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Northwest Atlantic Fisheries Organization

Report of the NAFO Joint Commission-Scientific Council Working Group on Risk-Based Management Strategies (WG-RBMS) Meeting

21 September 2019
Bordeaux, France

NAFO
Dartmouth, Nova Scotia, Canada
2019

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1. Opening by the co-Chairs, Carmen Fernández (European Union) and Jacqueline Perry (Canada)

The meeting was opened at 09:30 hours on Saturday, 21 September 2019. The co-Chairs, Carmen Fernández (European Union) and Jacqueline Perry (Canada), welcomed representatives from Canada, European Union, France (in respect of St. Pierre et Miquelon), Japan, Norway and United States of America (Annex 1).

2. Appointment of Rapporteur

NAFO Secretariat (Tom Blasdale, Scientific Council Coordinator and Ricardo Federizon, Senior Fisheries Management Coordinator) were appointed as co-Rapporteurs.

3. Adoption of Agenda

The agenda was adopted with the addition of the following under agenda item 5, "*Other Business*" (Annex 2):

- 5.c – Work items and preparations for the August 2020 meeting.

4. 3M cod Management Strategy Evaluation (MSE)

a. Review objectives for the current meeting

The co-Chair, Carmen Fernández (European Union), provided a summary of the 3M Cod MSE process in the last year.

A work plan was agreed in September 2018 that aimed to have the MSE process complete by the time of the NAFO Annual Meeting in September 2019. In line with the plan, Scientific Council (SC) had a meeting in January 2019 and this Working Group in April 2019. In addition, a very significant amount of intersessional work has been done by the Technical Team, and their dedication to this work and the quality of their contributions were greatly appreciated by the meeting participants. The initial objective of this meeting, according to the work plan, had been to finalize the 3M cod MSE for presentation the Commission. However, at the WG-RBMS meeting in April, it became clear that this original aim was not achievable (see below).

Significant progress was made during the SC meeting (SCS Doc. 19-04 Rev.) in January 2019 and WG-RBMS meeting (COM-SC Doc. 19-01) of April 2019. A total of 432 MSE scenarios were identified through combinations of different Operating Model (OM) settings (three settings for each of: natural mortality M in historical years, recruitment in future years and biological parameters in future years) and Harvest Control Rule (HCR) settings (model-free slope and model-free target HCR types, with some alternative options for tuning parameters, constraints on interannual TAC change and starting point for application of the HCR). Table 1 provides a summary of the different settings.

Table 1. Specifications of the scenarios (with Scenario naming convention in parenthesis). Base-Case OM in bold.

	Variables	Scenarios		
HCR settings	HCR names	Model-Free Slope (MFS)	Model-Free Target (MFT)	
	α (tuning parameter in HCR)	1.0 (A10)	1.5 (A15)	
	Constraint on inter-annual TAC change	None (Cnone)	±20% (C20)	
	Starting Point*	TAC(2019)=17500 t (SP0)	TAC(2019)–25%=13125 t (SP25)	
OM settings	Natural Mortality (until year 2017)	**M vector (MV)**	M GADGET (MG)	M Steps (MS)
	Recruitment (2018 onwards)	**Bin Ricker (BR)**	Hockey Stick (HS)	Low Bin Ricker (LBR)
	Biological parameters (2018 onwards)	**Random walk (RW)**	3 Years Mean (3Y)	Density Dependent (DD)
	Groups q (age groups for survey catchability)	**Flat Shape (F)**	Dome Shape (D)	

* *When the management strategy is applied for the first time (i.e. for year 2020 in the MSE simulation), the TAC obtained from the HCR is calculated starting from this value instead of starting from the adopted 2019 TAC.*

Due to time constraints it was not possible to run all of these MSE trials prior to the April meeting. For that meeting, a subset based on OMs including MV or MG settings for natural mortality, BR or HS settings for recruitment, and RW or 3Y settings for biological parameters was run.

A main observation emerging from the MSE results presented in April was the very wide range of uncertainty obtained in projections, which was linked to the high variability observed in the past in recruitment and biological parameters. This wide range of uncertainty makes it difficult to find HCRs fulfilling the risk criterion of no more than 10% probability of falling below B_{lim}. This difficulty is exacerbated by the poor recruitment observed since 2015, with the consequent strong stock declines expected over the next few years. All of the OMs resulted in more than 10% probability of the stock being below B_{lim} in some future years when the slope or target HCRs were applied. In scenarios where fishing mortality was set at zero (simulating a closed fishery for 2020 and beyond), the probability of being below B_{lim} did not exceed 10%. However, it was then noted that a scenario where the current low recruitment would continue for a few more years had not yet been tested and that this would likely result in the 10% probability being exceeded.

