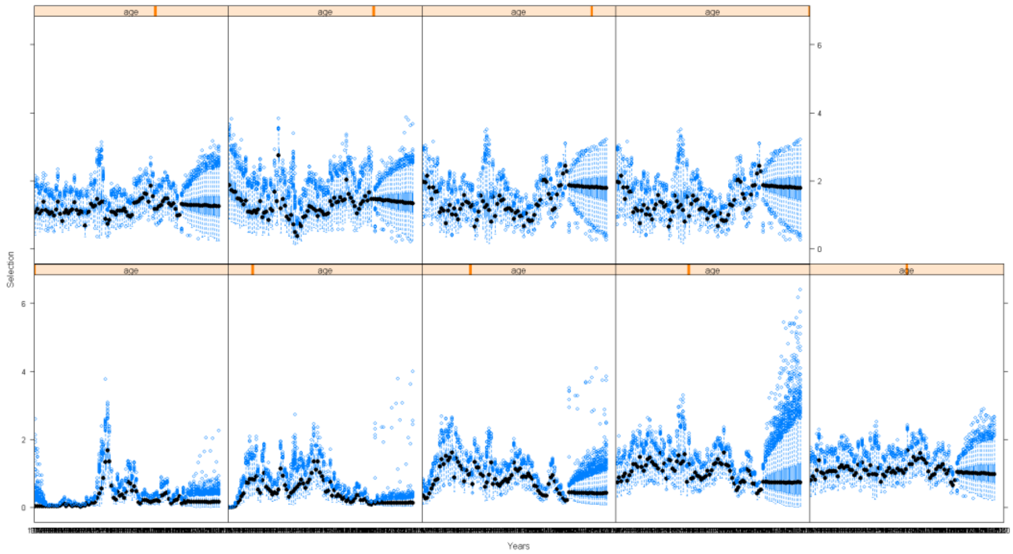


Figure 7.1.4.5: North Sea herring. Simulated selection pattern over time (x-axis). Ages range from 0 (bottom-left) to 8 (top-right)

7.1.5 Generating data from the operating model

Future catchabilities for the surveys are drawn from the variance-covariance matrix and are used to calculate future index values by multiplying OM estimated numbers-at-age by the catchability and added uncertainty based on residuals drawn from a log-normal distribution with mean 0 and sd, taken from the observation variance estimated by the SAM model without the LAI index that was used to condition the OM.

Catches are generated by the fishing fleet applying their selection patterns scaled such that they match the set TACs. Catch input to the stock assessment is taken as the catch generated by the fishing fleet with added uncertainty based on residuals drawn from a log-normal distribution with mean 0 and sd, taken from the observation variance estimated by the SAM model without the LAI index that was used to condition the OM.

7.1.6 Implementation error

The TAC setting procedures and allocation of catch to each of the fleets follows from the management strategy and potential transfers from one fleet to another. In practice, optimisation of the catches in the A-fleet according to the management strategy is also conditional on the B-fleet F_{target} given by the management strategy and the catches simulated for the C- and D-fleets. Both the C-fleet and D-fleet catches are assumed to derive from fixed quotas of 48 427 t (WBSS TAC set in 2018) and 6659 t (fixed TAC), respectively, with the C-fleet transferring between 40-50% of its quota to the A-fleet based on the last 10 years' observations. In the A, C and D fleets, however, the catches do not consist of one herring species alone, but contains a mixture of both NSAS (North Sea autumn-spawners) and WBSS (Western Baltic spring-spawners). As the MSE evaluated how precautionary the stocks were to certain management strategies, the mixed nature of the catches has to be accounted for in the simulations.

Over the past 10 years, on average, 32% of the C-fleet catch consists of NSAS and 68% of WBSS. On average, 64% of the D-fleet catch consist of NSAS and 36% of WBSS. The proportion of the A-fleet that comprises WBSS is negligible and is therefore ignored. The impact of this level of mixing for the catches of NSAS in the D-fleet is mimicked in the simulations by assuming that catches of NSAS in this fleet follows a normal distribution with mean equal to the 10-year average mix and variability equal to half the standard deviation (to prevent values smaller or bigger than 1, resulting in values that are in the same range as observed). For the C-fleet, this mixing is encapsulated in the $p_{\text{C-fleet}}$ parameter (see equations below). The utilisation of the B and D fleets are taken into account and simulated by taking a normal distribution with mean equal to the average utilisation and variability half the standard deviation (to prevent values smaller or bigger than 1, resulting in values that are in the same range as observed). The C-fleet catch after transfer is derived based on an F-constraint. Analyses of the past 10 years showed that the C-fleet had a varying contribution, though without a trend, in F_{bar} between 1 and 2%.in blocks up to ten years (2007-2017), similar to natural mortality, weight at age and maturity at age. In summary the catch for each of the fleets is set or derived as follows:

$\text{CatchNSAS}_C^1 = \text{CatchTot}_\text{C} \cdot \text{Trans}$

where $\text{CatchTot}_\text{C} = 48427\ \text{t}\,; \text{Trans} \sim \text{U}(0.4,0.5)$

$\text{CatchNSAS}_C^2 =$ catch resulting from application of: $p_{\text{C-fleet}} \cdot F_{2-6}$ target of the management strategy

where $p_{\text{C-fleet}}$ is the proportion of F for the C-fleet sampled in blocks up to ten years (2007-2017)

$\text{CatchNSAS}_\text{D} = \text{CatchTot}_\text{D} \cdot \text{Mix}_D \cdot \text{Util}_D$

where $\text{CatchTot}_\text{D} = 6659\ \text{t}\,;\ \text{Mix}_D \sim \text{N}(0.64, (\sigma_D'/2)^2)\,; \text{Util}_D \sim \text{N}(\text{mean last 10 years}, (\sigma_D''/2)^2)$

$\text{CatchNSAS}_\text{B} = \text{CatchTot}_\text{B} \cdot \text{Util}_B$

where CatchTot_B results from the F_{0-1} target of the management strategy ; $\text{Util}_B \sim \text{N}(\text{mean last 10 years}, (\sigma_B'/2)^2)$

$\text{CatchNSAS}_\text{A} =$ Catch resulting from F_{2-6} target from the management strategy + CatchNSAS_C^1

$$\text{CatchNSAS}_\text{Total} = \text{CatchNSAS}_\text{A} + \text{CatchNSAS}_\text{B} + \text{CatchNSAS}_C^2 + \text{CatchNSAS}_\text{D}$$

7.1.7 Number of replicates and projection years

For the grid search, 200 replicates were used; for the final evaluations, 1000 replicates were used. The grid-search for 200 replicates was more extensive and showed a clear and consistent relationship with decreasing F_{target} (lower risk) and decreasing $B_{trigger}$ (higher risk) (Figure 7.1.7.1). This guided the analyses for the 1000 replicates. The OM was projected forward using 1000 replicates and 20 years.

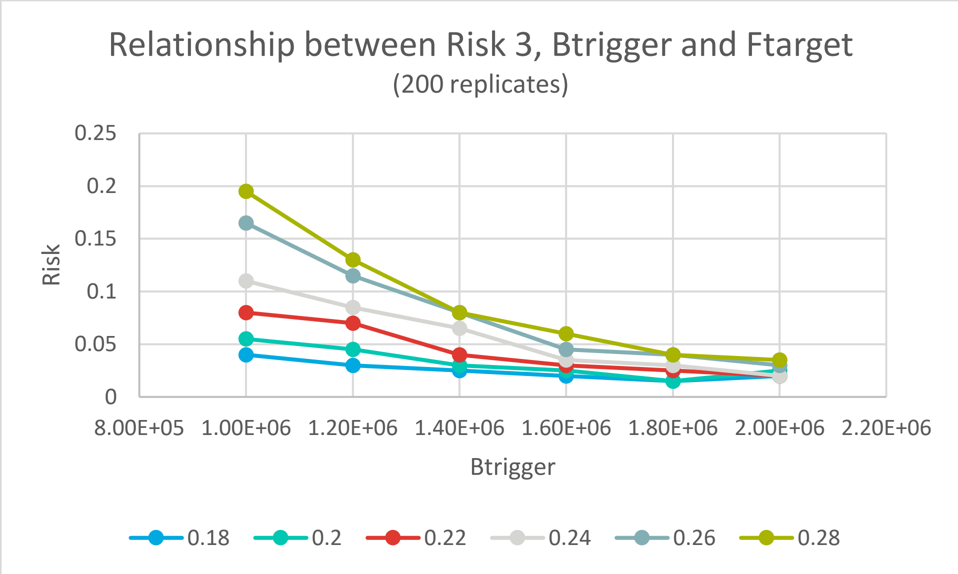


Figure 7.1.7.1. North Sea herring. Relationship between F_{target} (coloured lines), $B_{trigger}$ (horizontal axis) and risk3, based on 200 replicates.

7.2 Management procedure

The perception of the stock unit status in the period after 2017 is generated through explicit inclusion of stock assessments in the simulation, which is based on fishery-independent (surveys) and -dependent (catch) data.

The stock assessment process results in fishing mortality estimates for year y-1 (the final year of catch data), and survivor and SSB estimates for year y (the intermediate year, i.e. the year during which the assessment is conducted). The assessment output estimates may deviate from the true stock unit characteristics as modelled in the biological operating model because of the observation error associated with the data sources that go into the assessment.

A short-term forecast is used within the MSE to set annual TACs as described below. The short-term forecast for NSAS is similar to the multi-fleet forecast as currently used within the North Sea herring assessment, but ignores any catches that could be realized by the C and D fleet. Through this approach we disconnect the TAC setting procedure for North Sea herring from the Western Baltic TAC setting procedure.

Selectivity by fleet in the intermediate (y) and advice year (y+1, the year for which the management strategy provides advice) follow the exploitation pattern as estimated within the stock assessment multiplied with the proportional catch numbers by fleet. Recruitment in the advice year (y+1) is fixed to the weighted geometric mean of the period [y–10 : y-1], while recruitment in the intermediate year (y) is taken from the assessment prediction. Stock and catch weight-at-age and time of spawning are similar to the intermediate year settings (i.e. taken from terminal year of the assessment), while maturity in the intermediate and advice years equals the average maturity estimate over the past three years and natural mortality is averaged over the most recent five years. The exploitation pattern by fleet is scaled up or down to ensure that the catch equals the TAC in the intermediate year. In the advice year, the management strategy determines the increase or decrease in fleet effort and proposes a TAC for the A- and B-fleet. The short-term forecast is an exact replication of the way the short-term forecast is executed in the ICES assessment working group.

However, the proposed TAC is calculated based on numbers, landings selectivity and fleet selectivity obtained from the assessment results which differ from the numbers, landings selectivity and fleet selectivity in the 'true' stocks. Hence, the fishing mortality needed to realise catch equalling the TAC is not identical with the target fishing mortality as set within the management plan. As there is no analytical solution to this equation, an optimisation method is used (based on a combination of golden section search and successive parabolic interpolation (Brent, 1973)) to calculate 'true' fishing mortality.

7.3 Results

These results are bounded by the assumption that optimal strategies can be selected taking a 20-year projection period, 1000 replicates and risk3≤5% over the last 10 years of the simulation into account. If one would change any of these settings, it is likely that results and optimal strategies change, given that the risk criteria does not stabilize in the medium to long term. The results are therefore conditional on the assumptions and indicate that these HCRs are only precautionary within the 20 years tested and would require re-evaluation before ~2035.

Note that no optimal strategy for scenario B+E could be found. This is discussed in the discussion and conclusion sections. The "optimised" combinations for all the other management strategies, along with sensitivity analyses, are shown in Table 7.4.1.

7.3.1 Search grid for “optimal” combination of F_{target} and $B_{trigger}$

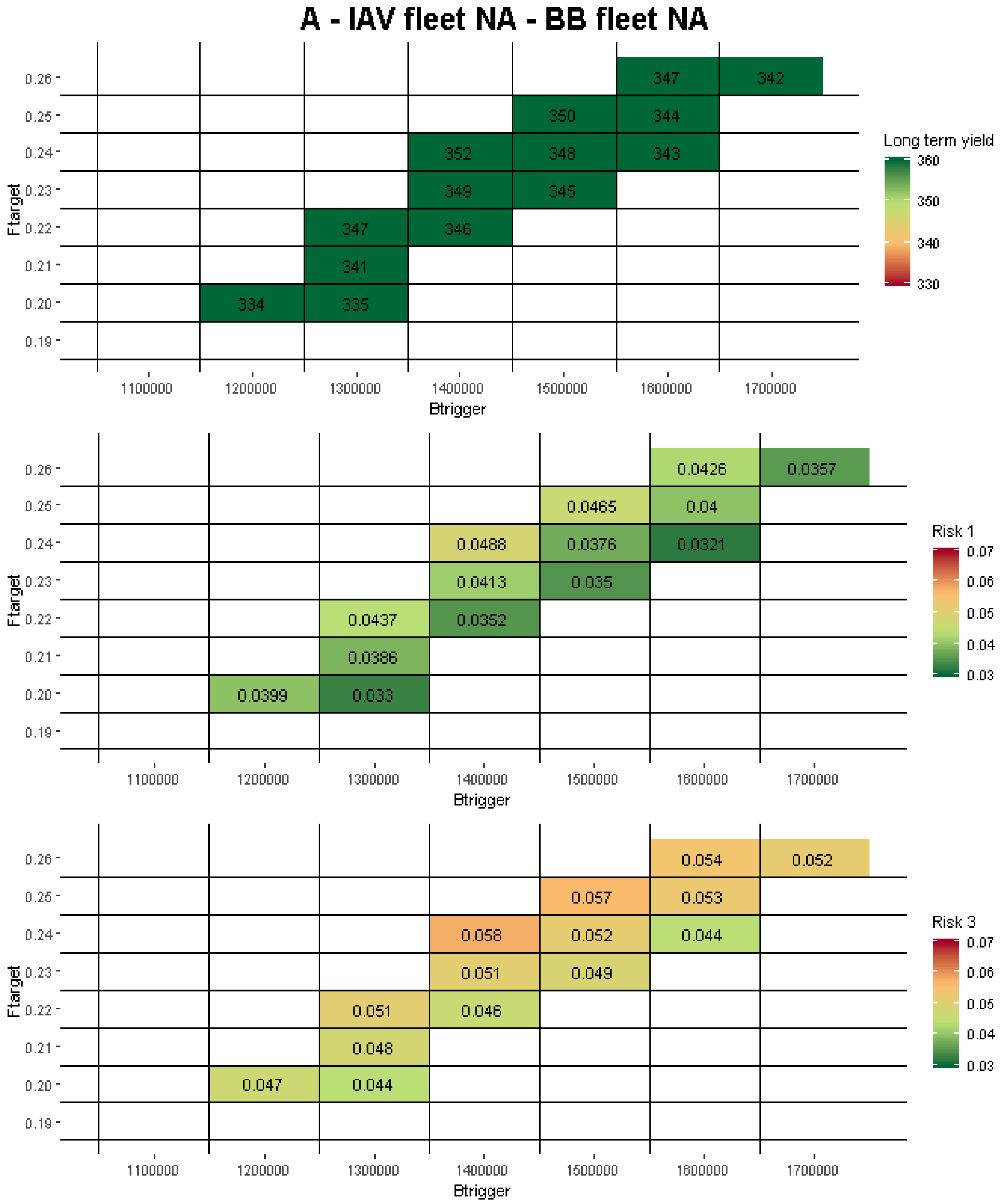


Figure 7.3.1.1: North Sea herring. Grid search for management strategy A (no stabilizers). Risk calculated over the last 10 years of the time-series.

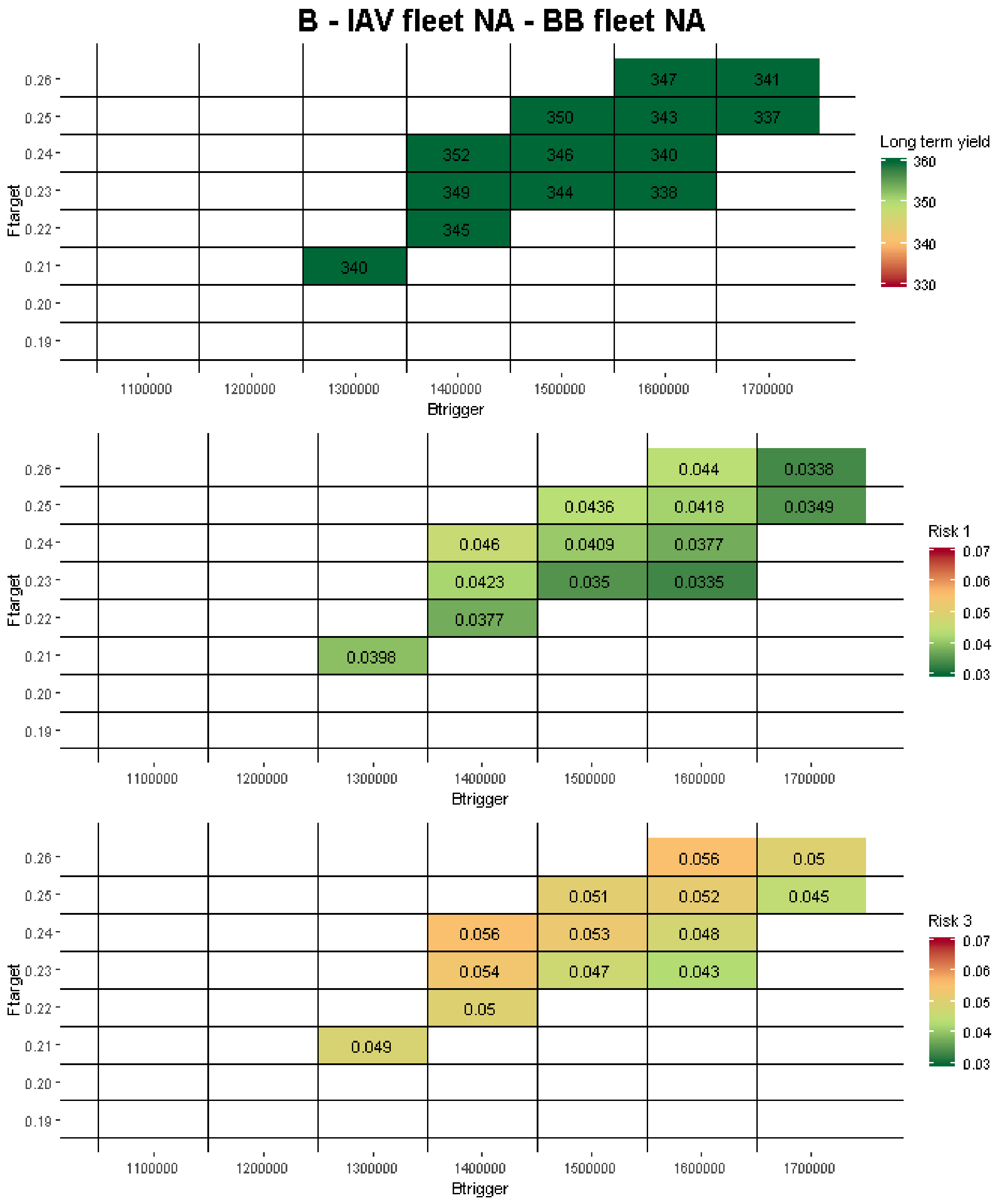


Figure 7.3.1.2: North Sea herring. Grid search for management strategy B (no stabilizers). Risk calculated over the last 10 years of the time-series.

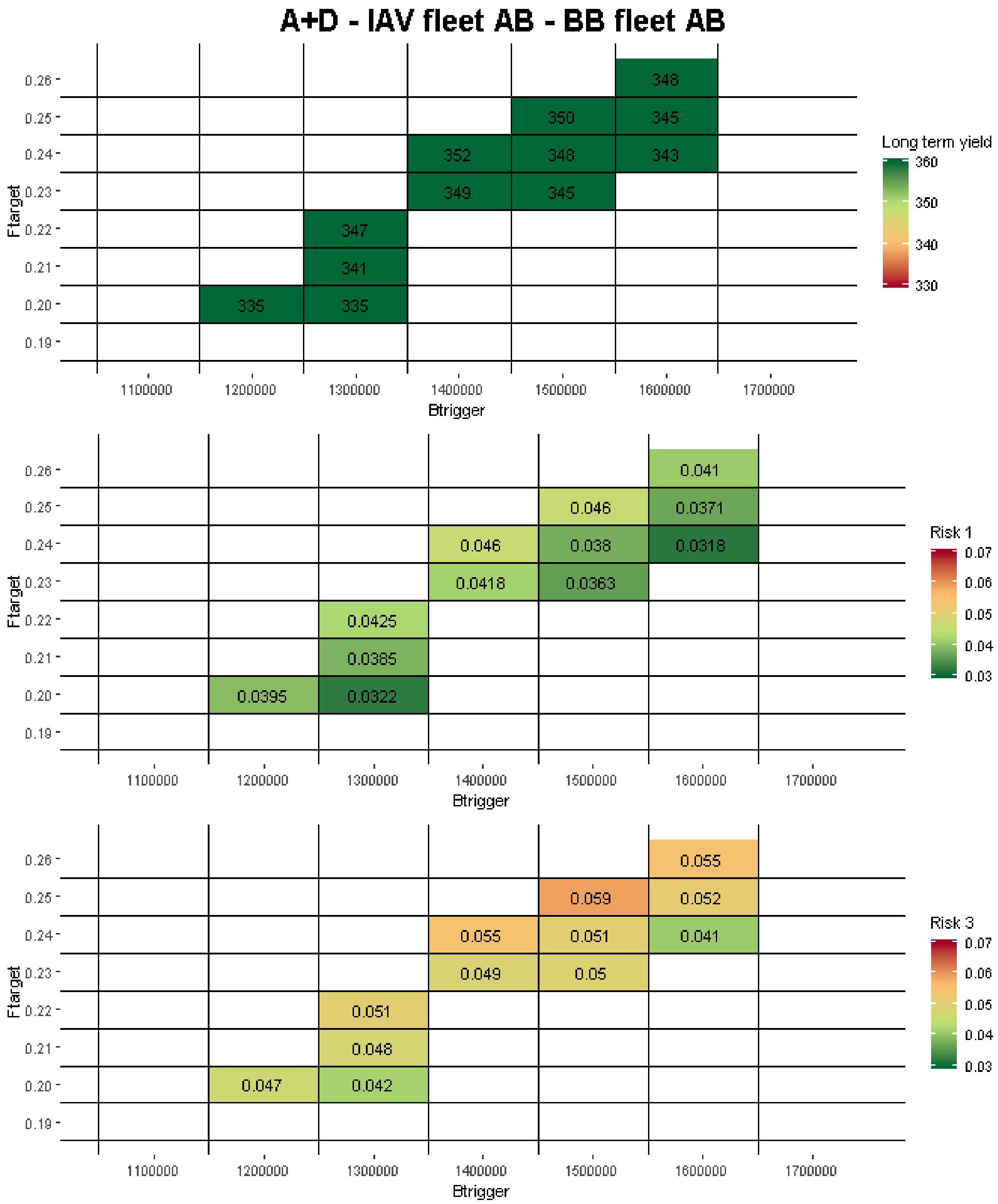


Figure 7.3.1.3: North Sea herring. Grid search for management strategy A+D (with TAC inter-annual variation cap on fleet A and B and banking and borrowing applicable to fleet A and B). Risk calculated over the last 10 years of the time-series.

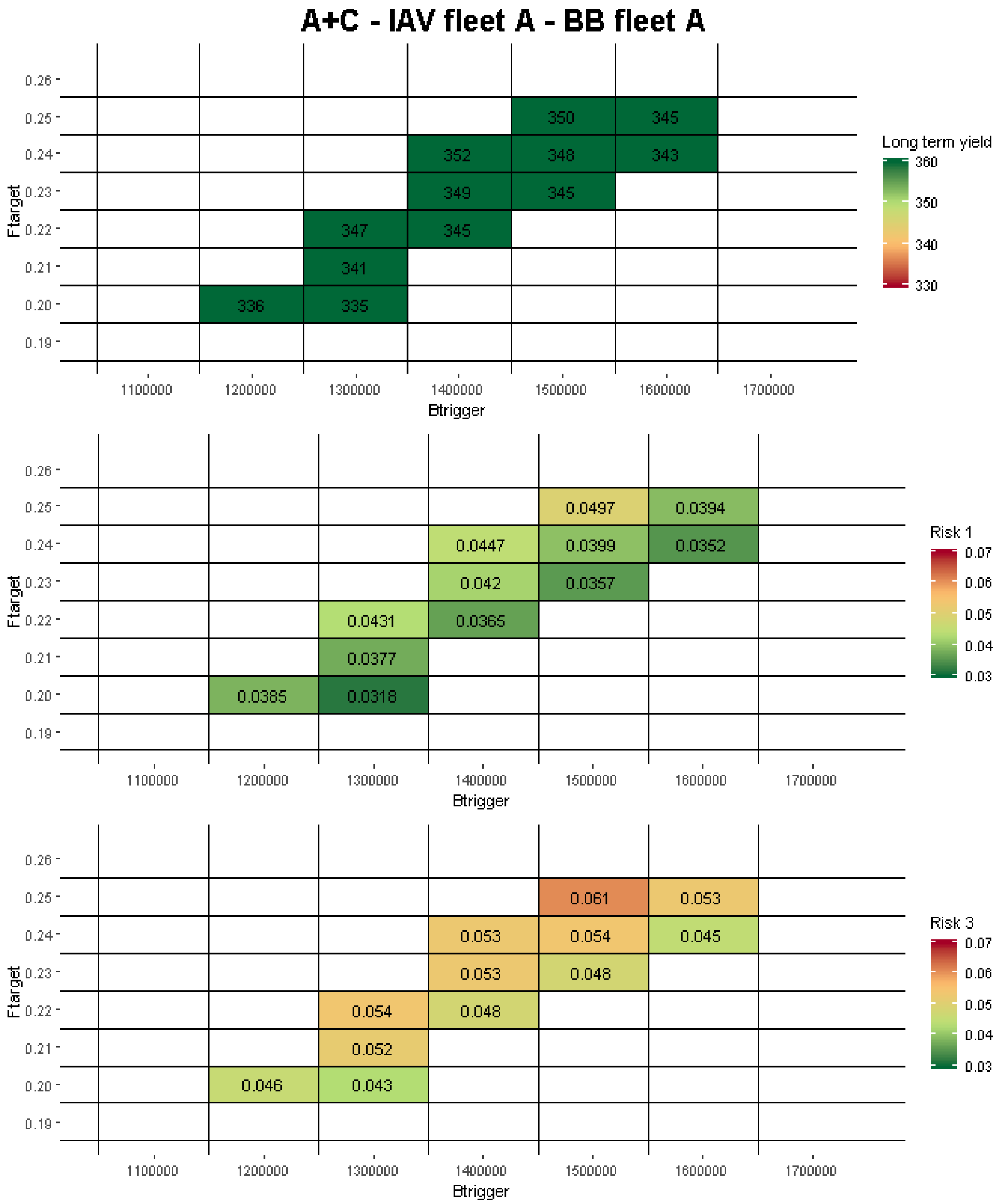


Figure 7.3.1.4: North Sea herring. Grid search for management strategy A+C (with TAC inter-annual variation cap on fleet A and banking and borrowing applicable to fleet A). Risk calculated over the last 10 years of the time-series.

7.3.2 Summary projections

All projections (excluding management strategy B+E) show that SSB increases under current F_{MSY} and MSY $B_{trigger}$ levels to ~1.35Mt (Table 7.4.1). In each of the management strategies evaluated, optimal $B_{trigger}$ is estimated above this level, between 1.4-1.5Mt. This implies that in all cases, management focusses on the slope of the HCR rather than the plateau.

The optimal F_{target} values are somewhat smaller than the F_{MSY} reference points as estimated by ICES (2018). One clear reason for this is the overshoot of the TAC owing to several biological process and managerial decisions in place. North Sea herring reside part of their life in Division 3.a where they are caught by the 3.a fishery. These catches are not accounted for in the 4-7.d fishery for North Sea herring, for which TACs are agreed upon. This has an additional impact on herring. Furthermore, in the past decade, herring quota was transferred from Division 3.a to the North Sea, imposing additional mortality on North Sea herring. Both aspects are fully considered in the MSE, but are accounted for in the OM and not in the MP (Figure 2.3), which allows ICES to advise on the A and B fleet in a precautionary manner.

Management strategy A+D (with TAC inter-annual variation cap on fleet A and B and banking and borrowing applicable to fleet A and B), gave an optimal F_{target} value of 0.23 compared to F_{MSY}=0.26. Both using the same SSB reference point (MSY $B_{trigger\ and}$ $B_{trigger}$) of 1.4 Mt (1.4 Mt). This option gave on average a B-fleet TAC of 17 365 tons.

There were no convergence issues in any of the simulations.

The optimal strategy of HCR A including stock trends are given in the figure below. Summary projections for all management strategies that were “optimised” are given in Annex 11.

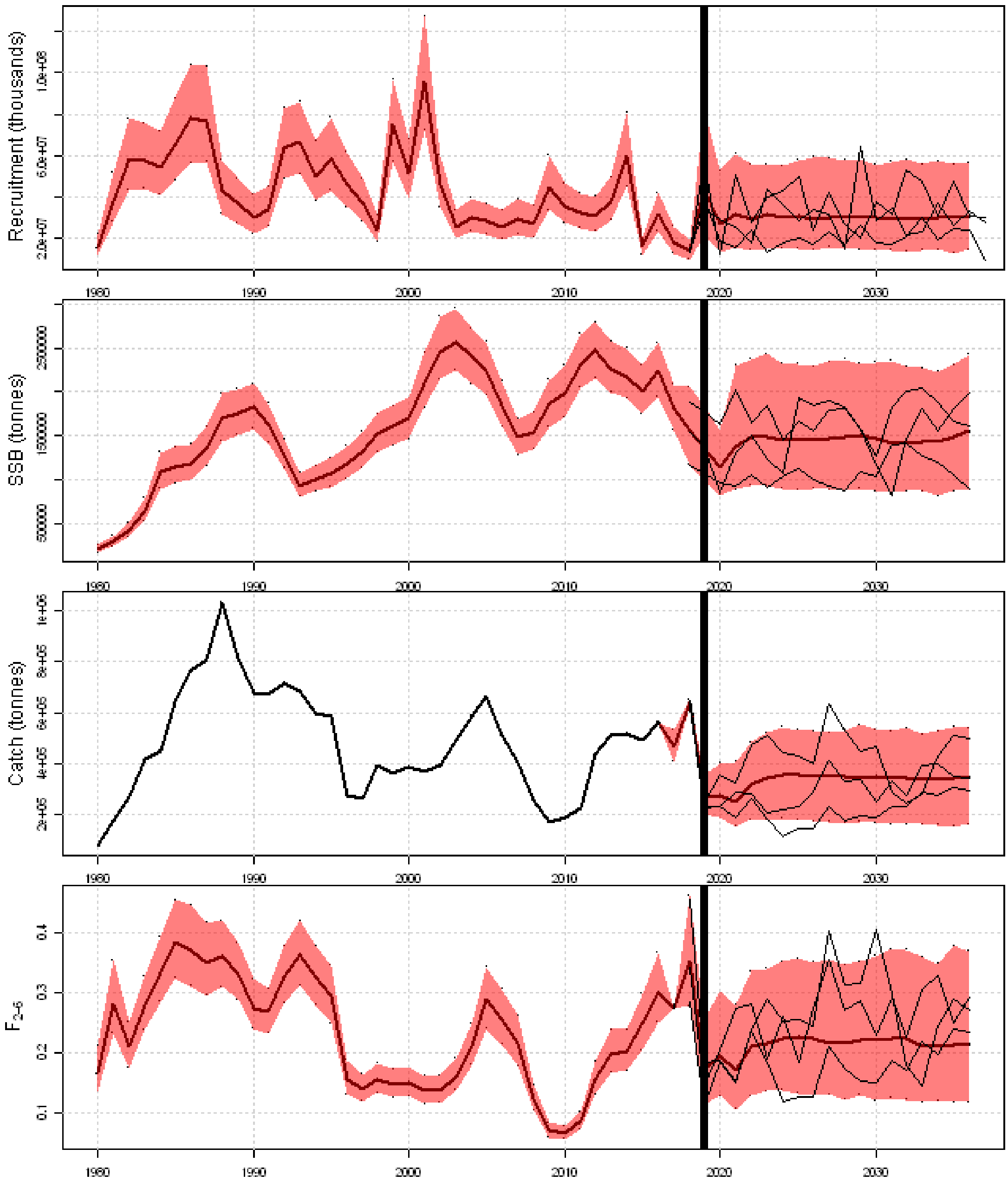


Figure 7.3.2.1: North Sea herring. Stock trends of the OM for the optimal HCR A strategy. Top panel shows recruitment, followed by SSB, followed by catch and finally Fbar on 2-6 (adult fishery). Individual replicates are shown as worm plots.

In general, there is less than 0.2% difference in long-term yield between these evaluated scenarios, while all being precautionary. As such, managers can decide what stability measures they would prefer because they appear to have a similar impact on the stock (Annex 11).

HCR B+E gives markedly different outcomes. The figure below shows that the uncertainty bound on SSB is very high from the start and only slowly reduces towards the end of the simulations. The results, from a random selection of the runs performed to illustrate the dynamics, are for an F_{target} level of 0.16 with $B_{trigger}$ equal to 1.6Mt, i.e. much lower F_{target} and higher $B_{trigger}$ than in any of the other optimized HCRs.

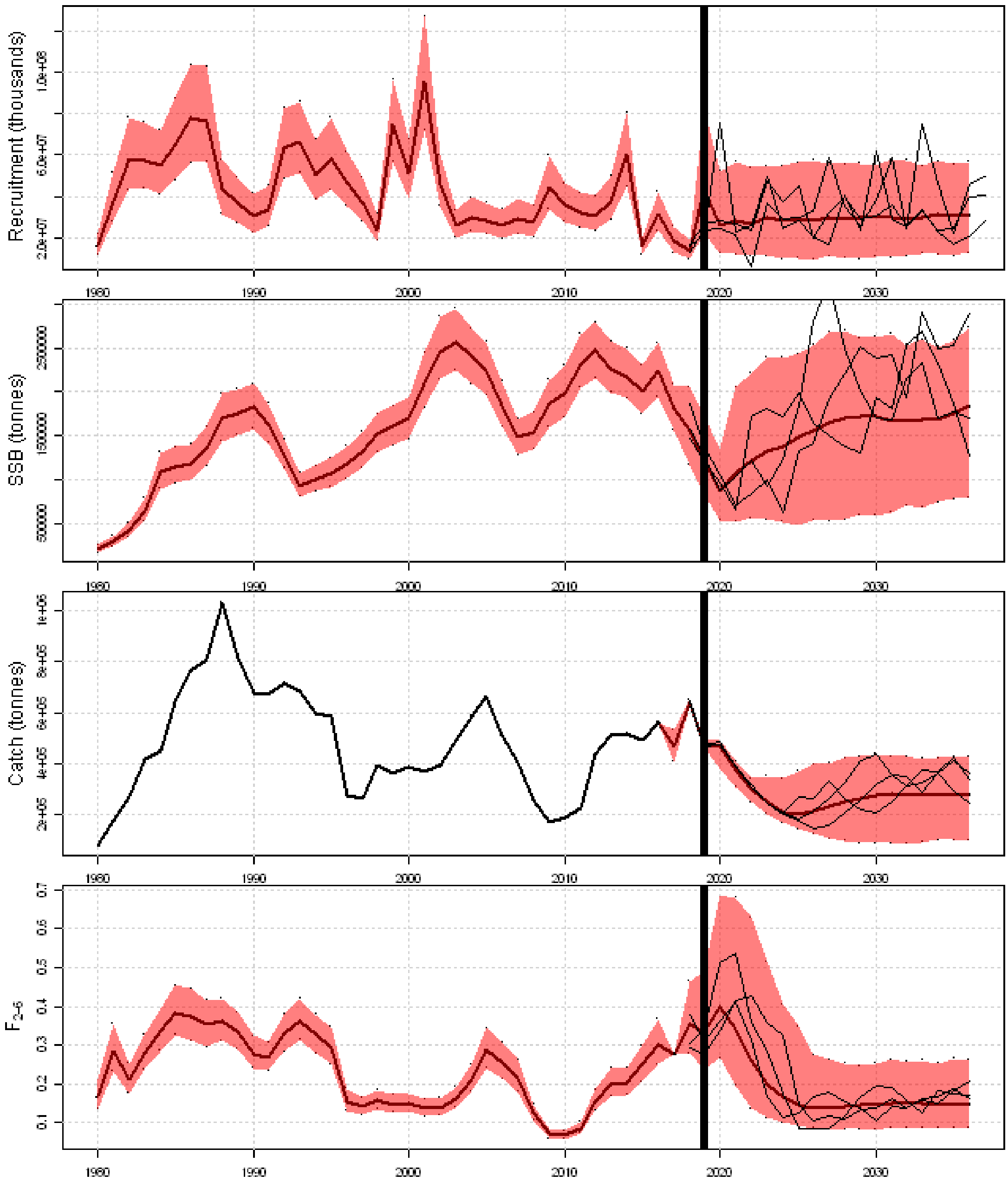


Figure 7.3.2.2: North Sea herring. Stock trends of the OM for one run under HCR B+E strategy. Top panel shows recruitment, followed by SSB, followed by catch and finally Fbar on 2-6 (adult fishery). Individual replicates are shown as worm plots.

7.3.3 Sensitivity of management strategies for the baseline OM

Three sensitivity runs were undertaken.

1. A run for which F was set to zero, to evaluate maximum stable biomass in the long term. This scenario is key to indicate how long it takes for the stock to stabilize in terms of SSB and to investigate the long-term risk.
2. A run in which an alternative implementation of the C-fleet catches is calculated. In this scenario, the C-fleet catch is calculated as 5.7% of the A-fleet TAC + 41% of the fixed WBSS catch multiplied with the mixing rate of WBSS vs NSAS to only account for the outtake of NSAS in Division 3.a.
3. A run in which the TAC of the bycatch fleets (B & D) was set to 0. This is implemented as setting the expected catches to 1% of their originally assigned TAC as for both numerical and practical reasons a 0-catch is highly unlikely in both these areas.

7.3.3.1 Zero F sensitivity scenario

Under a no-fishing regime, SSB increases rapidly after 2018 to around 2.7Mt in the long term. At around 2024 it reaches this level and fluctuates around the dynamic equilibrium. The assumption made in our study that a 20-year projection period would suffice in the need to reach a dynamic equilibrium hence seems valid. There are no replicates out of a 1000 that suggest the stock to go down B_{lim}. The uncertainty interval of future SSB shows a stable trajectory for both the 5th and 95th percentile. Note that the uncertainty interval of recruitment shows minor spikes. This does not affect the SSB stable trajectory as the fish need to grow older by ~2 years before they reach maturity.

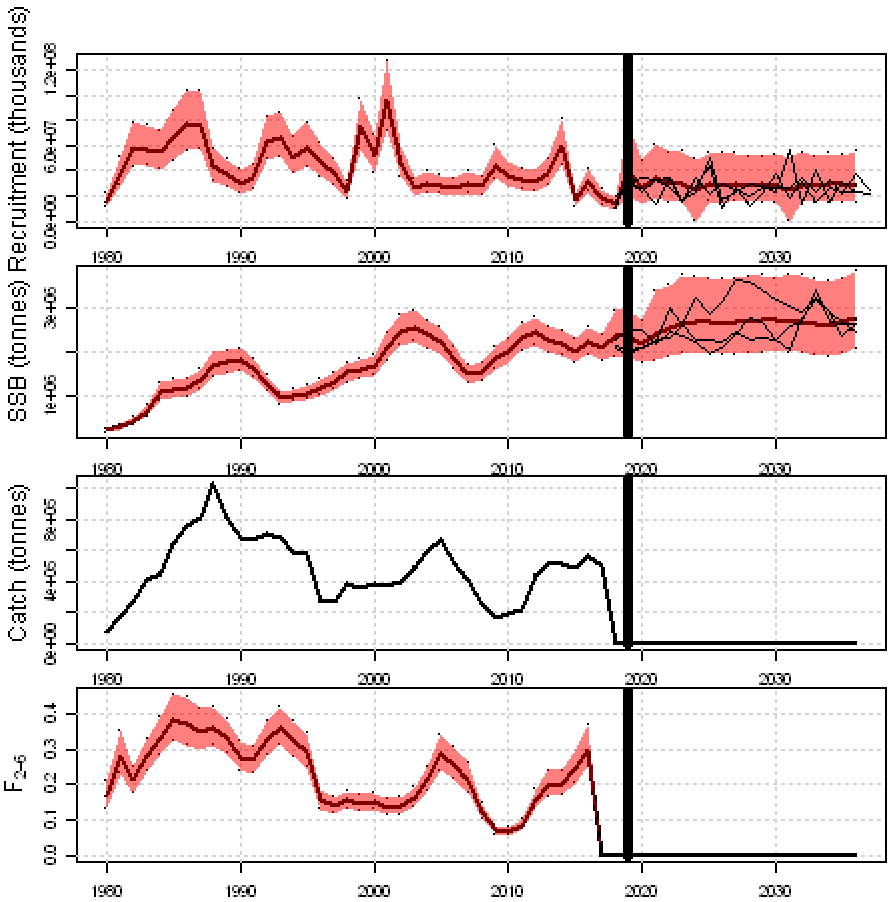


Figure 7.3.3.1.1: North Sea herring. Stock trajectories under a situation when no fishing mortality is applied. Individual replicates are shown as worm plots.

7.3.3.2 Alternative scenario on C-fleet catches

A comparison plot of the default C-fleet expected catches compared to the alternative formulation of the C-fleet catches are given below. Default (green) is plotted on top of the alternative (red). The figure clearly shows there is hardly any difference in the results.

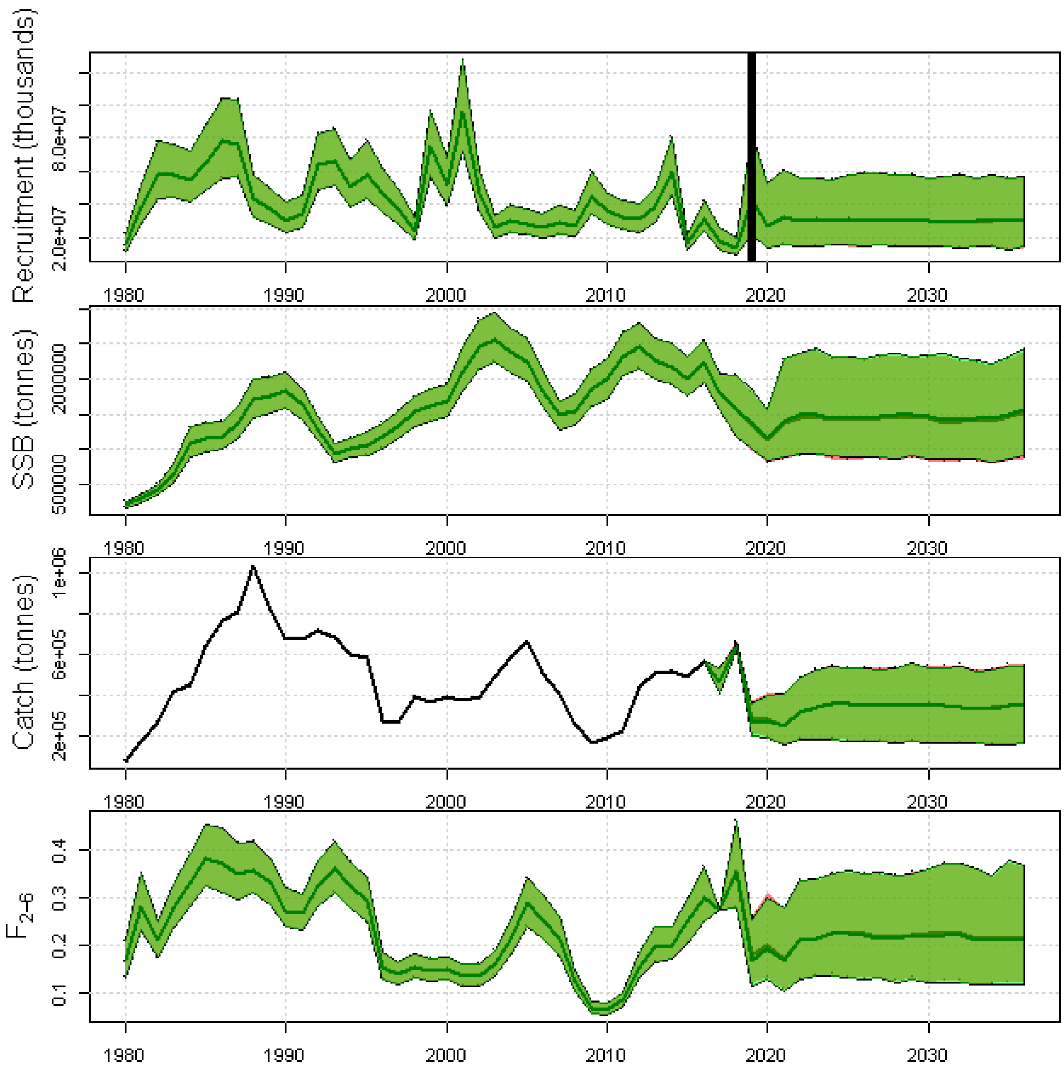


Figure 7.3.3.2.1: North Sea herring. Stock trajectories for case A (i.e. HCR A without IAV or banking and borrowing) using the default (red) and alternative (green) options for handling the C-fleet (200 replicates).

7.3.3.3 No catches of the B and D fleet

When minimal catches in the B and D fleet are assumed to be taken under "optimised" management strategy A+C (F_{target} of 0.22 and MSY $B_{trigger}$ of 1.4 Mt), the stock increases to above 1.5Mt in the medium- to long-term, well-above the 1.3Mt that was observed in the same scenario where B and D fleet catches are taken. There is an expected increase of around 15000t in the A-fleet TAC while the B-fleet TAC drops from 17 434 t in the long term to close to zero and the D fleet from 6659 t to close to zero. If one would optimize the scenario without B and D fleet catches, it is likely that A-fleet catches could increase even further as long term risk3 drops to 2.9% compared to the 4.8% in the optimized scenarios with B and D fleet catches.

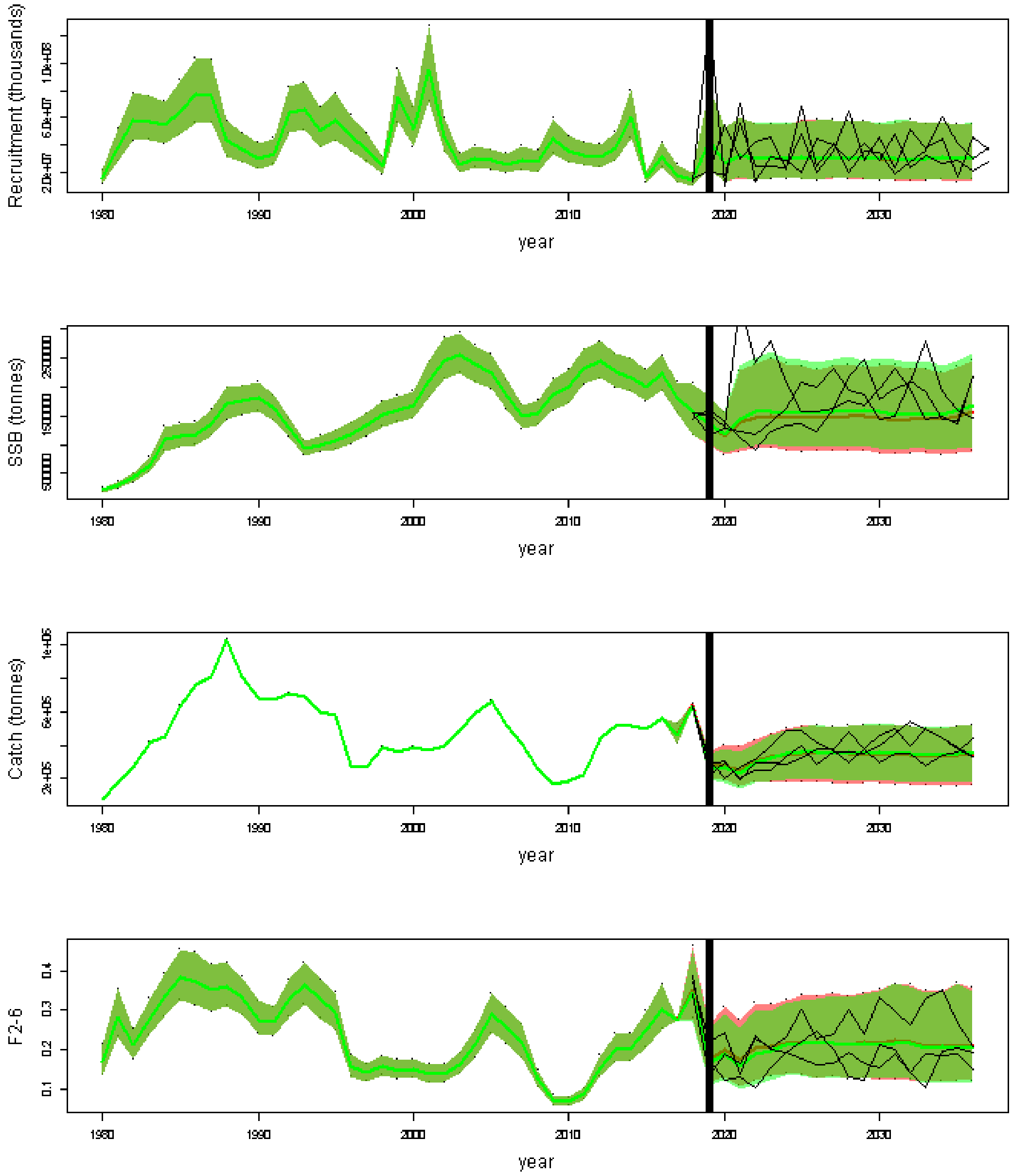


Figure 7.3.3.3.1: North Sea herring. Stock trajectories for the optimal management strategy A+C (red) and under a situation when catches of the B and D fleet are minimal (green). Individual replicates for the situation where there are no catches for the B and D fleets are shown as worm plots.

7.3.3.4 1000 vs 2000 replicates

There was concern raised that risk3 was not stable when 1000 replicates were used (see Section 2.6 in the main document). This would imply that the precautionary nature of the MSE would change if more (or less) replicates was used. It was tested whether increasing the number of replicates in the simulation would change this perception (Figure 7.3.3.4.1).

It should be noted that the runs shown in Figure 7.3.3.4.1 are based on different initialisations of the OM and therefore cannot be compared 1:1; however, the trends in each of these can be compared and here the overall trend seemed to be independent of the number of replicates.

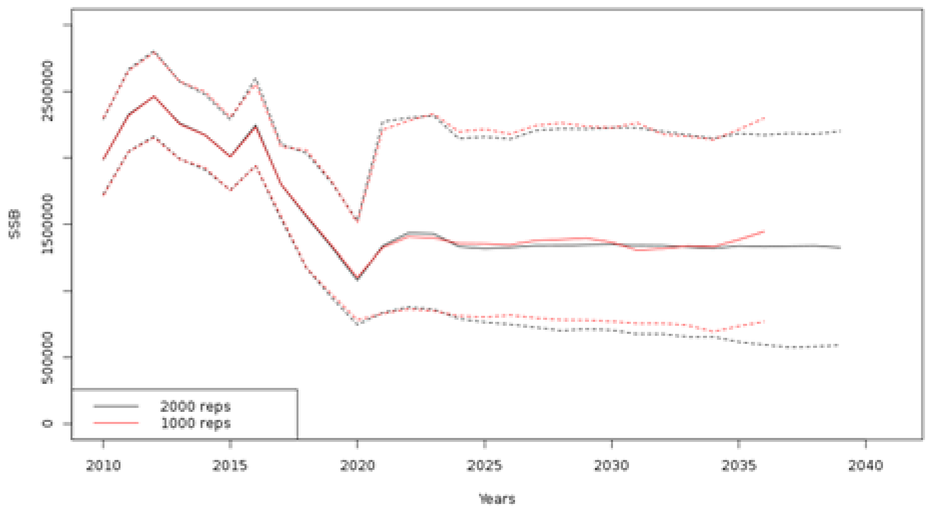


Figure 7.3.3.4.1: North Sea herring. SSB over time and it's 90% CI for similar management strategy runs with 1000 or 2000 replicates. Note that initialisation between the 1000 and 2000 reps is difference and therefore absolute values cannot be compared.

7.4 Discussion and Conclusions

Optimal strategies and the 0.9*F_{target}, 1.1*F_{target} scenarios are shown below. There are minimal differences among the management strategies for the short- and long-term yield. The development in SSB is very similar, as can be expected if outtakes are similar too.

Table 7.4.1: Short-, medium- and long-term yield (total catch) and SSB for the "optimised" strategies (in bold), for the sensitivity tests of 0.9Ftarget and 1.1Ftarget, and for F_{MSY} given the "optimal" $B_{trigger}$. Cases where risk3>5% are in red text. B+E is not included since no "optimum" was found for it. The time period are: short=2019:2021, med=2022:2026, long=2027:2036. Management strategies with an asterisk indicate F_{target}=F_{MSY} and $B_{trigger}$=MSY $B_{trigger}$.

Management Strategy	F case	F_{target}	$B_{trigger}$	Yield			SSB			risk3			IAV			Realised mean F(2-6)		
				short	med	long	short	med	long	short	med	Long	short	med	long	short	med	long
F=0	**F=0**	**0**	**0**	**0**	**0**	**0**	**2310249**	**2643789**	**2687033**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
A	**F_{target}**	**0.22**	**1400000**	**269747**	**339827**	**345646**	**1293350**	**1461235**	**1471026**	**0.037**	**0.025**	**0.046**	**0.186**	**0.147**	**0.151**	**0.179**	**0.219**	**0.219**
A	F_{target}*0.9	0.198	1400000	253590	324564	333095	1317390	1520520	1537223	0.029	0.018	0.033	0.184	0.138	0.140	0.163	0.198	0.198
A	F_{target}*1.1	0.242	1400000	283261	352466	352414	1271944	1415111	1415210	0.053	0.039	0.058	0.188	0.155	0.160	0.192	0.237	0.236
A*	F_{MSY}	0.26	1400000	296446	361936	358346	1253241	1370185	1363961	0.065	0.053	0.072	0.190	0.164	0.168	0.205	0.253	0.248
B	**F_{target}**	**0.22**	**1400000**	**271574**	**338313**	**344582**	**1291883**	**1456469**	**1467080**	**0.037**	**0.029**	**0.05**	**0.183**	**0.147**	**0.149**	**0.179**	**0.219**	**0.219**
B	F_{target}*0.9	0.198	1400000	255254	323178	332739	1316342	1513492	1533322	0.027	0.02	0.035	0.178	0.138	0.139	0.164	0.198	0.198
B	F_{target}*1.1	0.242	1400000	286813	351588	352563	1268880	1403626	1406114	0.052	0.039	0.058	0.186	0.156	0.159	0.194	0.238	0.237
B*	F_{MSY}	0.26	1400000	298388	359776	356365	1250953	1360849	1354684	0.061	0.054	0.081	0.188	0.165	0.168	0.205	0.251	0.247
A+C	**F_{target}**	**0.22**	**1400000**	**269690**	**335932**	**345095**	**1293654**	**1469648**	**1473686**	**0.037**	**0.025**	**0.048**	**0.186**	**0.158**	**0.157**	**0.179**	**0.219**	**0.219**
A+C	F_{target}*0.9	0.198	1400000	253640	320005	332873	1318603	1527892	1539721	0.028	0.017	0.031	0.185	0.151	0.148	0.164	0.198	0.198
A+C	F_{target}*1.1	0.242	1400000	283265	348086	352091	1274062	1421444	1419083	0.05	0.036	0.053	0.187	0.164	0.165	0.192	0.237	0.236
A*+C	F_{MSY}	0.26	1400000	296510	359024	358001	1253728	1377431	1365667	0.062	0.051	0.076	0.190	0.172	0.171	0.205	0.253	0.249
A+D	**F_{target}**	**0.23**	**1400000**	**276805**	**342173**	**349286**	**1283906**	**1446680**	**1446241**	**0.048**	**0.03**	**0.049**	**0.186**	**0.162**	**0.159**	**0.186**	**0.228**	**0.228**
A+D	F_{target}*0.9	0.207	1400000	260193	326776	338388	1308013	1504939	1513855	0.034	0.02	0.035	0.185	0.154	0.150	0.170	0.207	0.207
A+D	F_{target}*1.1	0.253	1400000	292294	355934	356450	1260687	1394828	1384855	0.056	0.044	0.072	0.188	0.169	0.169	0.201	0.249	0.245
A*+D	F_{MSY}	0.26	1400000	296510	359438	358937	1253750	1378526	1368652	0.061	0.047	0.076	0.189	0.171	0.171	0.205	0.254	0.249

No "optimum" could be found for HCR B+E within the projected time-frame (20 years). The design of the management strategy allows TAC constraints even if the stock is below B_{lim}. Given that the stock is on a downward trend in the most recent years, the TAC requires a substantial decrease to counter the downward trend. Under scenario B+E this reduction in TAC is not possible and for some replicates this results in very high F on the short term which on its turn require much longer time-frames to recover from. If one would need an optimal value for B+E, a longer projection period would be necessary in which the stock has given enough time to recover. This was beyond the scope of this study as the risk on the short term would be far too great.