Because of these observations, the April WG-RBMS meeting raised significant doubts as to the feasibility that the MSE would be able to find HCRs fulfilling management objectives, particularly the risk criterion relative to B_{lim}. It was concluded that the aim of having the MSE completed by September 2019 would certainly not be achieved and there was significant doubt as to whether it would be possible to complete the process at all. Consequently, it was agreed that the technical team would continue their work on low recruitment and density-dependent OMs for presentation at an additional meeting of WG-RBMS immediately prior to the 2019 Annual meeting, at which point WG-RBMS would make a recommendation on whether to proceed with the MSE and, if the recommendation were to proceed, propose revised timelines for the process.

b. Presentation of new results from the technical team for 3M cod MSE process

For documentation purposes, the report of the technical team, led by F. González-Costas, D. González-Troncoso, C. Fernández and A. Urtizberea, is annexed in this report (Annex 3). New MSE simulations were performed intersessionally for scenarios not available in April, including OMs with settings as follows: MS for natural mortality (historical natural mortality changing over time), HR for future recruitment (Historical Recruitment - the current run of poor recruitment continues for several more years), and DD for future biological parameters (density-dependent).

It was initially planned that the low recruitment scenario would consist of ten consecutive years of low recruitment followed by application of the bin-Ricker scenario (labelled as LBR in Table 1). However, it was observed that, at the low biomass levels following the low recruitment period, the Bin-Ricker gave continuing low recruitment, resulting in virtually zero probability of recovery, contrary to what has been observed for the stock in the past. Consequently, it was decided that the low recruitment scenario would consist of ten years of low recruitment followed by a period of medium to high recruitment.

Some main conclusions from the new and previous results were as follows:

- Recruitment and biological parameters have shown very high variability in the historical period with strong trends in the recent past. There are considerable difficulties to simulate recruitment in a realistic way going into the future.

- MSE results from DD scenarios for future biological parameters display lower uncertainty than 3Y and RW scenarios (Figure 1). However, the uncertainty associated with DD scenarios may be underestimated. On the other hand, the great uncertainty in projected outcomes under RW scenarios may be in part due to their difficulty in adequately capturing the behaviour observed in biological parameters in the past.

- MSE results of most of MS scenarios for natural mortality show much greater variability than for MG and MV scenarios. To reduce this great variability, scenarios with weight-related natural mortality could be considered in the future. The DD scenarios presently developed for biological parameters did not include density-dependence in future natural mortality.

- In the low recruitment scenario, there is a high probability of falling below B_{lim}, even with F=0 (Figure 2). The low recruitment OM developed (labelled HR) assumes a fairly long period of low recruitment in the future. This may be pessimistic; however, a similar period of continuous low recruitment has been observed in the past.

- The results show that none of the HCRs tested so far meets the accepted risk levels for SSB below B_{lim} and F above F_{lim}. These HCRs need a reformulation and a much deeper study, both in their formulation and the values of the parameters. Any alternative HCRs proposed in the future should allow the closure and opening of the fishery depending on the state of the resource (biomass levels, recruitments).