There were concerns regarding the trend in risk which seems to increase over time. This could be due to auto-correlation in recruitment or in the biological processes such as maturity-at-age and weight-at-age. Given that these processes are observed in the data available, it was considered advisable to include these in the MSE. The increasing risk over time however puts a limit to the due-date of the MSE results. Within 20-years' time, the MSE should be re-evaluated in order to remain precautionary.

The sensitivity run, reformulating the process to simulate the C-fleet catches, shows no difference to the default approach and is therefore considered appropriate. The benefit of the default approach is that it is no longer dependent on rules stipulated for Western Baltic spring-spawning herring and can therefore remain in place even if the advice procedure for WBSS changes. Substantially reducing the B and D fleet catch shows a clear reduction in risk and allows the A-fleet to catch more herring. These results are in line with previous results as obtained in ICES 2015 (WKHerTAC).

The current reference points as estimated using EqSim shows an F_{MSY} of 0.26 in combination with an MSY $B_{trigger}$ of 1.4mt. The analyses in this study show a risk > 5% for that specific combination for HCR A (most similar to the EqSim design). There are fundamental differences in the way EqSim and the MSE evaluate risk and make use of implementation error. To illustrate this, the MSE does not take catches of the C and D fleet into account in calculating a TAC for the advice year in the MP (although it is accounted for in the OM through the implementation model), which automatically results in an overshoot of the TAC as these fleets do catch NSAS. These dynamics are not explicitly modelled in EqSim and hence will result in different outcomes.

Time required to run a 1000 replicate scenario was around 500h (one single core computing, around 50 evaluated). Thus, the time needed goes well beyond the time available to address the request and high-performance clusters were necessary to do the job. Even in that situation, it took more than 3 weeks to evaluate all these scenarios, excluding time to build, check and validate the MSE model.

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Annex 2: EU-Norway Request

AGREED RECORD OF CONSULTATIONS ON LONG-TERM MANAGEMENT STRATEGIES ON JOINT STOCKS BETWEEN NORWAY AND THE EUROPEAN UNION

LONDON, 7 JUNE 2018

1 A Norwegian Delegation, headed by Ms Ann Kristin WESTBERG, and a European Union Delegation, headed by Mr Jacques VERBORGH, met in London from 6 to 7 June 2018 to consult on long term management strategies for the jointly managed stocks in the North Sea, as agreed in point 5.16.1 of the Agreed Record of fisheries consultations between Norway and the European Union for 2018 signed in Bergen on 1 December 2017.

2 The Delegations reiterated their determination to cooperate, in their mutual interest, in securing continued responsible fisheries and ensuring the long-term conservation and sustainable exploitation of the marine living resources for which they are responsible.

3 The Delegations agreed to request ICES to evaluate long-term management strategies for cod, haddock, saithe, whiting and North Sea autumn spawning herring, as outlined in Annex I and II.

The Delegations request ICES to provide the advice no later than 1 February 2019.

London 7 June 2018

For the Norwegian Delegation

Ann Kristin Westberg

Ann Kristin WESTBERG

For the European Union Delegation

Jacques VERBORGH

REQUEST TO ICES CONCERNING THE LONG-TERM MANAGEMENT STRATEGY FOR COD, HADDOCK, SAITHE, AND WHITING

The Strategy consists of the following elements:

Objective

The Parties agree to manage fishing opportunities, on the basis of a fishing pressure that maximises sustainable yield from the stock given additional elements regarding stability, consistent with a precautionary approach.

A	***Long-term yield***	
1.	When the spawning stock (SSB) at the start of the TAC year is at or above $B_{trigger}$ the yearly TAC will be set as to correspond to a fishing pressure equal F_{target}.	
2.	Should SSB in the start of the TAC year be below $B_{trigger}$, the TAC shall be set corresponding to a fishing mortality of F_{target}*SSB/$B_{trigger}$.	
B	***Long-term yield***	
1.	When the spawning stock (SSB) at the start of the TAC year is at or above $B_{trigger}$ the yearly TAC will be set as to correspond to a fishing pressure equal to F_{target}.	
2.	Should SSB in the start of the TAC year be below $B_{trigger}$ but above B_{lim}, the TAC shall be set corresponding to a fishing mortality of F_{target}*SSB/$B_{trigger}$.	
3.	Where the SSB is estimated to be below B_{lim} at the start of the TAC year, the TAC shall be set at a level corresponding to a fishing mortality rate at 0.25*F_{target}.	
C	***Long-term yield***	
1.	When the spawning stock (SSB) at the start of the TAC year is at or above $B_{trigger}$ the yearly TAC will be set as to correspond to a fishing pressure equal F_{target}.	
2.	Should SSB in the start of the TAC year be below $B_{trigger}$ but above B_{lim}, the TAC shall be set corresponding to a fishing mortality of F_{target}*SSB/$B_{trigger}$.	
3.	Where the SSB is estimated to be below B_{lim} at the start of the TAC year, the TAC shall be set at a level corresponding to a fishing mortality rate being the greater of F_{target}*SSB/$B_{trigger}$. and 0.25*F_{target}.	
D	***Stability***	

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1.	Where the rule in paragraph A1 leads to a TAC that deviates more than 25% up or 20% down from the preceding year, the change is limited to 25% up or 20% down[1].	
2.	The TAC given by paragraph A1 and D1 can be deviated with up to 10% according to the inter-annual quota flexibility provided for in paragraphs 1-3 of Annex VII of the Agreed Record of fisheries consultations between Norway and European Union for 2018 signed in Bergen on 1 December 2017. (the "banking and borrowing" scheme)	
E	***Stability***	
1.	Where the rule in paragraph B1 or C1 leads to a TAC that deviates more than 25% up or 20% down from the preceding year, the change is limited to 25% up or 20% down.	
2.	The TAC given by paragraph [B1, B2, B3 and E1] or [C1, C2, C3 and E1] can be deviated with up to 10% according to the "banking and borrowing" scheme.	

Evaluation

ICES is asked to tabulate the long-term yield, long term SSB, inter annual TAC variability and risk of SSB falling below B_{lim} for the range of combinations of $B_{trigger}$ and F_{target} values evaluated.

ICES will for each of the stocks be requested to estimate the combination of F_{target} and $B_{trigger}$ that maximises yield given the rules set out in six "sets" defined in the table above. The six sets are A, B, C, A+D, B+E and C+E.

ICES will be requested to evaluate the performance of the six sets of rules with corresponding pairs of F_{target} and $B_{trigger}$. Thereafter ICES is requested to evaluate the additional fishing pressure scenarios of $0.9*F_{target}$, F_{target}, $1.1*F_{target}$, $F_{MSY\ lower}$ and $F_{MSY\ upper}$. (5 pairs, 6 sets =30 scenarios per stock)

ICES will for haddock be requested to evaluate the two additional scenarios of F_{target} & $1.5*B_{trigger}$ and F_{target} & $2*B_{trigger}$. (2 pairs, rule sets A and A+D = 4 scenarios)

[1] In addition, for saithe, where the rule in paragraph A1 leads to a TAC that deviates more than 15% up or down from the preceding year, the change is limited to 15% up or down.

REQUEST TO ICES ON THE LONG-TERM MANAGEMENT STRATEGY FOR NORTH SEA AUTUMN SPAWNING HERRING

The Strategy consists of the following elements.

Objective

The Parties agree to manage fishing opportunities on the basis of a fishing pressure that maximises sustainable yield from the stock, consistent with a precautionary approach.

A	***Long-term yield***	
1.	When the SSB in the autumn (spawning time) of the TAC year is estimated to be above [$B_{trigger}$], yearly TAC will be set as to correspond to a fishing pressure at F_{target} for 2-ringers and older and at 0.05 for 0-1 ringers.	
2.	Should the spawning stock (SSB) in the autumn of the TAC year be below [$B_{trigger}$], the TAC will be set to correspond to a fishing mortality at F_{target}*SSB/[$B_{trigger}$] for 2-ringers and older and at 0.05*SSB/[$B_{trigger}$] for – 0 to 1 ringers.	
B	***Long-term yield***	
1.	When the SSB in the autumn (spawning time) of the TAC year is estimated to be above [$B_{trigger}$], yearly TAC will be set as to correspond to a fishing pressure at F_{target} for 2-ringers and older and at 0.05 for 0-1 ringers.	
2.	Should the spawning stock (SSB) in the autumn of the TAC year be below [Btrigger] but above Blim, the TAC will be set to correspond to a fishing mortality at F_{target}*SSB/[$B_{trigger}$] for 2-ringers and older and at 0.05 for 0-1 ringers.	
3.	Should the spawning stock (SSB) in the autumn of the TAC year be below B_{lim} the TAC will be set to correspond to a fishing mortality at 0.1 for 2 ringers and older and at 0.04 for 0-1 ringers.	
C	***Stability***	
1.	Where the rule in paragraph A1 leads to a TAC in the directed fishery that deviates more than 25% up or 20% down from the preceding year, the change is limited to 25% up or 20% down.	
2.	The TAC given in the directed fishery by paragraph A1 and C1 can be deviated with up to 10% according to the inter-annual quota flexibility provided for in paragraphs 1-3 of Annex VII of the Agreed Record of fisheries consultations between Norway and European Union for 2018 signed in Bergen on 1	

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	December 2017. (the "banking and borrowing" scheme)	
D	***Stability***	
1.	Where the rule in paragraph A1 leads to a TAC that deviates more than 25% up or 20% down from the preceding year, the change is limited to 25% up or 20% down.	
2.	The TAC given by paragraph A1 and D1 can be deviated with up to 10% according to the inter-annual quota flexibility provided for in paragraphs 1-3 of Annex VII of the Agreed Record of fisheries consultations between Norway and European Union for 2018 signed in Bergen on 1 December 2017. (the "banking and borrowing" scheme)	
E	***Stability***	
1.	Where the rules in paragraphs B1, B2 or B3 leads to a TAC that deviates more than 25% up or 20% down from the preceding year, the change is limited to 25% up or 20% down.	
2.	The TAC given by paragraph B1, B2, B3 and E1 can be deviated with up to 10% according to the "banking and borrowing" scheme.	

Evaluation

ICES is asked to tabulate the long-term yield, long term SSB, inter annual TAC variability and risk of SSB falling below B_{lim} for the range of combinations of $B_{trigger}$ and F_{target} values evaluated.

ICES will be requested to estimate the combination of F_{target} and $B_{trigger}$ that maximises yield given the rules set out in five "sets" defined in the table above. The five sets are A, B, A+C, A+D and B+D.

ICES will be requested to evaluate the performance of the four sets of rules with corresponding pairs of F_{target} and $B_{trigger}$ and the additional fishing pressure scenarios of 0.9*F_{target}, F_{target}, 1.1*F_{target}, $F_{MSY\ lower}$ and $F_{MSY\ upper}$. (5 pairs, 5 sets =25scenarios)

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Annex 3: Banking and Borrowing Scheme

This text is taken from Annex VII of the Agreed Record of Fisheries Consultations between Norway and the European Union for 2018, signed in Bergen on the 1st of December 2018.

INTER-ANNUAL QUOTA FLEXIBILITY

1. The Inter-annual quota flexibility scheme as described in this Annex is applicable for the quotas of herring, haddock, saithe, plaice and whiting established in this Agreed Record.

2. Each Party may transfer to the following year unutilised quantities of up to 10% of the quota allocated to it. The quantity transferred shall be in addition to the quota allocated to the Party concerned in the following year. This quantity cannot be transferred further to the quotas for subsequent years.

3. Each Party may authorise fishing by its vessels of up to 10% beyond the quota allocated. All quantities fished beyond the allocated quota for one year shall be deducted from the Party's quota allocated for the following year.

4. Complete catch statistics and quotas for the previous year should be made available to the other Party no later than 1 April in the format as set out below. The Delegations agreed that in order to ensure transparency in the operation of inter-annual quota flexibility, more detailed information on catch utilisation shall be exchanged.

5. The inter-annual quota flexibility scheme should be terminated if the stock is estimated to be under the precautionary biomass level (B_{pa}) and the fishing mortality is estimated to be above the precautionary mortality level (F_{pa}) the following year, or if the SSB is estimated to be below B_{pa} in two consecutive years.

Annex 4: Agenda

WKNSMSE: Meeting 1 (19-21 November 2018)
Provisional Agenda

Monday 19 November

Morning (09:30-13:00)

1. Introductions and ToRs
2. EU-Norway Request and Presentation
3. Current guidelines and general practice for conducting MSEs
4. So how are we doing it?

Afternoon (14:00-18:00)

5. Look at individual stocks
    a. Autumn-spawning herring (Benoit Berges/Niels Hintzen)
    b. Cod (Nicola Walker)
    c. Haddock (Harriet Cole)
    d. Saithe (Jennifer Devine)
    e. Whiting (Tanja Miethe)

    Presentations to cover input data, assessment and diagnostics, benchmark issues for possible alternative operating models, modelling recruitment, any other important feature for MSE

Item 11 may be moved here if time to make more room for sub-group work on Tuesday.

Tuesday 20 November

Morning (09:00-13:00)

6. GitHub presentation (Colin Millar)
7. Example MSE (Molly Brooks)
8. FLR MSE framework (Ernesto Jardim)
9. Cod application of FLR framework (Simon Fischer)
10. Banking and borrowing scenarios – how was it done? (David Miller)

Afternoon (14:00-18:00)

11. General themes and specifications of MSE, including
    a. Modelling uncertainty
    b. Generating data
    c. Modelling recruitment
12. Commence sub-group work

Wednesday 21 November

Morning (09:00-13:00)

13. Continue sub-group work

Afternoon (14:00-16:00)

14. Agree work plan for coming weeks
15. Wrap up

WKNSMSE: Meeting 2 (26-28 February 2019)
Provisional Agenda

Tuesday 26 February

Morning (09:30-13:00)

1. Introductions and recap of ToRs
2. Recap of Work Plan and decisions
3. WKGMSE2 guideline template and additional request on herring
4. General outline of report

Afternoon (14:00-18:00)

5. Look at individual stocks (operating models and results)
    a. General plenary for Cod (Nicola Walker/Simon Fischer)

    Then we break into two groups, with the first continuing the plenary to discuss the remaining gadoids, and the second (Subgroup 2) to discuss autumn-spawning herring. Herring will be brought back to plenary on Wednesday morning.

    Smaller plenary (Subgroup 1)

    b. Haddock (Harriet Cole)
    c. Whiting (Tanja Miethe)
    d. Saithe (Jennifer Devine)

    Subgroup 2

    e. Autumn-spawning herring (Benoit Berges/Niels Hintzen)

    Presentations to cover the baseline operating model (OM) in detail and the alternative OMs, the grid-optimisation, and results. Results should cover a comparison of the management strategies for the baseline OM, and sensitivity of these. Then any results for the alternative OMs, comparing the performance of each management strategy across the alternative OMs (thus looking at robustness).

Wednesday 27 February

Morning (09:00-13:00)

6. General Plenary for Autumn-spawning herring
7. Discussion of what to include in the report
8. Continue any work needed/start working on report

Afternoon (14:00-18:00)

9. Continue any work needed/work on report

Thursday 28 February

Morning (09:00-13:00)

10. Progress update on work and report
11. Continue any work needed/work on report

Afternoon (14:00-16:00)

12. Agree conclusions for each stock
13. Continue any work needed/work on report
14. Wrap up

Annex 5: Template Summaries

A5.1. Cod

Operating Model (OM) conditioning	
Biology and Fishery Model (Base Case)	
Basis for the Base Case	The Base Case operating model (OM1) corresponds to the ICES stock assessment for cod (SAM; ICES 2018a).
Recruitment	Segmented regression fitted to recent time period (1998-2017), including estimation of breakpoint. Modelled stochastically, with resampling smoothed residual frequencies relative to the spawning stock-recruitment relationship. Autocorrelation not included (not significant).
Growth	Resampled from recent 5 years (2013-2017), unsmoothed weights at age, no density dependence (following EqSim settings). Resampling for growth, maturity and natural mortality vectors (within replicate) done by selecting a year at random and taking all vectors together for this year.
Natural mortality	Resampled from recent 5 years (2013-2017) of smoothed WGSAM estimates (following EqSim settings).
Maturity	Resampled from recent 5 years (2013-2017) smoothed maturity ogives, no density dependence (following EqSim settings).
Fishery selectivity	Resampled F at age over recent 5 years (2013-2017), but separately to growth, natural mortality and maturity (following EqSim settings).
Initial stock numbers	From the stock assessment agreed by ICES for the stock (SAM), including a range of uncertainty defined by the variance-covariance matrix from this assessment.
Technical interactions (mixed fisheries)	Not included.
Biological interactions	Not included other than implicitly through multi-species Ms in the historical period.
Biology and Fishery Model (alternative dynamics)	
Alternative biology and fishery scenarios	OM2: same as OM1, but the recruitment period is extended back in time (1988-2017). OM3: same as OM1, but refits the SAM model under the assumption that there are year-effects in the IBTS Q1 and IBTS Q3 surveys (so includes observation error correlations for these surveys. OM4: same as OM1, but models density-dependent Ms for the projection period (no need to refit the SAM model because historical multispecies Ms already account for density-dependent Ms).
Observation Model	
Simulation of input data for a stock assessment or for direct use in a harvest rule (e.g. for survey-based harvest rule)	This is a full MSE, where the management procedure includes the ICES assessment and forecast, so data are generated from the operating model for the projection period and are added to the already-existing historical data. Therefore, at the start of the projection period, the management procedure produces an ICES assessment and forecast that should be near-identical to the most recent actual ICES assessment and forecast. Data were generated consistent with the way these data were fitted in the operating model. This implies that if, for example, the data were fitted assuming age-dependent variability, or assuming they were correlated across ages, then the data were generated under these same assumptions. Input data: Catch-at-age (lognormal with variance parameters from SAM) IBTS Q1 and Q3 indices-at-age (lognormal with variance parameters from SAM; note that for OM3, observation errors for the IBTS Q1 and Q3 surveys include correlation structure, with variance-covariance parameters from SAM)

	Weights-at-age, maturity and natural mortality were the means from the selected periods described above (so the operating model contained the variable re-sampled quantities, while the estimation model received the means)
Implementation Model	
Implementation error	Where included, banking and borrowing is modelled as implementation error. Furthermore, the operating model mean fishing mortality is not allowed to exceed a value of 2, so when this is breached, it becomes an additional source of implementation error.
Management Procedure	
Estimation Model (stock assessment for model-based harvest rules)	
If a full assessment is conducted in MSE loop	The estimation model in the management procedure is exactly the same as the assessment model used by ICES for advice (i.e. identical model configuration).
If a short-cut approach (instead of a full assessment) is used in the MSE loop	Not applicable.
Harvest rules requiring a stock assessment followed by a short-term forecast	The forecast is exactly the same as the forecast used by ICES for advice (i.e. the same code is used). In the forecast, recruitment is sampled from historic series (since 1998), and no autumn update with survey data from IBTS Q3 is included. Furthermore, the forecast uses an average over the 3 most recent years for biological parameters and selectivity (the exception being an additional year for maturity; see stock annex for this stock).
Decision Model (Harvest rule)	
Harvest rule design	The EU-Norway request asks to evaluate very specific management strategies (harvest control rules with/without stability mechanisms; see Annex 2). The harvest control rules (A, B, C)) require an input of SSB, as estimated by the ICES assessment and forecast, while the stability mechanism (D, E) include checks on SSB, but in some cases also include checks on F (Annex 3). The harvest control rules define an F dependent on SSB at the start of the TAC year, with a constant F (=F_{target}) when SSB is at or above $B_{trigger}$, and an initial linear reduction in F when SSB is below $B_{trigger}$. The harvest control rules differ when SSB is below B_{lim}, and one of them (B) has a discontinuity. F_{target} and $B_{trigger}$ are treated as control parameters, and the requests asks for the combination of F_{target} and $B_{trigger}$ that maximises long-term yield, while conforming to the ICES precautionary criterion, risk3≤5%.
Harvest rules that include stabilizers	An asymmetric TAC constraint (+25%, -20%) is applied in combination with baking and borrowing for some management strategies (A+D, B+E, C+E). TAC constraints are only applied when SSB at the start of the TAC year is at or above $B_{trigger}$, but banking and borrowing is applied differently for D compared to E; for the former, it only applies when SSB at the start of the TAC year is above $B_{trigger}$, but for the latter, it is applied regardless of SSB, but with additional safeguarding checks (see paragraph 5 of Annex 3).
Duration of decisions	Annual advice
Conditions for re-evaluating the MSE in the future	There is no revision clause in the EU-Norway request. This leaves two main situations under which the MSE would be re-evaluated in future: • If the performance of the stock assessment used to apply the decision rule deteriorates substantially relative to what was assumed in the MSE • If the observed conditions of the stock and/or fishery depart considerably from what was assumed in the MSE
Running the MSE simulation	
Number of replicates (number of independent realities simulated in the MSE)	An analysis for cod deemed 1000 replicates to be sufficient.
Projection time (number of future years included in the MSE)	This was not indicated by clients, but projecting the MSE forward based on F=0 and based on the MSY approach showed that a 20-year projection period was sufficient for cod.
Reporting outputs	Search grid (partial) for "optimal" combination of F_{target} and $B_{trigger}$.

	Summary projections for recruitment, SSB, F and catch. Comparison of "optimised" management strategies against performance statistics for the baseline OM1. Sensitivity of each "optimised" management strategies to alternative Fs for the baseline OM1. Robustness of each "optimised" management strategy against the alternative operating models (OM2, OM3 and OM4). ["Optimised" means finding the F_{target}-$B_{trigger}$ combination that maximises long-term yield and simultaneously conforms to the ICES precautionary criterion of risk3≤5%.]
Reality checks (for different components of MSE simulation)	F=0 projection performed. Recruitment generation approach checked against historical recruitment based on the same SSB. Summary projections indicated no obvious breaks between past and future dynamics, and included worm plots of selected replicates. Observation errors for future data consistent with estimated observation error structure, assuming the ICES assessment provides a plausible and acceptable model fit.
Reference points	
Reference points used in the MSE	Reference points in the operating model are relevant to the operating model. Since operating models OM1, OM2 and OM4 use the same model configuration and assumptions as the ICES assessment for cod, there was no need to re-estimate reference points and the current B_{lim} is used in the operating model to calculate P(SSB<B_{lim}). For OM3, which required SAM to be refitted assuming observation error correlations for the IBTS Q1 and Q3 surveys, B_{lim} was re-estimated, but was very close to the B_{lim} for the other operating models (108000t for OM3 compared to 107000t for the others). The reference points used in the management procedure (in the decision model) are the reference points as used by the ICES assessment working group (according to the most recent benchmark for the stock). In this instance, these reference points are the same in the operating model and management procedure (i.e. the same B_{lim} is used in both cases), and only differ for OM3 (here B_{lim}=108000t in the operating model, while B_{lim}=107000t in the management procedure).
Performance statistics and precautionary criterion	
Performance statistics	Clients specifically requested the following performance statistics: • Long-term yield • Long-term SSB • Interannual TAC variability • Risk of SSB falling below B_{lim} We define short-, medium- and long-term as years 1-5, 6-10 and 11-20 respectively in the projection period. We define "yield" as catch, and we calculate interannual catch variability (ICV). We use risk3 for the long-term in order to "optimise" the management strategies (i.e. search for the F_{target}-$B_{trigger}$ combination that maximises long-term yield while simultaneously conforming to long-term risk3≤5%). In addition to the above, we calculate realised F in the long-term, and check the number of times there is non-convergence of the estimation model in the management procedure (any replicates that have non-convergence of the estimation model are removed when calculating the performance statistics). We also track the number of times F is capped to the value of 2 in the operating model. Time to recovery above MSY $B_{trigger}$ is also calculated.
Risk type	risk3, defined as the maximum of the annual P(SSB<B_{lim}) for over a given period. For the purpose of "optimising" the management strategy, the long-term (defined as the final 10 years of the projection period) is used. risk1 (average of the annual P(SSB<Blim) for a given period) is also calculated.
Precautionary criterion	risk3≤5% over all years included in the management strategy (short-, medium- and long-terms).

Experiences and comments	
Use of ICES guidelines for MSE from WKGMSE2 (ICES 2019a)	The guidelines for MSE were followed as closely as possible through participation of several scientists from WKNSMSE in the WKGMSE2 meeting, despite the guidelines not being completed in time for the WKNSMSE series of meetings.

A5.2. Haddock

Operating Model (OM) conditioning	
Biology and Fishery Model (Base Case)	
Basis for the Base Case	The Base Case operating model (OM1) corresponds to a stock assessment for haddock using SAM developed from the exploratory SAM stock assessment fit used during WGNSSK as agreed during the most recent benchmark (ICES 2014).
Recruitment	Segmented regression fitted to recent time period (2000-2017) with freely-estimated breakpoint for each replicate. Modelled stochastically, with resampling smoothed residuals relative to the spawning stock-recruitment relationship.
Growth	Resampled from recent 10 years unsmoothed weights at age, no density dependence (following EqSim settings). Resampling for growth, maturity and natural mortality vectors (within replicate) done by selecting a year at random and taking all vectors together for this year.
Natural mortality	Resampled from recent 10 years of smoothed WGSAM estimates, no density dependence (following EqSim settings).
Maturity	Maturity ogives are knife-edged at age 3 and are fixed over time (following EqSim settings).
Fishery selectivity	Resampled F at age over recent 5 years (this deviates from EqSim settings due to strong trends in selectivity over the last 10 years).
Initial stock numbers	From the stock assessment for the stock (SAM), including a range of uncertainty defined by the variance-covariance matrix from this assessment.
Technical interactions (mixed fisheries)	Not included.
Biological interactions	Not included other than implicitly through multi-species Ms in the historical period.
Biology and Fishery Model (alternative dynamics)	
Alternative biology and fishery scenarios	OM2: conditioned on the stock assessment for haddock using TSA as agreed at the last benchmark. Resampling of fishery selectivities is over 10 years (following EqSim assumptions as no trend in selectivity is seen from TSA). Initial stock parameters are simulated from TSA parameter estimates. Estimates of recruits (all years) and n-at-age (1st year) and their standard errors are used to generate replicates. Time series of each replicate is filled by simulating forwards with replicates of fishing mortalities. The replicates of fishing mortalities at age are generated using the variances in F from transitory effects in the age and year model components. OM3: same as OM1, but “spikes” in recruitment are fixed to occur at semi-regular intervals.
Observation Model	
Simulation of input data for a stock assessment or for direct use in a harvest rule (e.g. for survey-based harvest rule)	This is a full MSE, where the management procedure includes the ICES assessment and forecast, so data are generated from the operating model for the projection period and are added to the already-existing historical data. Therefore, at the start of the projection period, the management procedure produces an ICES assessment and forecast that should be near-identical to the initial SAM assessment. Data were generated consistent with the way these data were fitted in the operating model. This implies that if, for example, the data were fitted assuming age-dependent variability, or assuming they were correlated across ages, then the data were generated under these same assumptions. Input data: Catch-at-age (lognormal with variance parameters from SAM) IBTS Q1 and Q3 indices-at-age (lognormal with variance parameters from SAM) Weights-at-age, maturity and natural mortality were the means from the selected periods described above (so the operating model contained the variable re-sampled quantities, while the estimation model received the means)

Implementation Model	
Implementation error	Where included, banking and borrowing is modelled as implementation error. Furthermore, the operating model mean fishing mortality is not allowed to exceed a value of 2, so when this is breached, it becomes an additional source of implementation error.
Management Procedure	
Estimation Model (stock assessment for model-based harvest rules)	
If a full assessment is conducted in MSE loop	The estimation model in the management procedure is not exactly the same as the assessment model used by ICES for advice, although it is used as an exploratory assessment model to compare to the model used for advice as it gives similar results.
If a short-cut approach (instead of a full assessment) is used in the MSE loop	Not applicable.
Harvest rules requiring a stock assessment followed by a short-term forecast	It was not possible to replicate the deterministic fleet-based forecast that is actually used for the ICES forecast for haddock (MFDP), so the stochastic forecast included with SAM is used (so no fleet separation). Therefore, total catch (implicitly including human consumption catches and industrial bycatch) is modelled without explicitly accounting for the proportion of industrial bycatch (though this is a very small (<1%) component of the stock. In the forecast, recruitment is sampled from historic series (since 2000) instead of using the final year estimate from the assessment model, and no autumn update with survey data from IBTS Q3 is included. The forecast uses an average over the 3 most recent years for natural mortality, maturity is knife-edged at age 3 and does not vary over time, future weights at age are derived through linear modelling of cohort growth, selectivity is assumed to be the same as the previous year (i.e. final data year).
Decision Model (Harvest rule)	
Harvest rule design	The EU-Norway request asks to evaluate very specific management strategies (harvest control rules with/without stability mechanisms; see Annex 2). The harvest control rules (A, B, C)) require an input of SSB, as estimated by the ICES assessment and forecast, while the stability mechanism (D, E) include checks on SSB, but in some cases also include checks on F (Annex 3). The harvest control rules define an F dependent on SSB at the start of the TAC year, with a constant F (=F_{target}) when SSB is at or above $B_{trigger}$, and an initial linear reduction in F when SSB is below $B_{trigger}$. The harvest control rules differ when SSB is below B_{lim}, and one of them (B) has a discontinuity. F_{target} and $B_{trigger}$ are treated as control parameters, and the request asks for the combination of F_{target} and $B_{trigger}$ that maximises long-term yield, while conforming to the ICES precautionary criterion, $P(SSB<B_{lim})\leq5\%$.
Harvest rules that include stabilizers	An asymmetric TAC constraint (+25%, -20%) is applied in combination with baking and borrowing for some management strategies (A+D, B+E, C+E). TAC constraints are only applied when SSB at the start of the TAC year is at or above $B_{trigger}$, but banking and borrowing is applied differently for D compared to E; for the former, it only applies when SSB at the start of the TAC year is above $B_{trigger}$, but for the latter, it is applied regardless of SSB, but with additional safeguarding checks (see paragraph 5 of Annex 3).
Duration of decisions	Annual advice
Conditions for re-evaluating the MSE in the future	There is no revision clause in the EU-Norway request. This leaves two main situations under which the MSE would be re-evaluated in future: • If the performance of the stock assessment used to apply the decision rule deteriorates substantially relative to what was assumed in the MSE • If the observed conditions of the stock and/or fishery depart considerably from what was assumed in the MSE.
Running the MSE simulation	
Number of replicates (number of independent realities simulated in the MSE)	This was not investigated for haddock specifically, but following an analysis for cod, 1000 replicates were deemed sufficient.

Projection time (number of future years included in the MSE)	This was not indicated by clients, and was not investigated for haddock specifically, but following an analysis of cod and whiting, a 20-year projection period was deemed sufficient.
Reporting outputs	Search grid (partial) for "optimal" combination of F_{target} and $B_{trigger}$. Summary projections for recruitment, SSB, F and catch. Comparison of "optimised" management strategies against performance statistics for the baseline OM1. Sensitivity of each "optimised" management strategies to alternative F_{target} and $B_{trigger}$ values (the latter for A and A+D only) for the baseline OM1. Robustness of each "optimised" management strategy against the alternative operating models (OM2 and OM3). ["Optimised" means finding the F_{target}-$B_{trigger}$ combination that maximises long-term yield and simultaneously conforms to the ICES precautionary criterion of risk3≤5%.]
Reality checks (for different components of MSE simulation)	Recruitment generation approach checked against historical recruitment based on the same SSB. Summary projections indicated no obvious breaks between past and future dynamics, and included worm plots of selected replicates. Observation errors for future data consistent with estimated observation error structure, assuming the SAM assessment (used by ICES as an exploratory alternative to TSA) provides a plausible and acceptable model fit. Comparison of stock assessment results from TSA (used for advice but incompatible with high performance computing) and SAM (used in baseline OM1 and in management procedure) showed similar results indicating that SAM is a viable alternative to using TSA in the MSE.
Reference points	
Reference points used in the MSE	Reference points in the operating model are relevant to the operating model. A comparison of stock assessment results from SAM to the results in the 2018 advice sheet for haddock indicated that they would be similar enough that there was no need to re-estimate reference points and the current B_{lim} is used in the operating model to calculate P(SSB<B_{lim}). The reference points used in the management procedure (in the decision model) are the reference points as used by the ICES assessment working group (according to the most recent benchmark for the stock). In this instance, these reference points are the same in the operating model and management procedure (i.e. the same B_{lim} is used in both cases).
Performance statistics and precautionary criterion	
Performance statistics	Clients specifically requested the following performance statistics: • Long-term yield • Long-term SSB • Interannual TAC variability • Risk of SSB falling below B_{lim} We define short-, medium- and long-term as years 1-5, 6-10 and 11-20 respectively in the projection period. We define "yield" as catch, and we calculate interannual catch variability (ICV). We use risk3 for the long-term in order to "optimise" the management strategies (i.e. search for the F_{target}-$B_{trigger}$ combination that maximises long-term yield while simultaneously conforming to long-term risk3≤5%). In addition to the above, we calculate realised F in the long-term, and check the number of times there is non-convergence of the estimation model in the management procedure (any replicates that have non-convergence of the estimation model are removed when calculating the performance statistics). We also track the number of times F is capped to the value of 2 in the operating model. Time to recovery above MSY $B_{trigger}$ is also calculated.
Risk type	risk3, defined as the maximum of the annual P(SSB<B_{lim}) for over a given period. For the purpose of "optimising" the management strategy, the long-term (defined as the final 10 years of the projection period) is used. risk1 (average of the annual P(SSB<Blim) for a given period) is also calculated.

Precautionary criterion	risk3≤5% over all years included in the management strategy (short-, medium- and long-terms).
Experiences and comments	
Use of ICES guidelines for MSE from WKGMSE2 (ICES 2019a)	The guidelines for MSE were followed as closely as possible through participation of several scientists from WKNSMSE in the WKGMSE2 meeting, despite the guidelines not being completed in time for the WKNSMSE series of meetings.

A5.3. Whiting

Operating Model (OM) conditioning	
Biology and Fishery Model (Base Case)	
Basis for the Base Case	The Base Case operating model (OM1) corresponds to the ICES stock assessment for whiting (SAM) agreed during the most recent benchmark (ICES 2018c).
Recruitment	Segmented regression fitted to recent time period (1983-2017) with freely-estimated breakpoint for each replicate. Modelled stochastically, with resampling smoothed residual frequencies relative to the spawning stock-recruitment relationship, including autocorrelated error (AR(1)).
Growth	Resampled from recent 10 years unsmoothed weights at age, no density dependence (following EqSim settings). Resampling for growth, maturity and natural mortality vectors (within replicate) done by selecting a year at random and taking all vectors together for this year.
Natural mortality	Resampled from recent 10 years of smoothed WGSAM estimates, no density dependence (following EqSim settings).
Maturity	Resampled from recent 10 years smoothed maturity ogives, no density dependence (following EqSim settings).
Fishery selectivity	Resampled F at age over recent 3 years (following EqSim settings).
Initial stock numbers	From the stock assessment agreed by ICES for the stock (SAM), including a range of uncertainty defined by the variance-covariance matrix from this assessment.
Technical interactions (mixed fisheries)	Not included.
Biological interactions	Not included other than implicitly through multi-species Ms in the historical period.
Biology and Fishery Model (alternative dynamics)	
Alternative biology and fishery scenarios	OM2: same as OM1, but allows for jumps to lower recruitment level, in random periods of 1-4 years duration. OM3: same as OM2, but models variability in amount of industrial bycatch that occurs every year as additional implementation error.
Observation Model	
Simulation of input data for a stock assessment or for direct use in a harvest rule (e.g. for survey-based harvest rule)	This is a full MSE, where the management procedure includes the ICES assessment and forecast, so data are generated from the operating model for the projection period and are added to the already-existing historical data. Therefore, at the start of the projection period, the management procedure produces an ICES assessment and forecast that should be near-identical to the most recent actual ICES assessment and forecast. Data were generated consistent with the way these data were fitted in the operating model. This implies that if, for example, the data were fitted assuming age-dependent variability, or assuming they were correlated across ages, then the data were generated under these same assumptions. Input data: Catch-at-age (lognormal with variance parameters from SAM) IBTS Q1 and Q3 indices-at-age (lognormal, but including correlation structure, with variance-covariance parameters from SAM) Weights-at-age, maturity and natural mortality were the means from the selected periods described above (so the operating model contained the variable re-sampled quantities, while the estimation model received the means)
Implementation Model	
Implementation error	Where included, banking and borrowing is modelled as implementation error. Furthermore, the operating model mean fishing mortality is not allowed to exceed a value of 2, so when this is breached, it becomes an additional source of implementation error. Finally, OM3 includes variable industrial bycatch as another source of implementation error.

Management Procedure	
Estimation Model (stock assessment for model-based harvest rules)	
If a full assessment is conducted in MSE loop	The estimation model in the management procedure is exactly the same as the assessment model used by ICES for advice.
If a short-cut approach (instead of a full assessment) is used in the MSE loop	Not applicable.
Harvest rules requiring a stock assessment followed by a short-term forecast	It was not possible to replicate the deterministic fleet-based forecast that is actually used for the ICES forecast for whiting (MFDP), so the stochastic forecast included with SAM is used (so no fleet separation). Therefore, total catch (implicitly including human consumption catches and industrial bycatch) is modelled without explicitly accounting for the proportion of industrial bycatch (apart from OM3). In the forecast, recruitment is sampled from historic series (since 2002) instead of using the geometric mean (since 2002), and no autumn update with survey data from IBTS Q3 is included. Furthermore, the forecast uses an average over the 3 most recent years for biological parameters and selectivity.
Decision Model (Harvest rule)	
Harvest rule design	The EU-Norway request asks to evaluate very specific management strategies (harvest control rules with/without stability mechanisms; see Annex 2). The harvest control rules (A, B, C)) require an input of SSB, as estimated by the ICES assessment and forecast, while the stability mechanism (D, E) include checks on SSB, but in some cases also include checks on F (Annex 3). The harvest control rules define an F dependent on SSB at the start of the TAC year, with a constant F (=F_{target}) when SSB is at or above $B_{trigger}$, and an initial linear reduction in F when SSB is below $B_{trigger}$. The harvest control rules differ when SSB is below B_{lim}, and one of them (B) has a discontinuity. F_{target} and $B_{trigger}$ are treated as control parameters, and the requests asks for the combination of F_{target} and $B_{trigger}$ that maximises long-term yield, while conforming to the ICES precautionary criterion, $P(SSB<B_{lim})\leq 5\%$.
Harvest rules that include stabilizers	An asymmetric TAC constraint (+25%, -20%) is applied in combination with baking and borrowing for some management strategies (A+D, B+E, C+E). TAC constraints are only applied when SSB at the start of the TAC year is at or above $B_{trigger}$, but banking and borrowing is applied differently for D compared to E; for the former, it only applies when SSB at the start of the TAC year is above $B_{trigger}$, but for the latter, it is applied regardless of SSB, but with additional safeguarding checks (see paragraph 5 of Annex 3).
Duration of decisions	Annual advice
Conditions for re-evaluating the MSE in the future	There is no revision clause in the EU-Norway request. This leaves three main situations under which the MSE would be re-evaluated in future: • If the performance of the stock assessment used to apply the decision rule deteriorates substantially relative to what was assumed in the MSE • If the observed conditions of the stock and/or fishery depart considerably from what was assumed in the MSE • Beyond a period of 20 years The reason for the last point is because there is some indication of non-stationarity for whiting, and long-term performance statistics are therefore dependent, to some extent, on the length of period modelled.
Running the MSE simulation	
Number of replicates (number of independent realities simulated in the MSE)	This was not investigated for whiting specifically, but following an analysis for cod, 1000 replicates were deemed sufficient.
Projection time (number of future years included in the MSE)	This was not indicated by clients, but projecting the MSE forward based on F=0 showed that a 20-year projection period was sufficient for whiting.
Reporting outputs	Search grid (partial) for “optimal” combination of F_{target} and $B_{trigger}$. Summary projections for recruitment, SSB, F and catch.

	Comparison of "optimised" management strategies against performance statistics for the baseline OM1. Sensitivity of each "optimised" management strategies to alternative Fs for the baseline OM1. Robustness of each "optimised" management strategy against the alternative operating models (OM2 and OM3). ["Optimised" means finding the F_{target}-$B_{trigger}$ combination that maximises long-term yield and simultaneously conforms to the ICES precautionary criterion of risk3≤5%.]
Reality checks (for different components of MSE simulation)	F=0 projection performed. Recruitment generation approach checked against historical recruitment based on the same SSB. Summary projections indicated no obvious breaks between past and future dynamics, and included worm plots of selected replicates. Observation errors for future data consistent with estimated observation error structure, assuming the ICES assessment provides a plausible and acceptable model fit. Implementation error for industrial bycatch modelled based on past observations of industrial bycatch.
Reference points	
Reference points used in the MSE	Reference points in the operating model are relevant to the operating model. Since all operating models use the same model configuration and assumptions as the ICES assessment for whiting, there was no need to re-estimate reference points and the current B_{lim} is used in the operating model to calculate P(SSB<B_{lim}). The reference points used in the management procedure (in the decision model) are the reference points as used by the ICES assessment working group (according to the most recent benchmark for the stock). In this instance, these reference points are the same in the operating model and management procedure (i.e. the same B_{lim} is used in both cases).
Performance statistics and precautionary criterion	
Performance statistics	Clients specifically requested the following performance statistics: • Long-term yield • Long-term SSB • Interannual TAC variability • Risk of SSB falling below B_{lim} We define short-, medium- and long-term as years 1-5, 6-10 and 11-20 respectively in the projection period. We define "yield" as catch, and we calculate interannual catch variability (ICV). We use risk3 for the long-term in order to "optimise" the management strategies (i.e. search for the F_{target}-$B_{trigger}$ combination that maximises long-term yield while simultaneously conforming to long-term risk3≤5%). In addition to the above, we calculate realised F in the long-term, and check the number of times there is non-convergence of the estimation model in the management procedure (any replicates that have non-convergence of the estimation model are removed when calculating the performance statistics). We also track the number of times F is capped to the value of 2 in the operating model. Time to recovery above MSY $B_{trigger}$ is also calculated.
Risk type	risk3, defined as the maximum of the annual P(SSB<B_{lim}) for over a given period. For the purpose of "optimising" the management strategy, the long-term (defined as the final 10 years of the projection period) is used. risk1 (average of the annual P(SSB<Blim) for a given period) is also calculated.
Precautionary criterion	risk3≤5% over all years included in the management strategy (short-, medium- and long-terms).

Experiences and comments	
Use of ICES guidelines for MSE from WKGMSE2 (ICES 2019a)	The guidelines for MSE were followed as closely as possible through participation of several scientists from WKNSMSE in the WKGMSE2 meeting, despite the guidelines not being completed in time for the WKNSMSE series of meetings.

A5.4. Saithe

Operating Model (OM) conditioning	
Biology and Fishery Model (Base Case)	
Basis for the Base Case	The Base Case operating model (OM1) corresponds to the ICES stock assessment for saithe (SAM) agreed during the most recent inter-benchmark (ICES 2019b).
Recruitment	Segmented regression fitted to recent time period (1998-2017), break-point at B_{loss}, where B_{loss} is from the time period from 1967. Modelled stochastically, with resampling smoothed residual frequencies relative to the spawning stock-recruitment relationship. Autocorrelation in recruitment not included (not significant).
Growth	Resampled from recent 10 years unsmoothed weights at age, no density dependence (following EqSim settings). Resampling for growth vectors (within replicate) done by selecting a year at random.
Natural mortality	Constant (M=0.2)
Maturity	Time-invariant maturity-at-age
Fishery selectivity	Resampled F at age over recent 5 years (2013-2017, following EqSim settings). Resampling procedure similar to growth, but they were not coupled.
Initial stock numbers	From the stock assessment agreed by ICES for the stock (SAM), including a range of uncertainty defined by the variance-covariance matrix from this assessment.
Technical interactions (mixed fisheries)	Not included.
Biological interactions	Not included.
Biology and Fishery Model (alternative dynamics)	
Alternative biology and fishery scenarios	OM2: same as OM1, but assumes M=0.1 OM3: same as OM1, but assumes M=0.3.
Observation Model	
Simulation of input data for a stock assessment or for direct use in a harvest rule (e.g. for survey-based harvest rule)	This is a full MSE, where the management procedure includes the ICES assessment and forecast, so data are generated from the operating model for the projection period and are added to the already-existing historical data. Therefore, at the start of the projection period, the management procedure produces an ICES assessment and forecast that should be near-identical to the most recent actual ICES assessment and forecast. Data were generated consistent with the way these data were fitted in the operating model. This implies that if, for example, the data were fitted assuming age-dependent variability, or assuming they were correlated across ages, then the data were generated under these same assumptions. Input data: Catch-at-age (lognormal with variance parameters from SAM) IBTS Q3 indices-at-age (lognormal, but including correlation structure, with variance-covariance parameters from SAM) Commercial CPUE index (treated as an exploitable biomass index; lognormal with variance parameter from SAM) Weights-at-age were the means from the selected periods described above (so the operating model contained the variable re-sampled quantities, while the estimation model received the means)
Implementation Model	
Implementation error	Where included, banking and borrowing is modelled as implementation error. Furthermore, the operating model mean fishing mortality is not allowed to exceed a value of 2, so when this is breached, it becomes an additional source of implementation error.

Management Procedure	
Estimation Model (stock assessment for model-based harvest rules)	
If a full assessment is conducted in MSE loop	The estimation model in the management procedure is exactly the same as the assessment model used by ICES for advice (i.e. identical model configuration).
If a short-cut approach (instead of a full assessment) is used in the MSE loop	Not applicable.
Harvest rules requiring a stock assessment followed by a short-term forecast	The forecast is exactly the same as the forecast used by ICES for advice (i.e. the same code is used). In the forecast, recruitment is sampled from historic series (since 1998), and no autumn update with survey data from IBTS Q3 is included. Furthermore, the forecast uses an average over the 10 most recent years for biological parameters and 5 most recent years for selectivity (as described in the stock annex for this stock).
Decision Model (Harvest rule)	
Harvest rule design	The EU-Norway request asks to evaluate very specific management strategies (harvest control rules with/without stability mechanisms; see Annex 2). The harvest control rules (A, B, C)) require an input of SSB, as estimated by the ICES assessment and forecast, while the stability mechanism (D, E) include checks on SSB, but in some cases also include checks on F (Annex 3). The harvest control rules define an F dependent on SSB at the start of the TAC year, with a constant F (=F_{target}) when SSB is at or above $B_{trigger}$, and an initial linear reduction in F when SSB is below $B_{trigger}$. The harvest control rules differ when SSB is below B_{lim}, and one of them (B) has a discontinuity. F_{target} and $B_{trigger}$ are treated as control parameters, and the requests asks for the combination of F_{target} and $B_{trigger}$ that maximises long-term yield, while conforming to the ICES precautionary criterion, $P(SSB<B_{lim})\leq 5\%$.
Harvest rules that include stabilizers	An asymmetric TAC constraint (+25%, -20%) is applied in combination with baking and borrowing for some management strategies (A+D, B+E, C+E). A special case of symmetric TAC constraints (+15%, -15%) is also tested (A1+D). TAC constraints are only applied when SSB at the start of the TAC year is at or above $B_{trigger}$, but banking and borrowing is applied differently for D compared to E; for the former, it only applies when SSB at the start of the TAC year is above $B_{trigger}$, but for the latter, it is applied regardless of SSB, but with additional safeguarding checks (see paragraph 5 of Annex 3).
Duration of decisions	Annual advice
Conditions for re-evaluating the MSE in the future	There is no revision clause in the EU-Norway request. This leaves two main situations under which the MSE would be re-evaluated in future: • If the performance of the stock assessment used to apply the decision rule deteriorates substantially relative to what was assumed in the MSE • If the observed conditions of the stock and/or fishery depart considerably from what was assumed in the MSE
Running the MSE simulation	
Number of replicates (number of independent realities simulated in the MSE)	This was not investigated for saithe specifically, but following an analysis for cod, 1000 replicates was deemed sufficient.
Projection time (number of future years included in the MSE)	This was not indicated by clients, but an analysis for cod, projecting the MSE forward based on F=0 and under the MSY approach, showed that a 20-year projection period was sufficient.
Reporting outputs	Search grid (partial) for “optimal” combination of F_{target} and $B_{trigger}$. Summary projections for recruitment, SSB, F and catch. Comparison of “optimised” management strategies against performance statistics for the baseline OM1. Sensitivity of each “optimised” management strategies to alternative Fs for the baseline OM1. Robustness of each “optimised” management strategy against the alternative operating models (OM2 and OM3).

	[“Optimised” means finding the F_{target}-$B_{trigger}$ combination that maximises long-term yield and simultaneously conforms to the ICES precautionary criterion of risk3≤5%.]
Reality checks (for different components of MSE simulation)	Recruitment generation approach checked against historical recruitment based on the same SSB. Summary projections indicated no obvious breaks between past and future dynamics, and included worm plots of selected replicates. Observation errors for future data consistent with estimated observation error structure, assuming the ICES assessment provides a plausible and acceptable model fit.
Reference points	
Reference points used in the MSE	Reference points in the operating model are relevant to the operating model. Since SAM is refitted for OM2 and OM3, reference points used in the operating model to calculate performance statistics are re-estimated for these two operating models. Whereas B_{lim}=107297t for OM1, B_{lim}=90094t for OM2, and B_{lim}=133650t for OM3. The reference points used in the management procedure (in the decision model) are the reference points as used by the ICES assessment working group (according to the most recent inter-benchmark for the stock). Therefore, B_{lim}=107297t is used in the management procedure, regardless of the operating model.
Performance statistics and precautionary criterion	
Performance statistics	Clients specifically requested the following performance statistics: • Long-term yield • Long-term SSB • Interannual TAC variability • Risk of SSB falling below B_{lim} We define short-, medium- and long-term as years 1-5, 6-10 and 11-20 respectively in the projection period. We define “yield” as catch, and we calculate interannual catch variability (ICV). We use risk3 for the long-term in order to “optimise” the management strategies (i.e. search for the F_{target}-$B_{trigger}$ combination that maximises long-term yield while simultaneously conforming to long-term risk3≤5%). In addition to the above, we calculate realised F in the long-term, and check the number of times there is non-convergence of the estimation model in the management procedure (any replicates that have non-convergence of the estimation model are removed when calculating the performance statistics). We also track the number of times F is capped to the value of 2 in the operating model. Time to recovery above MSY $B_{trigger}$ is also calculated.
Risk type	risk3, defined as the maximum of the annual P(SSB<B_{lim}) for over a given period. For the purpose of “optimising” the management strategy, the long-term (defined as the final 10 years of the projection period) is used. risk1 (average of the annual P(SSB<Blim) for a given period) is also calculated.
Precautionary criterion	risk3≤5% over all years included in the management strategy (short-, medium- and long-terms).
Experiences and comments	
Use of ICES guidelines for MSE from WKGMSE2 (ICES 2019a)	The guidelines for MSE were followed as closely as possible through participation of several scientists from WKNSMSE in the WKGMSE2 meeting, despite the guidelines not being completed in time for the WKNSMSE series of meetings.

A5.5. Autumn-spawning herring

Operating Model (OM) conditioning	
Biology and Fishery Model (Base Case)	
Basis for the Base Case	The Base Case and only operating model corresponds to the ICES stock assessment for herring (SAM) agreed during the most recent benchmark (ICES 2018d), apart from the omission of the LAI index (shown to have a small impact on the assessment) for computational tractability.
Recruitment	A mixture of models (15% segmented regression, 85% Ricker) fitted to recent time period (2002-2016). Future recruitment modelled stochastically, with residual used to generate future deviations from a stock-recruit curve (using an ARIMA process to account for auto-correlation).
Growth	To maintain a degree of correlation over time and between maturity-at-age and weight-at-age (both in the stock and in the fishery), previously observed vectors are sampled together (all ages at once) in blocks of up to ten years (2007-2017), similar to the low productivity phase for the stock, with year ranges shared among these processes. These blocks of years are glued together until the entire projection period is filled, and are randomized for each replicate.
Natural mortality	To maintain a certain level of autocorrelation, previously observed natural mortality vectors (all ages at once) are sampled in blocks up to ten years (2007–2017), similar to the low productivity phase for the stock, and glued together until the entire projection period is filled, and are randomised for each replicate. There is no evidence that M and weight-at-age or maturity-at-age are correlated, and hence M-at-age vectors are drawn separate from the other biological parameters.
Maturity	See growth above.
Fishery selectivity	Four fleets included (human consumption fleets A and C, and bycatch fleets B and D, with A and B operating in the North Sea, and C and D in Division 3.a). Selection pattern obtained from multi-fleet assessment, with future selection patterns assumed to follow an age-correlated random walk (similar to the design in the assessment). All steps from one year to the next for the entire time-series follow a normal distribution with mean 0 and variance estimated based on the covariance of log-transformed F-at-age change (from year y to year y+1) over the years 2007–2017. To prevent extreme changes, steps outside the 95% CI of the distribution were excluded.
Initial stock numbers	From the stock assessment agreed by ICES for the stock (SAM; LAI index omitted), including a range of uncertainty defined by the variance-covariance matrix from this assessment.
Technical interactions (mixed fisheries)	Not included.
Biological interactions	Not included.
Biology and Fishery Model (alternative dynamics)	
Alternative biology and fishery scenarios	No alternative operating models considered, save for a different implementation of the transfer from fleet C to fleet A (implementation model).
Observation Model	
Simulation of input data for a stock assessment or for direct use in a harvest rule (e.g. for survey-based harvest rule)	This is a full MSE, where the management procedure includes the ICES assessment and forecast (excluding the LAI index), so data are generated from the operating model for the projection period and are added to the already-existing historical data. Therefore, at the start of the projection period, the management procedure produces an ICES assessment and forecast that should be near-identical to the most recent actual ICES assessment and forecast. Data were generated consistent with the way these data were fitted in the operating model. This implies that if, for example, the data were fitted assuming age-dependent variability, or assuming they were correlated across ages, then the data were generated under these same assumptions.