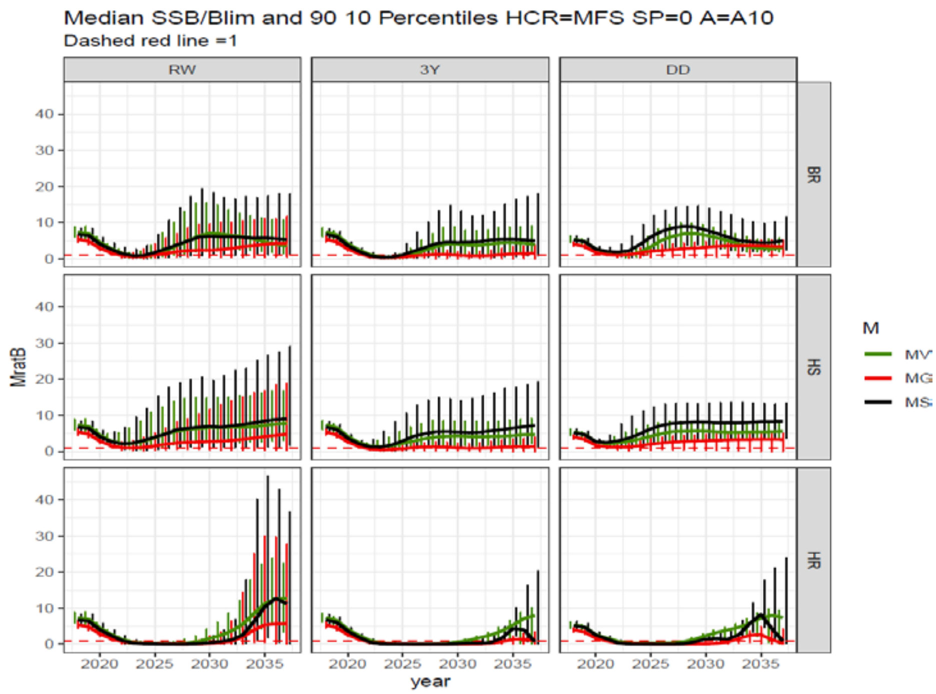

Figure 1. SSB/B_{lim} in future years under a slope-type HCR. Rows and columns correspond to scenarios for future recruitment and biological parameters, respectively. The different colours within each panel correspond to scenarios for historical natural mortality. For each scenario, the figures display median, 10th and 90th of the projected distribution of SSB/B_{lim}. The dashed horizontal line corresponds to SSB/B_{lim} =1 (i.e. SSB=B_{lim}).

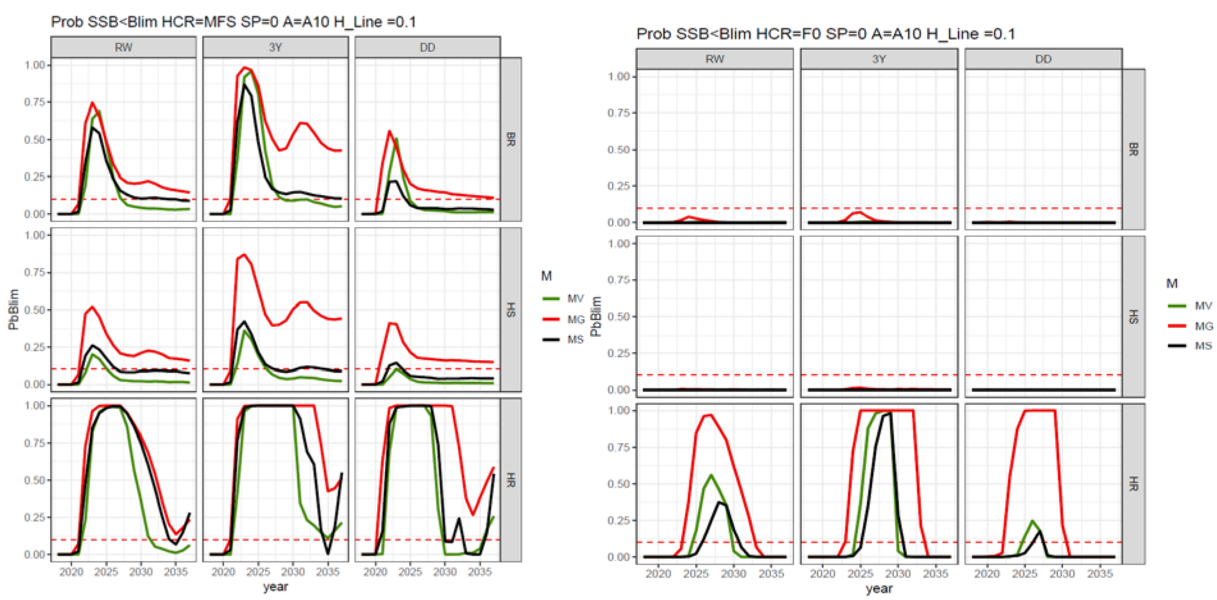

Figure 2. P(SSB<B_{lim}) in future years under a slope-type HCR (left panel) or F=0 (right panel). Rows and columns correspond to scenarios for future recruitment and biological parameters, respectively. The different colours within each panel correspond to scenarios for historical natural mortality. The dashed horizontal line corresponds to 0.1 (i.e. 10% probability of SSB< B_{lim}).

c. Discussion of next steps, including whether to proceed with or to halt the current 3M Cod MSE (If the decision is to proceed, a revision of the timeline should be provided)

WG-RBMS concluded that work in WG-RBMS on the 3M cod MSE should be suspended for the time being. This conclusion was reached based on the strong variability observed in the stock dynamics and biological parameters in the past, that create substantial difficulties for developing realistic future simulations and successful development of an HCR. This situation, coupled with the low recruitment observed in recent years that will likely result in a strong decline of the stock biomass even without a fishery, implies that developing an HCR is not considered feasible at this stage. Reopening this issue in WG-RBMS should occur when SC determines that conditions are such that there is a reasonable probability of success.