	Input data: Catch-at-age (lognormal with variance parameters from SAM) IBTS Q1 survey providing the IBTS0 (late larval) and IBTS1 (age 1) indices IBTS Q3 survey providing the IBTS Q3 index (ages 1-5) HERAS survey providing HERAS index (ages 1-8)
Implementation Model	
Implementation error	Optimisation of the catches in the A-fleet according to the management strategy is also conditional on the B-fleet $F_{0\text{-}1}$ target given by the management strategy and the catches simulated for the C- and D-fleets. This implies implementation error as realised catches will differ from catches advised by the management strategy due toy catches by the C and D fleets. Also, banking and borrowing is modelled as implementation error for specific fleets depending on the scenario: A+C: banking and borrowing implemented for fleet A only A+D: banking and borrowing implemented for fleet A and B B+E: banking and borrowing implemented for fleet A and B
Management Procedure	
Estimation Model (stock assessment for model-based harvest rules)	
If a full assessment is conducted in MSE loop	The estimation model in the management procedure is exactly the same as the assessment model used by ICES for advice, apart from the exclusion of the LAI index.
If a short-cut approach (instead of a full assessment) is used in the MSE loop	Not applicable.
Harvest rules requiring a stock assessment followed by a short-term forecast	The forecast procedure was very similar, but not identical, to the one actually used. Whilst during the working groupd the selection patterns for the different fleets are inferred from a multi-fleet assessment, the MSE uses a age-correlated random walk of selection patterns (drawn from latest multi-fleet assessment) over years 2007–2017. This ensures correlation
Decision Model (Harvest rule)	
Harvest rule design	The EU-Norway request asks to evaluate very specific management strategies (harvest control rules with/without stability mechanisms; see Annex 2). The harvest control rules (A, B) require an input of SSB, as estimated by the ICES assessment and forecast, while the stability mechanism (C, D, E) include checks on SSB, but in some cases also include checks on F (Annex 3). The harvest control rules 2-6 ringers (fleet A) define an F dependent on SSB at the spawning time of the TAC year, with a constant F (=F_{target}) when SSB is at or above $B_{trigger}$, and an initial linear reduction in F when SSB is below $B_{trigger}$. The harvest control rules differ when SSB is below B_{lim}, and one of them (HCR B) has a discontinuity. The harvest control rules for 0-1 ringers (fleet B) differ below $B_{trigger}$, using a specific target for 0-1 ringers $F_{0\text{-}1}$=0.05, with one linearly declining to zero below $B_{trigger}$, and the other remaining constant below $B_{trigger}$, but reducing to a lower constant level below B_{lim} (at $F_{0\text{-}1}$=0.04). F_{target} and $B_{trigger}$ are treated as control parameters, and the requests asks for the combination of F_{target} and $B_{trigger}$ that maximises long-term yield, while conforming to the ICES precautionary criterion, $P(SSB<B_{lim}) \leq 5\%$.
Harvest rules that include stabilizers	An asymmetric TAC constraint (+25%, -20%) is applied in combination with banking and borrowing for some management strategies (A+C, A+D, B+E). TAC constraints and banking and borrowing are applied differently for stability mechanisms C and D compared to E; for the former two, they only apply when SSB at spawning time of the TAC year is above $B_{trigger}$, but for the latter, the TAC constraint applies regardless of SSB, while banking and borrowing applies with additional safeguarding checks on B_{pa}/F_{pa} (see paragraph 5 of Annex 3). Stability mechanism C applies to the directed fleet only, while D applies to both directed and bycatch fleets.
Duration of decisions	Annual advice

<table>
<tr><td>Conditions for re-evaluating the MSE in the future</td><td>There is no revision clause in the EU-Norway request. This leaves three main situations under which the MSE would be re-evaluated in future:
• If the performance of the stock assessment used to apply the decision rule deteriorates substantially relative to what was assumed in the MSE
• If the observed conditions of the stock and/or fishery depart considerably from what was assumed in the MSE
• Beyond a period of 20 years
The reason for the last point is because there is some indication of non-stationarity for herring, and long-term performance statistics are therefore dependent, to some extent, on the length of period modelled.</td></tr>
<tr><td colspan="2"></td></tr>
<tr><td colspan="2">Running the MSE simulation</td></tr>
<tr><td>Number of replicates (number of independent realities simulated in the MSE)</td><td>Comparison of 2000 versus 1000 replicates (to check effect on estimation of risk3), and 200 versus 1000 replicates; 1000 replicates used for “optimisation” of management strategies, while 200 replicates used for initial grid search.</td></tr>
<tr><td>Projection time (number of future years included in the MSE)</td><td>Projection period of 20 years used.</td></tr>
<tr><td>Reporting outputs</td><td>Search grid (partial) for “optimal” combination of F_{target} and $B_{trigger}$.
Summary projections for recruitment, SSB, F and catch.
Comparison of “optimised” management strategies against performance statistics for the baseline OM.
Sensitivity of each “optimised” management strategies to alternative Fs for the baseline OM, and a sensitivity test for management strategy A+C to check the impact of near-zero catches for the B and D fleets.
Robustness of the “optimised” management strategy A against an alternative formulation for transfer of C-fleet TAC to A-fleet catches.
[“Optimised” means finding the F_{target}-$B_{trigger}$ combination that maximises long-term yield and simultaneously conforms to the ICES precautionary criterion of risk3≤5%.]</td></tr>
<tr><td>Reality checks (for different components of MSE simulation)</td><td>F=0 projection performed.
Recruitment generation approach checked against historical recruitment.
Summary projections indicated no obvious breaks between past and future dynamics, and included worm plots of selected replicates.
Observation errors for future data consistent with estimated observation error structure, assuming the ICES assessment (minus the LAI index) provides a plausible and acceptable model fit.
Implementation error resulting from fleet allocations checked against historical observations.</td></tr>
<tr><td colspan="2"></td></tr>
<tr><td colspan="2">Reference points</td></tr>
<tr><td>Reference points used in the MSE</td><td>Reference points in the operating model are relevant. Since the baseline operating model uses the same model configuration and assumptions as the ICES assessment and forecast for herring (apart from omitting the LAI index), there was no need to re-estimate reference points. Therefore, the current B_{lim} is used in the operating model to calculate $P(SSB<B_{lim})$.
The reference points used in the management procedure (in the decision model) are the reference points as used by the ICES assessment working group (according to the most recent benchmark for the stock). In this instance, these reference points are the same in the operating model and management procedure (i.e. the same B_{lim}, B_{pa}, F_{pa} are used in both cases).</td></tr>
<tr><td colspan="2"></td></tr>
<tr><td colspan="2">Performance statistics and precautionary criterion</td></tr>
<tr><td>Performance statistics</td><td>Clients specifically requested the following performance statistics:
• Long-term yield
• Long-term SSB</td></tr>
</table>

	• Interannual TAC variability • Risk of SSB falling below B_{lim} We define short-, medium- and long-term as years 1-5, 6-10 and 11-20 respectively in the projection period. We define "yield" as catch, and we calculate interannual catch variability (ICV). We use risk3 for the long-term in order to "optimise" the management strategies (i.e. search for the F_{target}-$B_{trigger}$ combination that maximises long-term yield while simultaneously conforming to long-term risk3≤5%). In addition, we checked the number of times there is non-convergence of the estimation model in the management procedure. There were no instances of non-convergence.
Risk type	risk3, defined as the maximum of the annual P(SSB<B_{lim}) for over a given period. For the purpose of "optimising" the management strategy, the long-term (defined as the final 10 years of the projection period) is used. risk1 (average of the annual P(SSB<B_{lim}) for a given period) is also calculated, and was used during the initial stage of the grid search,
Precautionary criterion	risk3≤5% over all years included in the management strategy (short-, medium- and long-terms).
Experiences and comments	
Use of ICES guidelines for MSE from WKGMSE2 (ICES 2019a)	The guidelines for MSE were followed as closely as possible through participation of several scientists from WKNSMSE in the WKGMSE2 meeting, despite the guidelines not being completed in time for the WKNSMSE series of meetings.

Annex 6: Reviewers' report

Review of the Workshop on North Sea Stocks Management Strategy Evaluation (WKNSMSE)

Matt Dunn[2] and Carryn de Moor[3]

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Carryn de Moor and Matthew Dunn acted as the external reviewers for the Workshop on North Sea Stocks Management Strategy Evaluation (WKNSMSE). This review covers the technical aspects of the Management Strategy Evaluations (MSEs) carried out on North Sea cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*), saithe (*Pollachius virens*), whiting (*Merlangius merlangus*) and autumn-spawning herring (*Clupea harengus*), in response to an EU-Norway special request to evaluate alternative Management Strategies (MS). The review included attendance at the 2nd workshop that took place from 26-28th February 2019 at the ICES Headquarters, as well as attendance at prior webex meetings, and access to working documents. Comments provided here are based on these meetings and the draft report of WKNSMSE available on 20th March 2019, which covered general aspects as well as the detailed methods and results for cod, saithe and whiting. The draft report section of herring, available on 29th March 2019, was also considered. The haddock section of the report was not completed in time for this review. This report reflects solely the views of the external reviewers.

The work undertaken was generally of a very high standard, and all participants are congratulated on undertaking these MSEs in a relatively short time period. Additionally, it appeared that there was some benefit from having similar MSs evaluated simultaneously for multiple species: it ensured some consistency in the implementation of the MSEs and analysists appeared to benefit from each other's help and advice when facing similar obstacles, this particularly so in cases where the same computing tools were used across stocks.

The interpretation of the request appeared appropriate as was the choice of performance statistics, such as interannual catch variability rather than interannual TAC variability.

An MSE consists of two primary components: the Operating Model (OM) and the Management Procedure (MP). In order to most accurately mimic the decision-making process within ICES, which involves Working Groups undertaking annual assessments to provide estimates of Spawning Stock Biomass (SSB) for use in Harvest Control Rules (HCRs), the MPs simulation tested during these MSEs were assessment-based rather than empirical MPs. The estimators used were SAM, which is either the assessment method currently used by the WGs concerned, or a close approximation thereof. This facilitates a good simulation of the future expected actual decision-making process under each alternative Management Strategy evaluated. For a particular species, the same estimator was correctly used for all alternative OMs, all alternative HCRs, and all simulations.

The OM is a means to model the underlying reality of the managed system, and alternative OMs facilitate the capturing of uncertainty about the true dynamics of the resource. The OM need not be the same as the estimator which is designed to mimic the Working Group's assessment. Thus the 'short-cut' method previously employed by some MSEs within ICES would fail to accurately mimic the WG's assessment if SSBs were generated directly from the OM in cases where the OMs differ from the estimator. While MSEs can facilitate the simulation testing of alternative MSs under a wide range of uncertainties, practical time constraints commonly constrain the range of uncertainties (OMs) considered during an MSE. In these MSEs, the analysists selected a baseline

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OM based on the most recent benchmark or inter-benchmark assessment. In doing so, the analysts ensured their baseline OMs represented the most recently accepted evaluation of the assessed species. This decision also facilitated a quicker start to the process as the assessment was already available and conditioned on historical data (a potentially time-consuming step to undertake). The optimisation of each MS was conducted based on this baseline OM only. Parametric uncertainty was incorporated by re-sampling OM parameters using the variance-covariance matrix.

How uncertainties were incorporated differed slightly between species (Table 1). Resampling recent data, e.g., from within the last 10 years, was consistent with the approach used in the assessments to estimate reference points. However, some stocks have demonstrated substantial temporal changes and trends in biological parameters, and more historical observations do not fall within the range considered in the OMs (examples are large historical YCS in haddock, lower maturity-at-age in cod and whiting, higher weights-at-age for whiting). For example, the maturity-at-age for age 3 cod, which has recently dominated the SSB along with age 4, has decreased over the last decade, and if this trend were to continue in future years the maturity-at-age would decline below the range considered in the OM. There were also trends in some fishery parameters, for example for saithe, where selectivity was resampled from a shorter period than the biological parameters, "because of clear declines in selectivity for age 4". As a result, the results of the MSE should be recognised as plausible only within the range of recent stock dynamics. If the stock dynamics move outside of the OM range, then the MSE should be revised. Time permitting, simulations could check the robustness of the selected Management Strategy to changes in these parameters back to pre-2000 values. Integration of the stock assessment and MSE working groups may help such issues to be identified and incorporated into advice.

Table 1: Summary of settings used for MSEs. Year ranges shown are those from which parameters were resampled. Selectivity was resampled separately from the biological parameters. Recruitment was resampled as residuals from a smoothed stock-recruit relationship, except for herring.

	Cod	Haddock	Whiting	Saithe	Herring
Fish weight, maturity, and natural mortality (*M*)	2013-2017	Weight and *M* 2008-2017. Maturity fixed.	Resampled weights, and smoothed maturity and *M*, from 2008-2017.	Weights 2008-2017. Maturity and *M* fixed.	2008-2017; resampled in blocks of years.
Recruitment	1998-2017	2000-2017	1983-2017 with autocorrelation.	1998-2017	2002-2016
Selectivity	2013-2017	2008-2017	2015-2017	2013-2017	2008-2017 resampled in blocks of years.
Alternative OMs	OM2: Recruitment from 1988-2017. OM3: Year effects in surveys. OM4: Density dependent *M*.	OM2: Random peak recruitments in the future based on 2005, 2009, 2014. *	OM2: Including occasional periods of low recruitment. OM3: Including occasional periods of low recruitment and additional IBC implementation error.	OM2: Lower *M* =0.1. OM3: Higher *M*=0.3	None regarding the population dynamics. One alternative OM considered implementation uncertainty of C-fleet catches.

* In the revised haddock MSE, OM2 will use TSA for the operating model (which will be SAM in OM1), and OM2 listed here will become OM3.

Key uncertainties were considered via robustness tests using alternative OMs (Table 1). These were selected by the analysts involved with each stock, given their opinion of the uncertainties most pertinent. While there is scope for further uncertainties to be considered (such as stock structure, some time-varying or trending parameters), we consider this method sufficient, particularly considering the time, computing and personnel constraints of this project. However, unfortunately no structural uncertainties were tested for herring.

The 5% level of acceptable risk was determined based on a particular (implicit) level of uncertainty. The more uncertainty that is included, the greater the risk. Whilst major uncertainties were included in the current MSEs, we would recommend that future research evaluate whether any further uncertainties substantially change risk and therefore should be included when determining the acceptable level of risk for a stock (e.g., *M*-at-age estimates from the Working Group on Multi Species Stock Assessment Methods do not include uncertainty). Alternatively, the issue of additional uncertainty not considered when setting the risk threshold of 5% might be encompassed by presenting results for a higher risk threshold (e.g., 10%).

Results showed that for management strategy A, risk3 had likely stabilised for cod and saithe. For whiting, risk3 continued to decrease with time. This trend would not be concerning in a precautionary sense, but if longer projections were run it might have been possible to select HCR parameters that allowed for a higher average catch while still satisfying risk3<5%. For some herring models, however, risk3 apparently continued to increase with time (Figure 2.5 for MS A). This would be concerning should the MS be in place for an extended period. However, Figure 7.3.2.1, also for MS A, does not indicate a decrease in the projected SSB 5%ile which would be expected were risk3 for MS A increasing. The text does not explain this apparent contradiction.

Given the wide range of dynamics that have been observed in long-term monitoring of these stocks, it would be wise to include a 'get-out clause', i.e., a recognition of "Exceptional Circumstances", which would allow the analyses to be revised should reality prove to be very different from the range of uncertainty considered when the MS was simulation tested (Rademeyer *et al*. 2008, Punt *et al*. 2016). Examples would include invoking the 'get out clause' if a future survey observation is outside the 95% CI of what was generated during simulation testing of the Management Strategy.

We note that the Management Strategies requested could result in discontinuous Harvest Control Rules, depending on the final selected $B_{trigger}$ and F_{target} values. Discontinuities in HCRs can be potentially problematic, giving rise to arguments about the best estimate of, in this case, the SSB, given the substantial impact on the resultant quota. One case of discontinuity is demonstrated for HCR B in Figure 2.1 of the report, where the level of F used to calculate the catch quota could decrease substantially for only a minor decrease in SSB if it is near to B_{lim}. A more disconcerting discontinuity can arise if the selected $B_{trigger}$ is more than 4 times greater than B_{lim} (Figure 1).

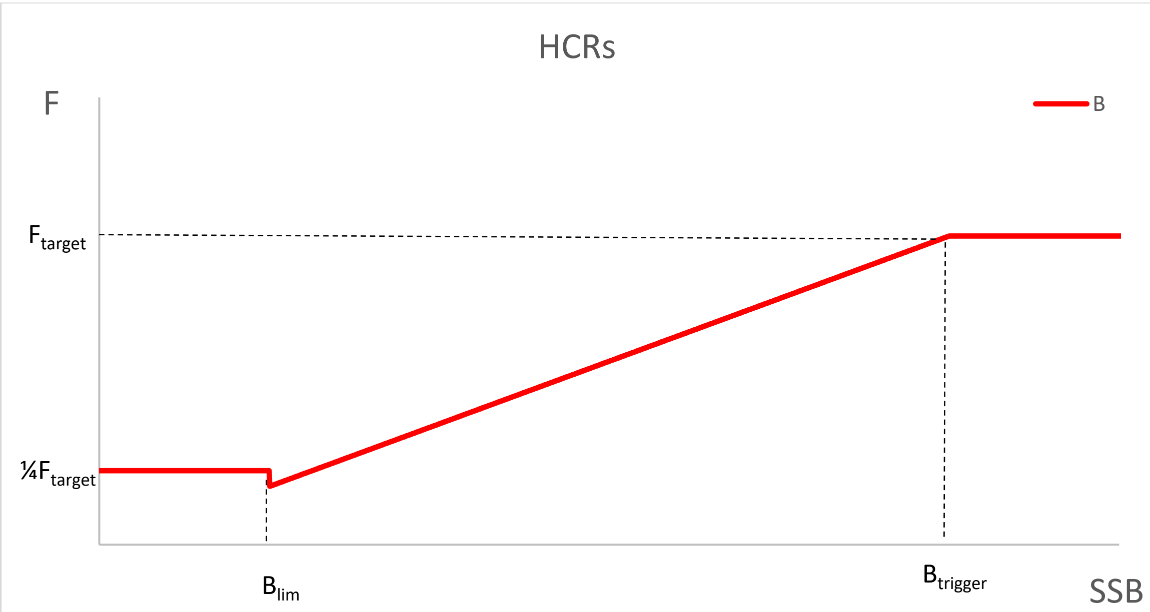

Figure 1. Harvest Control Rule B for cod, haddock, whiting and saithe where $B_{trigger}$>4xB_{lim}, indicating the F can be lower when SSB>B_{lim} than it is once SSB<B_{lim}. The same shape would arise for Harvest Control Rule B for herring 2+ ringers if 0.1x$B_{trigger}$>F_{target}xB_{lim}.

Validation checks were carried out to ensure future dynamics were consistent with that of the past, e.g. where parameters were randomly drawn from recent years, and particularly, that the generation of future recruitment would be consistent with that in the past time period selected given the same historical spawning biomass.

The decision to simulation tests the MS's for cod, saithe and whiting with 1000 different replicates and 20 years projection was based on a study undertaken only on cod. A separate similar study was undertaken for herring. Ideally such a study should be undertaken separately for each species as, for example, fish life span and recovery time can differ widely between species. However, it is understood that time constraints limited such analyses, and all five MSEs thus used 1000 replicates with 20 years projection.

In all cases the HCR was simulated to produce a total catch allowance. For example, the HCR calculated catch for haddock was assumed to cover directed catches as well as industrial bycatch, discards and below minimum size fish. For some species, this total catch allowance was assumed to cover any directed catches as well as bycatches. It is recommended that this always be clearly communicated (e.g. as in the whiting section 5.3) so that managers do not mistakenly assume the HCR calculated catch is for directed catch only, and then allow further bycatch over and above that limit (thereby potentially increasing the risk to the resource from that which was simulation tested).

We list further notable stock-specific comments here:

- Many of the biological parameters are drawn randomly from the most recent 10 year period for use in **whiting** projections. It appears strange, therefore that a 3 year period, rather than a 10 year period was used for selectivity. Unless there are compelling circumstances, one would expect the same time period to be used for all biological parameters. However, the impact of this may be small, impacting primarily the age 5 and to a lesser extent age 6 fish (Figure 5.1.19), and this is consistent with what the WG chose to use in their calculation of reference points for whiting.
- A single selectivity curve is used for combined directed catch and industrial bycatch of **whiting**. However, we understand IBC contains mostly small fish representing a very different selectivity pattern to that of the directed fishery. It is recommended that future OMs estimate separate selectivity curves for the two different sets of landings. This would better facilitate the testing of variable IBC levels as the changing proportions of IBC would be applied to a different selectivity pattern.
- The conclusion section for **saithe** notes that "the functional form of [Management Strategy] B is inherently more conservative than A". Note that B is only more conservative than A for a limited range below B_{lim}; once SSB falls below $0.25B_{trigger}$ HCR A gives lower F values than HCR B and C.
- The decision to exclude the LAI index from the set of data to which the **herring** models were conditioned appears justifiable.
- The sections on **whiting**, **cod** and **saithe** provide comparative plots (For example, Figure 3.1.10) between the range of historically estimated recruitments given SSB, and the corresponding recruitments that would be generated using their projection framework, should the exact same SSBs arise. This enables an easy check if the method to generate future recruitments will span the same range as that observed historically. The section on **herring** does not include such a plot making it difficult to perform such a check. Figure 7.3.2.1 indicates the future range of SSB is likely to be lower than that between 2002 – 2016. Figure 7.1.3.3 indicates future recruitment residuals will be higher than that estimated between 2002 and 2016. The residuals should span a similar range to that estimated historically. Furthermore, Figure 7.1.3.2 *appears* to indicate that the range of SSB over which the segmented regression curve is applied is lower than that over which the Ricker curve is applied. This latter concern may be an artefact of the method of plotting, but as future recruitments are generated randomly from both methods (with more recruitment generated using the Ricker curve), one would expect a similar SSB range for both.
- Figure 7.1.4.5 of the **herring** section shows changes over time in selectivity for each age separately. It would be useful to see the changes in the selectivity-at-age patterns over time, i.e. a plot with age on the x-axis, selectivity on the y-axis and different curves indicating the

different years. This was requested by the reviewers, but not provided in time for review. Future selection patterns are assumed to follow an age-correlated random walk based on that estimated between 2007 and 2017 (section 7.1.4), but the appropriateness of that choice cannot be reviewed by considering Figure 7.1.4.5 alone.

Summary

The reviewers agreed that the MSEs conducted for cod, whiting, and saithe were well-conducted and an acceptable compromise between an ideal MSE analysis, and what could be achieved in the available time. In most cases, reasonable technical decisions were made. Our most substantial recommendation is that further OMs should be considered (for example, two initially intended robustness tests for saithe could not be completed in the time given). In addition, and given this recommendation, 'get-out' clauses in the implementation of the HCR are recommended. The MSE conducted for herring was revised after the February meeting, and ultimately not as thoroughly implemented. The MSE conducted for haddock encountered problems, associated with the use of different assessment software for the OM and the estimator, and these analyses are being revised. Overall, we agree that the analyses and results were acceptable for answering the request, subject to the qualifications described above.

References

Butterworth DS (2007) Why a management procedure approach? Some positives and negatives. ICES Journal of Marine Science 64:613-617

Punt AE, Butterworth DS, de Moor CL, De Oliveira JAA, Haddon M (2016) Management strategy evaluation: best practices. Fish and Fisheries 17:303-334

Rademeyer RA, Butterworth DS, Plagányi EE (2008) A history of recent bases for management and the development of a species-combined Operational Management Procedure for the South African hake resource. African Journal of Marine Science 30:291-310.

Appendix to Reviewers Report

There was substantial discussion during the 2nd workshop with regards to whether or not historical data should be treated as unchanged during future simulations. The herring MSE was ultimately revised to be consistent with the approach used for the other stocks. Nevertheless, the issues underlying the discussion are described here. The herring simulations initially changed the time series of historically observed data provided to the Management Procedure's estimator (SAM) between simulations during projections.

When conducting an MSE, the following method is considered best-practice:

1) A single OM is conditioned to a single set of historical data, say D_{2000} to D_{2017}.
2) Parametric uncertainty is incorporated into the projections through the use of, for example, the variance-covariance matrix or Bayesian posterior distributions. For each simulation *i*, then, there will be one set of parameter values. These *i*=1 to 1000 sets of parameter values have, however, all resulted from conditioning the model to one set of historical data and then taking the estimated parameter uncertainty into account.
3) When projecting into the future, future "data" are generated from the OM. Thus, in a model projecting to 2020, the full time series of data available during simulation *i* would be D_{2000} to D_{2017} and D_{2018}^{i} to D_{2020}^{i}. Each simulation will thus differ in the future data it provides to the estimator (this in part based on the feedback mechanisms), but the historical data remain unchanged.
4) Another way of explaining this is that the MSE is designed to test a particular Management Procedure, which in the case of ICES, includes assessment-based Management Procedures. The estimator of the MP should thus mimic the annual assessment conducted by the WG as far as possible. This is because it is these assessments which will provide the estimate of spawning stock biomass to go into the HCR formula. The WGs in future years are expected to continue to fit their assessments to the unchanged historically observed data, and any future data (2018+) they receive.
5) Alternative OMs can be conditioned to alternative plausible sets of historical data, and the OMs can either be combined (each OM would be assigned a relative weight) to form a reference set of OMs, or alternative OMs used as robustness tests (as done for e.g. cod with time varying catchability)

In summary, a MP can be tested against multiple OMs. But when simulation testing a particular MP against a particular OM, the historical data (D_{2000} to D_{2017}) should remain the same for all simulations (*i*=1 to 1000).

In the initial MSE for herring, after steps (1) and (2) above, the analysts additionally generated a new set of historical data (e.g. D_{2000}^{i} to D_{2017}^{i}) corresponding to each of their draws from the variance covariance matrix. They did not condition the parameters *i* to historical data *i*. Thus, the method outlined in (5) above was not followed, where uncertainty in historical data is considered via alternative OMs. In simulation testing of a particular MS against their OM, this historical data *changed* between simulations. We would typically expect the WG's assessment in the first year of simulation, e.g. 2018, to be very close to that simulated, given they would only differ by one year of data (that which is generated in 2018). However, in the case of herring, the estimator in 2018 in the initial MSE varied widely, because the input data varied widely from the data the assessment WG would use.

A key part of MSE is the ability to incorporate uncertainty, and this should be done via the OMs. One cannot alter what the estimator is based upon for simulations from a single OM. For one set of simulations (e.g., i = 1-1000) of one Management Procedure (estimator + HCR) on one OM, the MP, and thus the estimator, cannot change. An example of the result of failing to pre-define the estimator and its data in a MSE was the International Whaling Commission's New Management Procedure, which needed to be replaced by the Revised Management Procedure to ensure the HCR, estimator and data input were all pre-defined as part of the Management Strategy (Butterworth 2007).

Annex 7: Additional Results for cod

A7.1. Search grid for short-term

Management strategy A

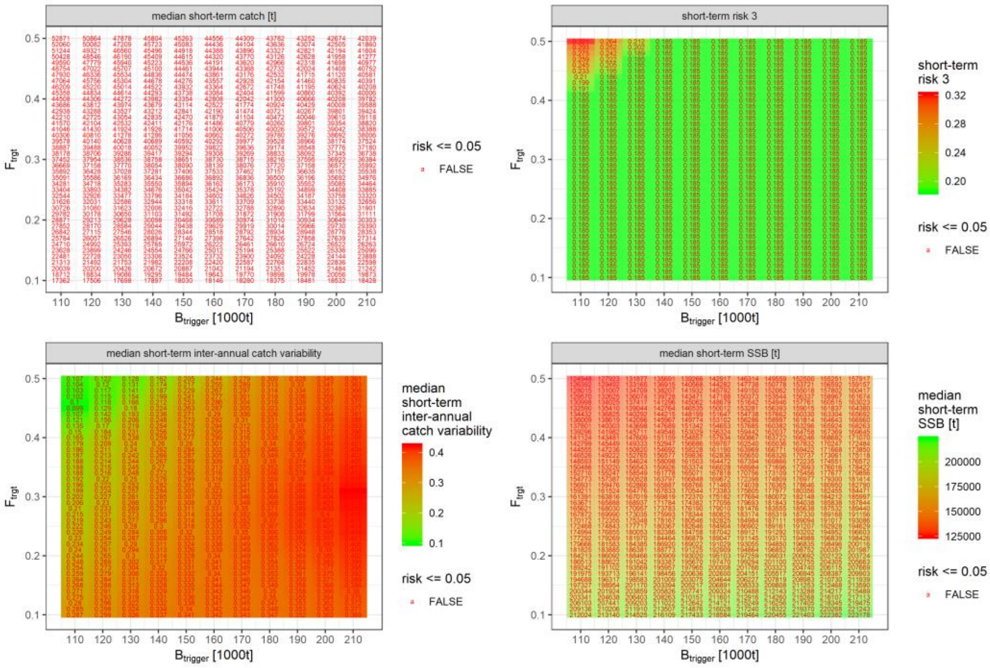

Figure A7.1.1. Cod in Subarea 4, Division 7.d and Subdivision 20: Grid search for "optimal" combination of F_{target} and $B_{trigger}$ for management strategy A for the short-term (i.e. first five years of the 20-year projection). The top-left plot is median short-term catch, top-right the short-term risk3, bottom left the median short-term inter-annual catch variability and bottom right the median short-term SSB. No combinations meet the precautionary criterion (risk3≤5%) and hence no "optimum" is found.

Management strategy B

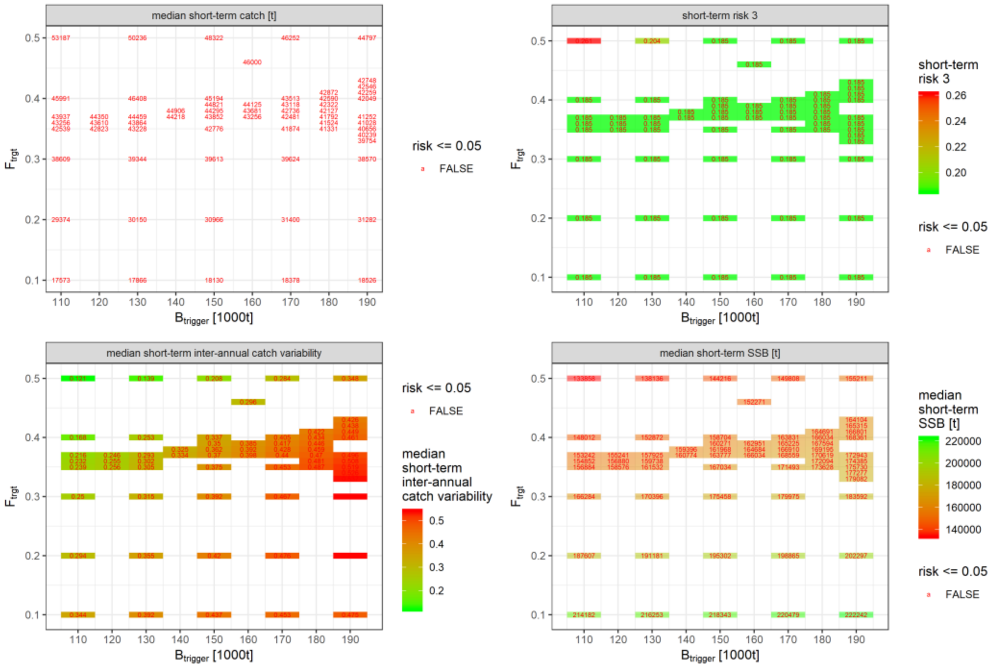

Figure A7.1.2. Cod in Subarea 4, Division 7.d and Subdivision 20: Grid search for "optimal" combination of F_{target} and $B_{trigger}$ for management strategy B for the short-term (i.e. first five years of the 20-year projection). See caption to Figure A7.1.1 for further details.

Management strategy C

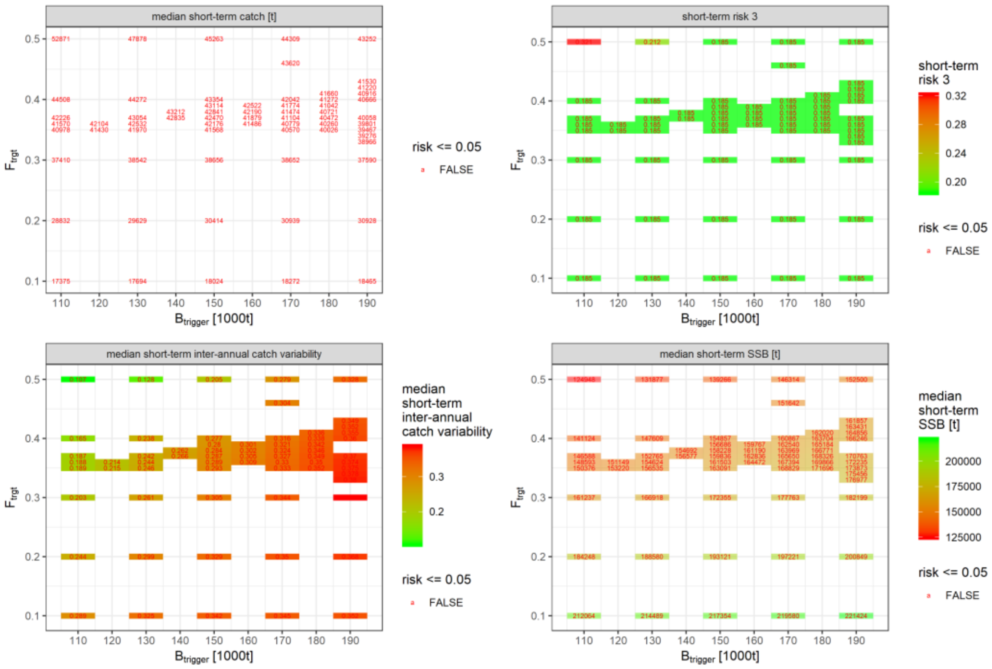

Figure A7.1.3. Cod in Subarea 4, Division 7.d and Subdivision 20: Grid search for "optimal" combination of F_{target} and $B_{trigger}$ for management strategy C for the short-term (i.e. first five years of the 20-year projection). See caption to Figure A7.1.1 for further details.

Management strategy A+D

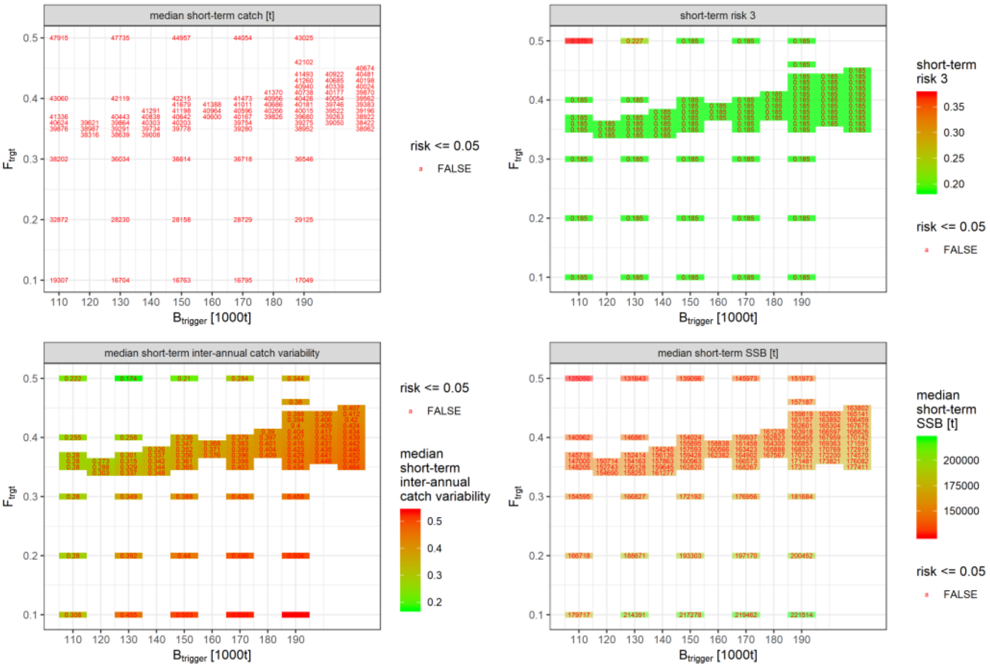

Figure A7.1.4. Cod in Subarea 4, Division 7.d and Subdivision 20: Grid search for "optimal" combination of F_{target} and $B_{trigger}$ for <u>management strategy A+D</u> for the short-term (i.e. first five years of the 20-year projection). See caption to Figure A7.1.1 for further details.

Management strategy B+E

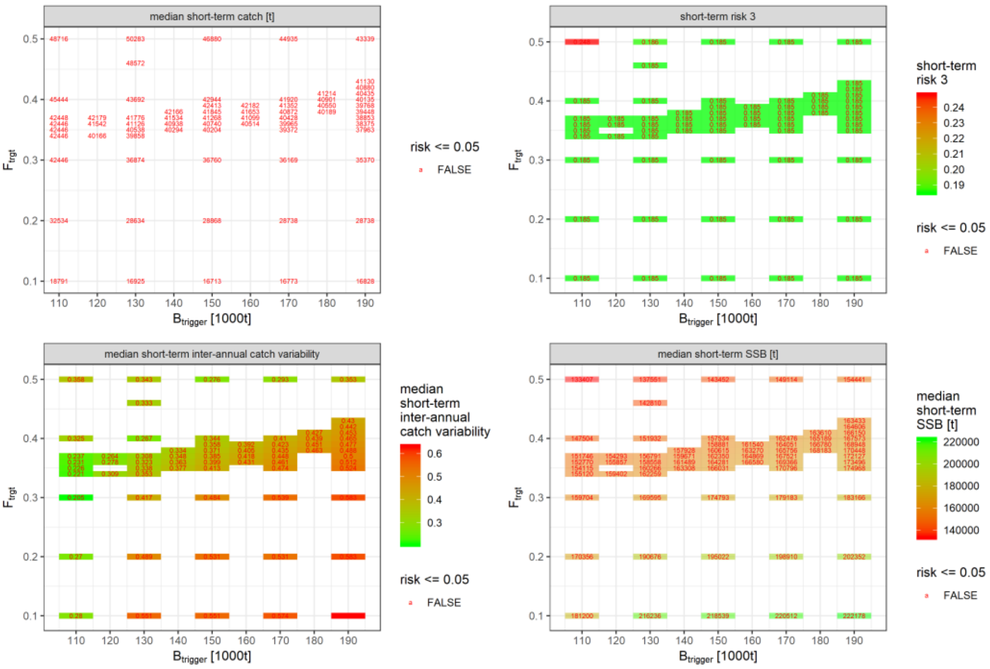

Figure A7.1.5. Cod in Subarea 4, Division 7.d and Subdivision 20: Grid search for "optimal" combination of F_{target} and $B_{trigger}$ for <u>management strategy B+E</u> for the short-term (i.e. first five years of the 20-year projection). See caption to Figure A7.1.1 for further details.

Management strategy C+E

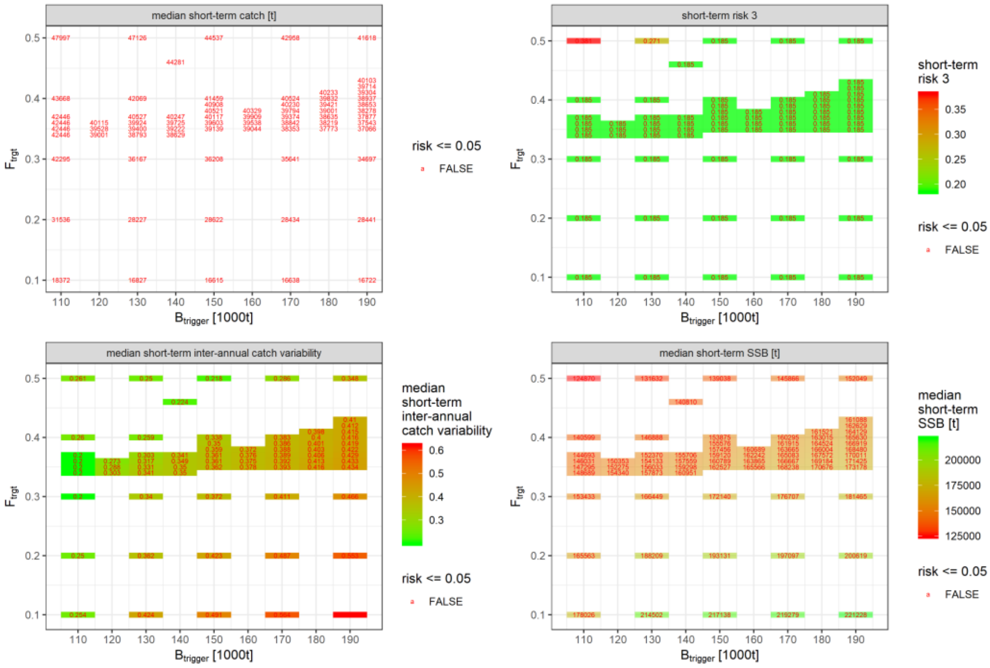

Figure A7.1.6. Cod in Subarea 4, Division 7.d and Subdivision 20: Grid search for "optimal" combination of F_{target} and $B_{trigger}$ for management strategy C+E for the short-term (i.e. first five years of the 20-year projection). See caption to Figure A7.1.1 for further details.

A7.2. Summary projection plots for OM2 (recruitment 1988+)

OM2, F=0

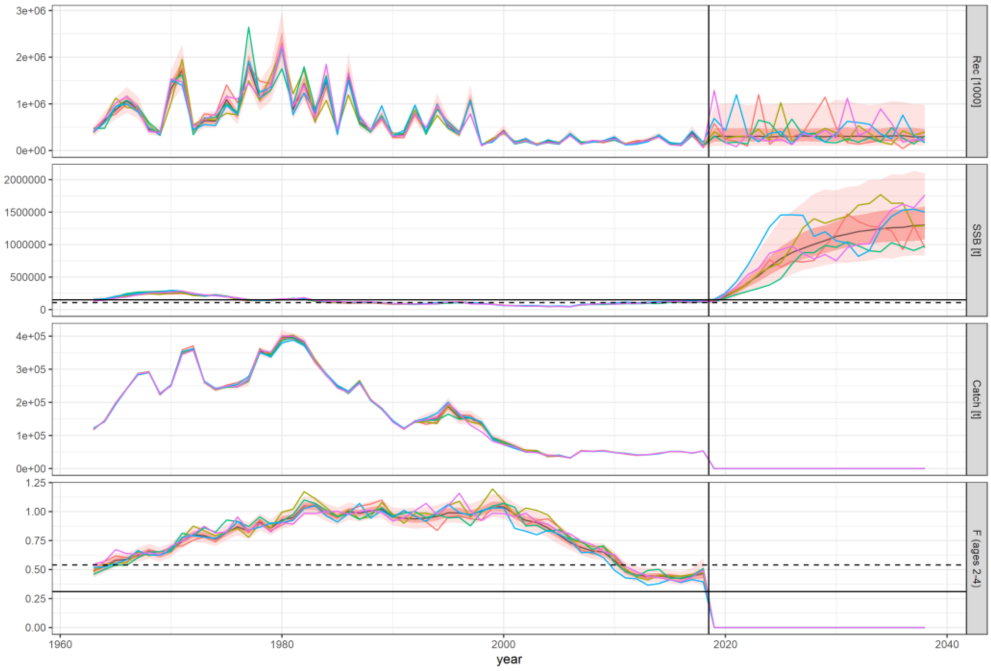

Figure A7.2.1. Cod in Subarea 4, Division 7.d and Subdivision 20: Summary projections for OM2 with F=0. Top plot is recruitment (age 1), second plot SSB, third plot catch and bottom plot mean F (ages 2-4). The vertical black line separates the historical period from the projection period. The SSB plot includes B_{pa}=MSY $B_{trigger}$ (horizontal solid line) and B_{lim} (horizontal hashed line), while the mean F plot includes F_{msy} (horizontal solid line) and F_{lim} (horizontal dashed line). The actual plots show medians (solid black line) with the darker shaded area indicating the 25th and 75th percentiles, and the light shaded area the 5th and 95th percentiles. The coloured lines indicate the first five replicates.

OM2, Management strategy A

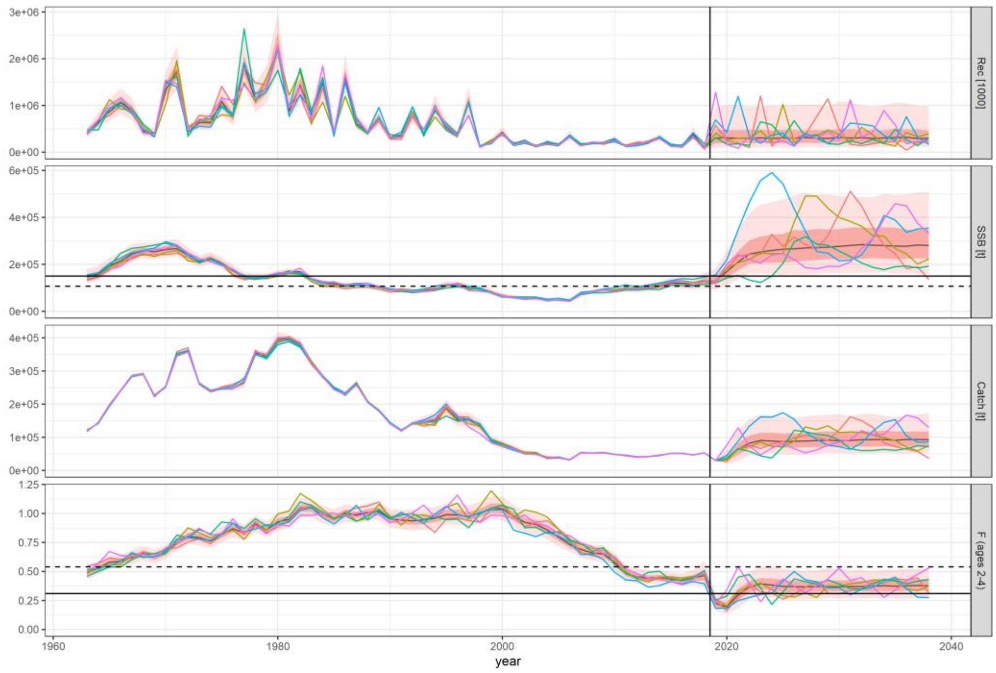

Figure A7.2.2. Cod in Subarea 4, Division 7.d and Subdivision 20: Summary projections for <u>OM2</u> with <u>management strategy A</u>. See the caption to Figure A7.2.1 for further details.

OM2, Management strategy B

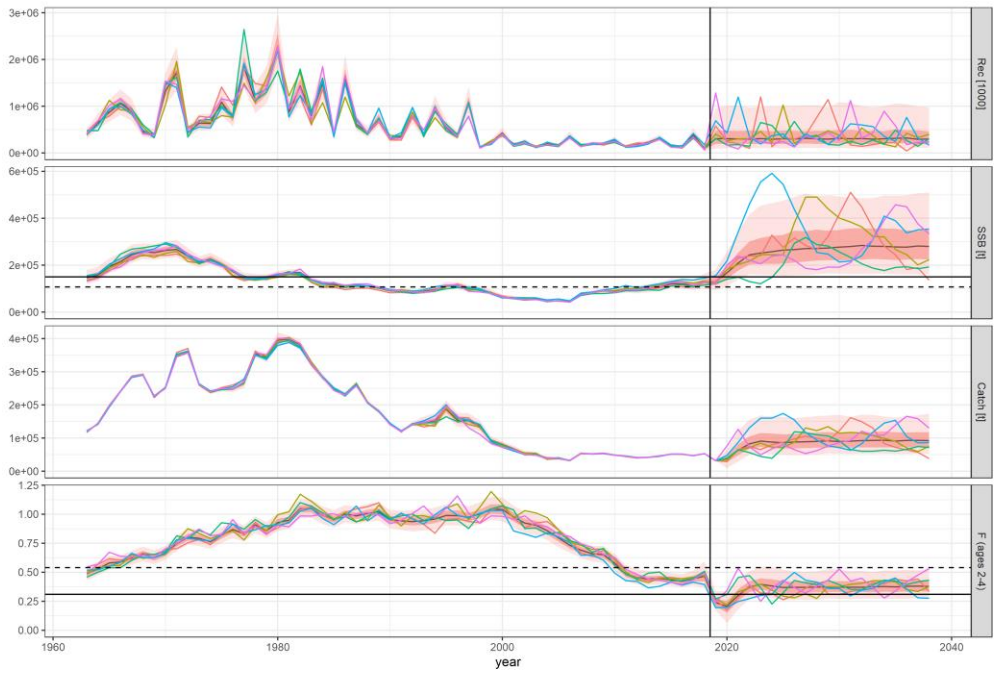

Figure A7.2.3. Cod in Subarea 4, Division 7.d and Subdivision 20: Summary projections for <u>OM2</u> with <u>management strategy B</u>. See the caption to Figure A7.2.1 for further details.

OM2, Management strategy C

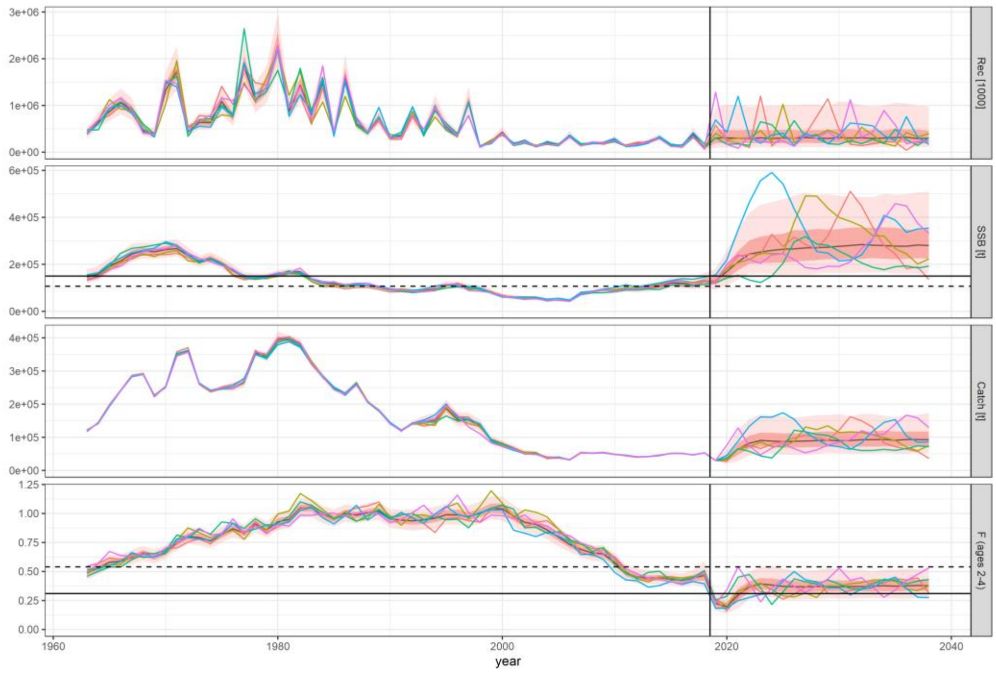

Figure A7.2.4. Cod in Subarea 4, Division 7.d and Subdivision 20: Summary projections for <u>OM2</u> with <u>management strategy C</u>. See the caption to Figure A7.2.1 for further details.

OM2, Management strategy A+D

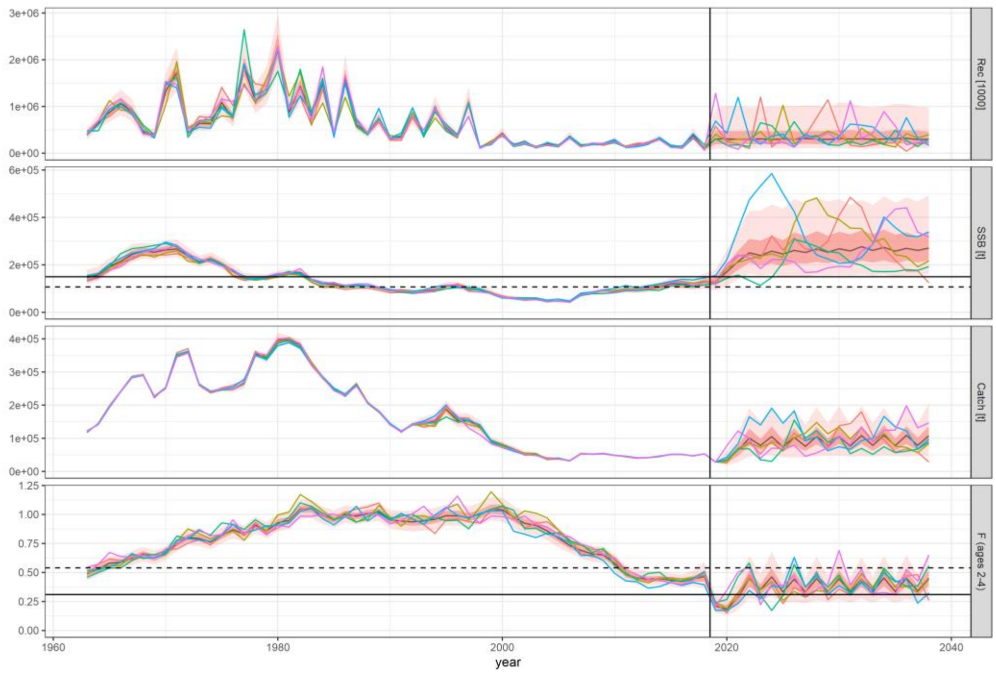

Figure A7.2.5. Cod in Subarea 4, Division 7.d and Subdivision 20: Summary projections for <u>OM2</u> with <u>management strategy A+D</u>. See the caption to Figure A7.2.1 for further details.

OM2, Management strategy B+E

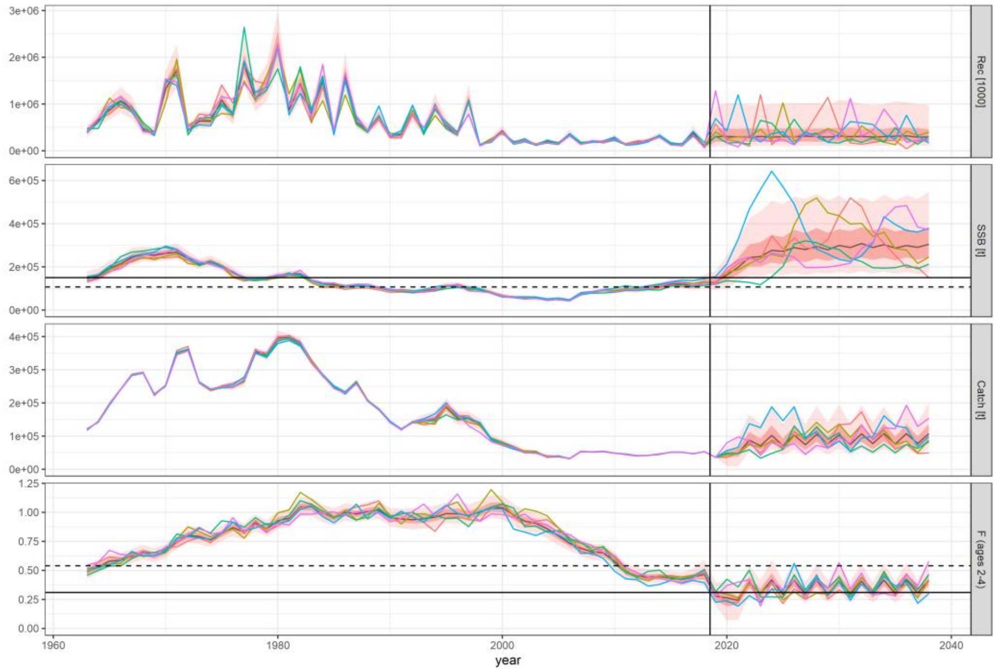

Figure A7.2.6. Cod in Subarea 4, Division 7.d and Subdivision 20: Summary projections for <u>OM2</u> with <u>management strategy B+E</u>. See the caption to Figure A7.2.1 for further details.

OM2, Management strategy C+E

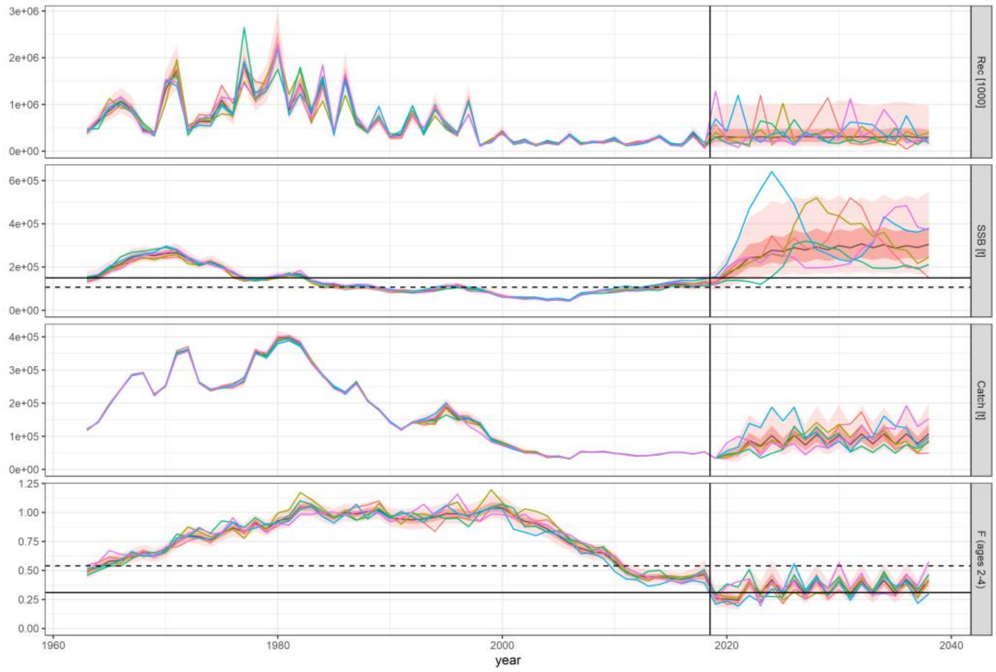

Figure A7.2.7. Cod in Subarea 4, Division 7.d and Subdivision 20: Summary projections for <u>OM2</u> with <u>management strategy C+E</u>. See the caption to Figure A7.2.1 for further details.

A7.3. Summary projection plots for OM3 (year-effects in IBTS surveys)

[Note, for OM3, the B_{lim} used in the OM and for performance statistics is re-calculated, and is 108 000 t instead of 107 000 t; the B_{lim} in the MP remains at 107 000 t (Table 2.1)]

OM3, F=0

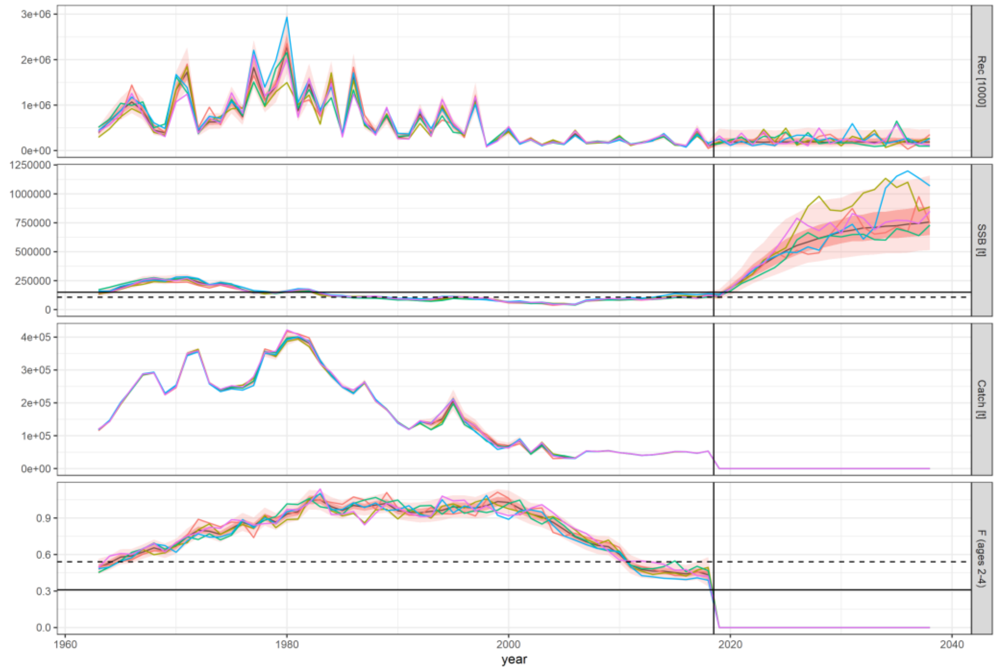

Figure A7.3.1. Cod in Subarea 4, Division 7.d and Subdivision 20: Summary projections for OM3 with F=0. See the caption to Figure A7.2.1 for further details.

OM3, Management strategy A

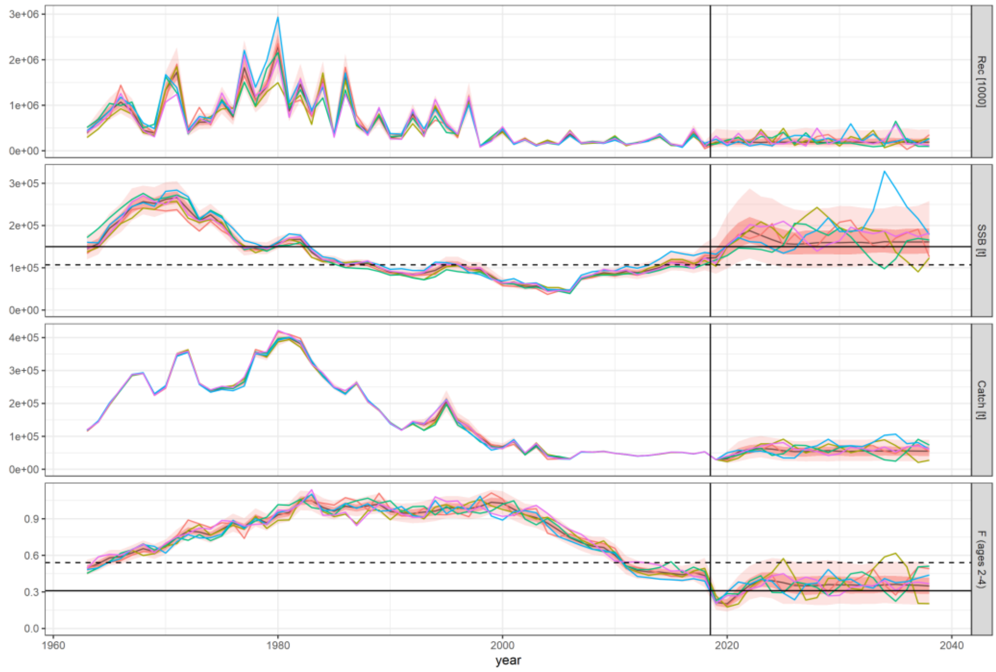

Figure A7.3.2. Cod in Subarea 4, Division 7.d and Subdivision 20: Summary projections for <u>OM3</u> with <u>management strategy A</u>. See the caption to Figure A7.2.1 for further details.

OM3, Management strategy B

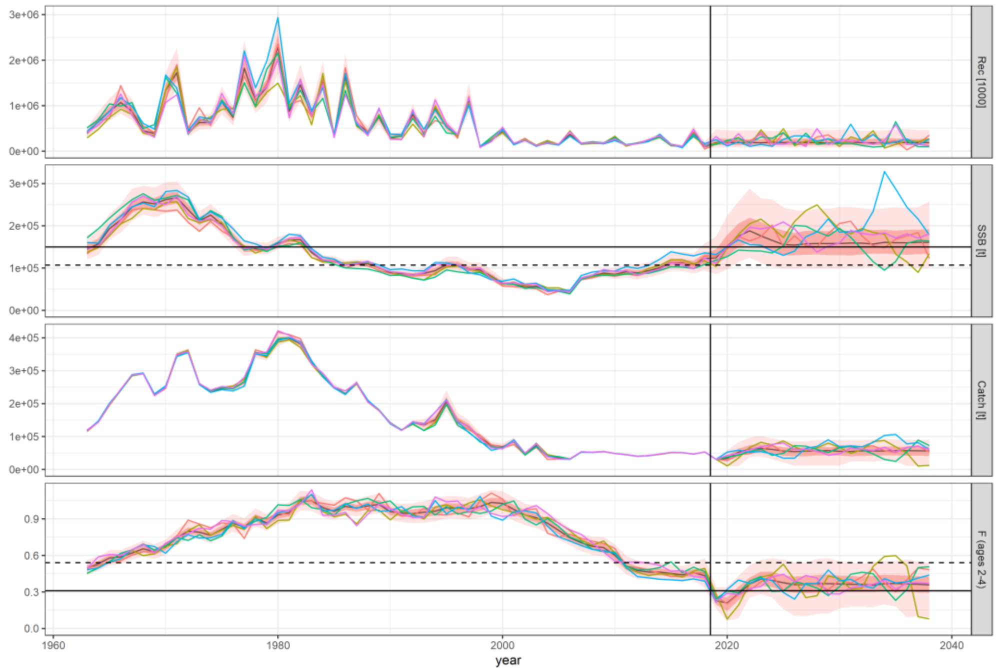

Figure A7.3.3. Cod in Subarea 4, Division 7.d and Subdivision 20: Summary projections for <u>OM3</u> with <u>management strategy B</u>. See the caption to Figure A7.2.1 for further details.

OM3, Management strategy C

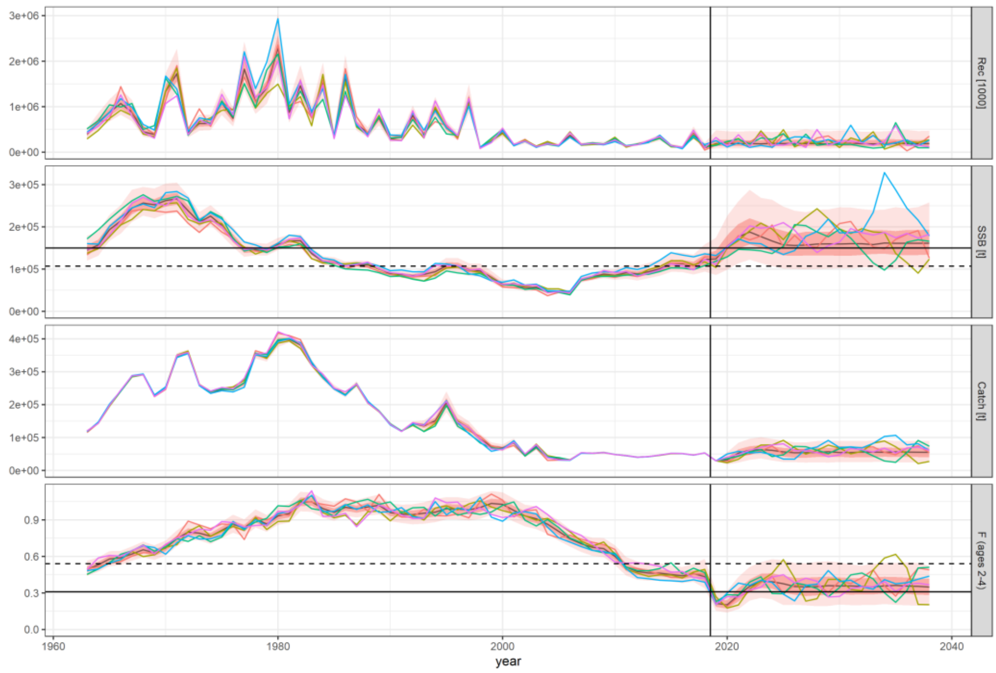

Figure A7.3.4. Cod in Subarea 4, Division 7.d and Subdivision 20: Summary projections for OM3 with management strategy C. See the caption to Figure A7.2.1 for further details.

OM3, Management strategy A+D

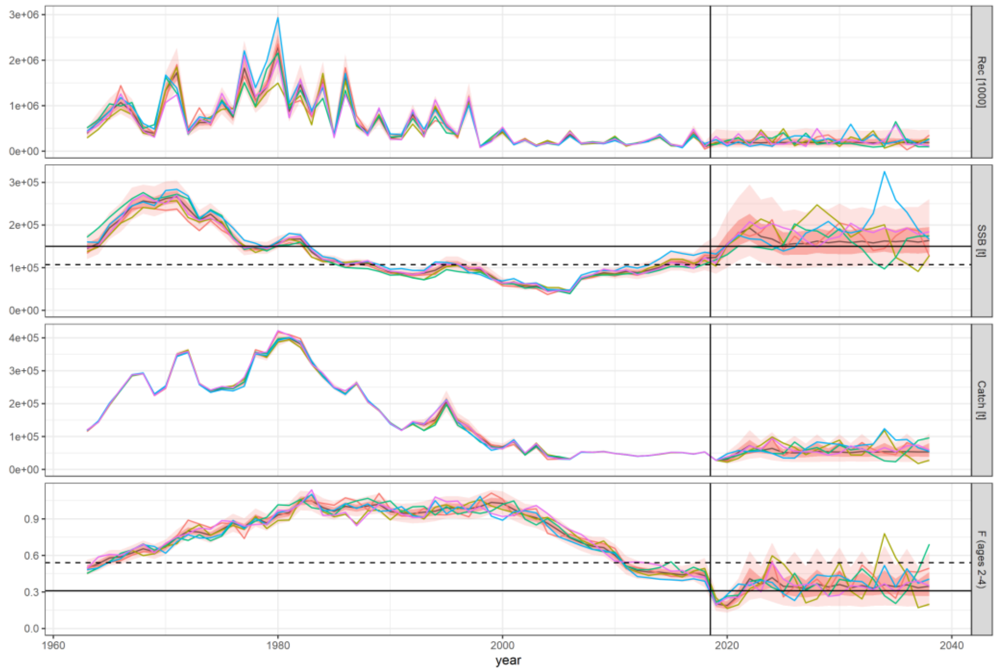

Figure A7.3.5. Cod in Subarea 4, Division 7.d and Subdivision 20: Summary projections for OM3 with management strategy A+D. See the caption to Figure A7.2.1 for further details.

OM3, Management strategy B+E

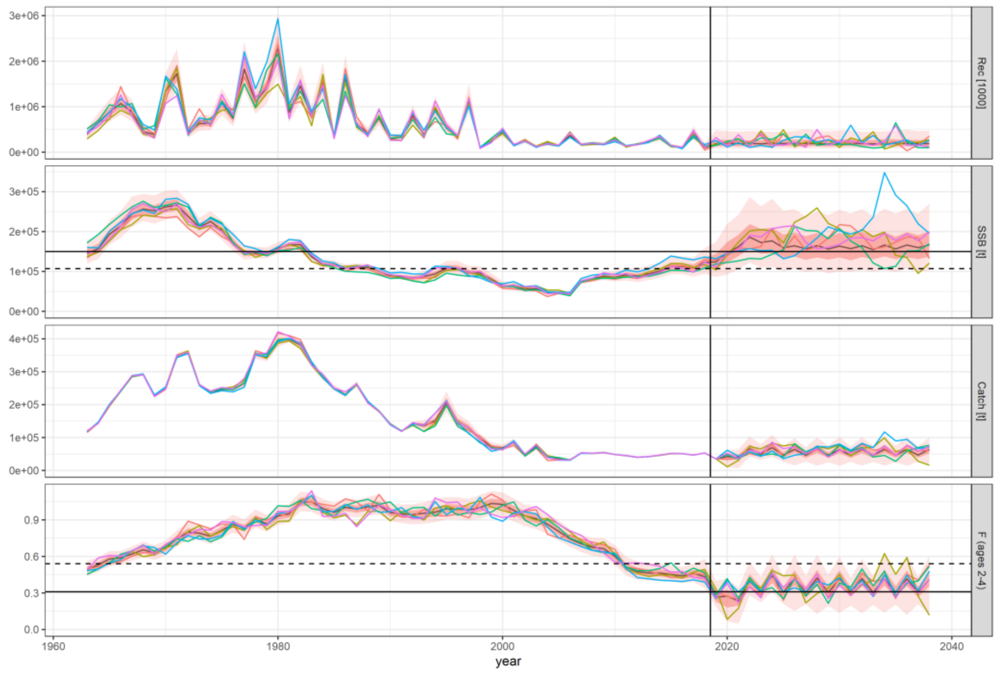

Figure A7.3.6. Cod in Subarea 4, Division 7.d and Subdivision 20: Summary projections for <u>OM3</u> with <u>management strategy B+E</u>. See the caption to Figure A7.2.1 for further details.

OM3, Management strategy C+E

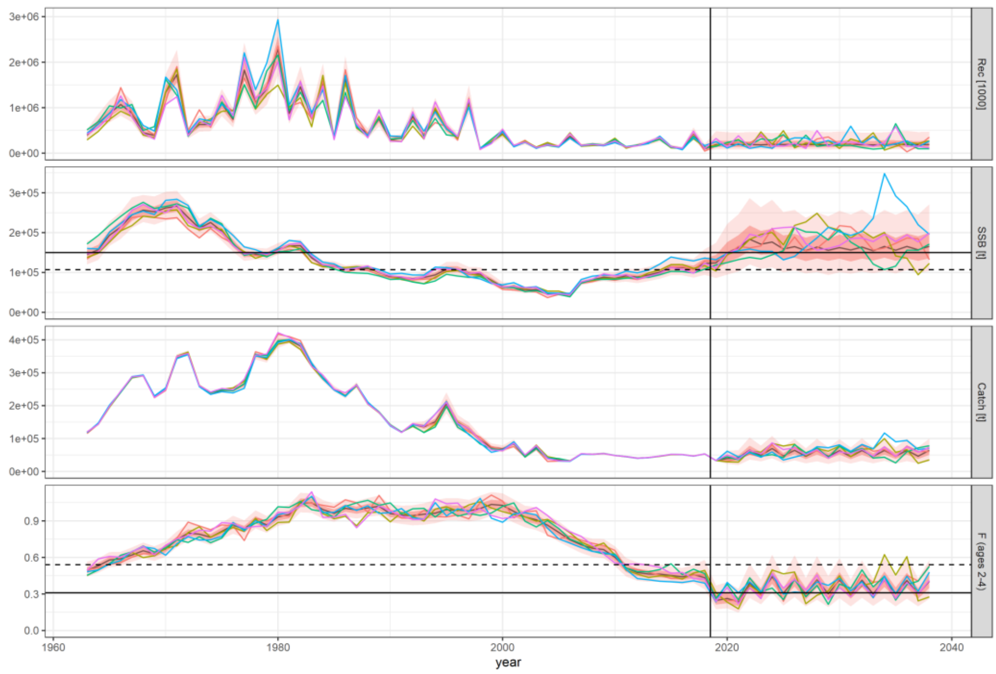

Figure A7.3.7. Cod in Subarea 4, Division 7.d and Subdivision 20: Summary projections for <u>OM3</u> with <u>management strategy C+E</u>. See the caption to Figure A7.2.1 for further details.

A7.4. Summary projection plots for OM4 (density-dependent Ms)

OM4, F=0

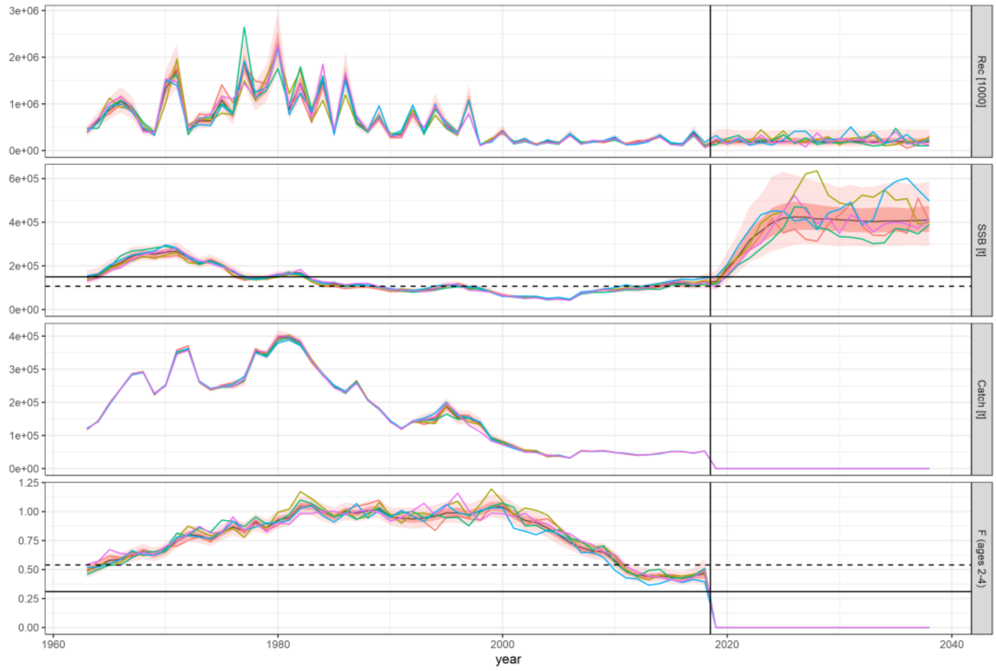

Figure A7.4.1. Cod in Subarea 4, Division 7.d and Subdivision 20: Summary projections for OM4 with F=0. See the caption to Figure A7.2.1 for further details.

OM4, Management strategy A

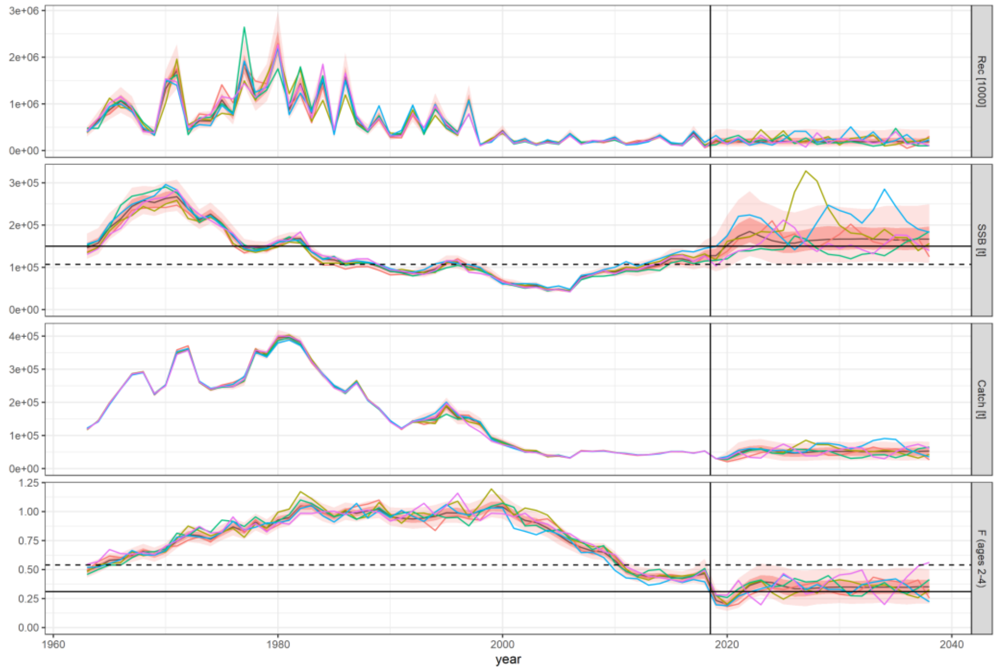

Figure A7.4.2. Cod in Subarea 4, Division 7.d and Subdivision 20: Summary projections for OM4 with management strategy A. See the caption to Figure A7.2.1 for further details.

OM4, Management strategy B

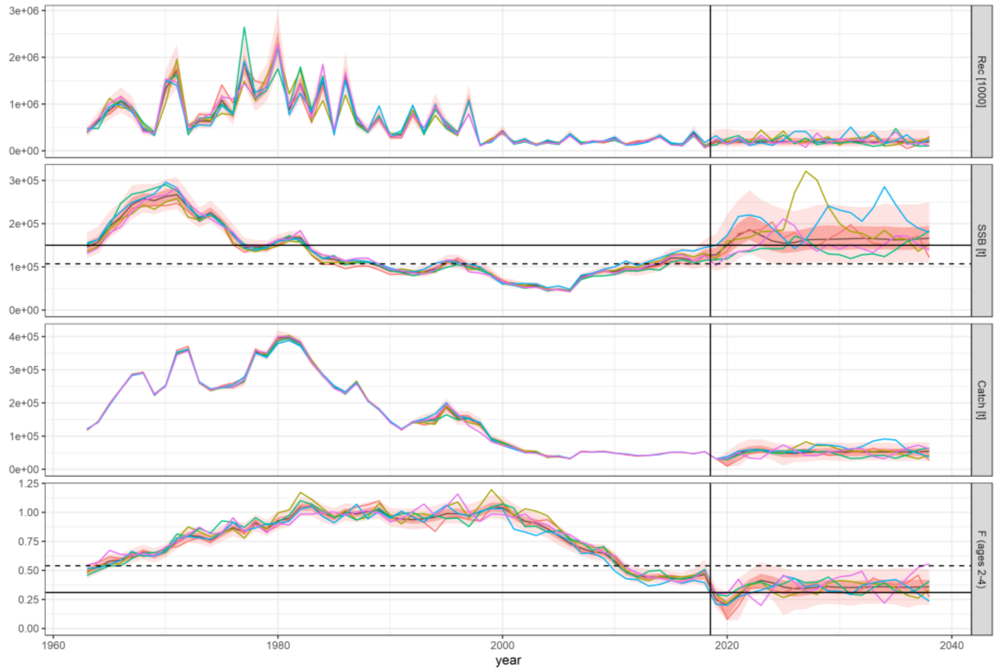

Figure A7.4.3. Cod in Subarea 4, Division 7.d and Subdivision 20: Summary projections for OM4 with management strategy B. See the caption to Figure A7.2.1 for further details.

OM4, Management strategy C

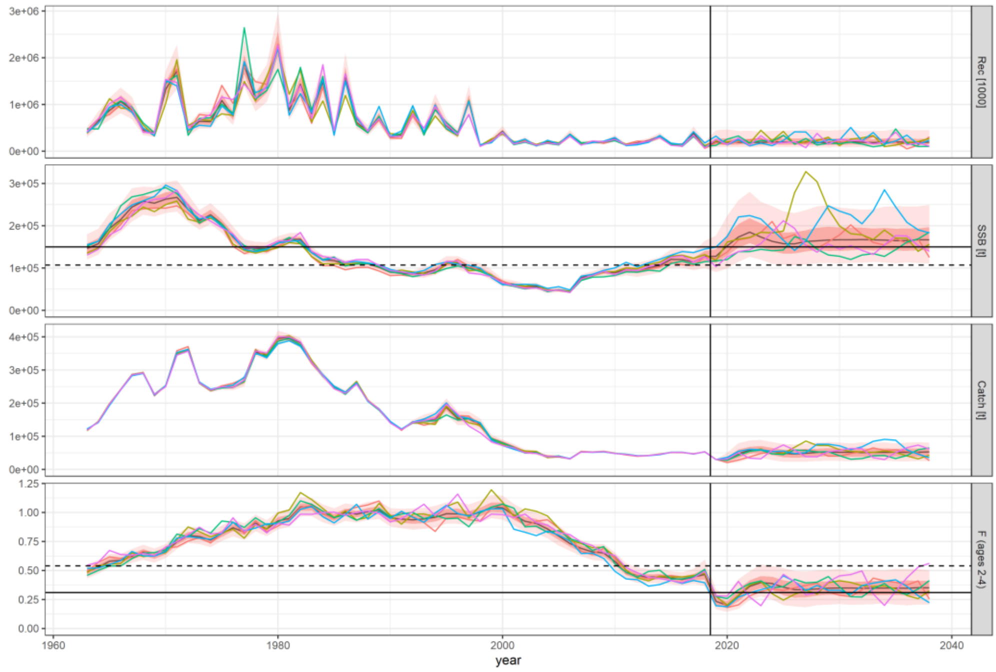

Figure A7.4.4. Cod in Subarea 4, Division 7.d and Subdivision 20: Summary projections for OM4 with management strategy C. See the caption to Figure A7.2.1 for further details.

OM4, Management strategy A+D

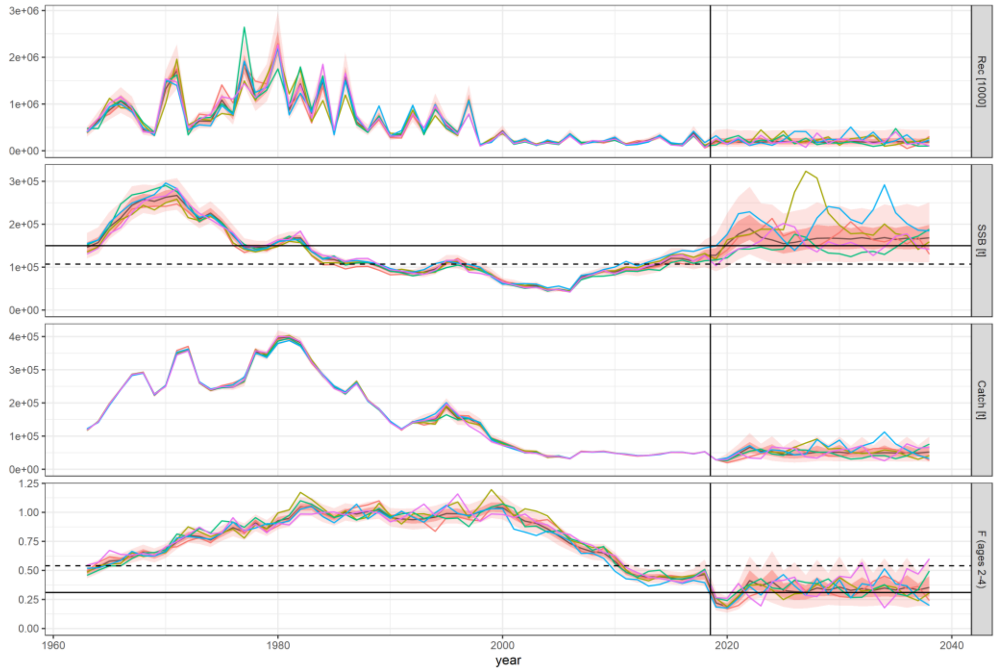

Figure A7.4.5. Cod in Subarea 4, Division 7.d and Subdivision 20: Summary projections for <u>OM4</u> with <u>management strategy A+D</u>. See the caption to Figure A7.2.1 for further details.

OM4, Management strategy B+E

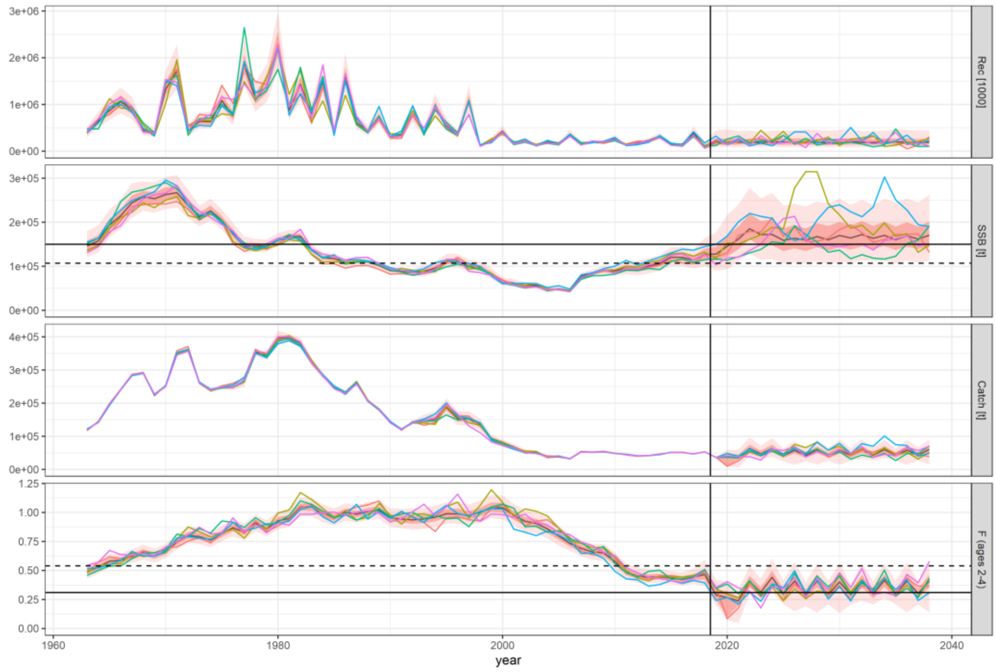

Figure A7.4.6. Cod in Subarea 4, Division 7.d and Subdivision 20: Summary projections for <u>OM4</u> with <u>management strategy B+E</u>. See the caption to Figure A7.2.1 for further details.

OM4, Management strategy C+E

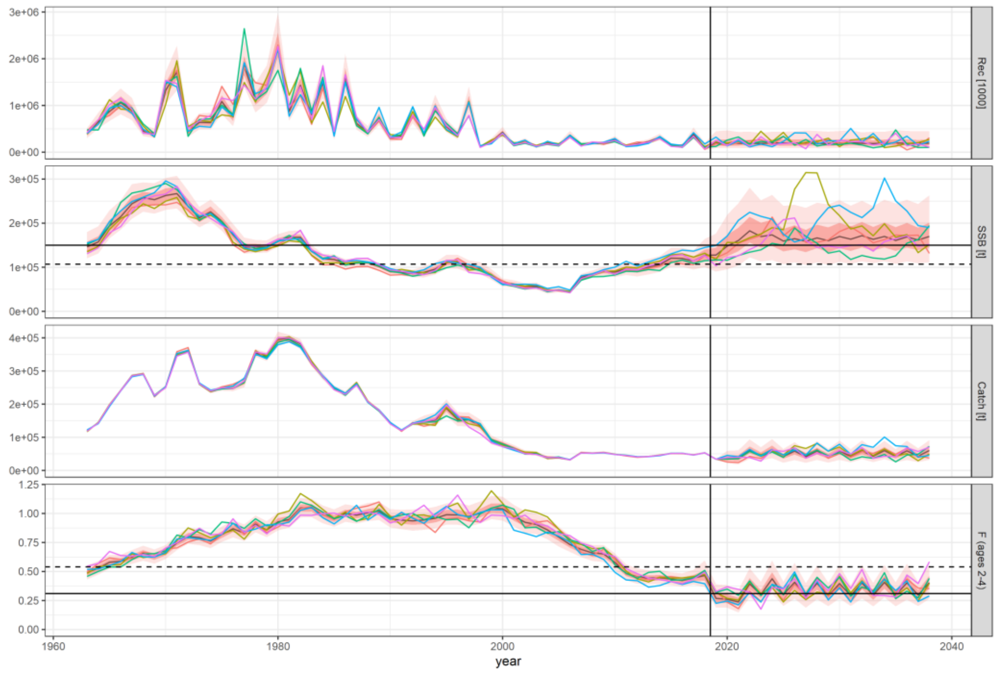

Figure A7.4.7. Cod in Subarea 4, Division 7.d and Subdivision 20: Summary projections for OM4 with management strategy C+E. See the caption to Figure A7.2.1 for further details.

A7.5. More detailed results for baseline OM1

Table 7.5.1. Cod in Subarea 4, Division 7.d and Subdivision 20: "optimal" combinations of F_{target} and $B_{trigger}$ for the baseline OM and nine management strategies, F=0 indicates no fishing and A* uses MSY values (F_{target} = F_{MSY} and $B_{trigger}$ = MSY $B_{trigger}$. Also reported are the median values for catch, SSB, realized mean F (ages 2-4), interannual catch variability (ICV), interannual TAC variability (ITV), risk3, and risk1. Statistics are reported for three time periods, short-term (first five years), medium-term (years 6-10) and long-term (final 10 years). Other statistics reported include the number of replicates where the estimation model (SAM) failed to converge, the number of replicates where F_{max} (F_{max} =2) was reached, the proportion of replicates that recover above B_{pa}=MSY $B_{trigger}$ and the number of years taken to recover above B_{pa}=MSY $B_{trigger}$ for the first time. Weights are in tonnes.

Scenario	F=0	A*	A*+D	A	B	C	A+D	B+E	C+E
F_{trgt}	0	0.31	0.31	0.38	0.38	0.38	0.40	0.36	0.36
$B_{trigger}$		150000	150000	170000	160000	170000	190000	130000	140000
long-term median catch	0	52610	51880	54597	54790	54597	52532	52728	52440
long-term median SSB	701275	195959	195477	167536	165561	167536	167587	168381	168157
long-term realized mean F	0	0.311	0.305	0.362	0.370	0.362	0.351	0.356	0.353
long-term ICV	0	0.113	0.315	0.171	0.166	0.171	0.260	0.329	0.318
long-term ITV	0	0.113	0.126	0.171	0.166	0.171	0.209	0.148	0.148
long-term risk3	0	0.011	0.011	0.036	0.04	0.036	0.038	0.046	0.049
long-term risk1	0	0.007	0.007	0.030	0.036	0.030	0.031	0.036	0.036
medium-term median catch	0	52778	54678	54538	54511	54538	52372	55593	55503
medium-term median SSB	541240	196723	198034	166656	165212	166656	166935	171711	171516
medium-term realized mean F	0	0.312	0.321	0.368	0.372	0.368	0.357	0.374	0.372
medium-term ICV	0	0.113	0.335	0.164	0.161	0.164	0.253	0.350	0.345
medium-term ITV	0	0.113	0.123	0.164	0.161	0.164	0.210	0.141	0.138
medium-term risk3	0	0.010	0.008	0.039	0.043	0.039	0.044	0.040	0.042
medium-term risk1	0	0.007	0.006	0.032	0.037	0.032	0.035	0.030	0.030
short-term median catch	0	39294	37344	41474	43681	41474	40426	41126	39725

Scenario	F=0	A*	A*+D	A	B	C	A+D	B+E	C+E
short-term median SSB	245098	170544	170092	163969	164684	163969	165455	158558	157559
short-term realized mean F	0	0.254	0.240	0.286	0.299	0.286	0.274	0.296	0.284
short-term ICV	0	0.305	0.384	0.324	0.392	0.324	0.407	0.323	0.349
short-term ITV	0	0.305	0.304	0.324	0.392	0.324	0.359	0.300	0.273
short-term risk3	0.185	0.185	0.185	0.185	0.185	0.185	0.185	0.185	0.185
short-term risk1	0.038	0.054	0.055	0.059	0.058	0.059	0.057	0.072	0.073
convergence failure		0	0	0	0	0	0	0	0
Fmax reached	0	0	0	0	0	0	0	0	0
recovery proportion	1	0.998	0.998	0.995	0.995	0.995	0.997	0.996	0.994
median recovery time	2	2	2	2	2	2	2	3	3

Table A7.5.2. Cod in Subarea 4, Division 7.d and Subdivision 20: sensitivity of performance statistics for the "optimised" six management strategies. Statistics are reported for three time periods, short-term (first five years), medium-term (years 6-10) and long-term (final 10 years). Other statistics reported include the number of replicates where the estimation model (SAM) failed to converge, the number of replicates where Fmax (Fmax =2) was reached, the proportion of replicates that recover above Bpa=MSY Btrigger and the number of years taken to recover above Bpa=MSY Btrigger for the first time. Weights are in tonnes.

Optimised scenario	Performance statistic	$F_{MSY\ lower}$	F_{trgt} * 0.9	F_{trgt}	F_{trgt} * 1.1	$F_{MSY\ upper}$
A	Ftrgt	0.198	0.342	0.38	0.418	0.46
A	Btrigger	170000	170000	170000	170000	170000
A	long-term median catch	48032	54026	54597	53922	52829
A	long-term median SSB	292228	181946	167536	156606	146779
A	long-term realized mean F	0.2	0.335	0.362	0.385	0.405
A	long-term ICV	0.088	0.142	0.171	0.202	0.238
A	long-term ITV	0.088	0.142	0.171	0.202	0.238
A	long-term risk3	0	0.018	0.036	0.07	0.117
A	long-term risk1	0	0.014	0.03	0.061	0.109
A	medium-term median catch	46276	54059	54538	53503	51873
A	medium-term median SSB	279227	182680	166656	154419	143116
A	medium-term realized mean F	0.197	0.338	0.368	0.389	0.406
A	medium-term ICV	0.091	0.137	0.164	0.193	0.229
A	medium-term ITV	0.091	0.137	0.164	0.193	0.229
A	medium-term risk3	0	0.014	0.039	0.083	0.158
A	medium-term risk1	0	0.012	0.032	0.068	0.122
A	short-term median catch	30758	40340	41474	42634	43620
A	short-term median SSB	197709	170375	163969	158050	151642
A	short-term realized mean F	0.162	0.263	0.286	0.309	0.333
A	short-term ICV	0.349	0.334	0.324	0.313	0.304
A	short-term ITV	0.349	0.334	0.324	0.313	0.304
A	short-term risk3	0.185	0.185	0.185	0.185	0.185
A	short-term risk1	0.043	0.054	0.059	0.068	0.083
A	convergence failure	0	0	0	0	0
A	Fmax reached	0	0	0	0	0
A	recovery proportion	1	0.998	0.995	0.99	0.982
A	median recovery time	2	2	2	2	3
B	Ftrgt	0.198	0.342	0.38	0.418	0.46
B	Btrigger	160000	160000	160000	160000	160000
B	long-term median catch	48052	53760	54790	55489	55832
B	long-term median SSB	292134	179994	165561	154982	146219
B	long-term realized mean F	0.2	0.339	0.37	0.397	0.426
B	long-term ICV	0.088	0.136	0.166	0.205	0.258
B	long-term ITV	0.088	0.136	0.166	0.205	0.258
B	long-term risk3	0	0.023	0.04	0.076	0.153
B	long-term risk1	0	0.018	0.036	0.069	0.118
B	medium-term median catch	46241	53785	54511	54858	53964
B	medium-term median SSB	279215	181658	165212	152679	142656
B	medium-term realized mean F	0.197	0.34	0.372	0.399	0.424
B	medium-term ICV	0.091	0.134	0.161	0.197	0.242

Optimised scenario	Performance statistic	$F_{MSY\ lower}$	F_{trgt} * 0.9	F_{trgt}	F_{trgt} * 1.1	$F_{MSY\ upper}$
B	medium-term ITV	0.091	0.134	0.161	0.197	0.242
B	medium-term risk3	0	0.016	0.043	0.092	0.176
B	medium-term risk1	0	0.015	0.037	0.075	0.128
B	short-term median catch	30930	42033	43681	45107	46000
B	short-term median SSB	197452	170700	164684	158565	152271
B	short-term realized mean F	0.163	0.271	0.299	0.326	0.353
B	short-term ICV	0.443	0.416	0.392	0.349	0.296
B	short-term ITV	0.443	0.416	0.392	0.349	0.296
B	short-term risk3	0.185	0.185	0.185	0.185	0.185
B	short-term risk1	0.044	0.054	0.058	0.069	0.083
B	convergence failure	0	0	0	0	0
B	Fmax reached	0	0	0	0	0
B	recovery proportion	1	0.998	0.995	0.993	0.987
B	median recovery time	2	2	2	3	3
C	Ftrgt	0.198	0.342	0.38	0.418	0.46
C	Btrigger	170000	170000	170000	170000	170000
C	long-term median catch	48032	54026	54597	53922	52829
C	long-term median SSB	292228	181946	167536	156606	146779
C	long-term realized mean F	0.2	0.335	0.362	0.385	0.405
C	long-term ICV	0.088	0.142	0.171	0.202	0.238
C	long-term ITV	0.088	0.142	0.171	0.202	0.238
C	long-term risk3	0	0.018	0.036	0.07	0.118
C	long-term risk1	0	0.014	0.03	0.061	0.109
C	medium-term median catch	46276	54059	54538	53503	51873
C	medium-term median SSB	279227	182680	166656	154419	143116
C	medium-term realized mean F	0.197	0.338	0.368	0.389	0.406
C	medium-term ICV	0.091	0.137	0.164	0.193	0.229
C	medium-term ITV	0.091	0.137	0.164	0.193	0.229
C	medium-term risk3	0	0.014	0.039	0.083	0.158
C	medium-term risk1	0	0.012	0.032	0.068	0.122
C	short-term median catch	30758	40340	41474	42634	43620
C	short-term median SSB	197709	170375	163969	158050	151642
C	short-term realized mean F	0.162	0.263	0.286	0.309	0.333
C	short-term ICV	0.349	0.334	0.324	0.313	0.304
C	short-term ITV	0.349	0.334	0.324	0.313	0.304
C	short-term risk3	0.185	0.185	0.185	0.185	0.185
C	short-term risk1	0.043	0.054	0.059	0.068	0.083
C	convergence failure	0	0	0	0	0
C	Fmax reached	0	0	0	0	0
C	recovery proportion	1	0.998	0.995	0.99	0.982
C	median recovery time	2	2	2	2	3
A+D	Ftrgt	0.198	0.36	0.4	0.44	0.46
A+D	Btrigger	190000	190000	190000	190000	190000
A+D	long-term median catch	47452	51934	52532	52220	51981
A+D	long-term median SSB	292209	179982	167587	157887	153503
A+D	long-term realized mean F	0.197	0.328	0.351	0.372	0.38
A+D	long-term ICV	0.338	0.257	0.26	0.272	0.281
A+D	long-term ITV	0.098	0.178	0.209	0.239	0.252
A+D	long-term risk3	0	0.016	0.038	0.067	0.079
A+D	long-term risk1	0	0.013	0.031	0.056	0.074
A+D	medium-term median catch	47930	52447	52372	51577	51110
A+D	medium-term median SSB	281574	180454	166935	155267	150220
A+D	medium-term realized mean F	0.206	0.338	0.357	0.374	0.381
A+D	medium-term ICV	0.359	0.253	0.253	0.259	0.264
A+D	medium-term ITV	0.101	0.177	0.21	0.236	0.25
A+D	medium-term risk3	0	0.014	0.044	0.085	0.114
A+D	medium-term risk1	0	0.011	0.035	0.065	0.085
A+D	short-term median catch	28958	39275	40426	41493	42102
A+D	short-term median SSB	200804	171481	165455	159819	157187
A+D	short-term realized mean F	0.145	0.252	0.274	0.295	0.306
A+D	short-term ICV	0.505	0.434	0.407	0.388	0.38
A+D	short-term ITV	0.368	0.372	0.359	0.346	0.339

Optimised scenario	Performance statistic	$F_{MSY\ lower}$	F_{trgt} * 0.9	F_{trgt}	F_{trgt} * 1.1	$F_{MSY\ upper}$
A+D	short-term risk3	0.185	0.185	0.185	0.185	0.185
A+D	short-term risk1	0.042	0.052	0.057	0.063	0.068
A+D	convergence failure	0	0	0	0	0
A+D	Fmax reached	0	0	0	0	0
A+D	recovery proportion	1	0.999	0.997	0.994	0.99
A+D	median recovery time	2	2	2	2	2
B+E	Ftrgt	0.198	0.324	0.36	0.396	0.46
B+E	Btrigger	130000	130000	130000	130000	130000
B+E	long-term median catch	47333	52094	52728	53627	55123
B+E	long-term median SSB	291653	186333	168381	155572	140349
B+E	long-term realized mean F	0.198	0.323	0.356	0.388	0.438
B+E	long-term ICV	0.342	0.326	0.329	0.349	0.425
B+E	long-term ITV	0.096	0.13	0.148	0.175	0.255
B+E	long-term risk3	0	0.025	0.046	0.116	0.194
B+E	long-term risk1	0	0.014	0.036	0.074	0.16
B+E	medium-term median catch	47433	54809	55593	56050	56172
B+E	medium-term median SSB	278066	189508	171711	157012	139159
B+E	medium-term realized mean F	0.206	0.338	0.374	0.407	0.453
B+E	medium-term ICV	0.369	0.35	0.35	0.357	0.425
B+E	medium-term ITV	0.097	0.126	0.141	0.161	0.226
B+E	medium-term risk3	0	0.013	0.04	0.089	0.229
B+E	medium-term risk1	0	0.011	0.03	0.067	0.162
B+E	short-term median catch	28467	38688	41126	43491	48572
B+E	short-term median SSB	191216	165162	158558	152767	142810
B+E	short-term realized mean F	0.158	0.264	0.296	0.328	0.379
B+E	short-term ICV	0.497	0.379	0.323	0.272	0.333
B+E	short-term ITV	0.35	0.308	0.3	0.259	0.169
B+E	short-term risk3	0.185	0.185	0.185	0.185	0.185
B+E	short-term risk1	0.046	0.062	0.072	0.088	0.123
B+E	convergence failure	0	0	0	0	0
B+E	Fmax reached	0	0	0	0	0
B+E	recovery proportion	1	0.998	0.996	0.99	0.98
B+E	median recovery time	2	2	3	3	3
C+E	Ftrgt	0.198	0.324	0.36	0.396	0.46
C+E	Btrigger	140000	140000	140000	140000	140000
C+E	long-term median catch	47340	52090	52440	52340	52332
C+E	long-term median SSB	291651	186509	168157	154060	136303
C+E	long-term realized mean F	0.197	0.321	0.353	0.38	0.422
C+E	long-term ICV	0.343	0.323	0.318	0.316	0.324
C+E	long-term ITV	0.096	0.13	0.148	0.169	0.223
C+E	long-term risk3	0	0.025	0.049	0.104	0.219
C+E	long-term risk1	0	0.014	0.036	0.076	0.175
C+E	medium-term median catch	47414	55014	55503	55283	53885
C+E	medium-term median SSB	277977	189368	171516	156598	136501
C+E	medium-term realized mean F	0.206	0.338	0.372	0.403	0.445
C+E	medium-term ICV	0.37	0.352	0.345	0.339	0.339
C+E	medium-term ITV	0.097	0.124	0.138	0.155	0.205
C+E	medium-term risk3	0	0.013	0.042	0.095	0.224
C+E	medium-term risk1	0	0.011	0.03	0.069	0.169
C+E	short-term median catch	28473	37731	39725	41585	44281
C+E	short-term median SSB	191406	164252	157559	151016	140810
C+E	short-term realized mean F	0.154	0.255	0.284	0.313	0.364
C+E	short-term ICV	0.396	0.352	0.349	0.307	0.224
C+E	short-term ITV	0.313	0.281	0.273	0.267	0.212
C+E	short-term risk3	0.185	0.185	0.185	0.185	0.185
C+E	short-term risk1	0.045	0.062	0.073	0.09	0.13
C+E	convergence failure	0	0	0	0	0
C+E	Fmax reached	0	0	0	0	0
C+E	recovery proportion	1	0.998	0.994	0.987	0.95
C+E	median recovery time	2	2	3	3	3

Annex 8: Additional Results for haddock

A8.1. Sensitivity and robustness of management strategy results

Table A8.1.1. Haddock in Subarea 4, Division 6.a and Subdivision 20: sensitivity of performance statistics for the "optimised" six management strategies to a range of F_{target} and $B_{trigger}$ scenarios. Statistics are reported for three time periods, short (first five years), medium (years 6–10) and long (final 10 years) term. Other statistics reported include the interannual variability (iav) in the catch and TAC, the proportion of replicates where the management strategy is operating "on the slope", the number of replicates where the estimation model (SAM) failed to converge, the number of replicates where F_{max} (F_{max} =2) was reached, the proportion of replicates that recover above B_{pa}=MSY $B_{trigger}$ and the number of years taken to recover above B_{pa}=MSY $B_{trigger}$ for the first time.