WG-RBMS highlights the enormous amount of hard work that has gone into this process, particularly from the technical team, whose efforts and good quality of their work were gratefully acknowledged. The MSE process has included additional meetings of SC with external invited experts and a very significant amount of intersessional work. As a consequence, even though this work has not resulted in immediate success, a lot of knowledge and expertise has been gained, which will be an asset to any future MSE process.

Concerning future MSE processes, WG-RBMS noted that significant challenges were encountered in meeting the timetable set for the MSE processes for both 3M Cod and 2+3KLMNO Greenland halibut. This resulted in insufficient time for adequate review and documentation of the results. WG-RBMS recommends that timeframes set for future MSE processes should be realistic, taking full account of the very large amount of work required. Sufficient time and human capacity should be allowed for the development of the technical work, review, communication with relevant actors and reporting of results.

d. Presentation of the single overall “guiding and summary” document for the 3M cod MSE process, including the main results and conclusions from the WG-RBMS meetings

The purpose of this document is to provide a single reference document where all of the main decisions are recorded with appropriate references so that someone not familiar with the MSE can follow the decision-making process. The development of this document began at the April 2019 meeting; however, due to time constraints, the draft was not further developed. The SC Coordinator will prepare a draft document incorporating the existing summaries of the January and April meetings, and a summary of the present meeting (to be provided by the co-chairs once the report is finalized), which will be circulated to the Working Group by end of October for review.

e. Archiving the code data sets and results

Archiving of code, data and results was discussed during the April meeting where it was decided that the Secretariat would investigate options. The SC Coordinator reported that there had been no progress towards storing and making code available through GitHub; however, the present meeting concluded that this is not what is what is required. Instead it was agreed that the data will be archived on the NAFO system with requests for access directed through the Secretariat. The technical team will prepare the files and the Secretariat will archive them on the NAFO server.

5. Other Business

a. Brief discussion on the Greenland halibut MSE process, as noted at the SC meeting in June 2019.

The SC Chair reported on difficulties encountered during the determination of exceptional circumstances (EC) for Greenland halibut in the June SC meeting. The EC criteria require comparison of the annual survey data with projections produced under the MSE. A problem was detected with the confidence intervals of projections produced under the SSM operating model, but it was not possible to determine the cause or extent of the issue within the timeframe of the June meeting. It will be necessary to look at the code for the SSM model to determine what the problem is: this could be simply an output or plotting problem, or may be something deeper in the OM. It is expected that this investigation will be done before the next June SC meeting.

As a result of the detected issue, it was not possible to do the comparison for the SSM model during the June meeting and, therefore, the EC assessment was based only on the SCAA model. SC advice has commented on the lack of complete documentation in the Greenland halibut MSE process as a result of the accelerated timelines followed in that MSE process. The complexity of the work implies that there is a substantial risk that mistakes will occur in any MSE process and it is necessary to build sufficient review time into the process so that any errors can be captured.

SC will advise WG-RBMS at its August 2020 meeting of the results of the investigation and of any implications for the Greenland halibut MSE implementation, should they be identified.

b. 3LN redfish Conservation Plan and Harvest Control Rule; planning for review/evaluation of the plan, which expires in 2020 (See Annex I.H of NAFO CEM)

The current 3LN redfish Conservation Plan and Harvest Control Rule provides direction on the TAC up to and including 2020. Annex I.H of the CEM requires to perform a "full review/evaluation" of the management strategy. WG-RBMS noted that this does not necessarily imply that the rule should be replaced. It was noted that the current rule was intended to maintain the biomass in the "safe zone", as defined by the NAFO PA Framework and that it had been tested by SC in 2014 against six operating models. It is however uncertain whether the current TAC of 18 100 tonnes is sustainable in the long term.