HCR		$F_{MSY-lower}$	$F_{MSY-upper}$	$0.9*F_{target}$	F_{target}	$1.1*F_{target}$	$1.5*B_{trigger}$	$2*B_{trigger}$
A	Ftarget	0.167	0.194	0.252	0.28	0.308	0.28	0.28
A	Btrigger	180000	180000	180000	180000	180000	270000	360000
A	risk1 long term	0.005	0.010	0.029	0.045	0.065	0.016	0.006
A	risk1 short term	0.037	0.046	0.071	0.087	0.107	0.045	0.031
A	risk1 medium term	0.012	0.016	0.039	0.056	0.079	0.020	0.011
A	risk3 long term	0.008	0.012	0.032	0.049	0.074	0.019	0.010
A	risk3 short term	0.056	0.069	0.127	0.153	0.185	0.066	0.045
A	risk3 medium term	0.021	0.025	0.050	0.061	0.086	0.026	0.016
A	Iav long term	0.208	0.222	0.256	0.275	0.296	0.310	0.323
A	Iav short term	0.370	0.374	0.258	0.213	0.218	0.419	0.449
A	Iav medium term	0.225	0.240	0.270	0.289	0.306	0.317	0.331
A	Median catch long term	42432	45573	49987	51358	51940	45634	40764
A	Median catch short term	25205	28849	36372	39799	43085	27880	21475
A	Median catch medium term	40330	43720	48841	50486	51231	44639	39647
A	Median ssb long term	283535	257030	213106	196587	183433	220068	242822
A	Median ssb short term	176689	171340	160675	155855	151362	171601	180174
A	Median ssb medium term	247880	229724	197966	185040	173163	208546	228860
A	Median Fbar long term	0.172	0.196	0.243	0.262	0.279	0.225	0.192
A	Median Fbar short term	0.148	0.170	0.216	0.238	0.258	0.174	0.136
A	Median Fbar median term	0.173	0.197	0.243	0.263	0.282	0.225	0.191
A	Iav TAC long term	0.207	0.220	0.255	0.273	0.295	0.309	0.322
A	Iav TAC short term	0.272	0.273	0.288	0.294	0.304	0.318	0.331
A	Iav TAC medium term	0.223	0.239	0.269	0.289	0.306	0.319	0.336
A	Slope long term	0.20	0.27	0.42	0.49	0.54	0.72	0.84
A	Slope short term	0.28	0.34	0.47	0.52	0.57	0.73	0.85
A	Slope medium term	0.67	0.70	0.75	0.77	0.78	0.89	0.94
A	Convergence failure	0	0	0	0	0	0	0
A	Fmax reached	0	0	0	0	1	1	1
A	Recovery proportion	1	1	1	1	1	1	1
A	Recovery time	1	1	1	1	1	1	1
B	Ftarget	0.167	0.194	0.261	0.29	0.319		
B	Btrigger	190000	190000	190000	190000	190000		
B	risk1 long term	0.019	0.024	0.043	0.024	0.014		
B	risk1 short term	0.006	0.010	0.029	0.017	0.007		
B	risk1 medium term	0.053	0.059	0.075	0.045	0.031		
B	risk3 long term	0.013	0.017	0.039	0.019	0.011		
B	risk3 short term	0.008	0.012	0.033	0.021	0.010		
B	risk3 medium term	0.086	0.098	0.138	0.066	0.045		
B	Iav long term	0.021	0.028	0.050	0.025	0.016		
B	Iav short term	0.352	0.345	0.342	0.341	0.335		
B	Iav medium term	0.336	0.316	0.257	0.421	0.456		
B	Median catch long term	0.332	0.329	0.333	0.343	0.343		
B	Median catch short term	41460	44310	48354	45400	40860		
B	Median catch medium term	27912	31241	37375	27880	21475		
B	Median ssb long term	38628	41440	46001	44674	39647		
B	Median ssb short term	282300	256938	212999	219849	242819		
B	Median ssb medium term	170045	167092	159693	171601	180212		
B	Median Fbar long term	244023	226940	196621	207976	228359		

HCR		$F_{MSY-lower}$	$F_{MSY-upper}$	0.9*F_{target}	F_{target}	1.1*F_{target}	1.5*$B_{trigger}$	2*$B_{trigger}$
B	Median Fbar short term	0.170	0.194	0.238	0.221	0.191		
B	Median Fbar median term	0.156	0.176	0.217	0.174	0.136		
B	Iav TAC long term	0.167	0.190	0.235	0.222	0.190		
B	Iav TAC short term	0.207	0.219	0.255	0.309	0.321		
B	Iav TAC medium term	0.346	0.325	0.297	0.318	0.332		
B	Slope long term	0.226	0.240	0.275	0.325	0.338		
B	Slope short term	0.20	0.27	0.42	0.72	0.84		
B	Slope medium term	0.28	0.34	0.47	0.73	0.85		
B	Convergence failure	0.71	0.72	0.75	0.89	0.94		
B	Fmax reached	1	1	1	1	1		
B	Recovery proportion	1	1	1	1	1		
B	Recovery time	0	0	0	0	0		
C	Ftarget	0.167	0.194	0.252	0.28	0.308		
C	Btrigger	180000	180000	180000	180000	180000		
C	risk1 long term	0.015	0.020	0.042	0.058	0.079		
C	risk1 short term	0.005	0.010	0.029	0.045	0.065		
C	risk1 medium term	0.037	0.046	0.071	0.087	0.107		
C	risk3 long term	0.012	0.016	0.039	0.056	0.079		
C	risk3 short term	0.008	0.012	0.032	0.049	0.074		
C	risk3 medium term	0.056	0.069	0.127	0.153	0.185		
C	Iav long term	0.021	0.025	0.050	0.061	0.086		
C	Iav short term	0.208	0.222	0.256	0.275	0.296		
C	Iav medium term	0.370	0.374	0.258	0.213	0.218		
C	Median catch long term	0.225	0.240	0.270	0.289	0.306		
C	Median catch short term	42432	45573	49987	51350	51931		
C	Median catch medium term	25205	28849	36372	39799	43085		
C	Median ssb long term	40330	43720	48841	50486	51231		
C	Median ssb short term	283535	257030	213106	196587	183433		
C	Median ssb medium term	176689	171340	160675	155855	151362		
C	Median Fbar long term	247880	229724	197966	185040	173163		
C	Median Fbar short term	0.172	0.196	0.243	0.262	0.279		
C	Median Fbar median term	0.148	0.170	0.216	0.238	0.258		
C	Iav TAC long term	0.173	0.197	0.243	0.263	0.282		
C	Iav TAC short term	0.207	0.220	0.255	0.273	0.295		
C	Iav TAC medium term	0.272	0.273	0.288	0.294	0.304		
C	Slope long term	0.224	0.239	0.269	0.289	0.306		
C	Slope short term	0.20	0.27	0.42	0.49	0.54		
C	Slope medium term	0.28	0.34	0.47	0.52	0.57		
C	Convergence failure	0.67	0.70	0.75	0.77	0.78		
C	Fmax reached	1	1	1	1	1		
C	Recovery proportion	1	1	1	1	1		
C	Recovery time	0	0	0	0	0		
A+D	Ftarget	0.167	0.194	0.252	0.28	0.308	0.28	0.28
A+D	Btrigger	180000	180000	180000	180000	180000	270000	360000
A+D	risk1 long term	0.019	0.024	0.043	0.058	0.079	0.024	0.014
A+D	risk1 short term	0.006	0.010	0.029	0.045	0.066	0.017	0.007
A+D	risk1 medium term	0.053	0.059	0.075	0.087	0.107	0.045	0.031
A+D	risk3 long term	0.013	0.017	0.039	0.055	0.079	0.019	0.011
A+D	risk3 short term	0.008	0.012	0.033	0.050	0.075	0.021	0.010
A+D	risk3 medium term	0.086	0.098	0.138	0.151	0.182	0.066	0.045
A+D	Iav long term	0.021	0.028	0.050	0.062	0.084	0.025	0.016
A+D	Iav short term	0.352	0.345	0.342	0.347	0.356	0.341	0.335
A+D	Iav medium term	0.336	0.316	0.257	0.232	0.235	0.421	0.456
A+D	Median catch long term	0.332	0.329	0.333	0.342	0.357	0.343	0.343
A+D	Median catch short term	41460	44310	48354	49628	50277	45400	40860
A+D	Median catch medium term	27912	31241	37375	39715	42983	27880	21475
A+D	Median ssb long term	38628	41440	46001	47690	48754	44674	39647
A+D	Median ssb short term	282300	256938	212999	196781	183455	219849	242819
A+D	Median ssb medium term	170045	167092	159693	156038	151374	171601	180212
A+D	Median Fbar long term	244023	226940	196621	184419	172462	207976	228359
A+D	Median Fbar short term	0.170	0.194	0.238	0.256	0.273	0.221	0.191
A+D	Median Fbar median term	0.156	0.176	0.217	0.236	0.256	0.174	0.136
A+D	Iav TAC long term	0.167	0.190	0.235	0.254	0.271	0.222	0.190

HCR		$F_{MSY-lower}$	$F_{MSY-upper}$	0.9*F_{target}	F_{target}	1.1*F_{target}	1.5*$B_{trigger}$	2*$B_{trigger}$
A+D	Iav TAC short term	0.207	0.219	0.255	0.275	0.298	0.309	0.321
A+D	Iav TAC medium term	0.346	0.325	0.297	0.296	0.304	0.318	0.332
A+D	Slope long term	0.226	0.240	0.275	0.291	0.313	0.325	0.338
A+D	Slope short term	0.20	0.27	0.42	0.48	0.54	0.72	0.84
A+D	Slope medium term	0.28	0.34	0.47	0.52	0.57	0.73	0.85
A+D	Convergence failure	0.71	0.72	0.75	0.77	0.78	0.89	0.94
A+D	Fmax reached	1	1	1	1	1	1	1
A+D	Recovery proportion	1	1	1	1	1	1	1
A+D	Recovery time	0	0	0	0	0	0	0
B+E	Ftarget	0.167	0.194	0.243	0.27	0.297		
B+E	Btrigger	170000	170000	170000	170000	170000		
B+E	risk1 long term	0.023	0.028	0.042	0.057	0.075		
B+E	risk1 short term	0.006	0.011	0.027	0.042	0.059		
B+E	risk1 medium term	0.064	0.069	0.078	0.091	0.106		
B+E	risk3 long term	0.014	0.019	0.036	0.052	0.076		
B+E	risk3 short term	0.010	0.015	0.030	0.049	0.071		
B+E	risk3 medium term	0.114	0.114	0.130	0.147	0.168		
B+E	Iav long term	0.023	0.031	0.051	0.060	0.090		
B+E	Iav short term	0.374	0.374	0.385	0.393	0.409		
B+E	Iav medium term	0.430	0.400	0.362	0.348	0.352		
B+E	Median catch long term	0.364	0.370	0.385	0.400	0.414		
B+E	Median catch short term	41598	44580	48382	49831	50577		
B+E	Median catch medium term	30561	34290	40439	42829	44876		
B+E	Median ssb long term	38407	41670	45466	46946	48062		
B+E	Median ssb short term	280600	255015	216624	200267	186847		
B+E	Median ssb medium term	168198	165606	159718	156338	151444		
B+E	Median Fbar long term	241525	223754	198538	185816	174896		
B+E	Median Fbar short term	0.172	0.196	0.236	0.256	0.273		
B+E	Median Fbar median term	0.158	0.181	0.217	0.237	0.256		
B+E	Iav TAC long term	0.167	0.191	0.228	0.248	0.265		
B+E	Iav TAC short term	0.206	0.219	0.253	0.274	0.302		
B+E	Iav TAC medium term	0.386	0.350	0.309	0.307	0.319		
B+E	Slope long term	0.229	0.242	0.275	0.295	0.318		
B+E	Slope short term	0.16	0.23	0.36	0.42	0.48		
B+E	Slope medium term	0.24	0.30	0.40	0.46	0.51		
B+E	Convergence failure	0.65	0.66	0.69	0.70	0.72		
B+E	Fmax reached	1	1	1	1	1		
B+E	Recovery proportion	1	1	1	1	1		
B+E	Recovery time	0	0	0	0	0		
C+E	Ftarget	0.167	0.194	0.234	0.26	0.286		
C+E	Btrigger	160000	160000	160000	160000	160000		
C+E	risk1 long term	0.024	0.030	0.044	0.059	0.079		
C+E	risk1 short term	0.007	0.013	0.027	0.044	0.063		
C+E	risk1 medium term	0.066	0.072	0.083	0.090	0.109		
C+E	risk3 long term	0.017	0.022	0.039	0.056	0.080		
C+E	risk3 short term	0.011	0.017	0.031	0.050	0.080		
C+E	risk3 medium term	0.114	0.114	0.134	0.143	0.166		
C+E	Iav long term	0.028	0.036	0.054	0.070	0.099		
C+E	Iav short term	0.373	0.372	0.375	0.378	0.382		
C+E	Iav medium term	0.413	0.383	0.349	0.329	0.322		
C+E	Median catch long term	0.362	0.362	0.367	0.374	0.385		
C+E	Median catch short term	41528	44620	47921	49398	50468		
C+E	Median catch medium term	31131	34809	40094	42961	44835		
C+E	Median ssb long term	38320	41456	44880	46427	47628		
C+E	Median ssb short term	279911	253574	220928	203534	188684		
C+E	Median ssb medium term	167376	164321	159193	156057	151320		
C+E	Median Fbar long term	239878	221410	200369	187096	175336		
C+E	Median Fbar short term	0.172	0.198	0.232	0.251	0.269		
C+E	Median Fbar median term	0.162	0.186	0.217	0.236	0.258		
C+E	Iav TAC long term	0.168	0.192	0.224	0.243	0.261		
C+E	Iav TAC short term	0.204	0.214	0.237	0.253	0.271		
C+E	Iav TAC medium term	0.356	0.316	0.283	0.278	0.289		
C+E	Slope long term	0.224	0.236	0.257	0.274	0.288		

HCR		$F_{MSY-lower}$	$F_{MSY-upper}$	$0.9*F_{target}$	F_{target}	$1.1*F_{target}$	$1.5*B_{trigger}$	$2*B_{trigger}$
C+E	**Slope short term**	0.14	0.20	0.30	0.37	0.43		
C+E	**Slope medium term**	0.21	0.26	0.35	0.40	0.46		
C+E	**Convergence failure**	0.42	0.43	0.46	0.47	0.49		
C+E	**Fmax reached**	1	1	1	1	1		
C+E	**Recovery proportion**	1	1	1	1	1		
C+E	**Recovery time**	0	0	0	0	0		

Table A8.1.2. Haddock in Subarea 4, Division 6.a and Subdivision 20: Performance statistics for the various management strategies with alternate operating models. The operating models are OM1 (Baseline), OM2 (Alt1) and OM3 (Alt2) and are described in Sections 4.1–4.2.

OM	Baseline (OM1)								Alt1 (OM2)								Alt2 (OM3)							
Scenario	F0	A*	A	B	C	AD	BE	CE	F0	A*	A	B	C	AD	BE	CE	F0	A*	A	B	C	AD	BE	CE
Ftarget	0	0.194	0.28	0.29	0.28	0.28	0.27	0.26	0	0.194	0.28	0.29	0.28	0.28	0.27	0.26	0	0.194	0.28	0.29	0.28	0.28	0.27	0.26
Btrigger	-	132000	180000	190000	180000	180000	170000	160000	-	132000	180000	190000	180000	180000	170000	160000	-	132000	180000	190000	180000	180000	170000	160000
risk1 long term	0.000	0.016	0.045	0.044	0.045	0.045	0.042	0.044	0.000	0.012	0.032	0.032	0.027	0.028	0.032	0.032	0.000	0.023	0.026	0.023	0.025	0.021	0.020	0.023
risk1 short term	0.012	0.056	0.087	0.082	0.087	0.087	0.091	0.092	0.000	0.011	0.028	0.029	0.023	0.026	0.029	0.028	0.011	0.077	0.072	0.077	0.076	0.081	0.081	0.077
risk1 medium term	0.000	0.027	0.056	0.053	0.056	0.055	0.052	0.056	0.000	0.022	0.027	0.027	0.026	0.025	0.026	0.027	0.000	0.035	0.035	0.035	0.038	0.032	0.032	0.035
risk3 long term	0.000	0.019	0.049	0.048	0.049	0.050	0.049	0.050	0.001	0.017	0.043	0.044	0.035	0.037	0.043	0.044	0.000	0.033	0.034	0.033	0.035	0.033	0.029	0.033
risk3 short term	0.033	0.090	0.153	0.148	0.153	0.151	0.147	0.143	0.000	0.022	0.040	0.043	0.035	0.037	0.043	0.039	0.033	0.143	0.139	0.143	0.142	0.141	0.137	0.143
risk3 medium term	0.001	0.041	0.061	0.055	0.061	0.062	0.060	0.070	0.000	0.029	0.045	0.047	0.040	0.040	0.047	0.045	0.001	0.060	0.055	0.060	0.064	0.061	0.066	0.060
Iav catch long term	-	0.207	0.275	0.296	0.275	0.347	0.393	0.378	-	0.228	0.048	0.057	0.049	0.045	0.058	0.049	-	0.276	0.294	0.276	0.354	0.384	0.376	0.276
Iav catch short term	-	0.300	0.213	0.225	0.213	0.232	0.348	0.329	-	0.321	0.318	0.417	0.439	0.352	0.406	0.317	-	0.206	0.217	0.206	0.234	0.347	0.330	0.206
Iav catch medium term	-	0.221	0.289	0.310	0.289	0.342	0.400	0.374	-	0.248	0.216	0.273	0.291	0.234	0.278	0.218	-	0.289	0.309	0.289	0.375	0.410	0.395	0.289
Median catch long term	0	45296	51358	51574	51350	49628	49831	49398	0	49121	0.328	0.424	0.450	0.361	0.412	0.329	0	61102	61861	61102	59583	59683	58781	61102
Median catch short term	0	30699	39799	39181	39799	39715	42829	42961	0	31536	53866	51733	52647	53934	52328	53945	0	40256	39627	40256	40195	44627	43655	40256
Median catch medium term	0	43300	50486	50969	50486	47690	46946	46427	0	50066	40693	37032	37494	40042	36527	40663	0	57821	58565	57821	54875	54552	53559	57821
Median ssb long term	578988	252152	196587	194672	196587	196781	200267	203534	618791	271438	212799	212860	218274	210487	220464	212625	649283	222951	219772	222951	223225	227141	231818	222951
Median ssb short term	213913	167527	155855	156911	155855	156038	156338	156057	221786	177686	167494	167462	167597	168354	167672	167495	220984	163099	164056	163099	163663	163366	163486	163099
Median ssb medium term	427970	222095	185040	183986	185040	184419	185816	187096	478222	246554	201708	203480	207469	201938	208345	202117	468220	201472	199337	201425	200533	203450	206123	201472
Median Fbar long term	0	0.203	0.262	0.265	0.262	0.256	0.256	0.251	0	0.184	0.228	0.223	0.223	0.231	0.219	0.228	0	0.275	0.279	0.275	0.269	0.266	0.260	0.275
Median Fbar short term	0	0.189	0.238	0.236	0.238	0.236	0.237	0.236	0	0.181	0.226	0.218	0.219	0.225	0.217	0.226	0	0.244	0.244	0.244	0.242	0.242	0.239	0.244
Median Fbar median term	0	0.205	0.263	0.268	0.263	0.254	0.248	0.243	0	0.189	0.234	0.236	0.236	0.238	0.232	0.233	0	0.275	0.281	0.275	0.265	0.260	0.254	0.275
Iav TAC long term	-	0.207	0.273	0.295	0.273	0.275	0.274	0.253	-	0.225	0.318	0.325	0.333	0.351	0.300	0.316	-	0.274	0.294	0.274	0.275	0.267	0.251	0.274
Iav TAC short term	-	0.225	0.294	0.316	0.294	0.296	0.307	0.278	-	0.240	0.298	0.304	0.313	0.321	0.283	0.299	-	0.292	0.312	0.292	0.293	0.305	0.276	0.292
Iav TAC medium term	-	0.221	0.289	0.310	0.289	0.291	0.295	0.274	-	0.249	0.328	0.336	0.340	0.361	0.310	0.327	-	0.282	0.304	0.282	0.278	0.276	0.258	0.282
Slope long term	-	0.11	0.26	0.26	0.26	0.26	0.26	0.25	-	0.20	0.55	0.55	0.50	0.58	0.46	0.55	-	0.37	0.43	0.37	0.37	0.31	0.24	0.37
Slope short term	-	0.15	0.24	0.24	0.24	0.24	0.24	0.24	-	0.24	0.55	0.55	0.50	0.58	0.46	0.55	-	0.44	0.48	0.44	0.43	0.36	0.30	0.44
Slope medium term	-	0.22	0.26	0.27	0.26	0.25	0.25	0.24	-	0.27	0.78	0.78	0.63	0.81	0.49	0.78	-	0.70	0.74	0.70	0.70	0.64	0.42	0.70
Convergence failure	-	0	0	0	0	0	0	0	-	2	8	6	5	4	5	6	-	0	0	0	0	0	0	0
Fmax reached	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Recovery proportion	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Recovery time	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

A8.2. Summary projections for alternative OM2 (Alt1)

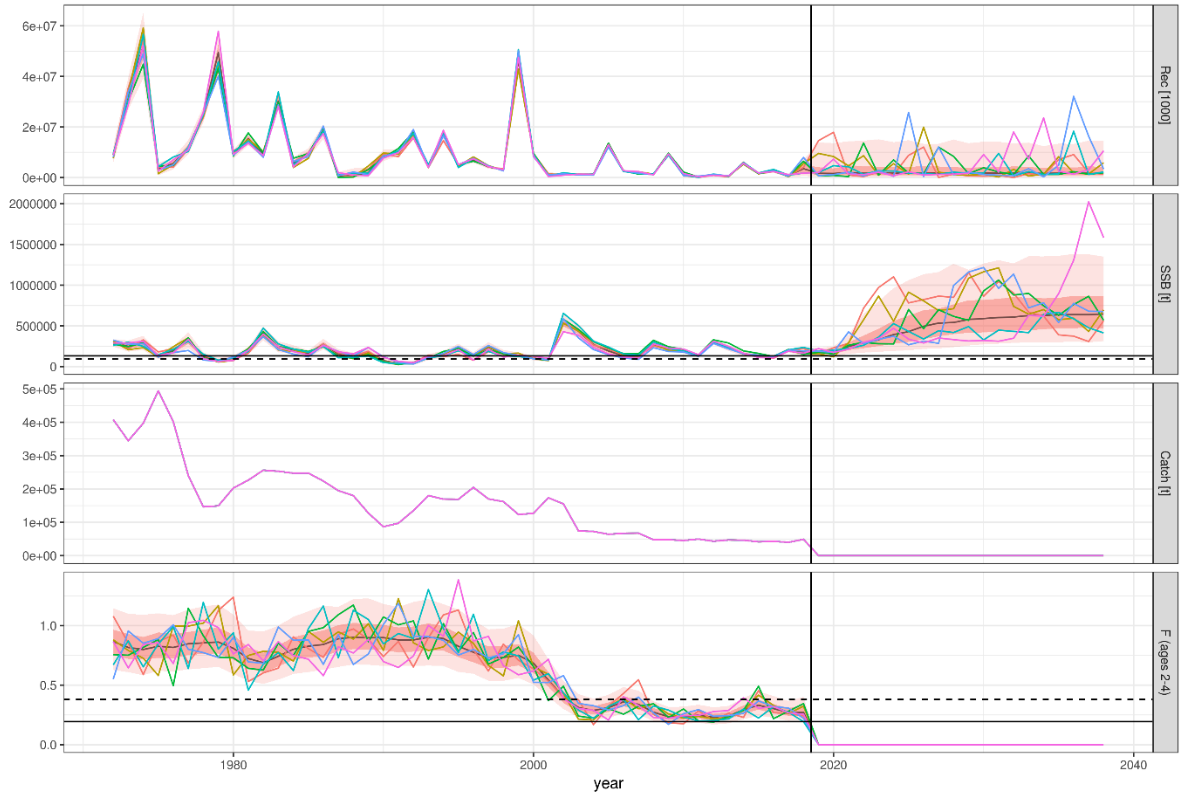

Figure A8.2.1. Haddock in Subarea 4, Division 6.a and Subdivision 20: Summary projections for F0 (i.e. F=0) for OM2 (Alt1). Top plot is recruitment (age 0), second plot SSB, third plot catch and bottom plot mean F (ages 2-4). The vertical black line separates the historic period from the projection period. The SSB plot includes B_{pa}=MSY $B_{trigger}$ (horizontal solid line) and B_{lim} (horizontal hashed line), while the mean F plot includes F_{msy} (horizontal solid line) and F_{lim} (horizontal dashed line). The actual plots show medians (solid black line) with the darker shaded area indicating the 25^th^ and 75^th^ percentiles, and the light shaded area the 5^th^ and 95^th^ percentiles. The results for 5 individual replicates are shown in solid coloured lines.

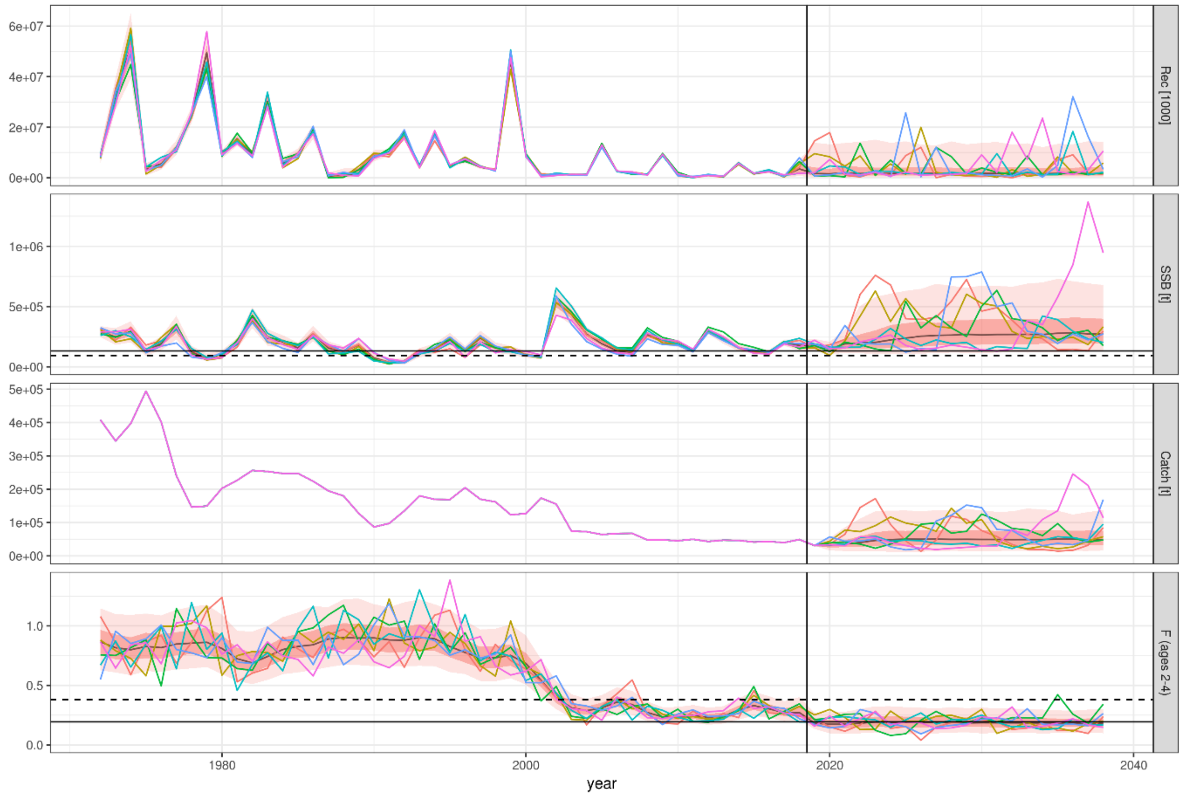

Figure A8.2.2. Haddock in Subarea 4, Division 6.a and Subdivision 20: Summary projections for <u>management strategy A*</u> (i.e. with F_{target}=F_{msy}=0.194 and $B_{trigger}$=MSY $B_{trigger}$=132000 t) for OM2 (Alt1). See the caption to Figure A8.2.1 for further details.

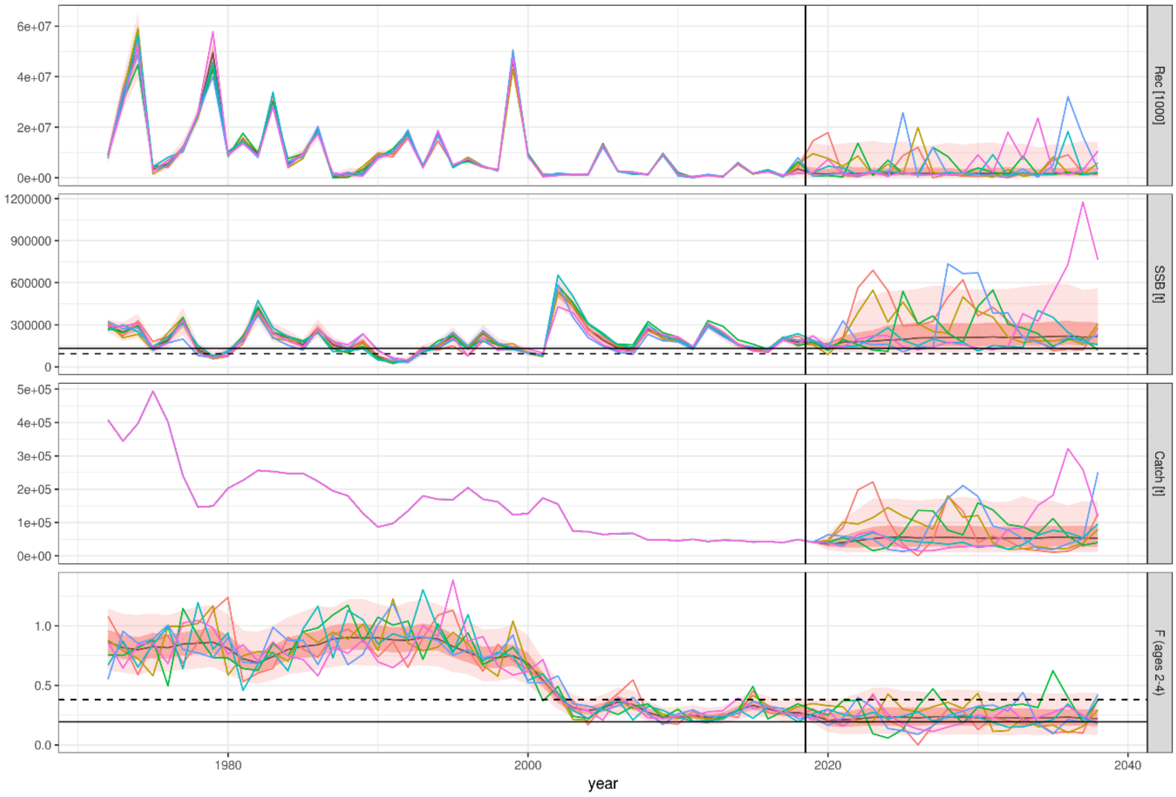

Figure A8.2.3. Haddock in Subarea 4, Division 6.a and Subdivision 20: Summary projections for <u>management strategy A</u> for OM2 (Alt1). See the caption to Figure A8.2.1 for further details.

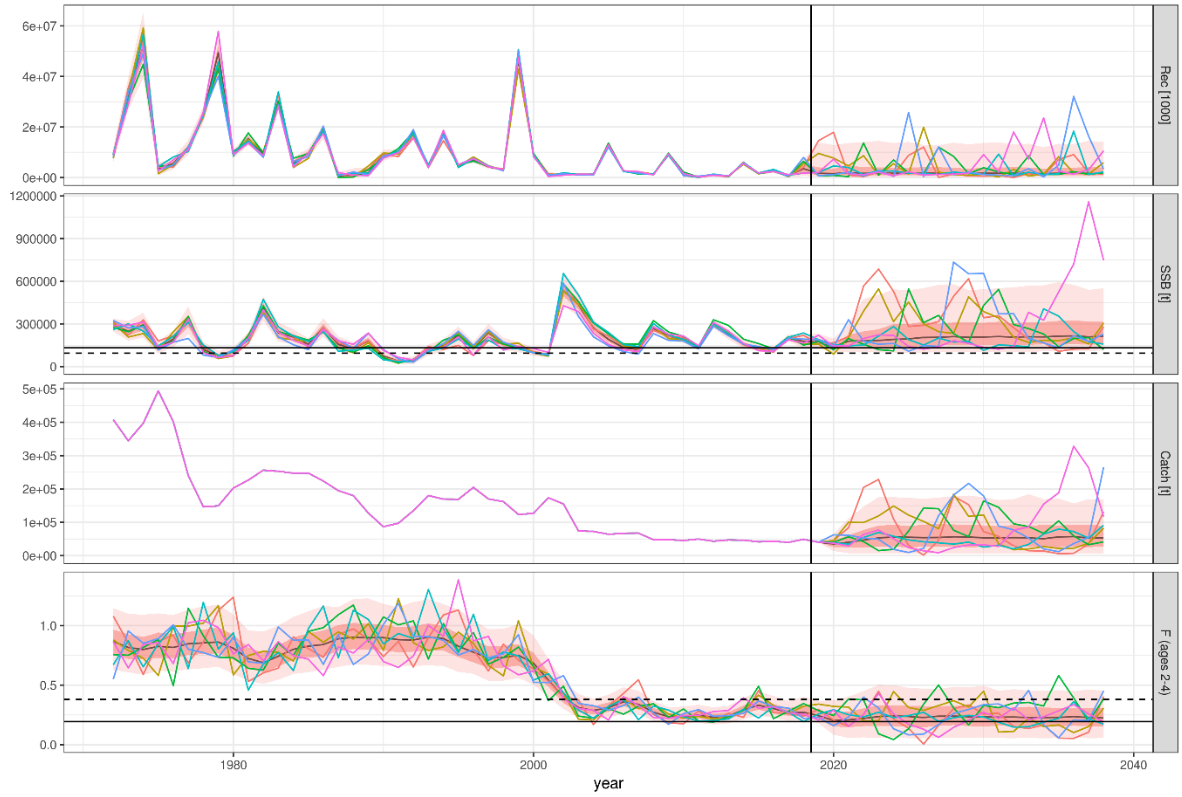

Figure A8.2.4. Haddock in Subarea 4, Division 6.a and Subdivision 20: Summary projections for "optimised" management strategy B for OM2 (Alt1). See the caption to Figure A8.2.1 for further details.

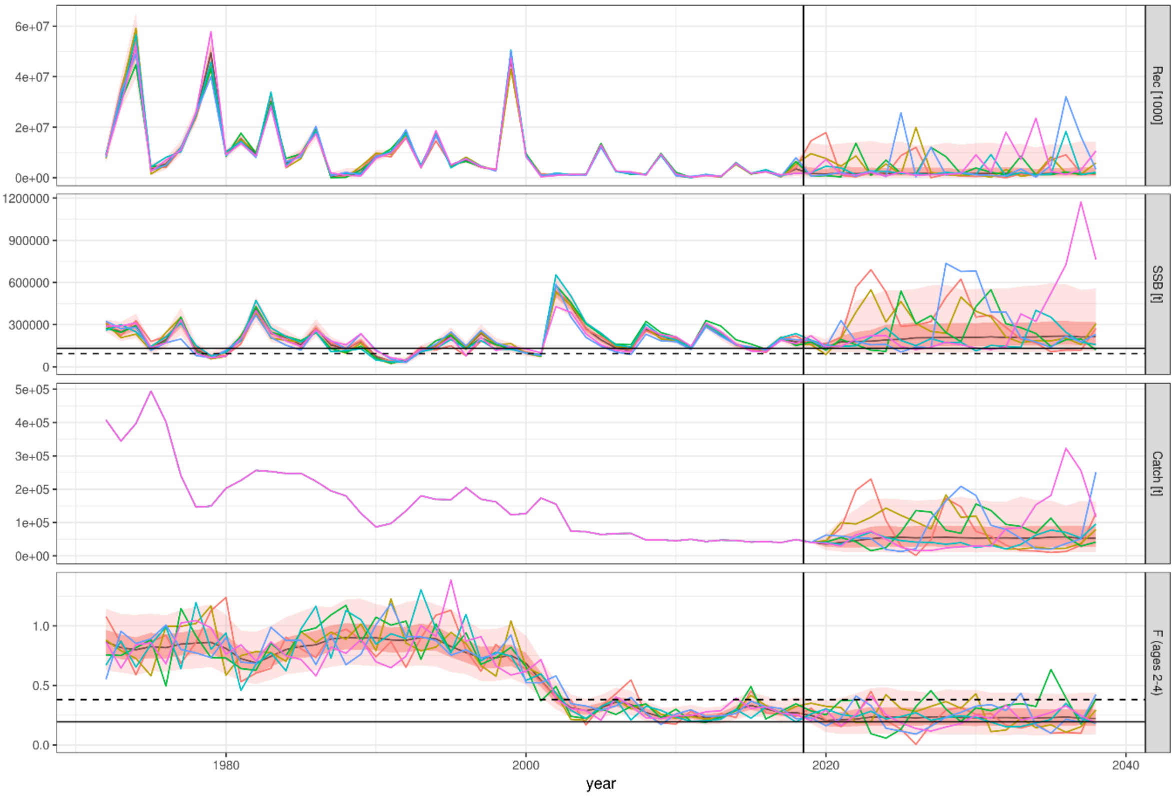

Figure A8.2.5. Haddock in Subarea 4, Division 6.a and Subdivision 20: Summary projections for "optimised" <u>management strategy C</u> for OM2 (Alt1). See the caption to Figure A8.2.1 for further details.

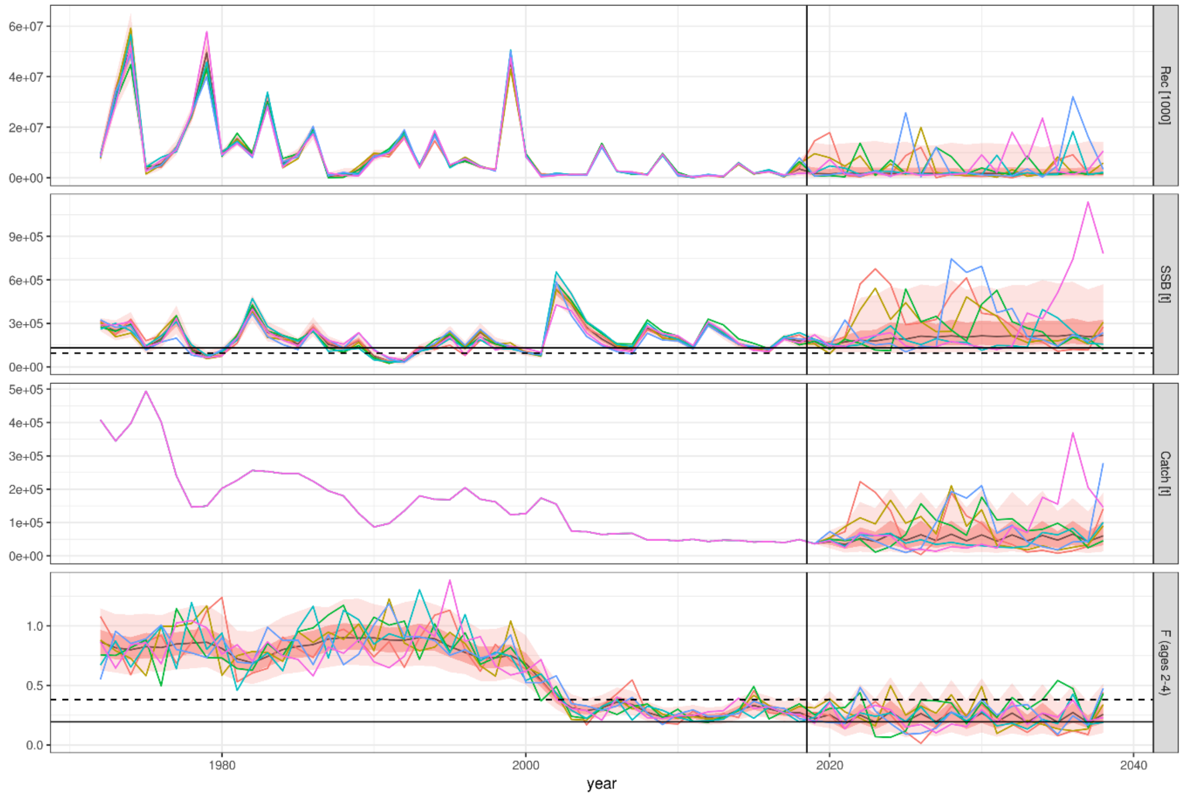

Figure A8.2.6. Haddock in Subarea 4, Division 6.a and Subdivision 20: Summary projections for "optimised" management strategy A+D for OM2 (Alt1). See the caption to Figure A8.2.1 for further details.

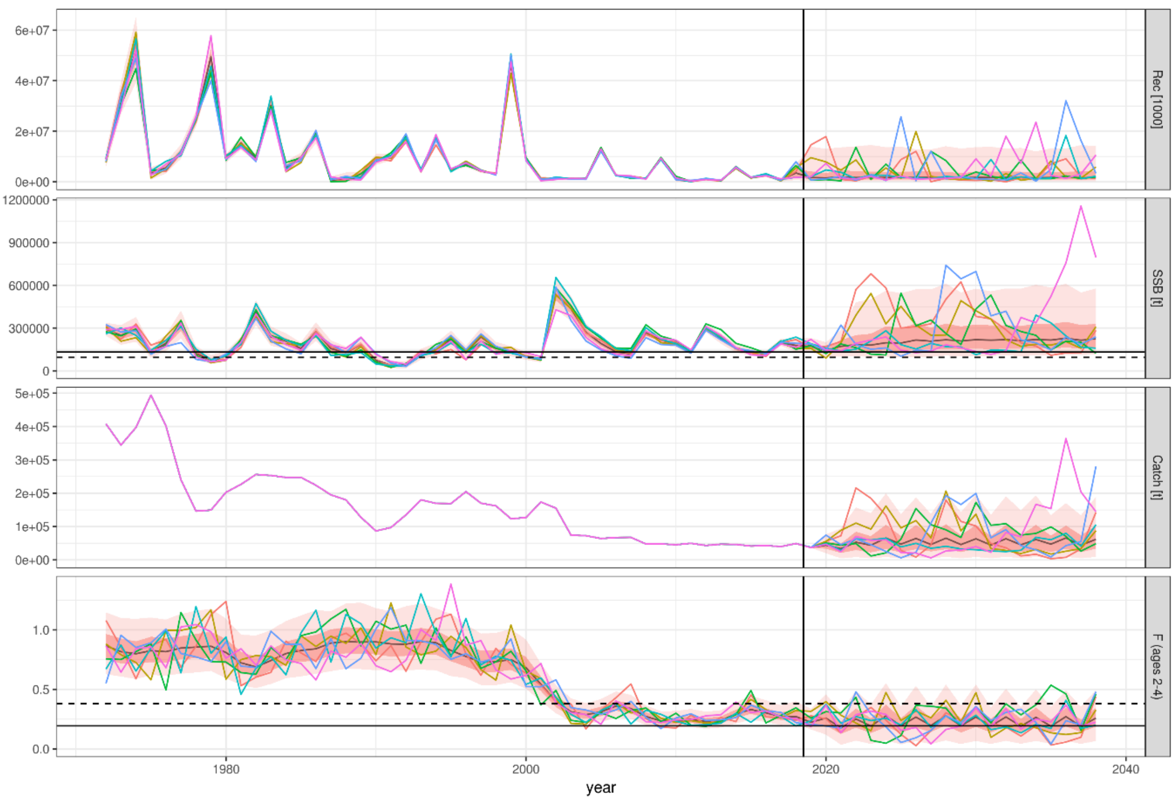

Figure A8.2.7. Haddock in Subarea 4, Division 6.a and Subdivision 20: Summary projections for "optimised" management strategy B+E for OM2 (Alt1). See the caption to Figure A8.2.1 for further details.

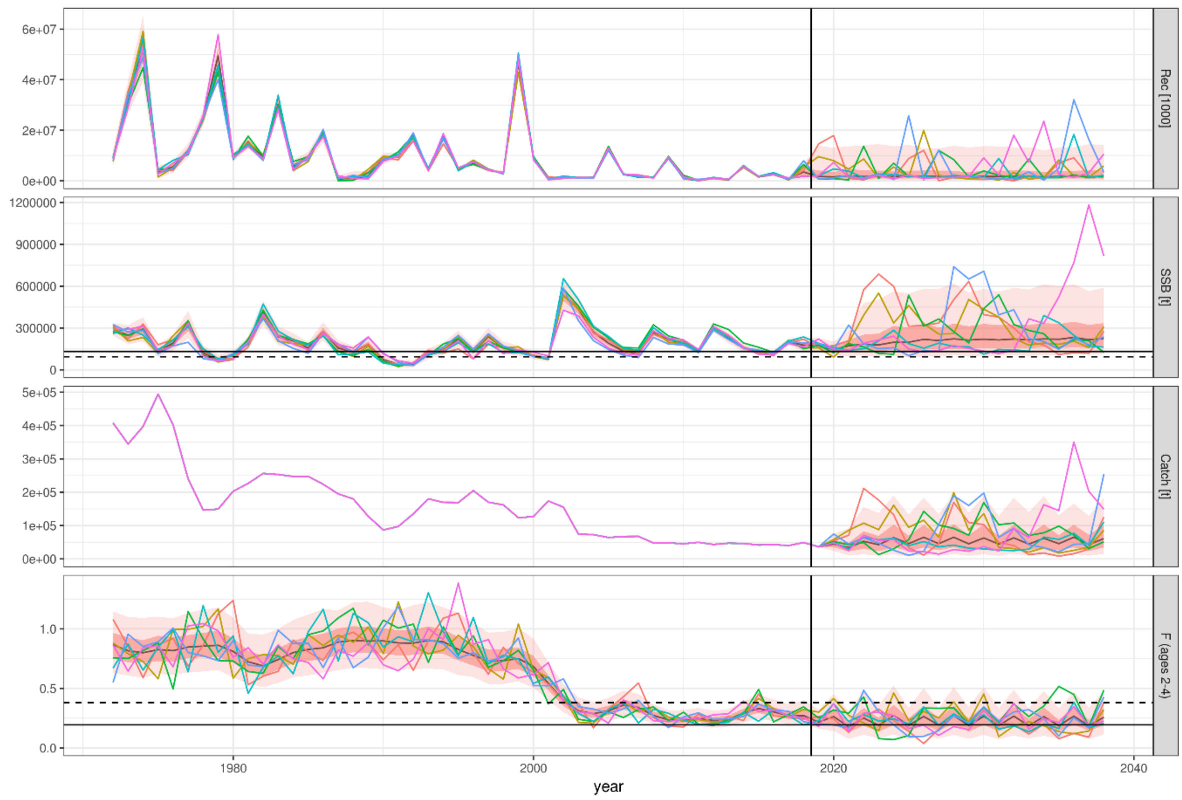

Figure A8.2.8. Haddock in Subarea 4, Division 6.a and Subdivision 20: Summary projections for "optimised" management strategy C+E for OM2 (Alt1). See the caption to Figure A8.2.1 for further details.

A8.3. Summary projections for alternative OM3 (Alt2)

Figure A8.3.1. Haddock in Subarea 4, Division 6.a and Subdivision 20: Summary projections for F0 (i.e. F=0) for OM3 (Alt2). Top plot is recruitment (age 0), second plot SSB, third plot catch and bottom plot mean F (ages 2-4). The vertical black line separates the historic period from the projection period. The SSB plot includes B_{pa}=MSY $B_{trigger}$ (horizontal solid line) and B_{lim} (horizontal hashed line), while the mean F plot includes F_{msy} (horizontal solid line) and F_{lim} (horizontal dashed line). The actual plots show medians (solid black line) with the darker shaded area indicating the 25th and 75th percentiles, and the light shaded area the 5th and 95th percentiles. The results for 5 individual replicates are shown in solid coloured lines.

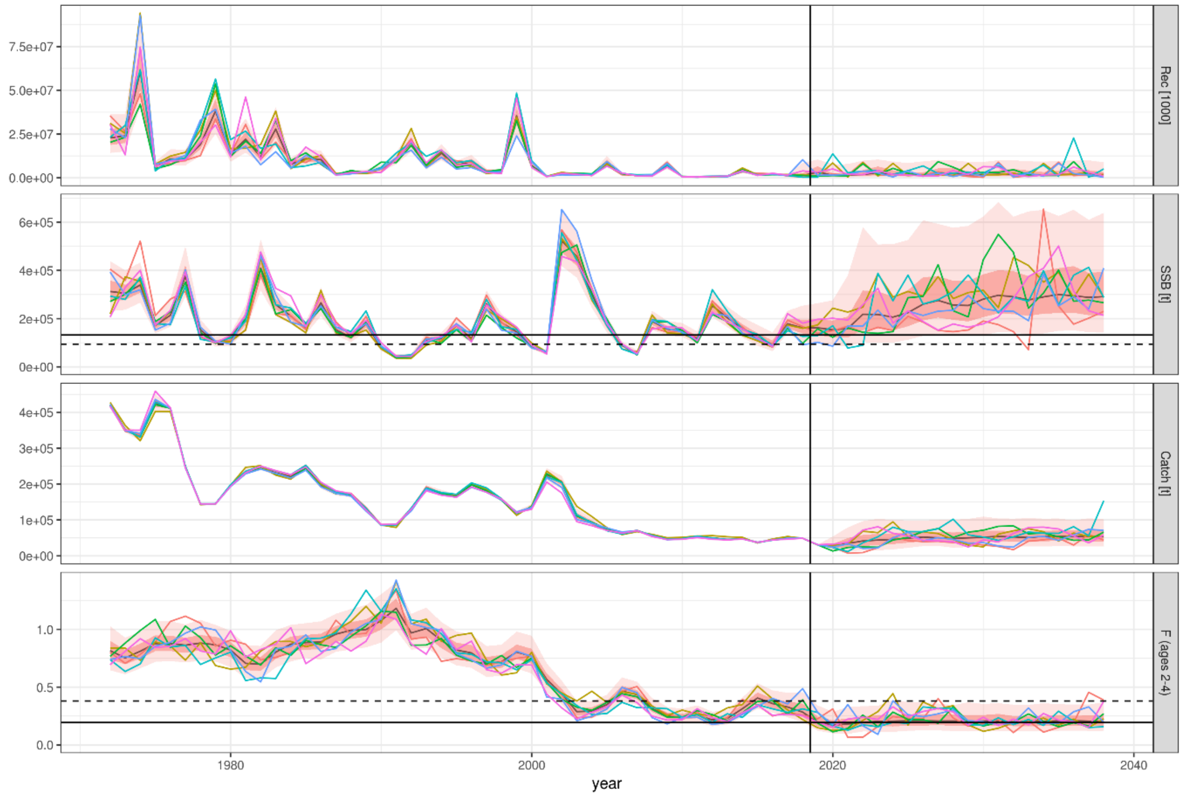

Figure A8.3.2. Haddock in Subarea 4, Division 6.a and Subdivision 20: Summary projections for management strategy A* (i.e. with F_{target}=F_{msy}=0.194 and $B_{trigger}$=MSY $B_{trigger}$=132000 t) for OM3 (Alt2). See the caption to Figure A8.3.1 for further details.

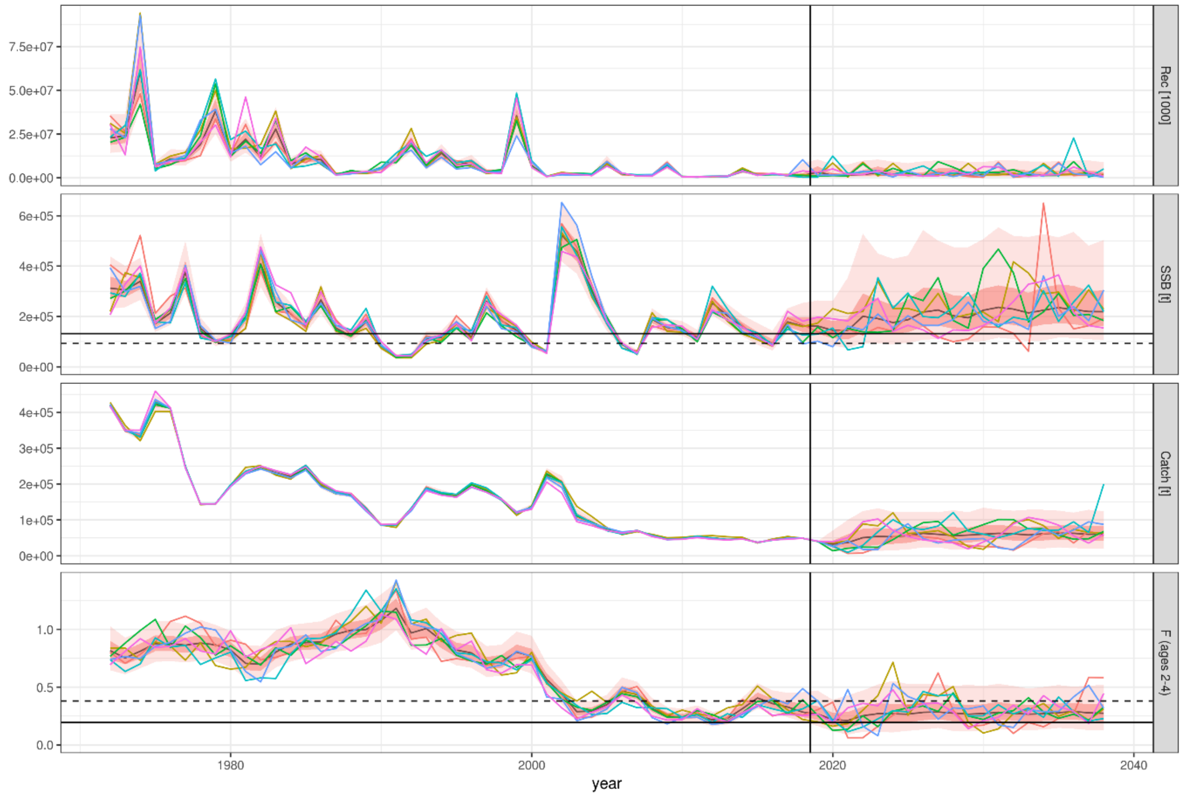

Figure A8.3.3. Haddock in Subarea 4, Division 6.a and Subdivision 20: Summary projections for <u>management strategy A</u> for OM3 (Alt2). See the caption to Figure A8.3.1 for further details.

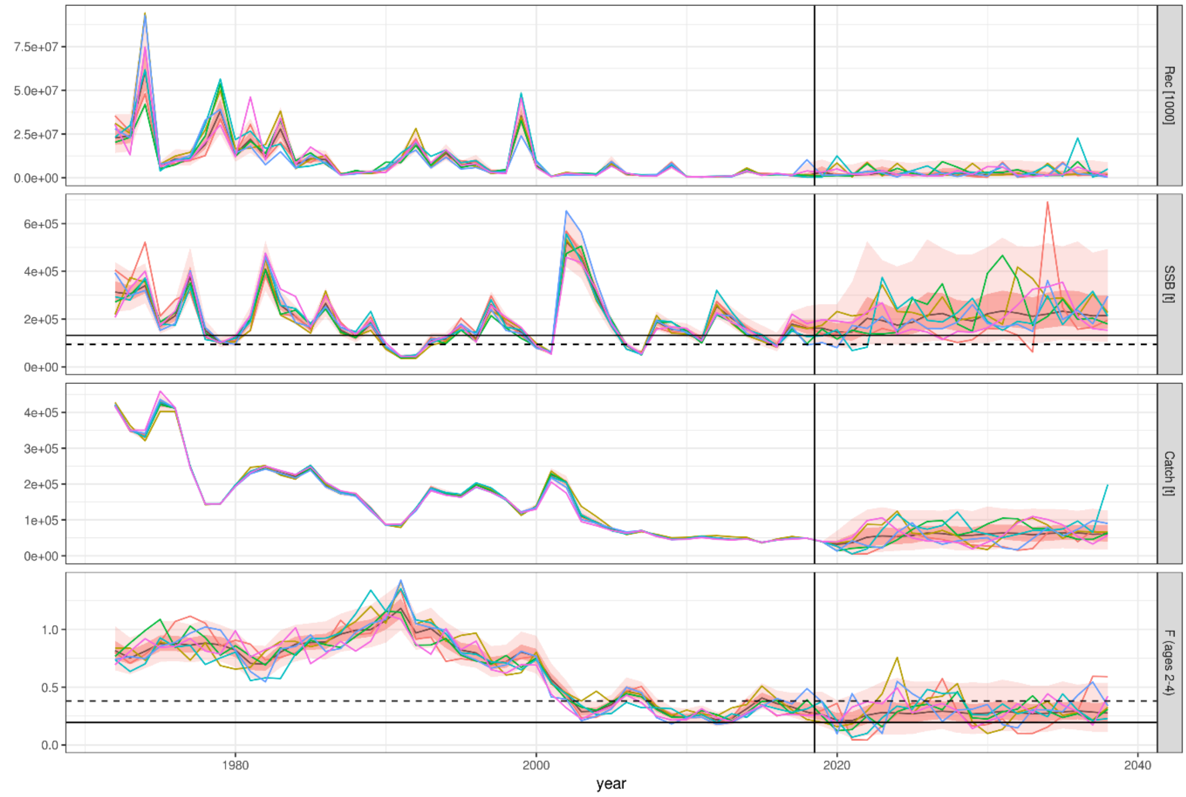

Figure A8.3.4. Haddock in Subarea 4, Division 6.a and Subdivision 20: Summary projections for "optimised" <u>management strategy B</u> for OM3 (Alt2). See the caption to Figure A8.3.1 for further details.

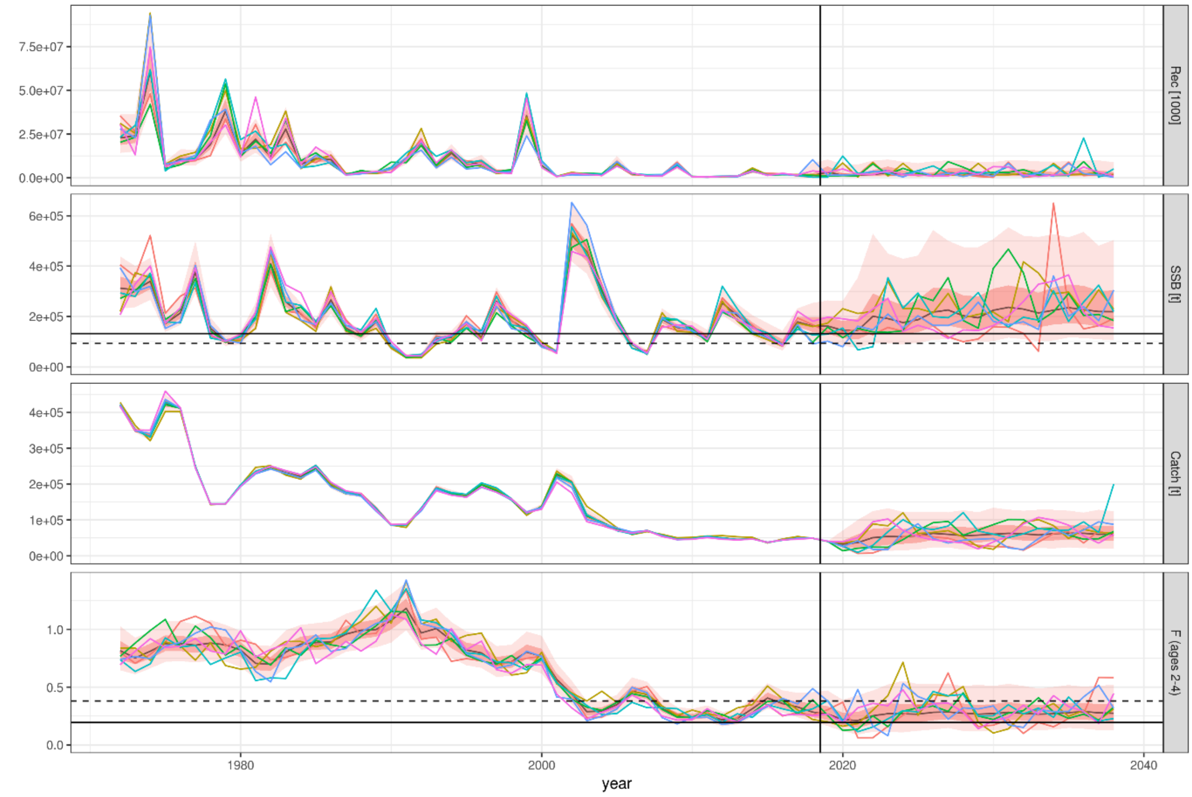

Figure A8.3.5. Haddock in Subarea 4, Division 6.a and Subdivision 20: Summary projections for "optimised" management strategy C for OM3 (Alt2). See the caption to Figure A8.3.1 for further details.