After discussing the matter, WG-RBMS concluded the following:

WG-RBMS recommends to the Commission that SC be asked in 2020 to do an update assessment and five-year projections (2021 to 2025) to evaluate the impact of annual removals at 18 100 tonnes against the following performance statistics (from NCEM annex I.H):

(a) Very low (< 10%) probability of biomass declining below B_{lim}.

(b) Low (< 30%) probability of fishing mortality >F_{msy}

(c) Less than 50% probability of declining below 80% B_{msy} on or before 2026

If this level of catch does not result in fulfilling these performance statistics, SC should advise the level of catch that would.

WG-RBMS will consider the SC response at its August 2020 meeting and discuss next steps for review/evaluation of the management strategy.

c. Work items and preparations for the August 2020 meeting.

Since it was decided to suspend the 3M cod MSE work, the focus of the WG-RBMS agenda for 2020 shifted to the NAFO Precautionary Approach Framework review.

It was noted that the PA review has been a standing agenda item of the WG for several years (see Annex 3 of FC-SC Doc. 16-01), and the Commission have classified this item as a priority. The NAFO external performance review has also highlighted the importance of this work. However, there is no development on this review. Problems that hindered the development, as noted in the previous meeting reports of this Working Group and of the Commission, include:

- original experts moved on and are no longer available,
- heavy workload due to the competing priority with MSE work.

It was decided that there will be a WebEx meeting of WG-RBMS in the early part of 2020 to scope what has to be prepared in regards to the PA framework review, which will be a main agenda item in the August meeting. The co-Chairs will prepare the draft agenda for this Web-Ex meeting. Work items will include (but not be limited to): compilation of work undertaken to date; approaches taken in other RMFOs/CPs; consideration of the use of F_{msy} as a target vs limit; application in data-limited stocks; definition and application of risk.

6. Recommendations

The WG-RBMS recommends that:

- **On the 3M cod MSE:**

  WG-RBMS concludes that work in WG-RBMS on the 3M cod MSE should be suspended for the time being. This conclusion was reached based on the strong variability observed in the stock dynamics and biological parameters in the past, that create substantial difficulties for developing realistic future simulations and successful development of an HCR. This situation, coupled with the low recruitment observed in recent years that will likely result in a strong decline of the stock biomass even without a fishery, implies that developing an HCR is not considered feasible at this stage. Reopening this issue in WG-RBMS should occur when SC determines that conditions are such that there is a reasonable probability of success.

- **On future MSE processes:**

  Noting that significant challenges were encountered in meeting the timetables set for the MSE process for both 3M cod and 2+3KLMNO Greenland halibut, and that this resulted in insufficient time being available for adequate review and documentation of the results, WG-RBMS recommends that timeframes set for future MSE processes should be realistic, taking full account of the very large amount of work required. Sufficient time and human capacity should be allowed for the development of the technical work, review, communication with relevant actors and reporting of results.

- **On 3LN redfish:**

  WG-RBMS recommends to the Commission that SC be asked in 2020 to do an update assessment and five-year projections (2021 to 2025) to evaluate the impact of annual removals at 18 100 tonnes against the following performance statistics (from NCEM annex I.H):

  (a) Very low (< 10%) probability of biomass declining below B_{lim}.

  (b) Low (< 30%) probability of fishing mortality >F_{msy}

  (c) Less than 50% probability of declining below 80% B_{msy} on or before 2026

  If this level of catch does not result in fulfilling these performance statistics, SC should advise the level of catch that would.

7. Date and Time of Next Meeting

The next meeting will be held in August 2020.

8. Adoption of Report

The report was adopted via correspondence. The recommendations from this meeting were compiled into COM-SC WP 19-08 for presentation at the upcoming 41st Annual Meeting of NAFO.

9. Adjournment

The meeting adjourned at 18:00 hours on 21 September 2019.

Gratitude was expressed to the WG-RBMS members for their effective cooperation at the meeting, and to the NAFO Secretariat for its excellent support.