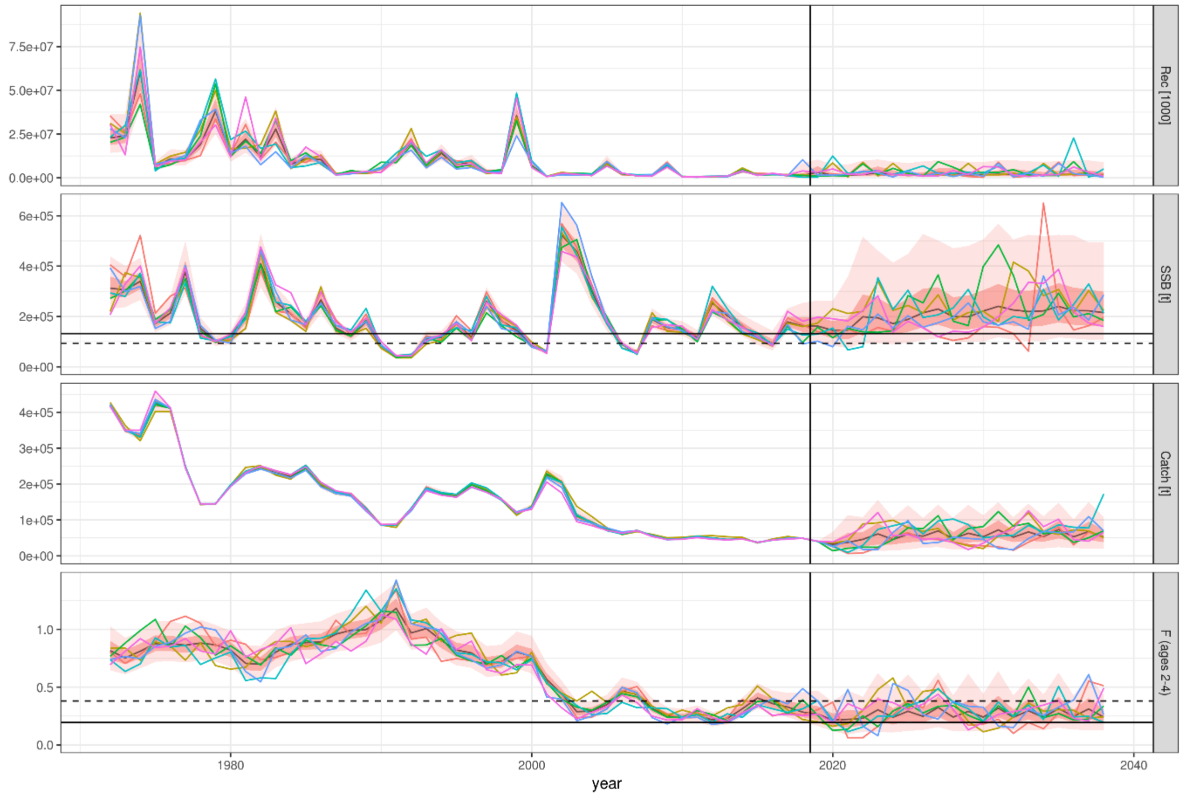

Figure A8.3.6. Haddock in Subarea 4, Division 6.a and Subdivision 20: Summary projections for "optimised" management strategy A+D for OM3 (Alt2). See the caption to Figure A8.3.1 for further details.

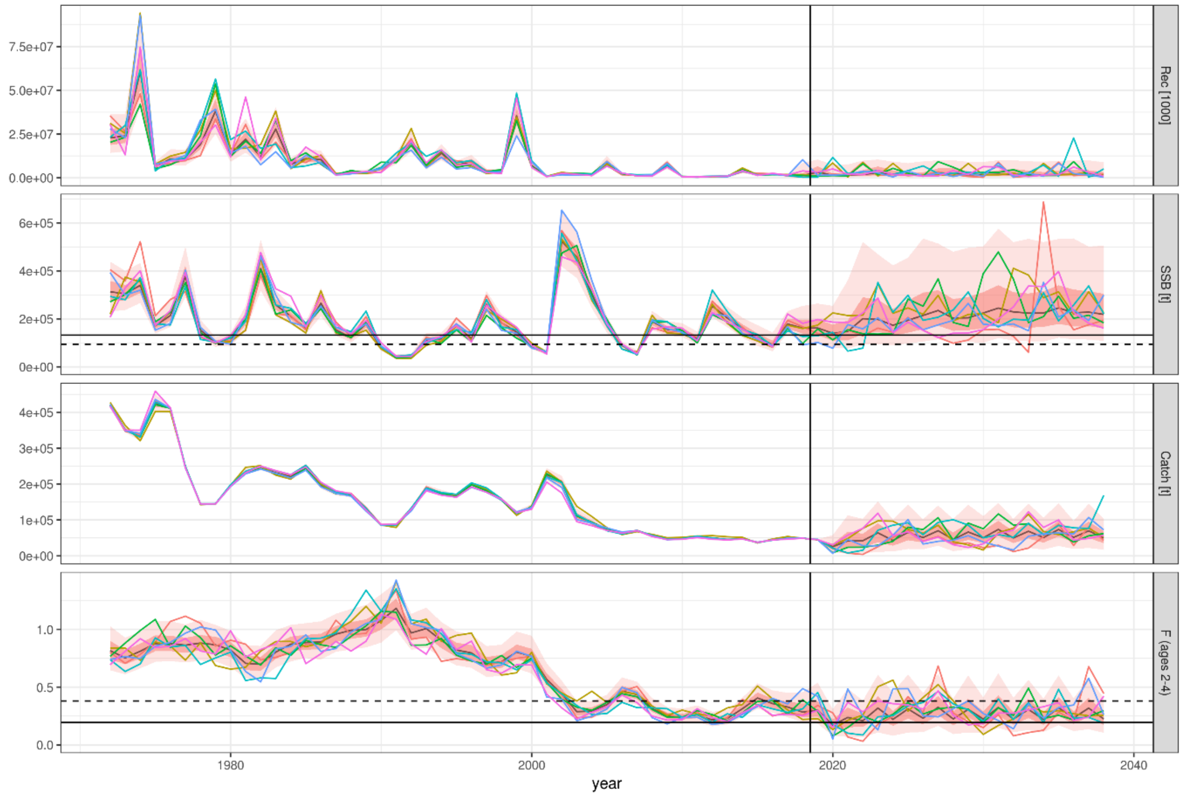

Figure A8.3.7. Haddock in Subarea 4, Division 6.a and Subdivision 20: Summary projections for “optimised” <u>management strategy B+E</u> for OM3 (Alt2). See the caption to Figure A8.3.1 for further details.

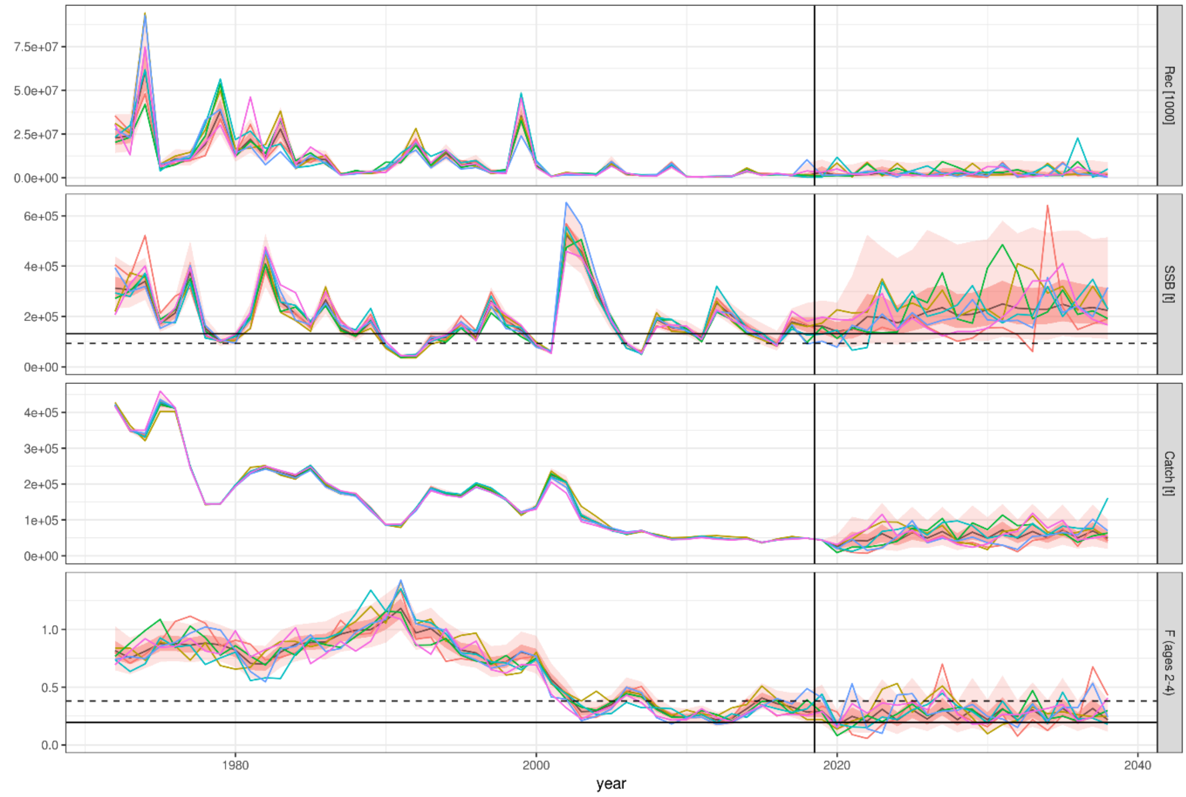

Figure A8.3.8. Haddock in Subarea 4, Division 6.a and Subdivision 20: Summary projections for "optimised" management strategy C+E for OM3 (Alt2). See the caption to Figure A8.3.1 for further details.

A8.4. Results of management strategy A*+D

Table A8.4.1. Haddock in Subarea 4, Division 6.a and Subdivision 20: sensitivity of performance statistics for the A*+D management strategy (i.e. with $F_{target}=F_{msy}=0.194$ and $B_{trigger}$=MSY $B_{trigger}$=132000 t). Statistics are reported for three time periods, short (first five years), medium (years 6-10) and long (final 10 years) term. Other statistics reported include the interannual variability (iav) in the catch and TAC, the proportion of replicates where the management strategy is operating "on the slope", the number of replicates where the estimation model (SAM) failed to converge, the number of

replicates where F_{max} (F_{max} =2) was reached, the proportion of replicates that recover above B_{pa}=MSY $B_{trigger}$ and the number of years taken to recover above B_{pa}=MSY $B_{trigger}$ for the first time.

Performance statistic	A*+D
Ftarget	0.194
Btrigger	132000
risk1 long term	0.016
risk1 short term	0.077
risk1 medium term	0.030
risk3 long term	0.021
risk3 short term	0.126
risk3 medium term	0.046
Iav long term	0.361
Iav short term	0.338
Iav medium term	0.346
Median catch long term	44480
Median catch short term	35820
Median catch medium term	41328
Median ssb long term	251788
Median ssb short term	162502
Median ssb medium term	218557
Median Fbar long term	0.201
Median Fbar short term	0.194
Median Fbar median term	0.197
Iav TAC long term	0.208
Iav TAC short term	0.283
Iav TAC medium term	0.222
Slope long term	0.10
Slope short term	0.15
Slope medium term	0.26
Convergence failure	0
Fmax reached	0
Recovery proportion	1
Recovery time	1

Annex 9: Additional Results for whiting

A9.1. Cannibalism

Considerable predation mortality by whiting on whiting (cannibalism) in the historical period was observed for age 1 as estimated by WGSAM (ICES 2018, Figure A9.1.1). To evaluate, whether cannibalism (and thereby predation mortality) varies with whiting stock size, the relationship between SSB and predation mortality at age 1 was plotted (Figure A9.1.2). SSB is dominated by individuals aged 2+, and a small proportion of 1-year-olds. However, there appears to be no relationship between SSB and predation mortality M2 (age 1) (Figure A9.1.2). There for no density-dependent effects in natural mortality were considered. As it is not expected, that whiting stock size affects the degree of cannibalism in the future, natural mortality is assumed to be independent from the stock size in the MSE. Therefore, no density-dependent effects in natural mortality were considered in the MSE.

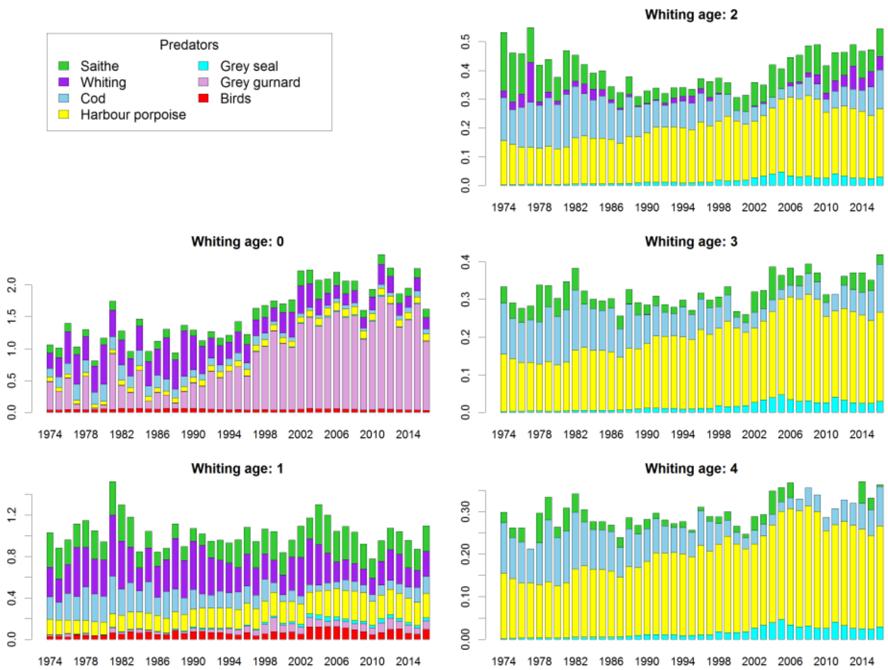

Figure A9.1.1. Whiting in Subarea 4 and Division 7.d. Predation mortality on whiting as estimated by WGSAM

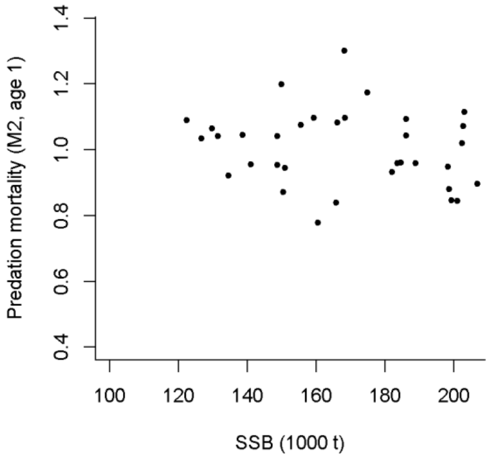

Figure A9.1.2. Whiting in Subarea 4 and Division 7.d. SSB and predation mortality at age 1.

A9.2. Search grids for short-term, baseline OM1

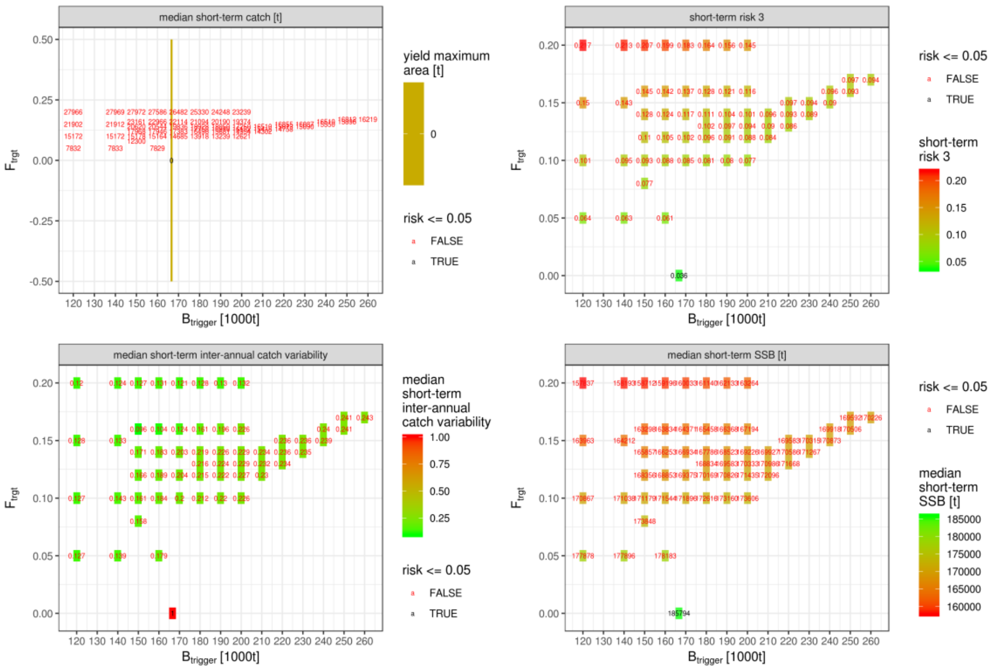

Figure A9.2.1. Whiting in Subarea 4 and Division 7.d. Short-term results grid search for management strategy A, OM1 (short-term: first five years of the 20-year projection). The top-left plot is median short-term catch, top-right the short-term risk3, bottom left the median short-term inter-annual catch variability and bottom right the median short-term SSB. No combinations meet the precautionary criterion (risk3≤5%) and hence no “optimum” is found.

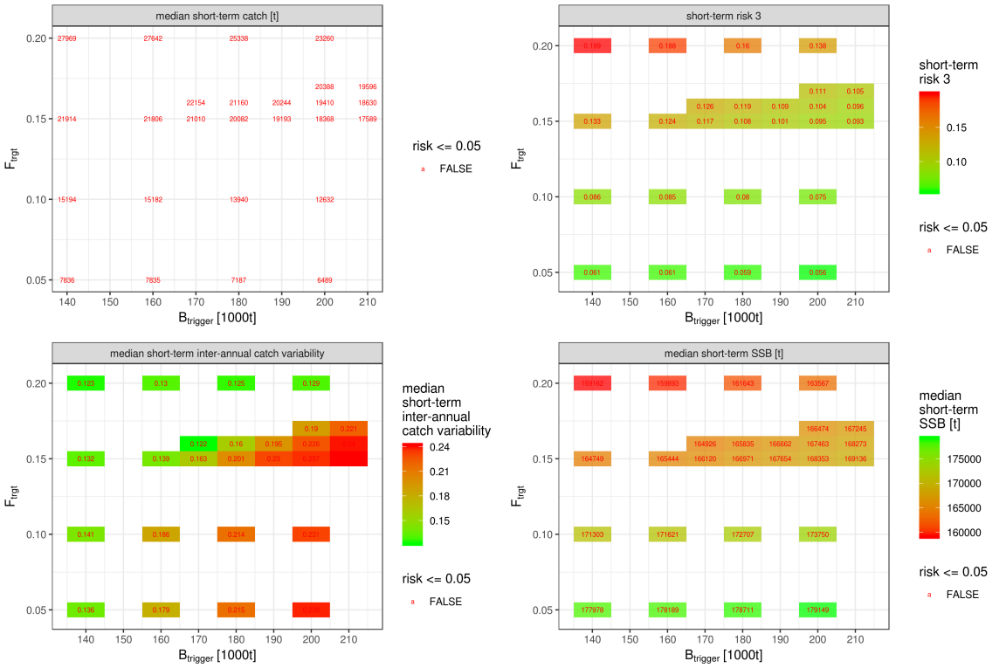

Figure A9.2.2. Whiting in Subarea 4 and Division 7.d. Short-term results grid search for <u>management strategy B, OM1</u>. See caption Figure A9.2.1 for details.

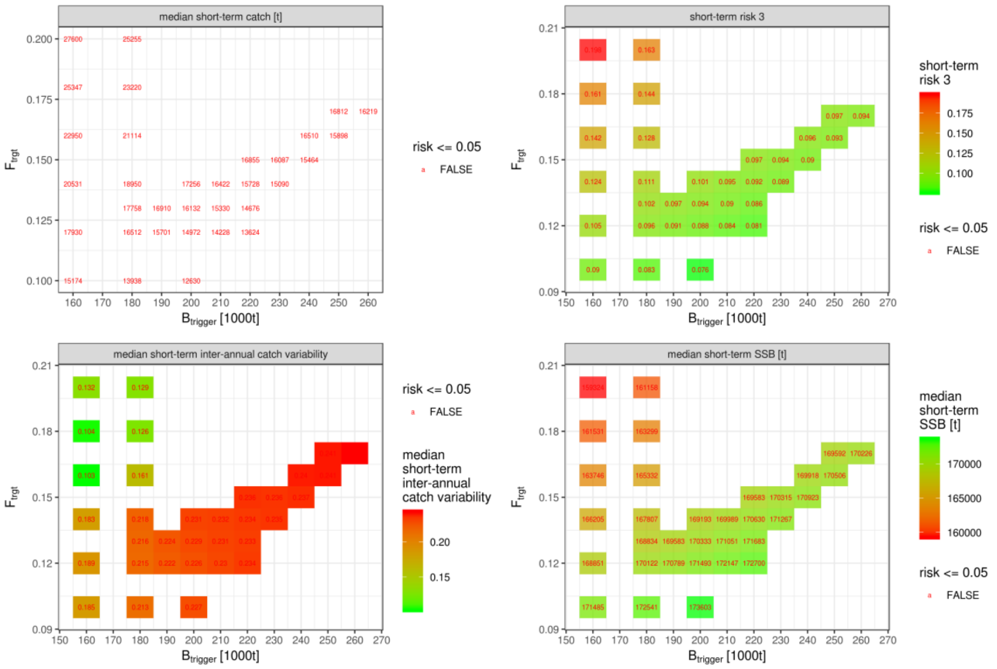

Figure A9.2.3. Whiting in Subarea 4 and Division 7.d. Short-term results grid search for <u>management strategy C, OM1</u>. See caption Figure A9.2.1 for details.

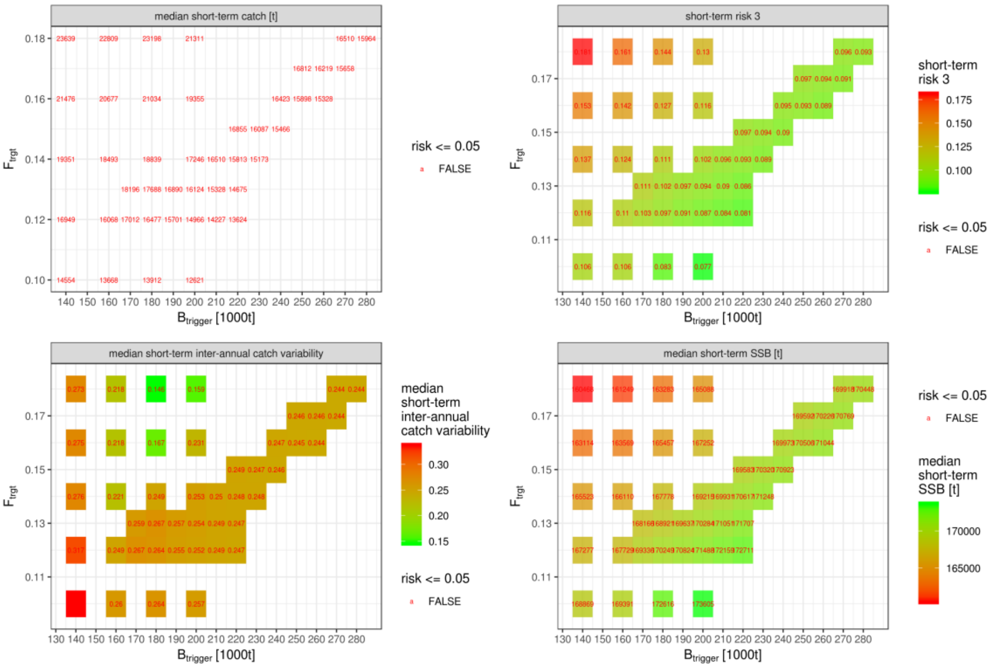

Figure A9.2.4. Whiting in Subarea 4 and Division 7.d. Short-term results grid search for management strategy A+D, OM1. See caption Figure A9.2.1 for details.

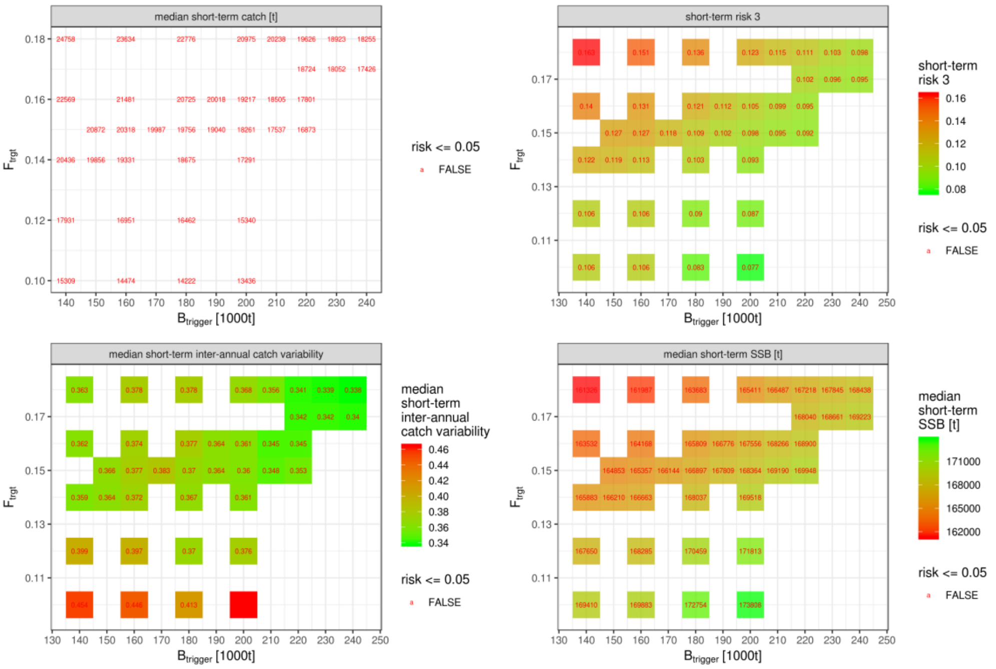

Figure A9.2.5. Whiting in Subarea 4 and Division 7.d. Short-term results grid search for management strategy B+E, OM1. See caption Figure A9.2.1 for details.

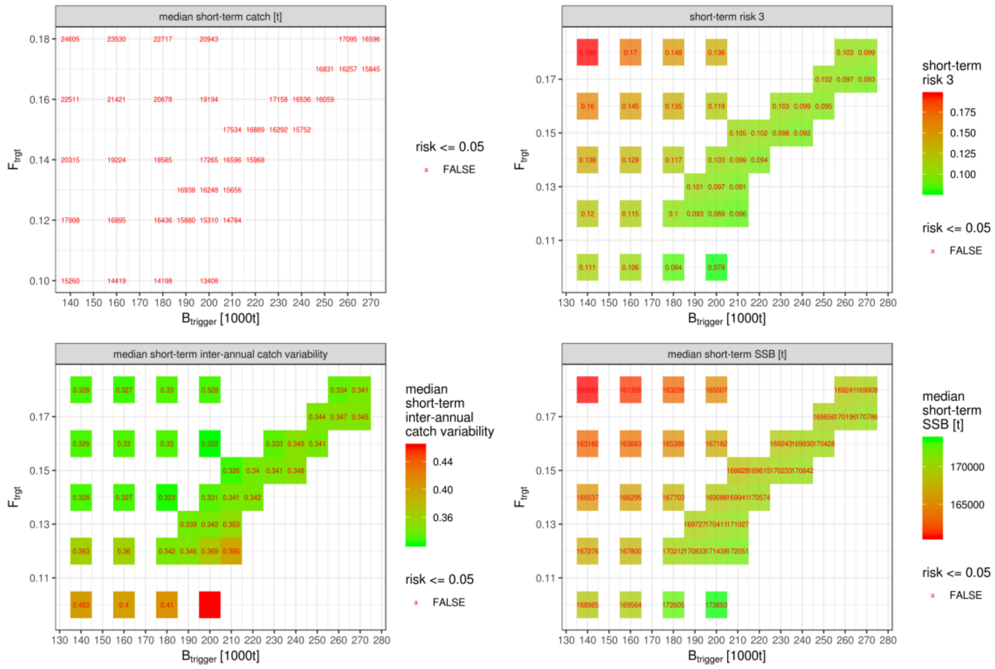

Figure A9.2.6. Whiting in Subarea 4 and Division 7.d. Short-term results grid search for management strategy C+E, OM1. See caption Figure A9.2.1 for details.

A9.3. MSE results alternative operating model OM2

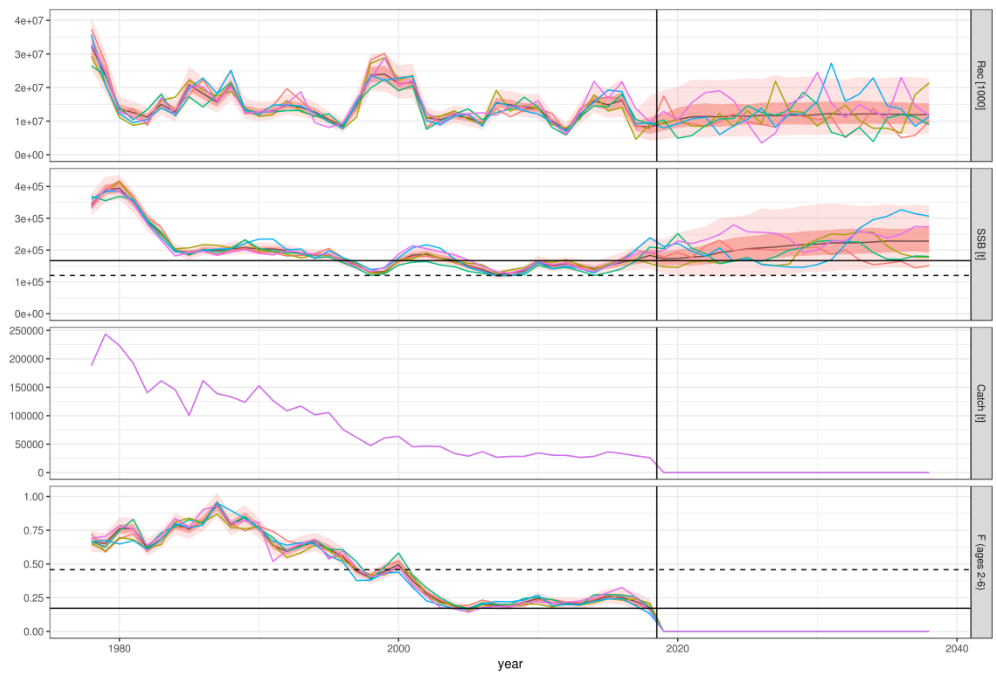

Figure A9.3.1. Whiting in Subarea 4 and Division 7.d. Summary MSE results with individual replicates for F=0, alternative OM2. Solid black horizontal line MSY $B_{trigger}$ or F_{msy}, dashed black horizontal line B_{lim} or F_{lim}. Top plot is recruitment (age 0), second plot SSB, third plot catch and bottom plot mean F (ages 2-6). The vertical black line separates the historical period from the projection period. The actual plots show medians (solid black line) with the darker shaded area indicating the 25th and 75th percentiles, and the light shaded area the 5th and 95th percentiles. The coloured lines indicate the first five replicates.

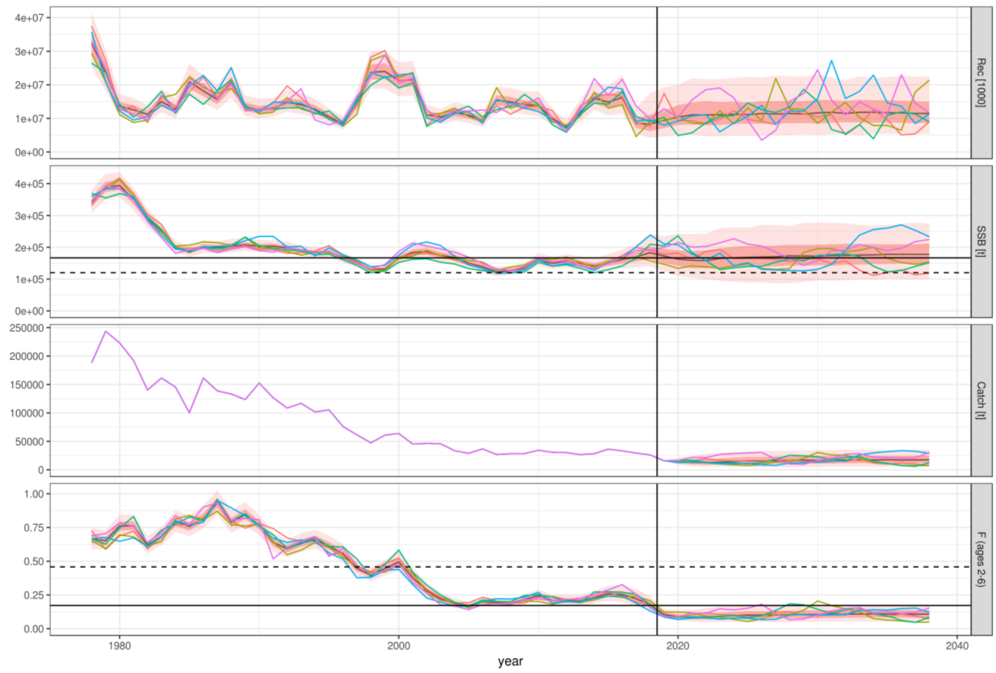

Figure A9.3.2. Whiting in Subarea 4 and Division 7.d. Summary MSE results with individual replicates for <u>management strategy A, alternative OM2</u>. Solid black horizontal line MSY $B_{trigger}$, F_{msy}, dashed black horizontal line B_{lim}, F_{lim}. See caption Figure A9.3.1 for details.

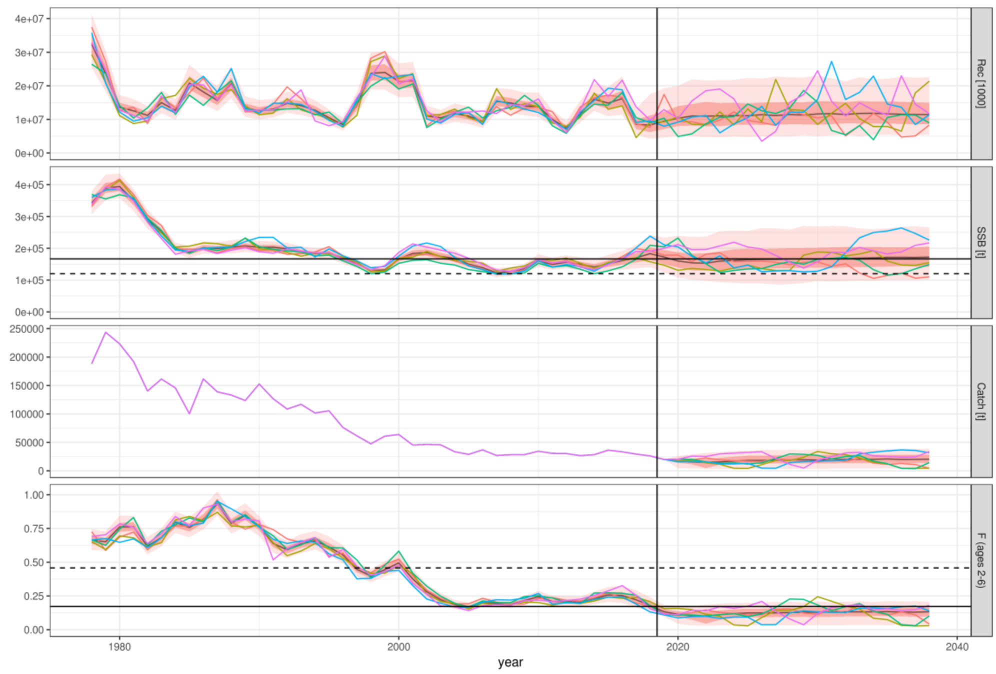

Figure A9.3.3. Whiting in Subarea 4 and Division 7.d. Summary MSE results with individual replicates for <u>management strategy B, alternative OM2</u>. Solid black horizontal line MSY $B_{trigger}$, F_{msy}, dashed black horizontal line B_{lim}, F_{lim}. See caption Figure A9.3.1 for details.

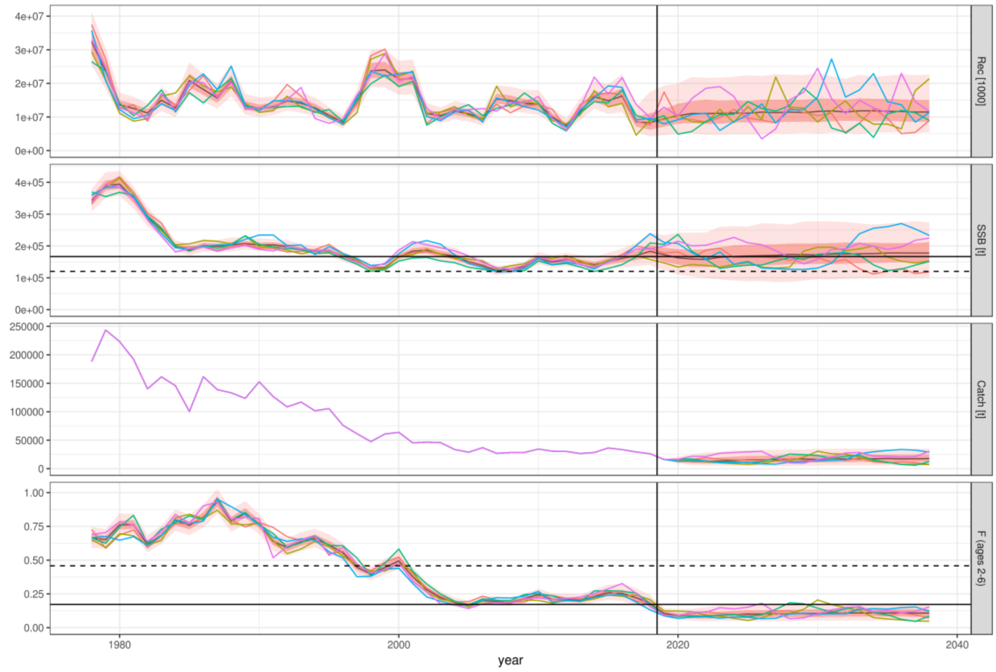

Figure A9.3.4. Whiting in Subarea 4 and Division 7.d. Summary MSE results with individual replicates for <u>management strategy C, alternative OM2</u>. Solid black horizontal line MSY $B_{trigger}$, F_{msy}, dashed black horizontal line B_{lim}, F_{lim}. See caption Figure A9.3.1 for details.

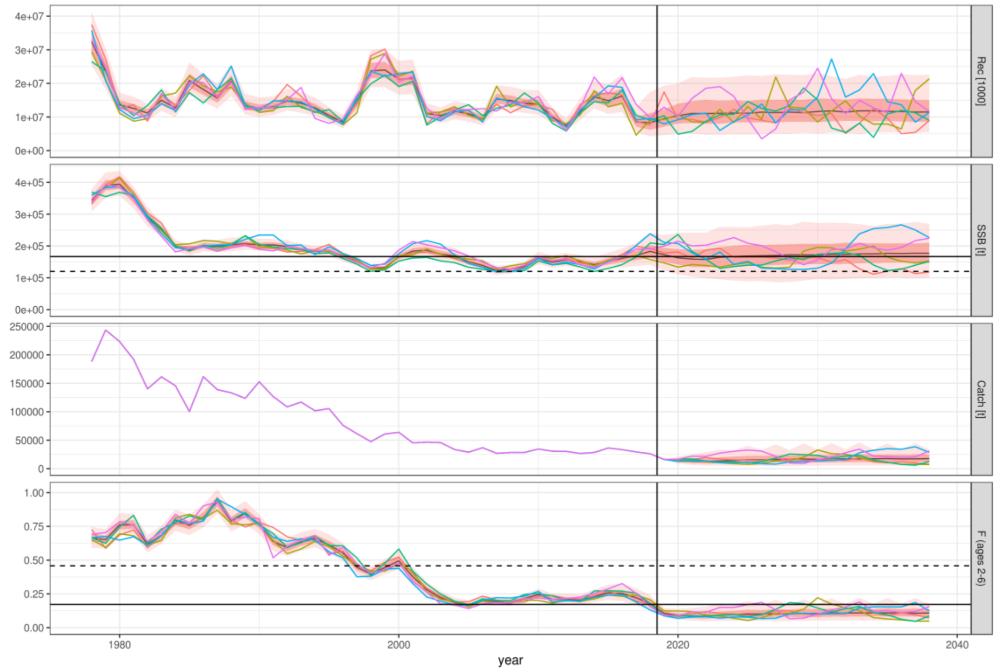

Figure A9.3.5. Whiting in Subarea 4 and Division 7.d. Summary MSE results with individual replicates for <u>management strategy C, alternative OM2</u>. Solid black horizontal line MSY $B_{trigger}$, F_{msy}, dashed black horizontal line B_{lim}, F_{lim}. See caption Figure A9.3.1 for details.

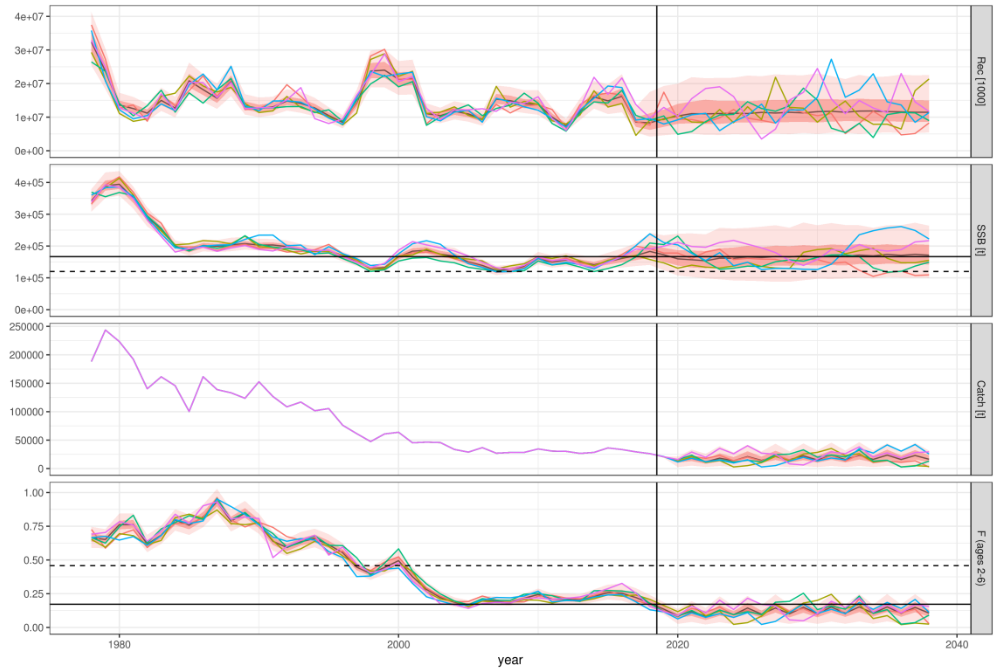

Figure A9.3.6. Whiting in Subarea 4 and Division 7.d. Summary MSE results with individual replicates for <u>management strategy B+E, alternative OM2</u>. Solid black horizontal line MSY $B_{trigger}$, F_{msy}, dashed black horizontal line B_{lim}, F_{lim}. See caption Figure A9.3.1 for details.

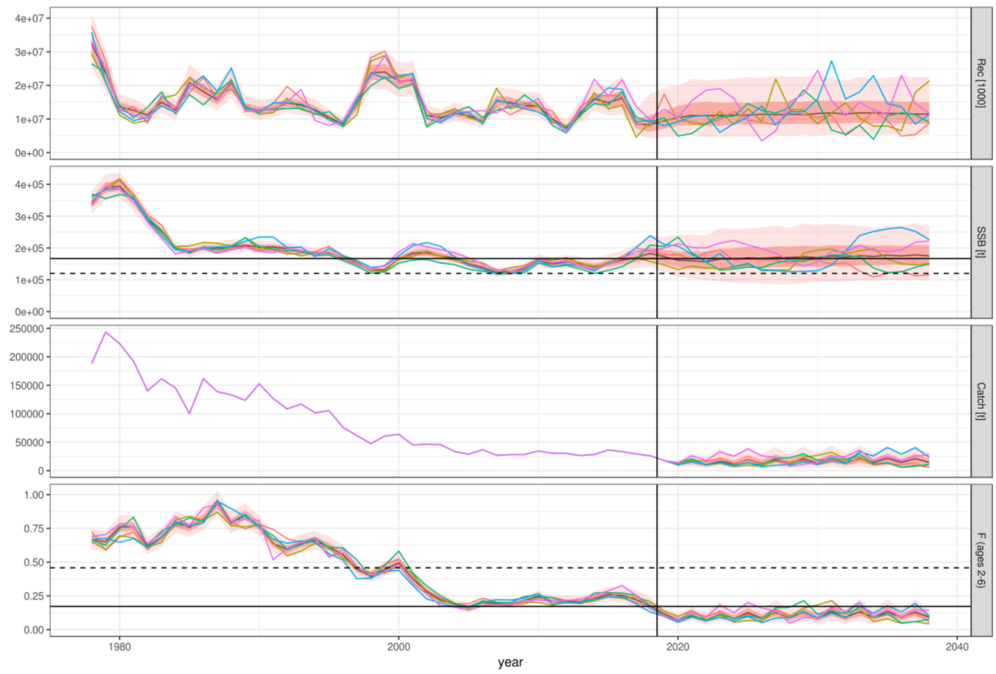

Figure A9.3.7. Whiting in Subarea 4 and Division 7.d. Summary MSE results with individual replicates for <u>management strategy C+E, alternative OM2</u>. Solid black horizontal line MSY $B_{trigger}$, F_{msy}, dashed black horizontal line B_{lim}, F_{lim}. See caption Figure A9.3.1 for details.

A9.4. MSE results alternative operating model OM3

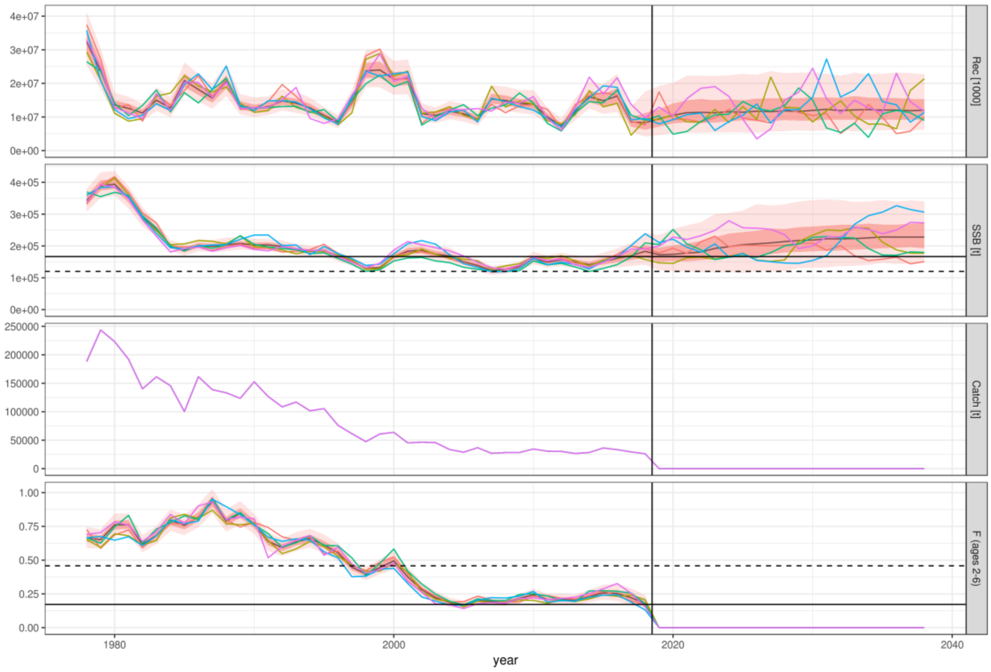

Figure A9.4.1. Whiting in Subarea 4 and Division 7.d. Summary MSE results with individual replicates for <u>F=0, alternative OM3</u>. Solid black horizontal line MSY $B_{trigger}$, F_{msy}, dashed black horizontal line B_{lim}, F_{lim}. See caption Figure A9.3.1 for details.

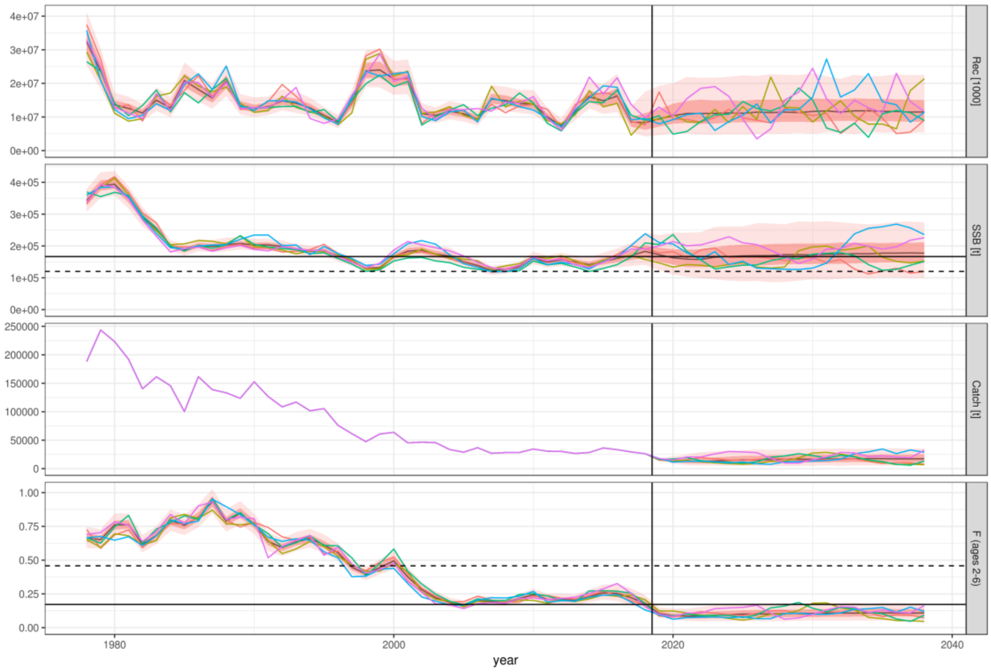

Figure A9.4.2. Whiting in Subarea 4 and Division 7.d. Summary MSE results with individual replicates for <u>management strategy A, alternative OM3</u>. Solid black horizontal line MSY $B_{trigger}$, F_{msy}, dashed black horizontal line B_{lim}, F_{lim}. See caption Figure A9.3.1 for details.

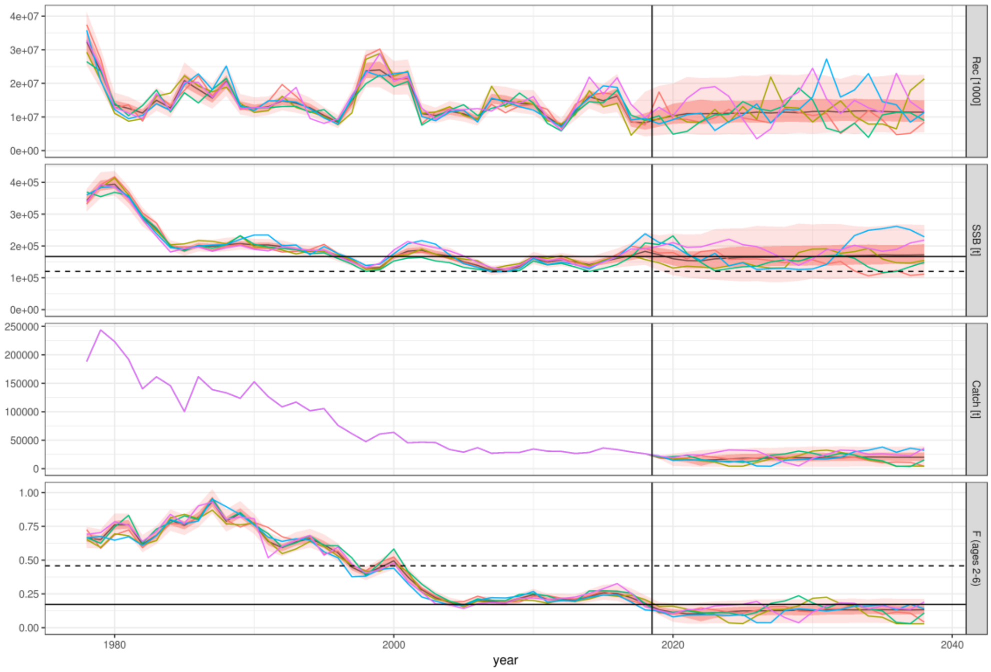

Figure A9.4.3. Whiting in Subarea 4 and Division 7.d. Summary MSE results with individual replicates for management strategy B, alternative OM3. Solid black horizontal line MSY $B_{trigger}$, F_{msy}, dashed black horizontal line B_{lim}, F_{lim}. See caption Figure A9.3.1 for details.

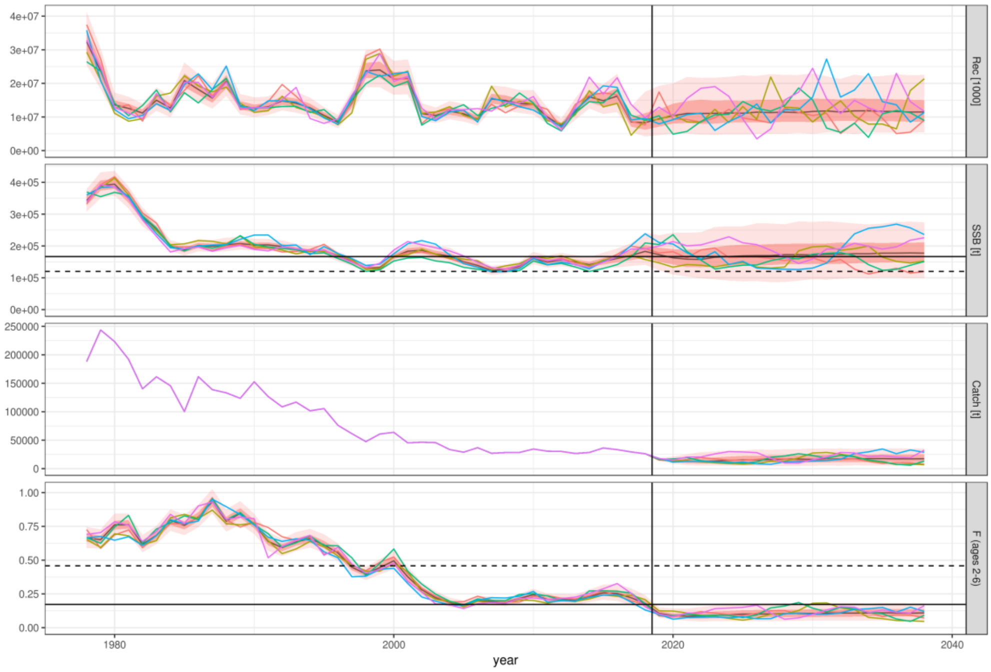

Figure A9.4.4. Whiting in Subarea 4 and Division 7.d. Summary MSE results with individual replicates for management strategy C, alternative OM3. Solid black horizontal line MSY $B_{trigger}$, F_{msy}, dashed black horizontal line B_{lim}, F_{lim}. See caption Figure A9.3.1 for details.