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Annex 2. Agenda

1. Opening by the co-Chairs, Carmen Fernández (European Union) and Jacqueline Perry (Canada)
2. Appointment of Rapporteur
3. Adoption of Agenda
4. 3M cod Management Strategy Evaluation (MSE)
    a. Review objectives for the current meeting
    b. Presentation of new results from the 3M cod MSE technical team
    c. Discussion of next steps, including whether to proceed with or to halt the current 3M cod MSE (If the decision is to proceed, a revision of the timeline should be provided)
    d. Presentation of a draft "*guiding and summary*" document
    e. Archiving of code date sets and results
5. Other Business
    a. Brief discussion on the Greenland halibut MSE process, as noted at the SC meeting in June 2019
    b. 3LN redfish Conservation Plan and Harvest Control Rule: planning for review/evaluation of the plan, which expires in 2020 (see Annex I.H of NAFO CEM)
    c. Preparations for the August 2020 meeting
6. Recommendations
7. Date and Time of Next Meeting
8. Adoption of Report
9. Adjournment

Annex 3. 3M cod MSE results (Presented by Technical Team)

[COM-SC RBMS-WP 19-04]

Technical Team:
F. González-Costas, D. González-Troncoso, C. Fernández and A. Urtizberea

Introduction

The SC meeting of January 2019 (NAFO, 2019 a) agreed the different Operating Models (OMs) and initial Harvest Control Rules (HCR) to be tested in the 3M cod Management Strategies Evaluation (MSE). Table 1 contains the variables, both HCR and OMs, which will be included in the MSE trials. In this meeting a calendar was approved to present a total of 89 scenarios that came out of the relationship between OMs and HCRs (Table 2). The calendar was modified at the WG-RBMS meeting in April 2019 (NAFO, 2019 b).

According to that calendar, the technical team has been developing and presenting the results of the different OMs and HCRs. In the April 2019 WG-RBMS meeting the OMs and results of the scenarios were presented, except those related to M steps, low recruitment and density-dependent parameter estimation. The M steps scenarios were defined and formulated by González-Troncoso and Avila de Melo (2019) in the SC January 2019. In June 2019 NAFO SC meeting the results of the scenarios related with the low recruitment were defined and presented (González-Costas *et al.*, 2019).

In this document we summarize the formulation of the low recruitment scenarios that were presented at the SC of June 2019 and explain the formulation of the new scenarios with the density-dependent estimation of the biological parameters. Subsequently, a summary of the results of the 88 scenarios (Table 2) agreed by the SC of January 2019 to perform the MSE of 3M cod are presented.

Point out that the SC of January 2019 approved one extra scenario based on the dome shape catchability as "robustness trial" of the Base Case scenario with the slope HCR. The technical team has not had time to develop and present the results of this scenario at this meeting.

Low Recruitment OM

This OM was discussed and approved in the June 2019 SC meeting. Low recruitments were defined as those below the 2005-2006 levels, which allowed the recovery of the stock in the past. Taking into account this definition, Figure 1 shows that for the assessment approved in 2018 (Base Case), the longest period of low recruitment goes from 1993 to 2004 (i.e. 12 consecutive years). The three most recent recruitments (2015-2017) are also low.

It was decided to implement the low recruitment scenarios in the following way. Bearing in mind that we have already observed 3 years of low recruitment (2015-2017), that we want to simulate a continuous period of low recruitment of about 10/11-years duration and that the projection period is from 2018 to 2037, it was decide that, for each OM and iteration, the annual recruitment values observed in the period 1998-2017 will be taken directly and applied to the projected period (2018-2037). This results in a continuous period of 10 years of low recruitment (2015-2024), followed by a period of medium and high recruitment to recover SSB as was observed in the past. These low recruitment scenarios in the results are named as HR (Historic Recruitment).

Density-dependent OM

This OM tries to estimate the biological parameters taking into account the density-dependent effect to be tested within the 3M cod MSE. The stock and catch weights-at-age of this OM are estimated by the method proposed by Brunel (2019). The model used is the classical von Bertalanffy equation, modified so that growth is reduced when stock size increases. The correlation between growth and temperature was also analyzed. This empirical model was able to reproduce the trends in the observed historical weight-at-age data (Figure 2). Most of the changes in growth operate on individuals during the first 2 years of their lives, and less variability occurs during the growth of the subsequent years. Growth during the first year (length at age 1) was inversely related to the size of the cohort. Growth during second year (but also later ages, although less significantly) correlated best with total stock biomass.

This framework was proposed by the SC in January 2019 to simulate future weights at age for 3M cod in which changes in growth are driven by changes in stock size, thereby reproducing a density-dependent growth mechanism. It was agreed that this will be further developed as a potential additional OM variant. The OM to be designed would use this model to estimate the mean weights at age in the future catches and stock, but it would be necessary to decide how the values at age of the other necessary parameters such as maturity, M, etc are obtained. It was noted that both maturity and M are likely to be density-dependent. These density-dependent scenarios in the results are named as DD.

Maturity

Figure 3 shows for the period 1988-2017 how the maturity varies with the weights and their correlation by age. It can be observed that for ages 1-2 maturity almost does not change with weight and is very close to zero. For ages 3-5 there is a clear positive relationship of maturity with weights, while for ages 6-7 that relationship is almost not appreciated and practically maturity is 1.

Figure 4 shows the relationship of the maturity with respect to the weights and the fit (line) to a logistic function. Biologically it makes more sense that maturity varies with logistic function of weight. It can be observed that the maturity for individuals with weights less than 0.4 kg is practically zero and for heavier than 2.5 kg it is 1. What is proposed is to estimate the maturity by iteration and year of the projection depending on the mean weights at age estimated with the density-dependent growth model; once the weight is known, maturity can be estimated by the following method:

$$\begin{cases} mat_{i,y}^{a} = 0 & if\ weight-at-age_{i,y}^{a} < 0.4 \\ mat_{i,y}^{a} = \dfrac{1}{1+e^{\left(-\alpha_i - weight-at-age_{i,y}^{a} * \beta_i\right)}} & if\ 0.4 \le weight-at-age_{i,y}^{a} \le 2.5 \\ mat_{i,y}^{a} = 1 & if\ weight-at-age_{i,y}^{a} > 2.5 \end{cases}$$

for all the ages (a=1-8) and years in the future (y=2018-2037). As the maturity in the assessment of the 3M cod has uncertainty via a Bayesian model, 1000 different logistic fits, one by iteration (i=1-1000), were adjusted. In Figure 5 the fit of the median maturity versus the weights is shown.

Natural Mortality (M)

During the discussion of the density-dependent OM during the SC of June 2019, the need to implement natural mortality in this OM was discussed. Possible ways to implement density-dependent M were discussed but none in particular was approved. Due to the lack of time it has not been possible to implement the estimate of M in a density-dependent manner. The results presented for the scenarios of the density-dependent OM (DD) are estimated assuming that the M by age in the projection years (2018-2037) is equal to the average M at age of the last three years (2015-2017).

Fishery Selectivity / Partial Recruitment

For the fishery PR pattern, it was agreed by the NAFO SC January 2019 meeting to use the average of the last 3 years (independently for each iteration of the MSE) for all the OMs that are developed, since it is considered that the recent fleets composition as well as the fishing gears is the most realistic for the projection period.

Results

The results of some of the Table 2 scenarios were already presented in previous WG-RBMS working groups and SC meetings according to the work plan approved. In this document we present a summary of the results of the all Table 2 scenarios (except scenario 89).

Two different HCRs have been tested: one based on the trend (MFS) and one based on a goal (MFT). Apart from these two HCRs, all the scenarios have been run with F = 0.

Model-Free Slope (MFS) HCR:

$$TAC_{y+1} = TAC_y[1 + \lambda_y \cdot slope_y], \text{ where}$$

$slope_y$ is the slope of a regression line fit to the four previous total biomass indices (indices in log-scale), and:

$$\lambda_y = \begin{cases} \min(\alpha, RR_y), & \text{if } slope_y \geq 0 \\ 2 - \min(\alpha, RR_y), & \text{if } slope_y < 0 \end{cases}, \quad \text{with } \alpha \in [1,1.5] \text{ used as a tuning parameter.}$$

Model-Free Target (MFT) HCR:

$$TAC_{y+1} = TAC_y[1 + \lambda_y \cdot (J_y - 1)], \quad \text{where}$$

J_y is the ratio of recent (three-year) average of total biomass indices to a "*target*" biomass level, as follows:

$$J_y = \frac{1}{3} \cdot (I_{y-1} + I_{y-2} + I_{y-3})/I_{target}, \text{ with } I_{target} = (\tfrac{1}{10}) \cdot \sum_{i=2008}^{2017} I_i, \quad \text{and}$$

$$\lambda_y = \begin{cases} \min(\alpha, RR_y), & \text{if } J_y \geq 1 \\ 2 - \min(\alpha, RR_y), & \text{if } J_y < 1 \end{cases}, \quad \text{with } \alpha \in [1,1.5] \text{ used as a tuning parameter.}$$

First the results of the different OMs applying the "standard" settings of the HCRs are presented. The standard settings are:

HCR setting	Value	Results Name
HCR α parameter	1.0	A10
Constraint on inter-annual TAC change	None	Cnone
Starting Point	TAC(2019)=17500 t	SP0

SSB for the scenarios under different HCRs: fishing mortality=0 (F0), model free slope (MFS), model free target (MFT).