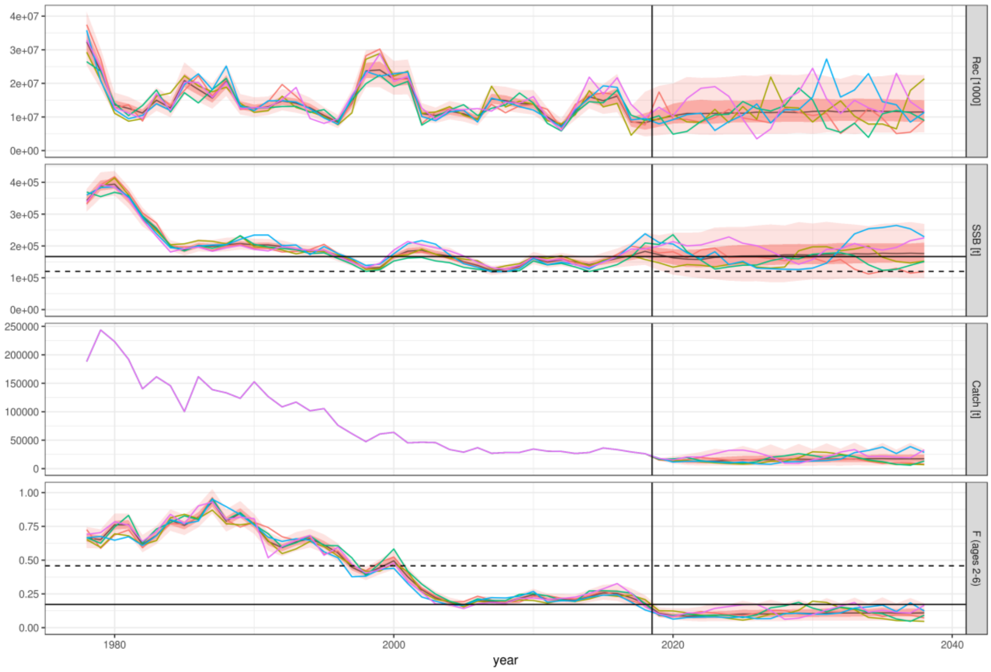

Figure A9.4.5. Whiting in Subarea 4 and Division 7.d. Summary MSE results with individual replicates for management strategy A+D, alternative OM3. Solid black horizontal line MSY $B_{trigger}$, F_{msy}, dashed black horizontal line B_{lim}, F_{lim}. See caption Figure A9.3.1 for details.

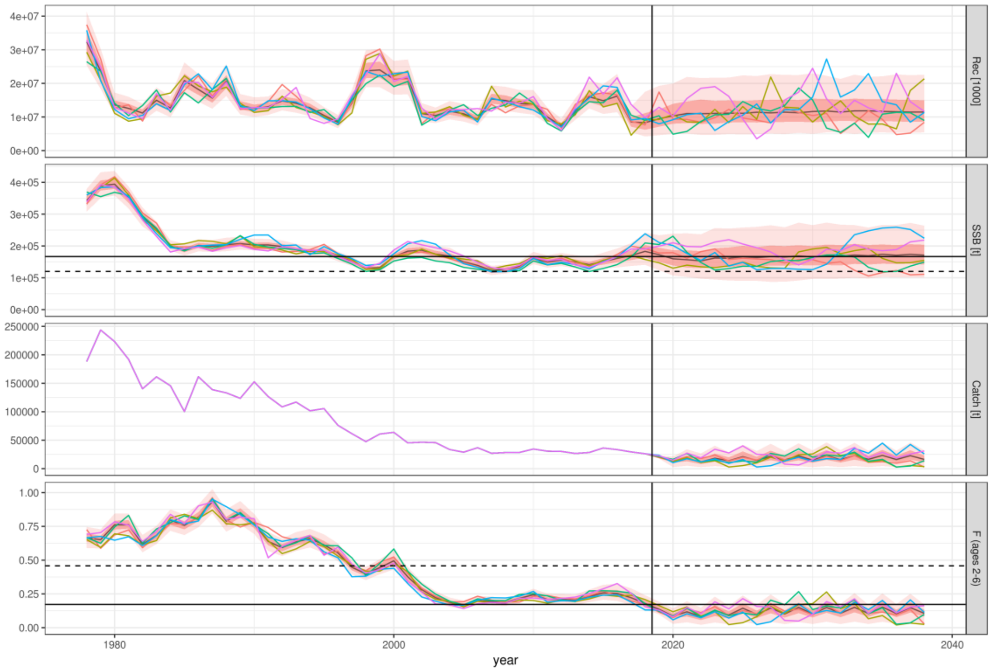

Figure A9.4.6. Whiting in Subarea 4 and Division 7.d. Summary MSE results with individual replicates for management strategy B+E, alternative OM3. Solid black horizontal line MSY $B_{trigger}$, F_{msy}, dashed black horizontal line B_{lim}, F_{lim}. See caption Figure A9.3.1 for details.

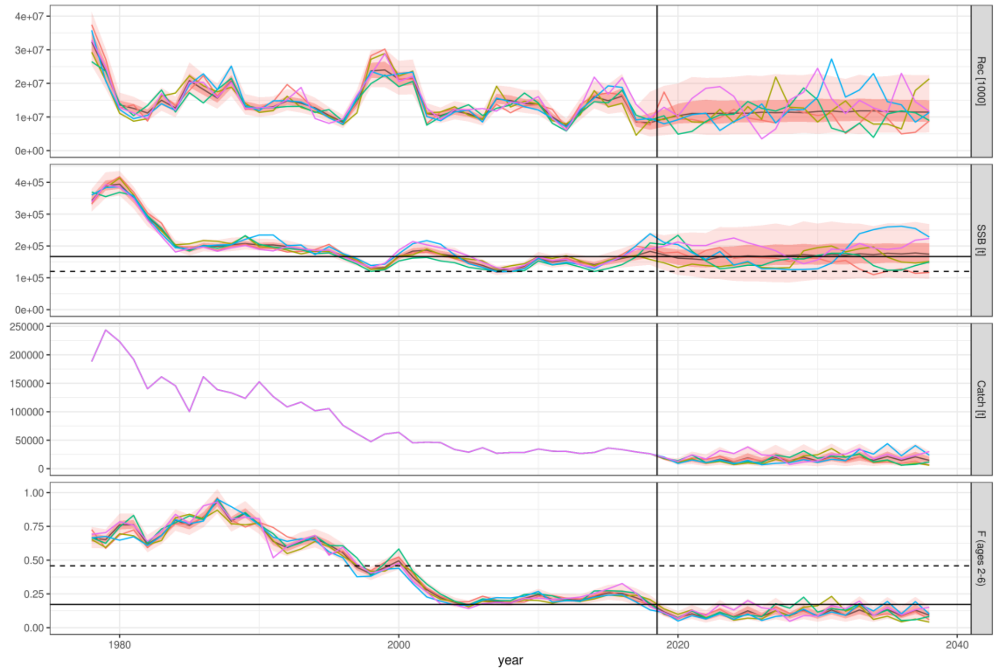

Figure A9.4.7. Whiting in Subarea 4 and Division 7.d. Summary MSE results with individual replicates for <u>management strategy C+E, alternative OM3</u>. Solid black horizontal line MSY $B_{trigger}$, F_{msy}, dashed black horizontal line B_{lim}, F_{lim}. See caption Figure A9.3.1 for details.

A9.5. More detailed results for baseline OM1

Table A9.5.1. Whiting in Subareas 4 and Division 7d: "optimal" combinations of F_{target} and $B_{trigger}$ for the baseline OM for the six management scenarios, F=0 and A* (F_{target} = F_{MSY} and $B_{trigger}$ = MSY $B_{trigger}$). Also reported are the median values for catch, SSB, realized mean F (ages 3-6), interannual catch variability (ICV), interannual TAC variability (ITV), risk3, and risk1. Statistics are reported for three time periods, short (first five years), medium (years 6-10) and long (final 10 years) term. Scenarios in red are not precautionary in the short-term.

Scenario	F=0	A*	A	B	C	A+D	B+E	C+E
F_{target}	0	0.172	0.14	0.16	0.14	0.16	0.16	0.15
$B_{trigger}$	–	166708	220000	200000	220000	250000	210000	230000
Median catch long term	0	27974	22832	26308	22844	22534	24846	22855
Median SSB long term	259460	189125	202702	195791	202678	201011	196370	200634
Median realized F long term	0	0.163	0.123	0.146	0.123	0.124	0.139	0.124
ICV long term	–	0.118	0.14	0.131	0.14	0.205	0.369	0.363
ITV long term	–	0.118	0.139	0.131	0.139	0.16	0.142	0.15
risk3 long term	0.01	0.084	0.05	0.049	0.05	0.05	0.05	0.05
risk1 long term	0.0069	0.0679	0.0369	0.0419	0.0369	0.0378	0.0409	0.0395
Median catch medium term	0	26102	20202	23578	20198	20132	21705	19516
Median SSB medium term	236594	179523	193216	186925	193208	191932	187488	191256
Median realized F medium term	0	0.157	0.115	0.139	0.115	0.116	0.127	0.112
ICV medium term	–	0.129	0.154	0.142	0.153	0.197	0.368	0.352
ITV medium term	–	0.176	0.203	0.254	0.202	0.223	0.256	0.213
risk3 medium term	0.027	0.135	0.083	0.091	0.083	0.085	0.091	0.088
risk1 medium term	0.0202	0.1134	0.068	0.0736	0.0678	0.0686	0.0734	0.07
Median catch short term	0	23784	15813	19410	15728	15898	18505	16292
Median SSB short term	185794	162835	170586	167463	170630	170506	168266	170233
Median realized F short term	0	0.149	0.095	0.118	0.095	0.096	0.114	0.099
ICV short term	–	0.11	0.236	0.226	0.234	0.245	0.345	0.341
ITV short term	–	0.159	0.179	0.175	0.178	0.181	0.178	0.182
risk3 short term	0.036	0.149	0.093	0.104	0.092	0.093	0.099	0.098
risk1 short term	0.0344	0.1184	0.077	0.0866	0.0768	0.077	0.0814	0.0778
Convergence failure	0	0	0	0	0	0	0	0
F_{max} reached	0	0	0	0	0	0	0	0
Recovery proportion	0.995	0.953	0.973	0.972	0.973	0.973	0.972	0.973
Recovery time	1	1	1	1	1	1	1	1

Table A9.5.2. Whiting in Subareas 4 and Division 7d: sensitivity of performance statistics for the "optimised" six management strategies to a range of F_{target} and $B_{trigger}$ scenarios. Statistics are reported for three time periods, short (first five years), medium (years 6-10) and long (final 10 years) term. Other statistics reported include the number of replicates where the estimation model (SAM) failed to converge, the number of replicates where Fmax (Fmax =2) was reached, the proportion of replicates that recover above B_{pa}=MSY $B_{trigger}$ and the number of years taken to recover above B_{pa}=MSY $B_{trigger}$ for the first time.

HCR		$F_{MSY-lower}$	0.9*F_{trgt}	F_{trgt}	1.1*F_{trgt}	$F_{MSY-upper}$
A	F_{target}	0.158	0.126	0.14	0.154	0.172
A	$B_{trigger}$	220000	220000	220000	220000	220000
A	Median catch long term	24349	21540	22832	24030	25436
A	Median SSB long term	198289	206615	202702	199230	194840
A	Median realized F long term	0.136	0.113	0.123	0.133	0.146
A	ICV long term	0.146	0.135	0.14	0.145	0.151
A	ITV long term	0.145	0.134	0.139	0.144	0.15
A	risk3 long term	0.055	0.045	0.05	0.055	0.059
A	risk1 long term	0.0438	0.0331	0.0369	0.0426	0.0486
A	Median catch medium term	21704	18930	20202	21374	22795
A	Median SSB medium term	189130	196414	193216	189993	185886
A	Median realized F medium term	0.128	0.105	0.115	0.125	0.137
A	ICV medium term	0.159	0.15	0.154	0.158	0.163
A	ITV medium term	0.209	0.198	0.203	0.208	0.214
A	risk3 medium term	0.094	0.077	0.083	0.092	0.1
A	risk1 medium term	0.0766	0.0616	0.068	0.075	0.0832
A	Median catch short term	17588	14259	15813	17185	18975
A	Median SSB short term	168803	172097	170586	169224	167723

HCR		$F_{MSY-lower}$	$0.9*F_{trgt}$	F_{trgt}	$1.1*F_{trgt}$	$F_{MSY-upper}$
A	Median realized F short term	0.107	0.086	0.095	0.104	0.116
A	ICV short term	0.236	0.233	0.236	0.235	0.238
A	ITV short term	0.179	0.176	0.179	0.179	0.18
A	risk3 short term	0.103	0.084	0.093	0.101	0.112
A	risk1 short term	0.084	0.0716	0.077	0.0824	0.09
A	Convergence failure	0	0	0	0	0
A	F_{max} reached	0	0	0	0	0
B	F_{target}	0.158	0.144	0.16	0.176	0.172
B	$B_{trigger}$	200000	200000	200000	200000	200000
B	Median catch long term	26150	24833	26308	27555	27256
B	Median SSB long term	196231	200042	195791	191953	192844
B	Median realized F long term	0.145	0.133	0.146	0.159	0.156
B	ICV long term	0.131	0.126	0.131	0.136	0.135
B	ITV long term	0.13	0.125	0.131	0.136	0.134
B	risk3 long term	0.049	0.046	0.049	0.056	0.054
B	risk1 long term	0.0414	0.036	0.0419	0.0466	0.0452
B	Median catch medium term	23400	22184	23578	24802	24536
B	Median SSB medium term	187437	190631	186925	183421	184370
B	Median realized F medium term	0.137	0.126	0.139	0.151	0.148
B	ICV medium term	0.142	0.138	0.142	0.146	0.145
B	ITV medium term	0.253	0.245	0.254	0.266	0.263
B	risk3 medium term	0.09	0.086	0.091	0.101	0.099
B	risk1 medium term	0.0732	0.0686	0.0736	0.0808	0.0798
B	Median catch short term	19204	17722	19410	20954	20581
B	Median SSB short term	167607	169085	167463	165846	166197
B	Median realized F short term	0.117	0.107	0.118	0.13	0.127
B	ICV short term	0.232	0.237	0.226	0.168	0.183
B	ITV short term	0.175	0.174	0.175	0.175	0.176
B	risk3 short term	0.101	0.092	0.104	0.117	0.115
B	risk1 short term	0.085	0.078	0.0866	0.0952	0.0938
B	Convergence failure	0	0	0	0	0
B	F_{max} reached	0	0	0	0	0
C	F_{target}	0.158	0.126	0.14	0.154	0.172
C	$B_{trigger}$	220000	220000	220000	220000	220000
C	Median catch long term	24348	21554	22844	24028	25424
C	Median SSB long term	198296	206621	202678	199221	194879
C	Median realized F long term	0.136	0.113	0.123	0.133	0.146
C	ICV long term	0.146	0.134	0.14	0.145	0.151
C	ITV long term	0.145	0.134	0.139	0.144	0.15
C	risk3 long term	0.056	0.045	0.05	0.055	0.059
C	risk1 long term	0.0439	0.0332	0.0369	0.0426	0.0486
C	Median catch medium term	21685	18926	20198	21385	22784
C	Median SSB medium term	189111	196411	193208	189980	185884
C	Median realized F medium term	0.128	0.105	0.115	0.125	0.137
C	ICV medium term	0.159	0.15	0.153	0.158	0.163
C	ITV medium term	0.209	0.198	0.202	0.207	0.213
C	risk3 medium term	0.094	0.077	0.083	0.092	0.1
C	risk1 medium term	0.0766	0.0616	0.0678	0.075	0.083
C	Median catch short term	17668	14333	15728	17254	19009
C	Median SSB short term	168698	172058	170630	169177	167650
C	Median realized F short term	0.107	0.086	0.095	0.104	0.116
C	ICV short term	0.238	0.234	0.234	0.237	0.238
C	ITV short term	0.18	0.178	0.178	0.179	0.181
C	risk3 short term	0.103	0.084	0.092	0.102	0.113
C	risk1 short term	0.0844	0.0718	0.0768	0.0828	0.0908
C	Convergence failure	0	0	0	0	0
C	F_{max} reached	0	0	0	0	0
A+D	F_{target}	0.158	0.144	0.16	0.176	0.172
A+D	$B_{trigger}$	250000	250000	250000	250000	250000
A+D	Median catch long term	22364	21225	22534	23713	23450
A+D	Median SSB long term	201498	204796	201011	197410	198260
A+D	Median realized F long term	0.123	0.114	0.124	0.134	0.132
A+D	ICV long term	0.205	0.206	0.205	0.204	0.204

HCR		$F_{MSY-lower}$	0.9*F_{trgt}	F_{trgt}	1.1*F_{trgt}	$F_{MSY-upper}$
A+D	ITV long term	0.159	0.155	0.16	0.164	0.162
A+D	risk3 long term	0.05	0.045	0.05	0.055	0.054
A+D	risk1 long term	0.0373	0.0339	0.0378	0.0433	0.0419
A+D	Median catch medium term	19959	18900	20132	21280	21010
A+D	Median SSB medium term	192490	195320	191932	188751	189576
A+D	Median realized F medium term	0.115	0.106	0.116	0.126	0.124
A+D	ICV medium term	0.198	0.197	0.197	0.198	0.199
A+D	ITV medium term	0.222	0.218	0.223	0.227	0.226
A+D	risk3 medium term	0.084	0.077	0.085	0.092	0.091
A+D	risk1 medium term	0.0674	0.0622	0.0686	0.0752	0.0734
A+D	Median catch short term	15711	14411	15898	17346	16994
A+D	Median SSB short term	170703	171945	170506	169056	169416
A+D	Median realized F short term	0.095	0.087	0.096	0.105	0.103
A+D	ICV short term	0.245	0.244	0.245	0.245	0.245
A+D	ITV short term	0.182	0.181	0.181	0.182	0.181
A+D	risk3 short term	0.091	0.085	0.093	0.103	0.099
A+D	risk1 short term	0.0766	0.073	0.077	0.0832	0.082
A+D	Convergence failure	0	0	0	0	0
A+D	F_{max} reached	0	0	0	0	0
B+E	F_{target}	0.158	0.144	0.16	0.176	0.172
B+E	$B_{trigger}$	210000	210000	210000	210000	210000
B+E	Median catch long term	24659	23253	24846	26263	25901
B+E	Median SSB long term	196843	200429	196370	192558	193452
B+E	Median realized F long term	0.138	0.127	0.139	0.151	0.148
B+E	ICV long term	0.369	0.369	0.369	0.369	0.369
B+E	ITV long term	0.141	0.135	0.142	0.146	0.146
B+E	risk3 long term	0.049	0.043	0.05	0.057	0.055
B+E	risk1 long term	0.0397	0.0349	0.0409	0.0449	0.0444
B+E	Median catch medium term	21550	20432	21705	22796	22582
B+E	Median SSB medium term	187988	191150	187488	184143	184951
B+E	Median realized F medium term	0.125	0.116	0.127	0.137	0.135
B+E	ICV medium term	0.368	0.366	0.368	0.366	0.368
B+E	ITV medium term	0.255	0.244	0.256	0.267	0.262
B+E	risk3 medium term	0.088	0.082	0.091	0.101	0.098
B+E	risk1 medium term	0.0726	0.0652	0.0734	0.0802	0.0768
B+E	Median catch short term	18305	16952	18505	19953	19657
B+E	Median SSB short term	168413	169856	168266	166871	167184
B+E	Median realized F short term	0.112	0.103	0.114	0.125	0.122
B+E	ICV short term	0.345	0.353	0.345	0.346	0.343
B+E	ITV short term	0.178	0.176	0.178	0.177	0.179
B+E	risk3 short term	0.098	0.092	0.099	0.113	0.109
B+E	risk1 short term	0.0808	0.0754	0.0814	0.0904	0.087
B+E	Convergence failure	0	0	0	0	0
B+E	F_{max} reached	0	0	0	0	0
C+E	F_{target}	0.158	0.135	0.15	0.165	0.172
C+E	$B_{trigger}$	230000	230000	230000	230000	230000
C+E	Median catch long term	23496	21544	22855	24000	24492
C+E	Median SSB long term	198585	204447	200634	197126	195372
C+E	Median realized F long term	0.13	0.113	0.124	0.135	0.14
C+E	ICV long term	0.362	0.364	0.363	0.361	0.361
C+E	ITV long term	0.154	0.145	0.15	0.156	0.159
C+E	risk3 long term	0.055	0.046	0.05	0.055	0.058
C+E	risk1 long term	0.0425	0.0349	0.0395	0.0448	0.0468
C+E	Median catch medium term	20081	18365	19516	20527	20997
C+E	Median SSB medium term	189561	194934	191256	188145	186756
C+E	Median realized F medium term	0.117	0.102	0.112	0.122	0.126
C+E	ICV medium term	0.352	0.353	0.352	0.353	0.353
C+E	ITV medium term	0.216	0.208	0.213	0.218	0.22
C+E	risk3 medium term	0.094	0.082	0.088	0.098	0.1
C+E	risk1 medium term	0.0742	0.0646	0.07	0.0776	0.0818
C+E	Median catch short term	16977	14922	16292	17589	18200
C+E	Median SSB short term	169556	171683	170233	168791	168311
C+E	Median realized F short term	0.104	0.09	0.099	0.108	0.113

HCR		$F_{MSY\text{-}lower}$	0.9*F_{trgt}	F_{trgt}	1.1*F_{trgt}	$F_{MSY\text{-}upper}$
C+E	ICV short term	0.34	0.384	0.341	0.323	0.315
C+E	ITV short term	0.182	0.181	0.182	0.182	0.183
C+E	risk3 short term	0.102	0.088	0.098	0.105	0.111
C+E	risk1 short term	0.0806	0.072	0.0778	0.0838	0.0874
C+E	Convergence failure	0	0	0	0	0
C+E	F_{max} reached	0	0	0	0	0

Annex 10: Additional Results for saithe

A10.1. Search grids for short-term, baseline OM1

Management strategy A

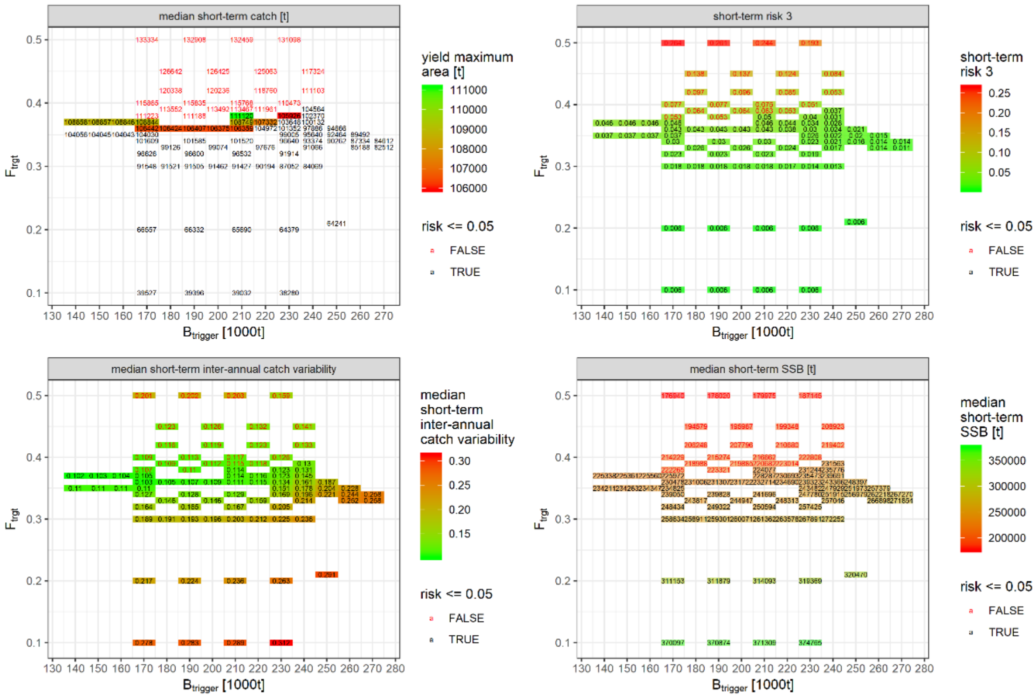

Figure A10.1.1. Saithe in Subareas 4 and 6 and Division 3a: Grid search for "optimal" combination of F_{target} and $B_{trigger}$ for <u>management strategy A for the short-term</u> (i.e. first five years of the 20-year projection). The top-left plot is median short-term catch, top-right the short-term risk3, bottom left the median short-term inter-annual catch variability and bottom right the median short-term SSB.

Management strategy B

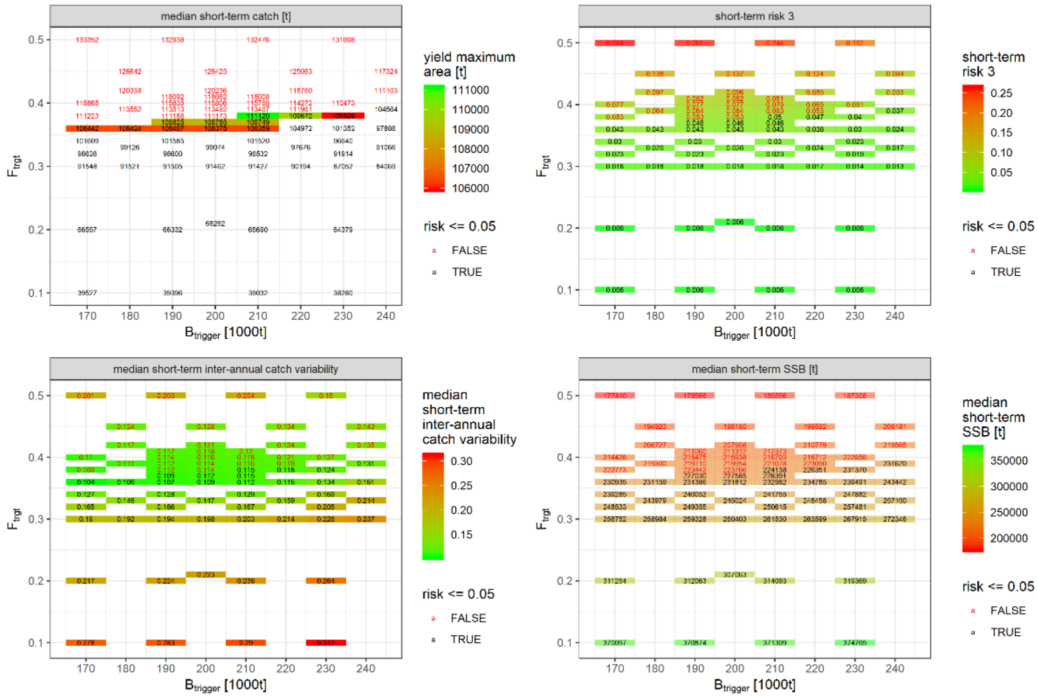

Figure A10.1.2. Saithe in Subareas 4 and 6 and Division 3a: Grid search for "optimal" combination of F_{target} and $B_{trigger}$ for <u>management strategy B for the short-term</u> (i.e. first five years of the 20-year projection). See the caption to Table A10.1.1 for more details.

Management strategy C

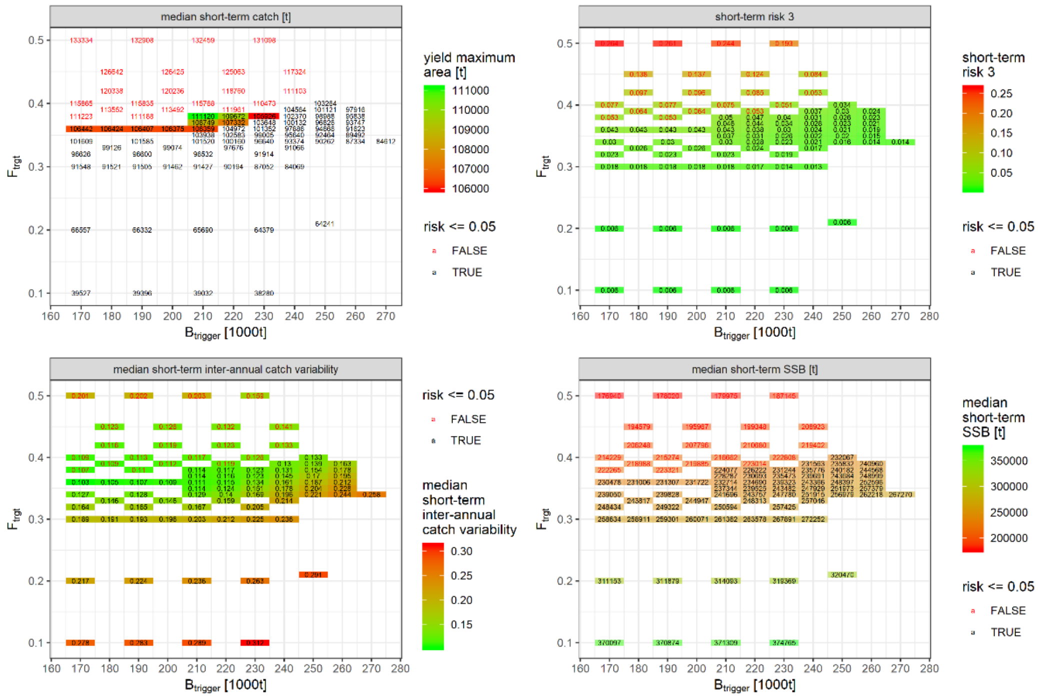

Figure A10.1.3. Saithe in Subareas 4 and 6 and Division 3a: Grid search for "optimal" combination of F_{target} and $B_{trigger}$ for <u>management strategy C for the short-term</u> (i.e. first five years of the 20-year projection). See the caption to Table A10.1.1 for more details.

Management strategy A+D

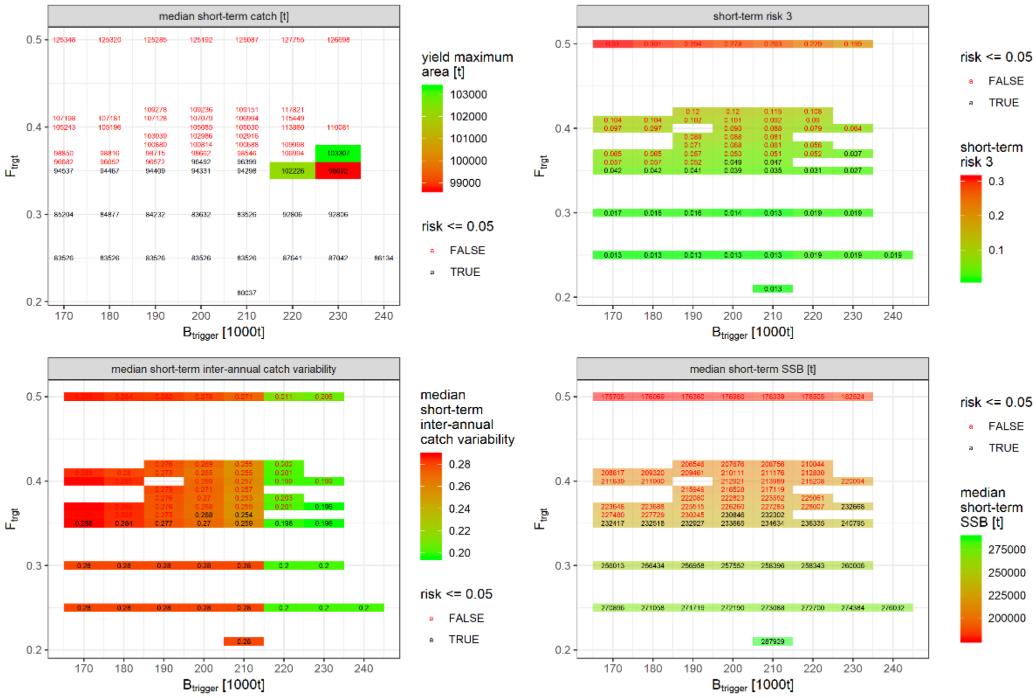

Figure A10.1.4. Saithe in Subareas 4 and 6 and Division 3a: Grid search for "optimal" combination of F_{target} and $B_{trigger}$ for <u>management strategy A+D for the short-term</u> (i.e. first five years of the 20-year projection). See the caption to Table A10.1.1 for more details.

Management strategy B+E

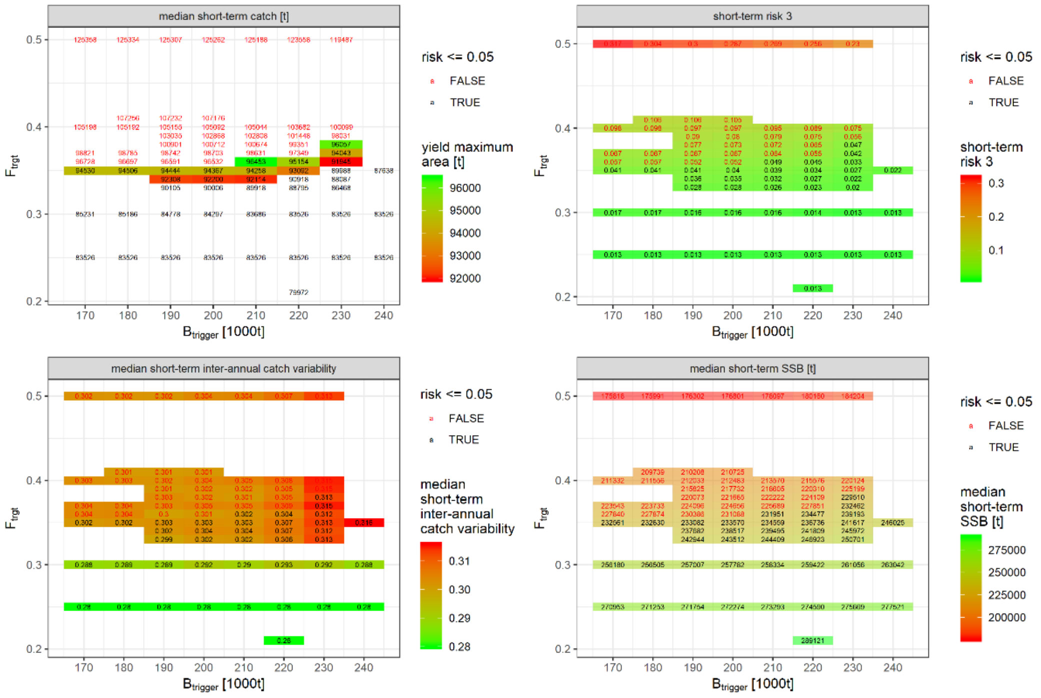

Figure A10.1.5. Saithe in Subareas 4 and 6 and Division 3a: Grid search for "optimal" combination of F_{target} and $B_{trigger}$ for management strategy B+E for the short-term (i.e. first five years of the 20-year projection). See the caption to Table A10.1.1 for more details.

Management strategy C+E

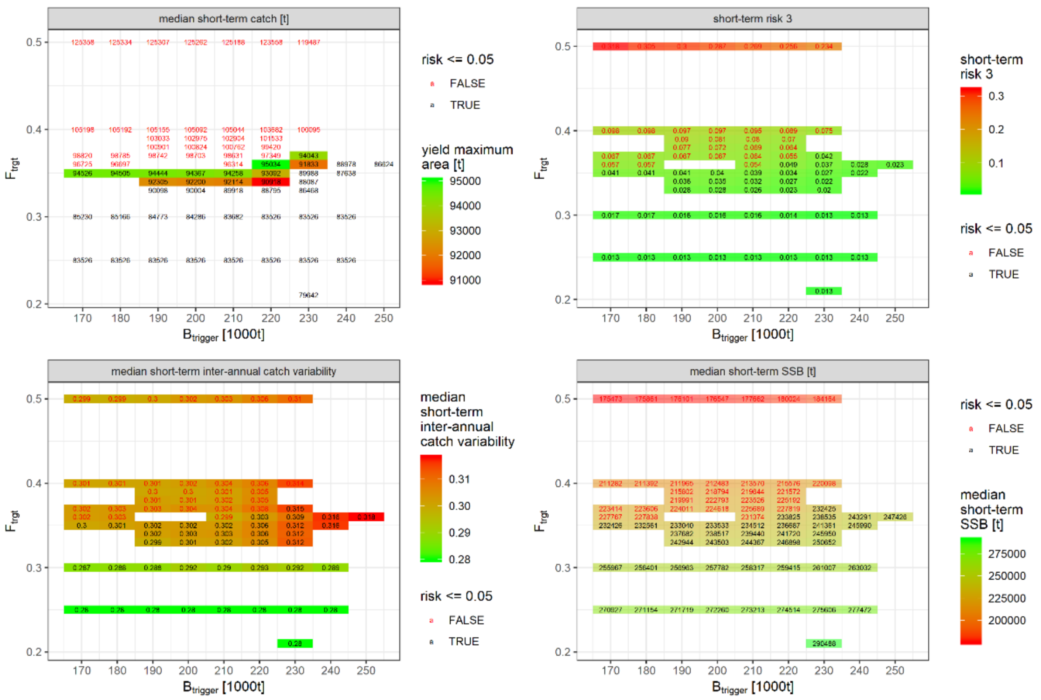

Figure A10.1.6. Saithe in Subareas 4 and 6 and Division 3a: Grid search for "optimal" combination of F_{target} and $B_{trigger}$ for management strategy C+E for the short-term (i.e. first five years of the 20-year projection). See the caption to Table A10.1.1 for more details.

Management strategy A1+D

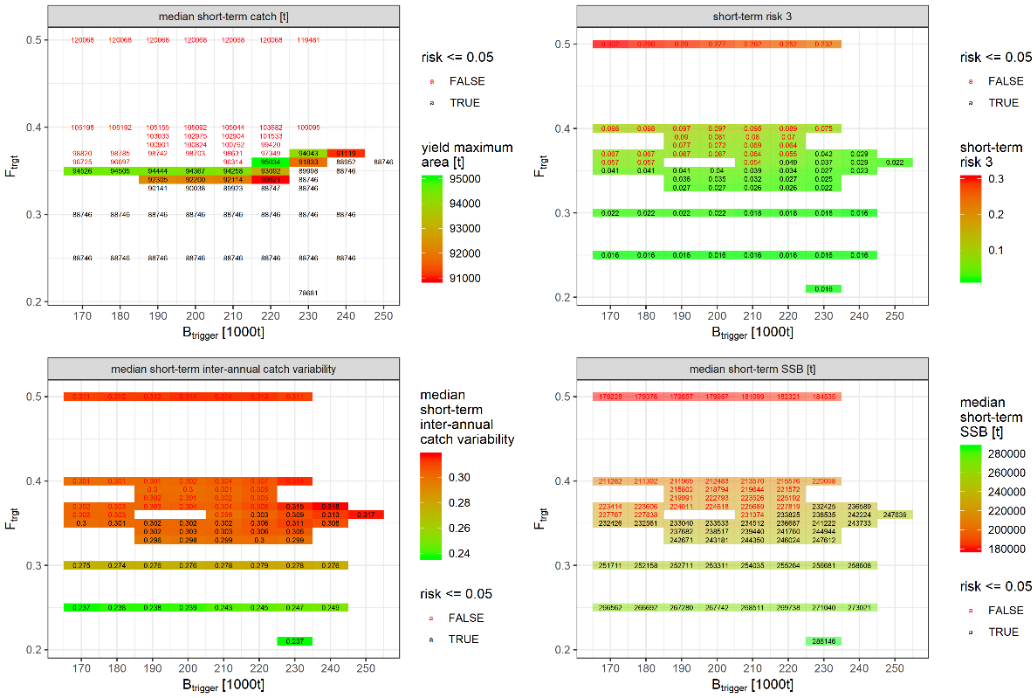

Figure A10.1.7. Saithe in Subareas 4 and 6 and Division 3a: Grid search for "optimal" combination of F_{target} and $B_{trigger}$ for <u>management strategy A1+D for the short-term</u> (i.e. first five years of the 20-year projection). See the caption to Table A10.1.1 for more details.

A10.2. Summary projection plots for OM2 (M=0.1)

Management strategy A

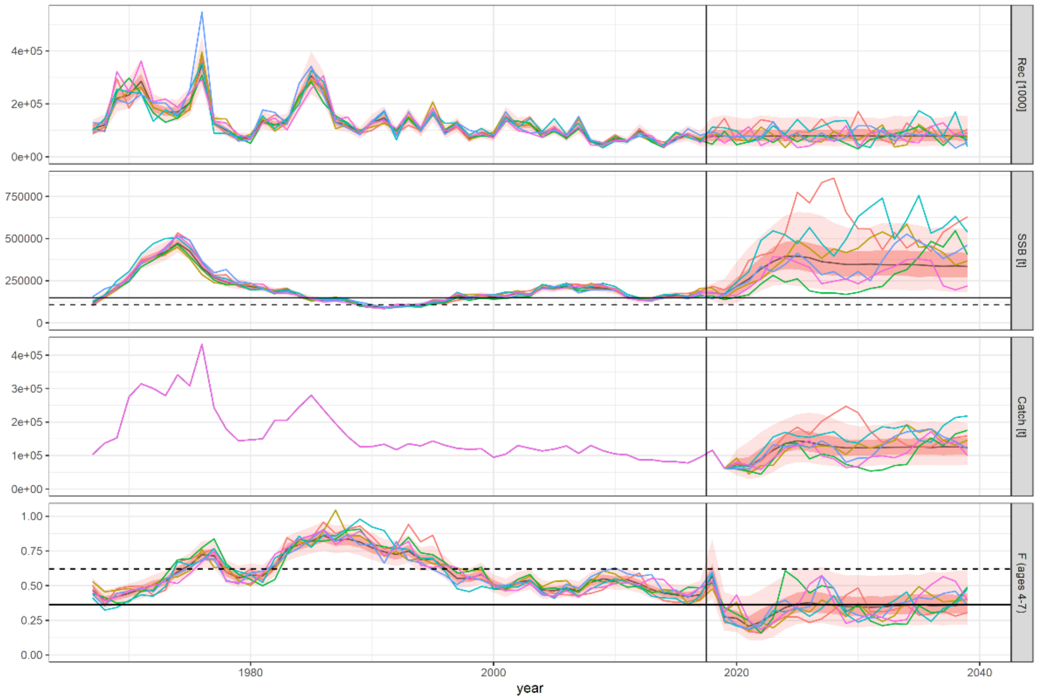

Figure A10.2.1. Saithe in Subareas 4 and 6 and Division 3a: Summary projections for <u>management strategy A</u> with individual replicates, <u>alternative OM2 (M=0.1)</u>. Top plot is recruitment (age 0), second plot SSB, third plot catch and bottom plot mean F (ages 4-7). The vertical black line separates the historic period from the projection period. The SSB plot includes B_{pa}=MSY $B_{trigger}$ (horizontal solid line) and B_{lim} (horizontal hashed line), while the mean F plot includes F_{msy} (horizontal solid line) and F_{lim} (horizontal dashed line). The actual plots show medians (solid black line) with the darker shaded area indicating the 25th and 75th percentiles, and the light shaded area the 5th and 95th percentiles. The results for 5 individual replicates are shown in solid coloured lines.

Management strategy B

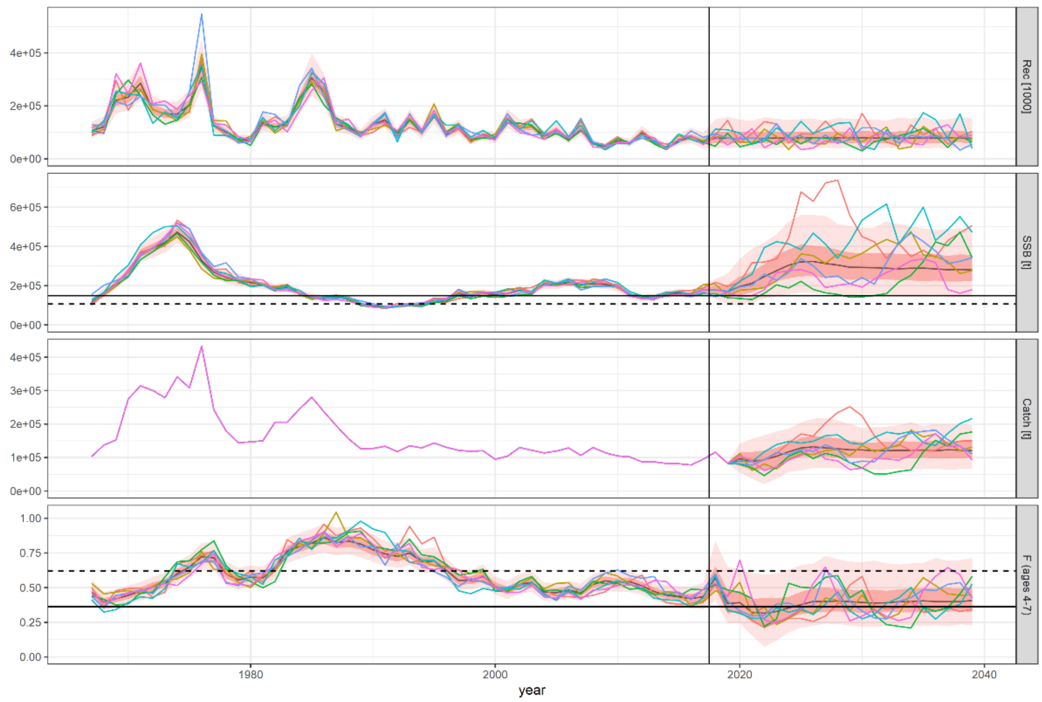

Figure A10.2.2. Saithe in Subareas 4 and 6 and Division 3a: Summary projections for <u>management strategy B</u> with individual replicates, <u>alternative OM2 (M=0.1)</u>. Solid black horizontal lines are MSY $B_{trigger}$ and F_{msy}, dashed black horizontal lines are B_{lim} and F_{lim}. See caption Figure A10.2.1 for details.

Management strategy C

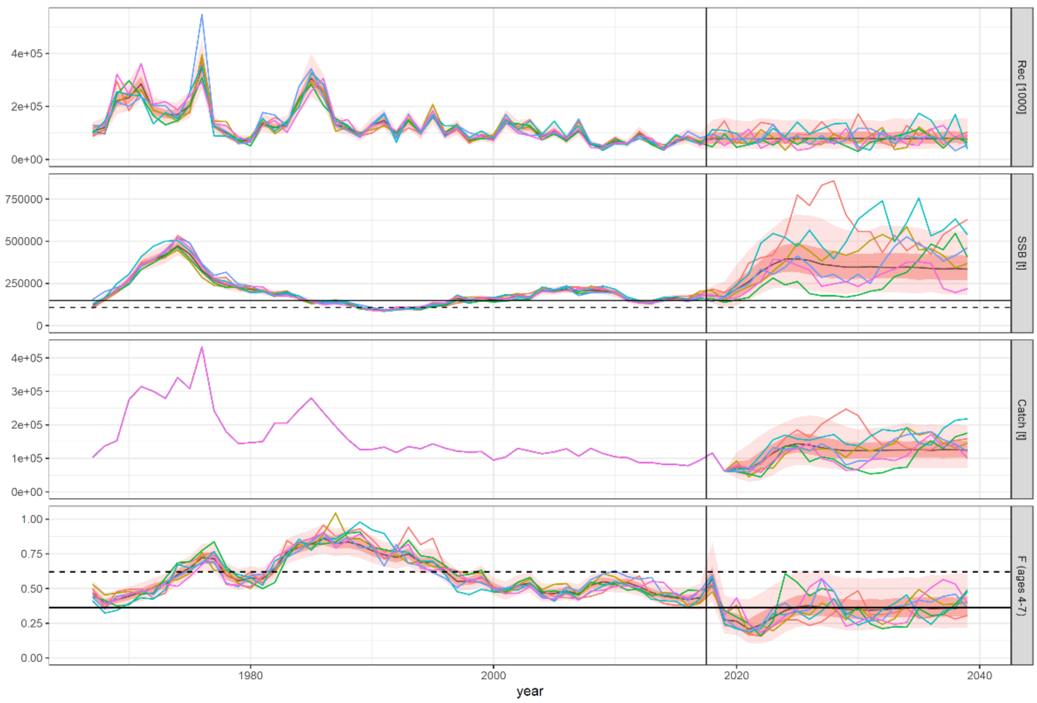

Figure A10.2.3. Saithe in Subareas 4 and 6 and Division 3a: Summary projections for <u>management strategy C</u> with individual replicates, <u>alternative OM2 (M=0.1)</u>. Solid black horizontal lines are MSY $B_{trigger}$ and F_{msy}, dashed black horizontal lines are B_{lim} and F_{lim}. See caption Figure A10.2.1 for details.

Management strategy A+D

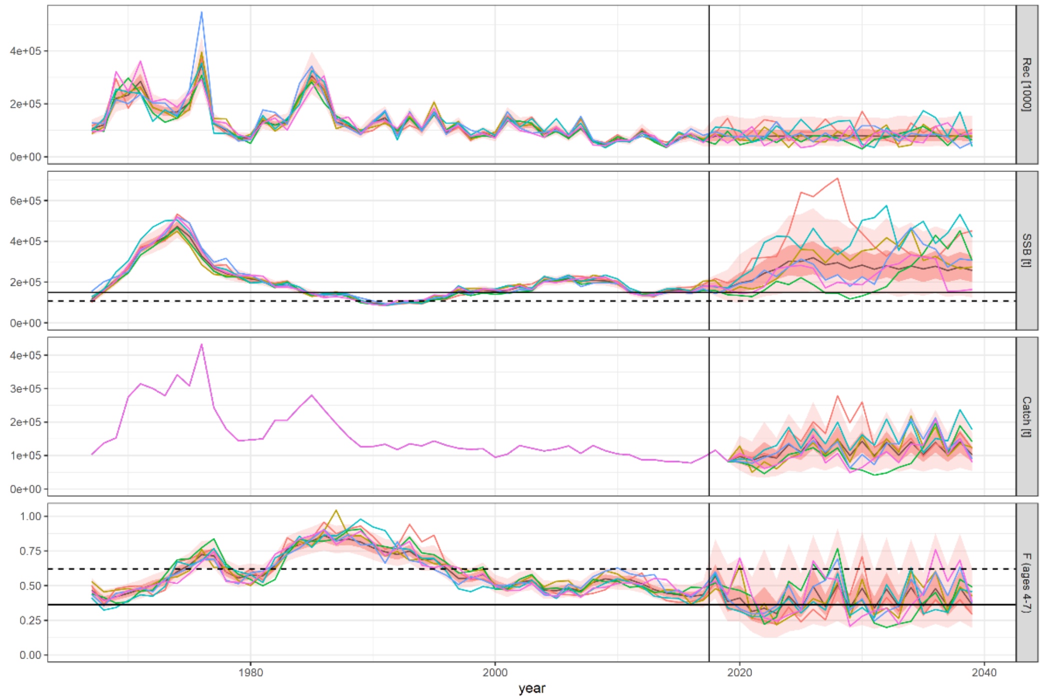

Figure A10.2.4. Saithe in Subareas 4 and 6 and Division 3a: Summary projections for management strategy A+D with individual replicates, alternative OM2 (M=0.1). Solid black horizontal lines are MSY $B_{trigger}$ and F_{msy}, dashed black horizontal lines are B_{lim} and F_{lim}. See caption Figure A10.2.1 for details.

Management strategy B+E

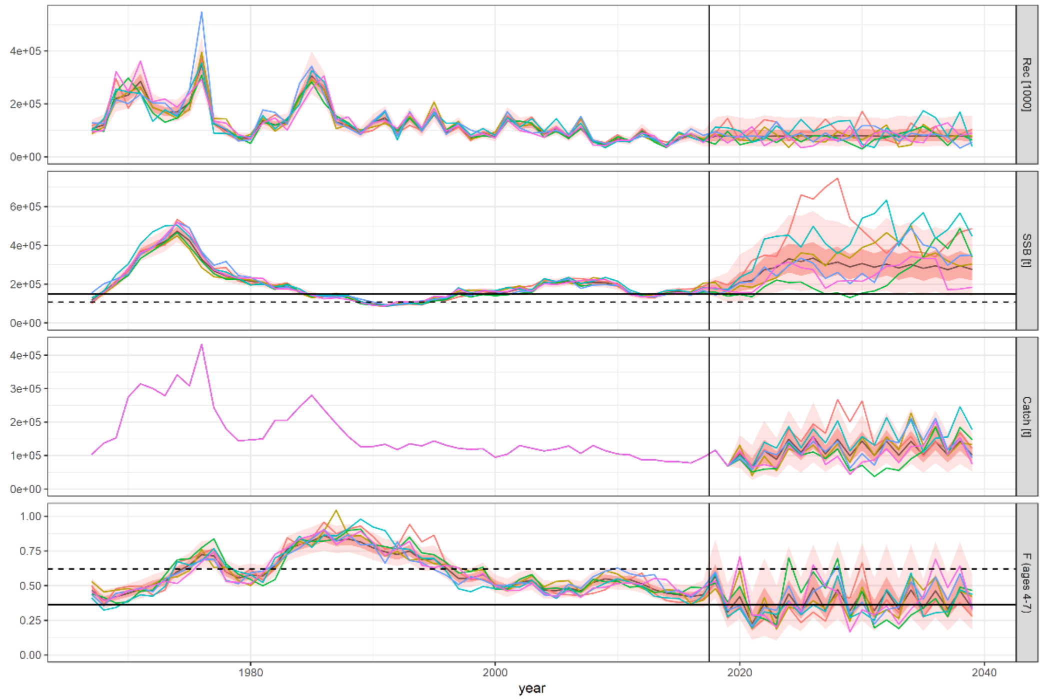

Figure A10.2.5. Saithe in Subareas 4 and 6 and Division 3a: Summary projections for <u>management strategy B+E</u> with individual replicates, <u>alternative OM2 (M=0.1)</u>. Solid black horizontal lines are MSY $B_{trigger}$ and F_{msy}, dashed black horizontal lines are B_{lim} and F_{lim}. See caption Figure A10.2.1 for details.

Management strategy C+E

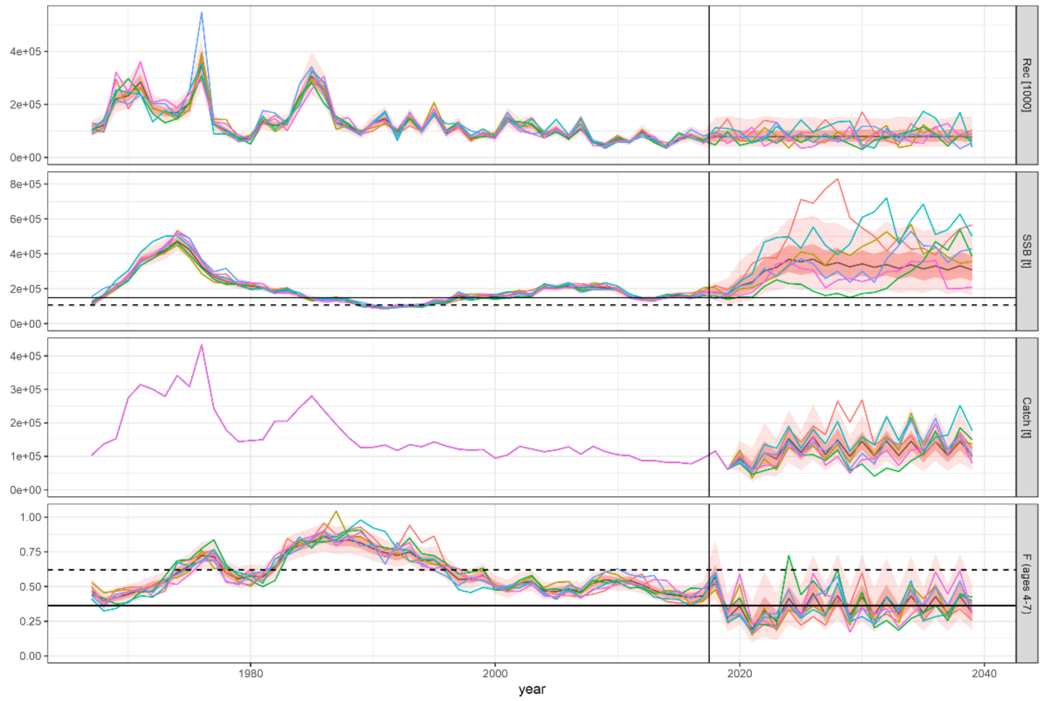

Figure A10.2.6. Saithe in Subareas 4 and 6 and Division 3a: Summary projections for <u>management strategy C+E</u> with individual replicates, <u>alternative OM2 (M=0.1)</u>. Solid black horizontal lines are MSY $B_{trigger}$ and F_{msy}, dashed black horizontal lines are B_{lim} and F_{lim}. See caption Figure A10.2.1 for details.

Management strategy A1+D

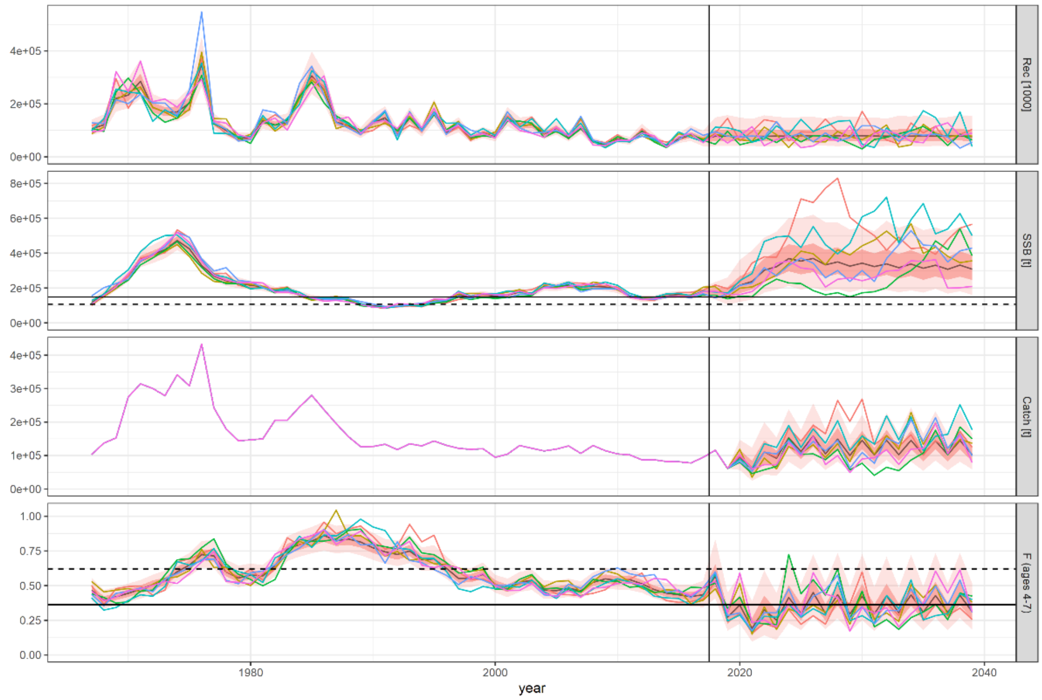

Figure A10.2.7. Saithe in Subareas 4 and 6 and Division 3a: Summary projections for management strategy A1+D with individual replicates, alternative OM2 (M=0.1). Solid black horizontal lines are MSY $B_{trigger}$ and F_{msy}, dashed black horizontal lines are B_{lim} and F_{lim}. See caption Figure A10.2.1 for details.

A10.3. Summary projection plots for OM3 (M=0.3)

Management strategy A

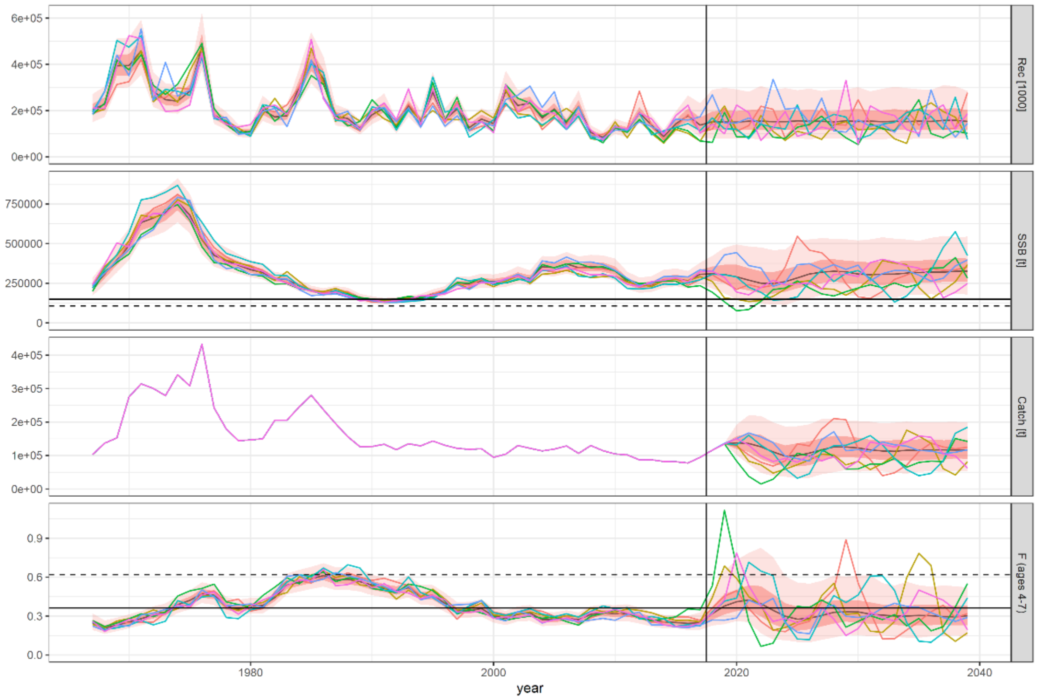

Figure A10.3.1. Saithe in Subareas 4 and 6 and Division 3a: Summary projections for management strategy A with individual replicates, alternative OM3 (M=0.3). Top plot is recruitment (age 0), second plot SSB, third plot catch and bottom plot mean F (ages 4-7). The vertical black line separates the historic period from the projection period. The SSB plot includes B_{pa}=MSY $B_{trigger}$ (horizontal solid line) and B_{lim} (horizontal hashed line), while the mean F plot includes F_{msy} (horizontal solid line) and F_{lim} (horizontal dashed line). The actual plots show medians (solid black line) with the darker shaded area indicating the 25th and 75th percentiles, and the light shaded area the 5th and 95th percentiles. The results for 5 individual replicates are shown in solid coloured lines.

Management strategy B

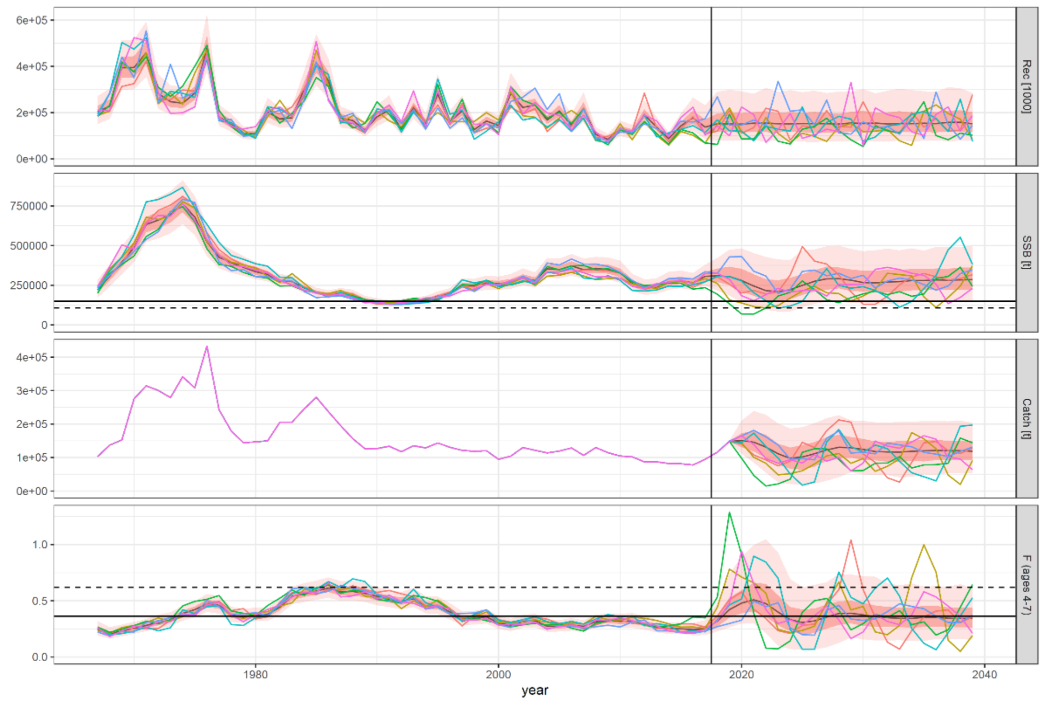

Figure A10.3.2. Saithe in Subareas 4 and 6 and Division 3a: Summary projections for management strategy B with individual replicates, alternative OM3 (M=0.3). Solid black horizontal lines are MSY $B_{trigger}$ and F_{msy}, dashed black horizontal lines are B_{lim} and F_{lim}. See caption Figure A10.3.1 for details.

Management strategy C

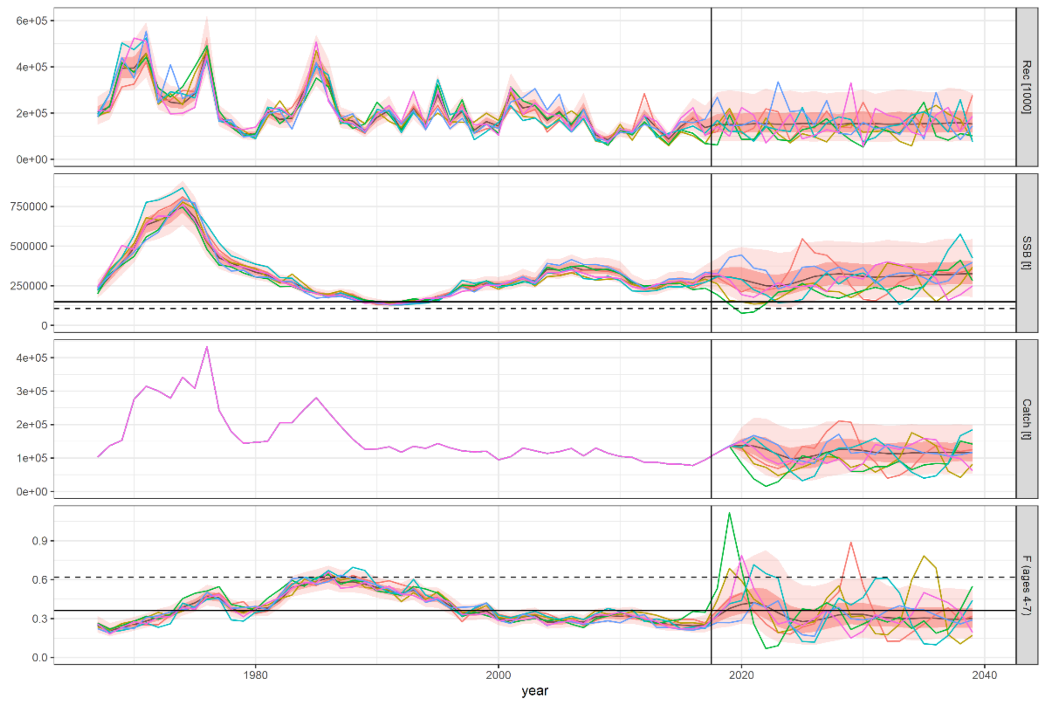

Figure A10.3.3. Saithe in Subareas 4 and 6 and Division 3a: Summary projections for management strategy C with individual replicates, alternative OM3 (M=0.3). Solid black horizontal lines are MSYB$_{trigger}$ and F_{msy}, dashed black horizontal lines are B_{lim} and F_{lim}. See caption Figure A10.3.1 for details.

Management strategy A+D

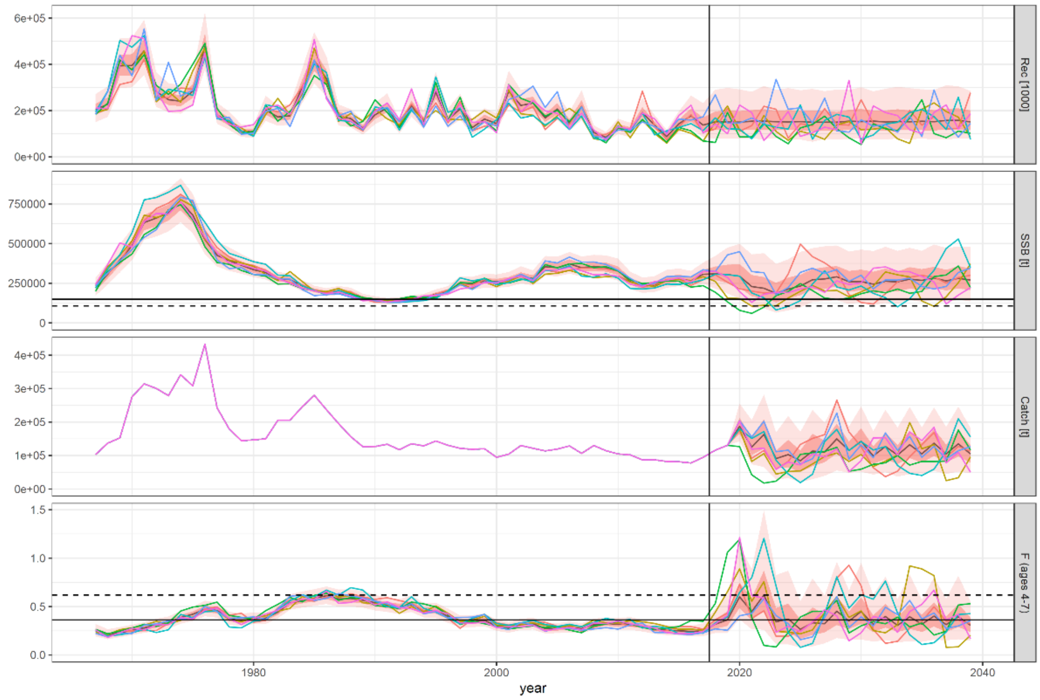

Figure A10.3.4. Saithe in Subareas 4 and 6 and Division 3a: Summary projections for <u>management strategy A+D</u> with individual replicates, <u>alternative OM3 (M=0.3)</u>. Solid black horizontal lines are MSYB$_{trigger}$ and F$_{msy}$, dashed black horizontal lines are B$_{lim}$ and F$_{lim}$. See caption Figure A10.3.1 for details.

Management strategy B+E

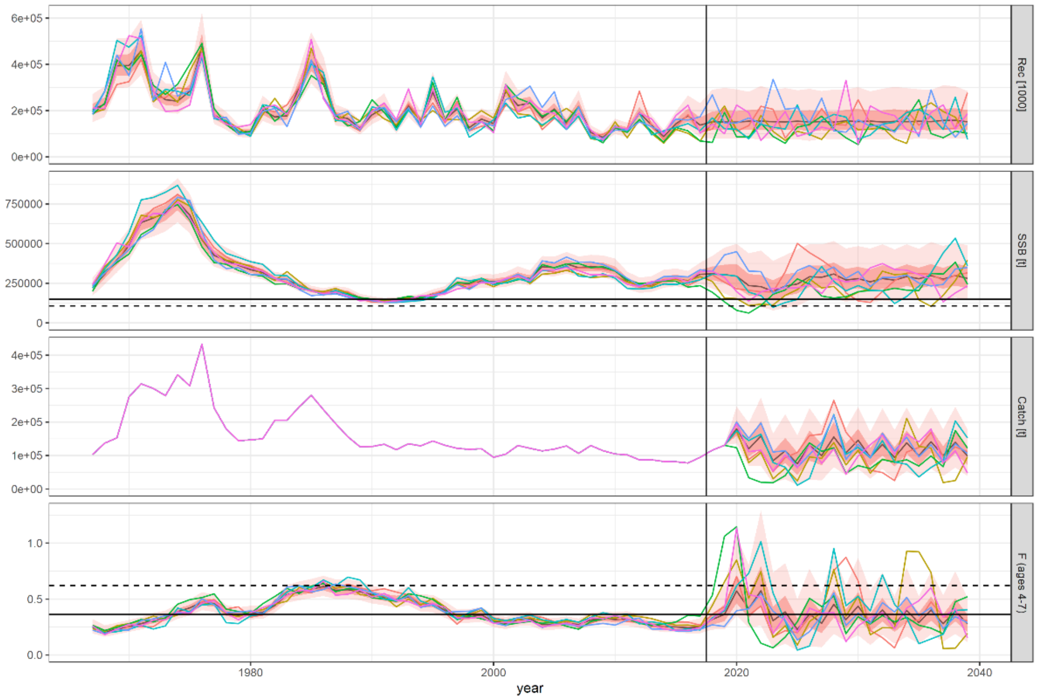

Figure A10.3.5. Saithe in Subareas 4 and 6 and Division 3a: Summary projections for <u>management strategy B+E</u> with individual replicates, <u>alternative OM3 (M=0.3)</u>. Solid black horizontal lines are MSYB$_{trigger}$ and F$_{msy}$, dashed black horizontal lines are B$_{lim}$ and F$_{lim}$. See caption Figure A10.3.1 for details.

Management strategy C+E

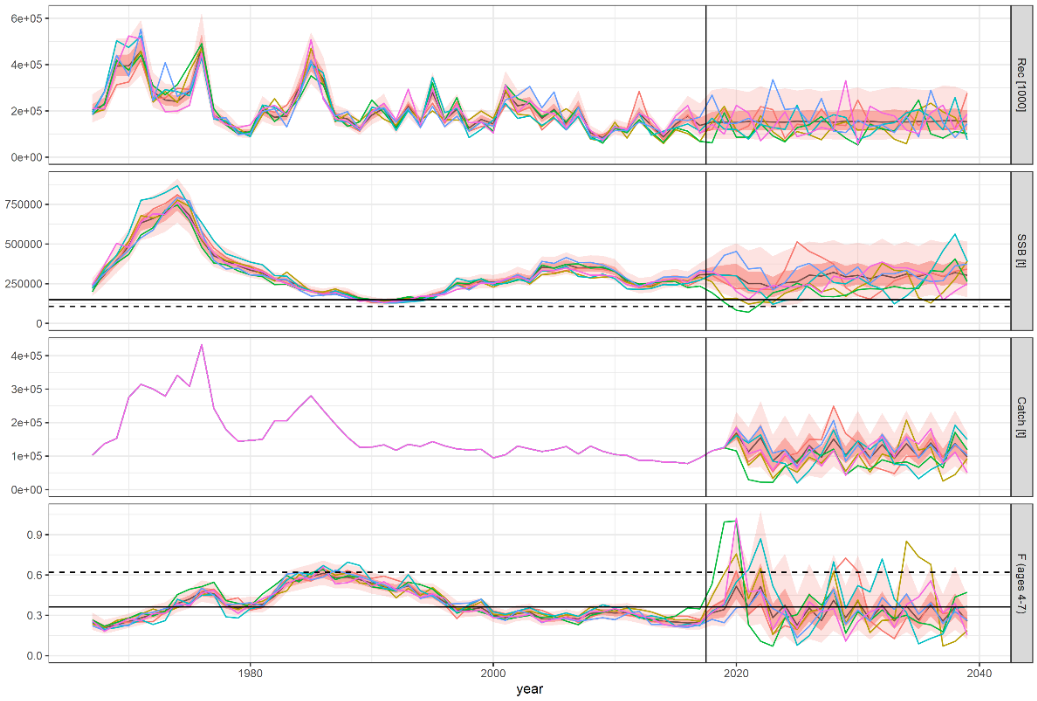

Figure A10.3.6. Saithe in Subareas 4 and 6 and Division 3a: Summary projections for <u>management strategy C+E</u> with individual replicates, <u>alternative OM3 (M=0.3)</u>. Solid black horizontal lines are MSYB$_{trigger}$ and F$_{msy}$, dashed black horizontal lines are B$_{lim}$ and F$_{lim}$. See caption Figure A10.3.1 for details.

Management strategy A1+D

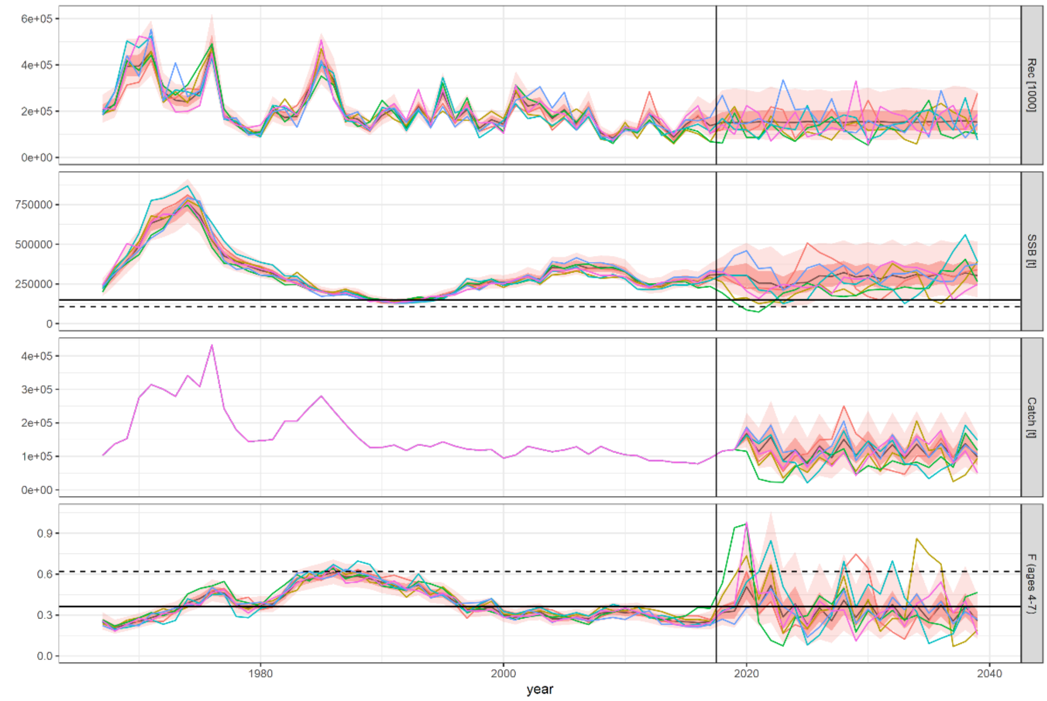

Figure A10.3.7. Saithe in Subareas 4 and 6 and Division 3a: Summary projections for management strategy A1+D with individual replicates, alternative OM3 (M=0.3). Solid black horizontal lines are MSYB$_{trigger}$ and F$_{msy}$, dashed black horizontal lines are B$_{lim}$ and F$_{lim}$. See caption Figure A10.3.1 for details.

A10.4. Sensitivity and robustness of management strategy results

Table A10.4.1. Saithe in Subareas 4 and 6 and Division 3a: sensitivity of performance statistics for the "optimised" six management strategies to a range of F$_{target}$ and B$_{trigger}$ scenarios. Statistics are reported for three time periods, short (first five years), medium (years 6-10) and long (final 10 years) term. Other statistics reported include the number of replicates where the estimation model (SAM) failed to converge, the number of replicates where F$_{max}$ (F$_{max}$ =2) was reached, the proportion of replicates that recover above B$_{pa}$=MSY B$_{trigger}$ and the number of years taken to recover above B$_{pa}$=MSY B$_{trigger}$ for the first time.

HCR		F$_{MSY-lower}$	0.9*F$_{trgt}$	F$_{trgt}$	1.1*F$_{trgt}$	F$_{MSY-upper}$
A	Ftarget	0.21	0.315	0.35	0.385	0.536
A	Btrigger	250000	250000	250000	250000	250000
A	Median catch long term	111553	115998	116700	115951	105512
A	Median SSB long term	466707	319029	292067	269275	201446
A	Realized mean F long term	0.212	0.309	0.336	0.358	0.424
A	ICV long term	0.123	0.154	0.177	0.206	0.359
A	risk3 long term	0.000	0.005	0.015	0.033	0.224
A	risk1 long term	0.000	0.003	0.010	0.023	0.166
A	Median catch medium term	115113	124307	123747	122434	108711
A	Median SSB medium term	470809	332337	302726	278572	230145
A	Realized mean F medium term	0.216	0.321	0.350	0.370	0.386
A	ICV medium term	0.141	0.168	0.185	0.210	0.369

HCR		$F_{MSY-lower}$	$0.9*F_{trgt}$	F_{trgt}	$1.1*F_{trgt}$	$F_{MSY-upper}$
A	**risk3 medium term**	0.001	0.005	0.015	0.031	0.188
A	**risk1 medium term**	0.000	0.003	0.010	0.025	0.124
A	**Median catch short term**	64241	84663	92464	100068	130018
A	**Median SSB short term**	320470	269121	251973	238157	186001
A	**Realized mean F short term**	0.177	0.276	0.312	0.350	0.525
A	**ICV short term**	0.291	0.245	0.204	0.146	0.166
A	**risk3 short term**	0.006	0.014	0.020	0.027	0.215
A	**risk1 short term**	0.002	0.005	0.010	0.018	0.136
A	**Convergence failure**	0	0	0	0	0
A	**Fmax reached**	0	1	2	11	287
B	**Ftarget**	0.21	0.351	0.39	0.429	0.536
B	**Btrigger**	200000	200000	200000	200000	200000
B	**Median catch long term**	111595	116147	116835	116200	107045
B	**Median SSB long term**	466061	280862	254513	233126	185709
B	**Realized mean F long term**	0.212	0.346	0.379	0.407	0.464
B	**ICV long term**	0.120	0.159	0.186	0.223	0.358
B	**risk3 long term**	0.000	0.013	0.034	0.072	0.258
B	**risk1 long term**	0.000	0.010	0.027	0.058	0.189
B	**Median catch medium term**	112444	119555	118752	116681	110076
B	**Median SSB medium term**	463001	289849	263398	245202	215686
B	**Realized mean F medium term**	0.214	0.348	0.377	0.397	0.419
B	**ICV medium term**	0.138	0.172	0.197	0.234	0.408
B	**risk3 medium term**	0.001	0.014	0.032	0.068	0.230
B	**risk1 medium term**	0.000	0.010	0.026	0.055	0.138
B	**Median catch short term**	68262	104210	113492	122190	136360
B	**Median SSB short term**	307063	235739	219954	204247	167825
B	**Realized mean F short term**	0.192	0.349	0.399	0.452	0.607
B	**ICV short term**	0.223	0.112	0.114	0.123	0.262
B	**risk3 short term**	0.006	0.037	0.064	0.105	0.371
B	**risk1 short term**	0.002	0.020	0.040	0.067	0.216
B	**Convergence failure**	0	0	0	0	0
B	**Fmax reached**	0	0	11	27	309
C	**Ftarget**	0.21	0.315	0.35	0.385	0.536
C	**Btrigger**	250000	250000	250000	250000	250000
C	**Median catch long term**	111553	115998	116700	115946	105105
C	**Median SSB long term**	466707	319029	292013	269184	200777
C	**Realized mean F long term**	0.212	0.309	0.336	0.358	0.422
C	**ICV long term**	0.123	0.154	0.177	0.206	0.356
C	**risk3 long term**	0.000	0.005	0.015	0.033	0.222
C	**risk1 long term**	0.000	0.003	0.010	0.023	0.164
C	**Median catch medium term**	115113	124307	123747	122434	108398
C	**Median SSB medium term**	470809	332337	302726	278572	229557
C	**Realized mean F medium term**	0.216	0.321	0.350	0.370	0.385
C	**ICV medium term**	0.141	0.168	0.185	0.210	0.369
C	**risk3 medium term**	0.001	0.005	0.015	0.031	0.188
C	**risk1 medium term**	0.000	0.003	0.010	0.025	0.124
C	**Median catch short term**	64241	84663	92464	100068	130018
C	**Median SSB short term**	320470	269121	251973	238157	185972
C	**Realized mean F short term**	0.177	0.276	0.312	0.350	0.525
C	**ICV short term**	0.291	0.245	0.204	0.146	0.166
C	**risk3 short term**	0.006	0.014	0.020	0.027	0.215
C	**risk1 short term**	0.002	0.005	0.010	0.018	0.136

HCR		$F_{MSY\text{-}lower}$	$0.9*F_{trgt}$	F_{trgt}	$1.1*F_{trgt}$	$F_{MSY\text{-}upper}$
C	Convergence failure	0	0	0	0	0
C	Fmax reached	0	1	2	11	283
A+D	Ftarget	0.21	0.369	0.41	0.451	0.536
A+D	Btrigger	210000	210000	210000	210000	210000
A+D	Median catch long term	107988	111781	112250	110654	103949
A+D	Median SSB long term	464418	267908	249213	222015	187787
A+D	Realized mean F long term	0.206	0.347	0.380	0.402	0.443
A+D	ICV long term	0.364	0.337	0.335	0.345	0.387
A+D	risk3 long term	0.000	0.024	0.043	0.110	0.265
A+D	risk1 long term	0.000	0.016	0.033	0.079	0.183
A+D	Median catch medium term	113727	119551	117009	114394	107607
A+D	Median SSB medium term	463087	281003	262907	240807	217189
A+D	Realized mean F medium term	0.220	0.362	0.385	0.389	0.402
A+D	ICV medium term	0.405	0.371	0.361	0.365	0.409
A+D	risk3 medium term	0.000	0.018	0.037	0.091	0.224
A+D	risk1 medium term	0.000	0.015	0.028	0.065	0.128
A+D	Median catch short term	80037	98333	106994	115466	130509
A+D	Median SSB short term	287929	227936	211176	197507	168794
A+D	Realized mean F short term	0.198	0.356	0.416	0.460	0.570
A+D	ICV short term	0.280	0.255	0.255	0.257	0.276
A+D	risk3 short term	0.013	0.051	0.092	0.152	0.347
A+D	risk1 short term	0.005	0.027	0.048	0.091	0.213
A+D	Convergence failure	0	0	0	0	0
A+D	Fmax reached	0	6	15	57	298
B+E	Ftarget	0.21	0.351	0.39	0.429	0.536
B+E	Btrigger	220000	220000	220000	220000	220000
B+E	Median catch long term	108041	112214	112562	111413	103027
B+E	Median SSB long term	464202	282358	263268	236341	190758
B+E	Realized mean F long term	0.206	0.331	0.364	0.385	0.433
B+E	ICV long term	0.361	0.358	0.364	0.378	0.446
B+E	risk3 long term	0.000	0.014	0.032	0.079	0.255
B+E	risk1 long term	0.000	0.010	0.020	0.056	0.180
B+E	Median catch medium term	114524	122411	120358	118709	111740
B+E	Median SSB medium term	464755	295423	275878	252672	225351
B+E	Realized mean F medium term	0.222	0.357	0.383	0.394	0.412
B+E	ICV medium term	0.414	0.416	0.429	0.455	0.534
B+E	risk3 medium term	0.000	0.011	0.027	0.060	0.195
B+E	risk1 medium term	0.000	0.010	0.019	0.048	0.122
B+E	Median catch short term	79972	93257	101448	109598	130138
B+E	Median SSB short term	289121	238649	220310	207129	170766
B+E	Realized mean F short term	0.197	0.328	0.380	0.422	0.556
B+E	ICV short term	0.280	0.305	0.305	0.302	0.304
B+E	risk3 short term	0.013	0.037	0.075	0.120	0.336
B+E	risk1 short term	0.005	0.018	0.037	0.063	0.204
B+E	Convergence failure	0	0	0	0	0
B+E	Fmax reached	0	1	8	34	307
C+E	Ftarget	0.21	0.324	0.36	0.396	0.536
C+E	Btrigger	230000	230000	230000	230000	230000
C+E	Median catch long term	108059	112074	112351	111995	102769
C+E	Median SSB long term	464353	305913	285057	256130	193460
C+E	Realized mean F long term	0.206	0.309	0.339	0.361	0.422
C+E	ICV long term	0.360	0.356	0.360	0.367	0.432

HCR		$F_{MSY-lower}$	0.9*F_{trgt}	F_{trgt}	1.1*F_{trgt}	$F_{MSY-upper}$
C+E	risk3 long term	0.000	0.008	0.015	0.043	0.250
C+E	risk1 long term	0.000	0.004	0.010	0.029	0.171
C+E	Median catch medium term	115116	123581	122037	120936	109583
C+E	Median SSB medium term	466117	319800	295801	267874	224006
C+E	Realized mean F medium term	0.222	0.336	0.364	0.382	0.401
C+E	ICV medium term	0.413	0.407	0.414	0.432	0.506
C+E	risk3 medium term	0.000	0.005	0.012	0.034	0.192
C+E	risk1 medium term	0.000	0.004	0.009	0.028	0.119
C+E	Median catch short term	79642	84851	91833	99234	125950
C+E	Median SSB short term	290488	254805	238535	223323	175019
C+E	Realized mean F short term	0.195	0.290	0.336	0.369	0.538
C+E	ICV short term	0.280	0.306	0.309	0.313	0.306
C+E	risk3 short term	0.013	0.018	0.037	0.066	0.304
C+E	risk1 short term	0.005	0.009	0.017	0.033	0.183
C+E	Convergence failure	0	0	0	0	0
C+E	Fmax reached	0	1	2	12	301
A_1+D	Ftarget	0.21	0.324	0.36	0.396	0.536
A_1+D	Btrigger	230000	230000	230000	230000	230000
A_1+D	Median catch long term	108063	111960	112377	112003	103361
A_1+D	Median SSB long term	464403	305582	284997	256261	194569
A_1+D	Realized mean F long term	0.206	0.308	0.339	0.361	0.425
A_1+D	ICV long term	0.360	0.355	0.360	0.368	0.431
A_1+D	risk3 long term	0.000	0.007	0.015	0.043	0.248
A_1+D	risk1 long term	0.000	0.004	0.010	0.029	0.170
A_1+D	Median catch medium term	114881	123407	122050	120936	108785
A_1+D	Median SSB medium term	465419	321098	295801	267938	222640
A_1+D	Realized mean F medium term	0.221	0.335	0.364	0.382	0.402
A_1+D	ICV medium term	0.412	0.412	0.414	0.432	0.512
A_1+D	risk3 medium term	0.000	0.005	0.012	0.034	0.196
A_1+D	risk1 medium term	0.000	0.004	0.009	0.028	0.122
A_1+D	Median catch short term	78681	88746	91833	99234	120068
A_1+D	Median SSB short term	286146	250541	238535	223323	178851
A_1+D	Realized mean F short term	0.196	0.296	0.336	0.369	0.524
A_1+D	ICV short term	0.237	0.294	0.309	0.313	0.319
A_1+D	risk3 short term	0.016	0.024	0.037	0.066	0.303
A_1+D	risk1 short term	0.005	0.011	0.017	0.033	0.167
A_1+D	Convergence failure	0	0	0	0	0
A_1+D	Fmax reached	0	1	2	12	295

Table A10.4.2. Saithe in Subareas 4 and 6 and Division 3a: Performance statistics for the various management strategies with alternate operating models. The operating models are OM2 (M=0.1) and OM3 (M=0.3) and are described in Sections 6.1–6.2.

HCR	A	B	C	A+D	B+E	C+E	A_1+D	A	B	C	A+D	B+E	C+E	A_1+D
OM	OM2	OM2	OM2	OM2	OM2	OM2	OM2	OM3	OM3	OM3	OM3	OM3	OM3	OM3
F_{target}	0.35	0.39	0.35	0.41	0.39	0.36	0.36	0.35	0.39	0.35	0.41	0.39	0.36	0.36
$B_{trigger}$	250000	200000	250000	210000	220000	230000	230000	250000	200000	250000	210000	220000	230000	230000
Median catch long term	124462	121712	124462	116003	117901	119564	119564	117393	120134	117353	116240	115653	114223	114351
Median SSB long term	342538	288173	342538	269399	290196	324552	324552	315278	277186	315445	266187	280137	300738	300706
Realized mean F long term	0.355	0.398	0.355	0.401	0.385	0.357	0.357	0.308	0.354	0.308	0.352	0.335	0.310	0.310
ICV long term	0.142	0.146	0.142	0.340	0.350	0.346	0.345	0.191	0.205	0.191	0.322	0.370	0.363	0.363
risk3 long term	0.002	0.010	0.002	0.016	0.009	0.005	0.005	0.025	0.054	0.025	0.090	0.061	0.032	0.032

risk1 long term	0.001	0.006	0.001	0.011	0.005	0.002	0.002	0.013	0.038	0.013	0.056	0.039	0.018	0.018
Median catch medium term	135710	126381	135710	127927	131437	133290	133290	109313	112715	109255	109853	113294	113100	113062
Median SSB medium term	378628	313342	378628	299370	317679	355010	355010	301542	267336	301281	257750	273670	288433	288167
Realized mean F medium term	0.362	0.386	0.362	0.408	0.401	0.378	0.378	0.298	0.341	0.298	0.339	0.337	0.320	0.320
ICV medium term	0.169	0.167	0.169	0.366	0.396	0.388	0.388	0.229	0.247	0.229	0.350	0.455	0.432	0.432
risk3 medium term	0.003	0.009	0.003	0.012	0.008	0.003	0.003	0.077	0.147	0.077	0.189	0.132	0.082	0.082
risk1 medium term	0.001	0.004	0.001	0.007	0.003	0.001	0.001	0.034	0.073	0.034	0.091	0.068	0.043	0.044
Median catch short term	70972	83909	70972	83615	79214	75217	75217	134829	147141	134829	130509	130509	125258	120068
Median SSB short term	257697	214700	257697	212006	226933	242965	242965	272971	252356	272971	248056	254155	266622	269800
Realized mean F short term	0.257	0.353	0.257	0.352	0.316	0.279	0.279	0.394	0.459	0.394	0.466	0.440	0.399	0.394
ICV short term	0.329	0.255	0.329	0.282	0.409	0.467	0.467	0.165	0.217	0.165	0.309	0.311	0.308	0.319
risk3 short term	0.018	0.032	0.018	0.032	0.018	0.018	0.018	0.091	0.190	0.091	0.267	0.220	0.154	0.153
risk1 short term	0.007	0.015	0.007	0.017	0.011	0.007	0.007	0.053	0.104	0.053	0.122	0.105	0.074	0.069
Convergence failure	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fmax reached	0	1	0	5	2	0	0	0	17	0	27	18	8	6

Annex 11: Additional Results for autumn-spawning herring

Summary projections for the management strategies that were “optimised” (A, B, A+C, A+D), showing worm plots for the same randomly selected replicates. Note, it was not possible to “optimise” B+E, as explained in the main text.

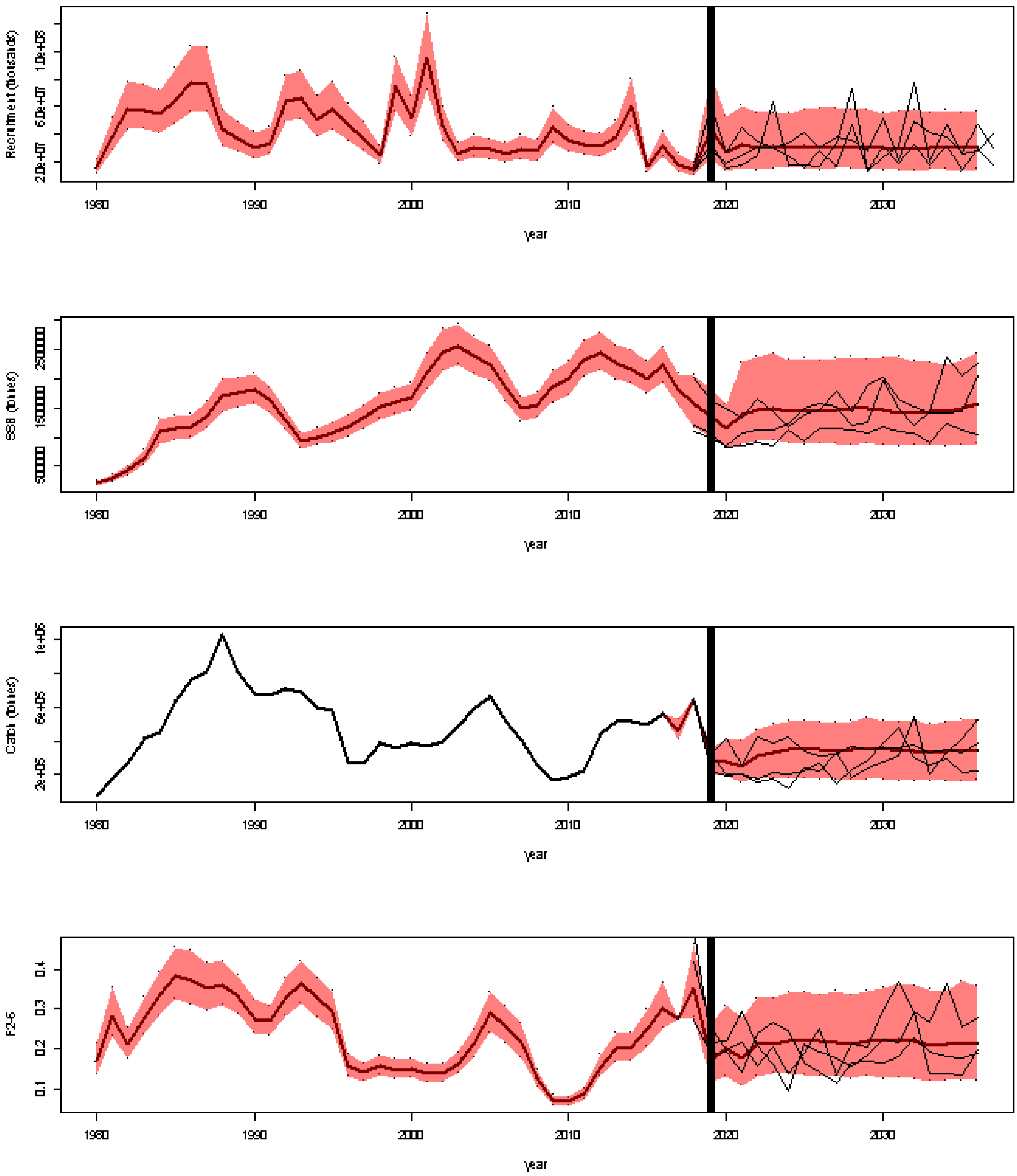

Figure A11.1: North Sea herring. Stock trends of the OM for the optimal HCR A strategy (F_{target}=0.22, $B_{trigger}$=1400000). Top panel shows recruitment, followed by SSB, followed by catch and finally Fbar on 2-6 (adult fishery). Individual replicates are shown as worm plots.

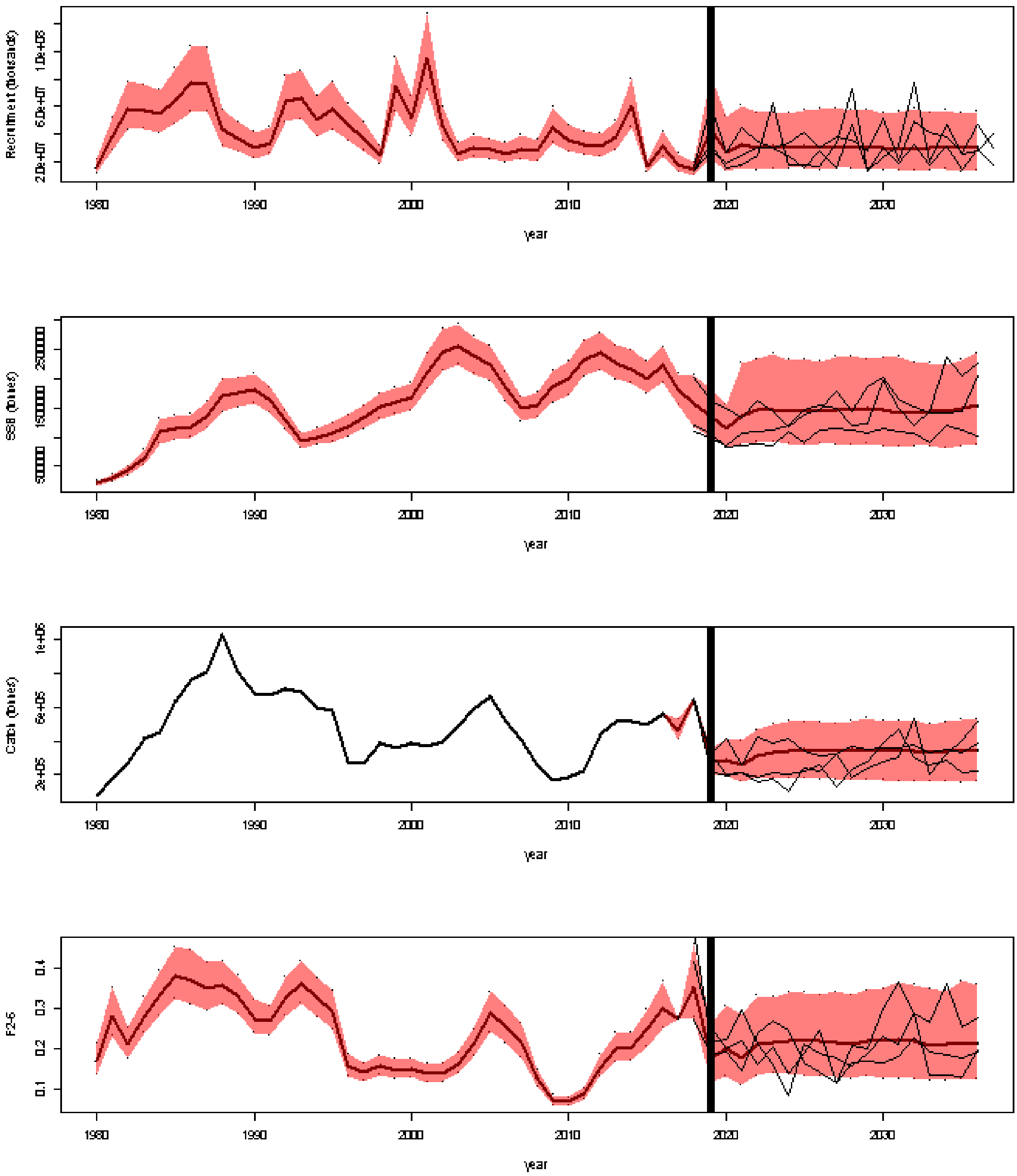

Figure A11.2: North Sea herring. Stock trends of the OM for the optimal HCR B strategy (F_{target}=0.22, $B_{trigger}$=1400000). Top panel shows recruitment, followed by SSB, followed by catch and finally Fbar on 2-6 (adult fishery). Individual replicates are shown as worm plots.

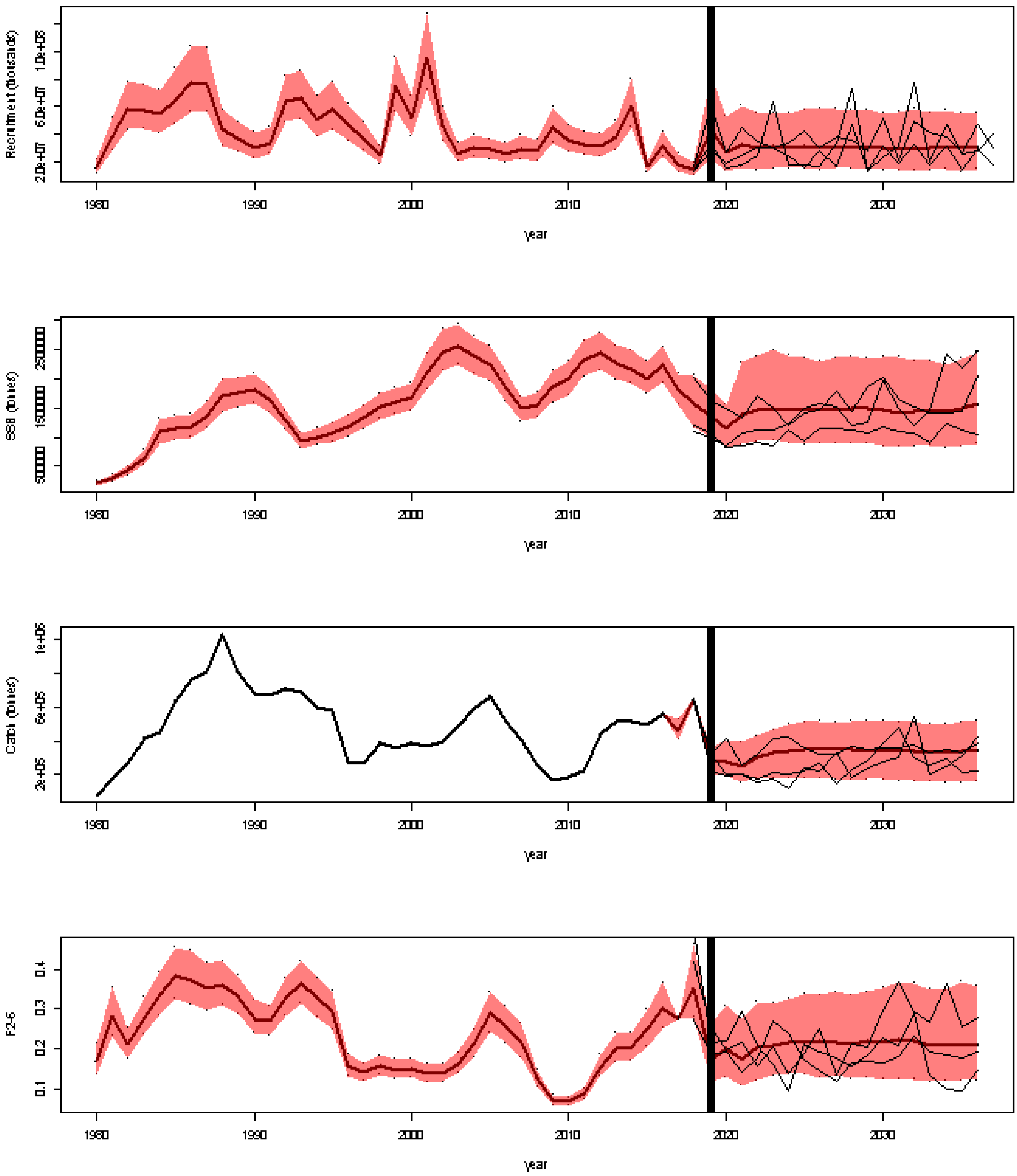

Figure A11.3: North Sea herring. Stock trends of the OM for the optimal HCR A+C strategy (F_{target}=0.22, $B_{trigger}$=1400000). Top panel shows recruitment, followed by SSB, followed by catch and finally Fbar on 2-6 (adult fishery). Individual replicates are shown as worm plots.

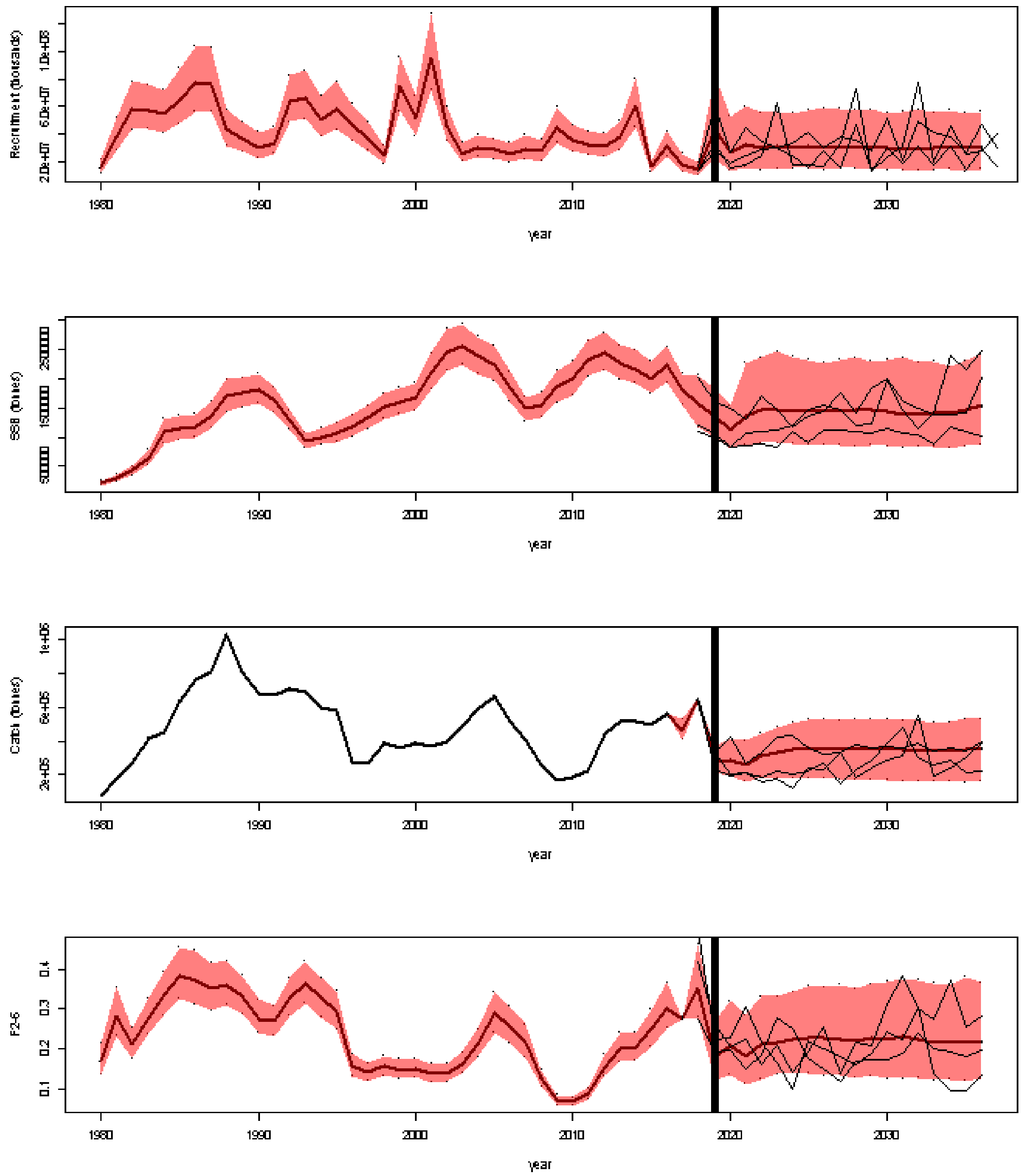

Figure A11.4: North Sea herring. Stock trends of the OM for the optimal HCR A+D strategy (F_{target}=0.23, $B_{trigger}$=1400000). Top panel shows recruitment, followed by SSB, followed by catch and finally Fbar on 2-6 (adult fishery). Individual replicates are shown as worm plots.