Figure 6 presents the trajectory of the median SSB by year for the different scenarios applying different HCRs (F0, MFS and MFT). It can be observed that the scenarios under the three different HCRs have very similar SSB trend for each recruitment OM, except the MFT with HS which is different from the tendency of the HS under the other HCRs. These trajectories of the SSB are determined by the type of recruitment used in the projections. All scenarios show a decline in SSB in the short medium term (2020-2025).

Figure 7 shows the SSB/B_{lim} median and percentiles (10,90) by year (2018-2037) for the different OMs under the three different standard HCRs. The scenarios with 3Y and RW have a fairly similar level of uncertainty in the different groups. RW is a bit higher; especially the RW-HR combination gives a very large uncertainty. The scenarios with less uncertainty are the DD ones; it is possible that this uncertainty is underestimated because no noise has been included in maturity and M. To note that in all groups the scenarios with the greatest variability are the scenarios with MS.

Figure 8 illustrates the probability of SSB being less than B_{lim} by year (2018-2037) for the different OMs under the three different standard HCRs. It is noteworthy that for the scenarios without catches (F = 0), this probability is very low (<10%) in all years for scenarios with BR and HS recruitment. However, it is quite high (> 30%) in all low recruitment (HR) scenarios in the 2025-2030 period, being higher in cases with M Gadget (MG). For scenarios with catches (MFS and MFT), all scenarios have a probability of SSB being less than B_{lim} greater than 10% in the 2020-2025 period. That period is wider in the scenarios with HR. In the scenarios with MFS and HS or BR, from 2025 the probability is less than 10% for cases with MV and MS. Almost all the cases with MG have a probability greater than 10%.

Fishing mortality (F) for the scenarios under the model free trend (MFS) and model free target (MFT) HCR.

Figure 9 shows the median F for the scenarios under the HCRs MFS and MFT. All scenarios with both HCRs and recruitment BR or HS have a similar trend, with small F increments in the period 2020-2025 that later fall to low levels that remain more or less constant until the end of the projection period. The scenarios with both HCRs and MV-HR have similar trends. But the rest of the scenarios with HR recruitment have a different trend. In these cases, the F increases to maximums in the period 2020-2030. For the HR scenarios and MG or MS under MFS, the F falling and rising again to highs levels in the 2030-2037 period, while in MFT scenarios the F only decreases in the 2030-2037 period.

Figure 10 presents the median F (horizontal lines) and the percentiles 10 and 90 (vertical lines) for the period 2018-2037. All scenarios under the MFT and those of MFS with HR have great uncertainty and the 90th percentile in almost all cases is around the maximum F allowed in many years of the projection. In the cases of MFS with BR or HS this uncertainty is quite minor except the scenarios with MG.

Figure 11 plots the probability of F being above F_{lim} by year. The red line marks the 0.3 probability. This is the proposed limit for management objective 2 established in the WG-RBMS of August 2018. All scenarios exceed this limit several years in the 2020-2025 period. In all scenarios with HR, the period where this limit is exceeded is much longer. While in the scenarios with recruitment BR and HS, after 2025 until the end of the period the risk is less than the limit for almost all cases.

Catch for the scenarios under the model free trend (MFS) and model free target (MFT) HCR.

Figure 12 shows the median catches (horizontal lines) and the percentiles 10 and 90 (vertical lines) for the period 2018-2037 under the HCRs MFS and MFT. All scenarios under the MFT show a similar trend in the median catches by year. Between 2020-2025 the catches decrease from their current level to minimum levels, being constant since then at those levels. In the MFS, catches also fall in the first period but subsequently they recover to levels similar to the current ones in the case of the HR, a little lower in the case of HS and quite lower in the case of BR. The catches uncertainty in the MFS scenarios are quite wide in cases with HR recruitment, a little lower in HS cases and rather less in cases with BR.

HCR parameters

In order to start the study of the different parameters of the HCRs, different HCRs with different parameters values have been applied to the OM Base Case. The results of these tests have been compared with the values obtained in the Base Case under the HCRs with the standard parameters values. The Base Case has the following configuration: random walk parameters (RW), M age vector constant over time (MV), Bin Ricker recruitment (BR). The standard HCR has the following configuration: α parameter equal to 1.0 (A10), there is not limit for TAC variation between years (Cnone) and the starting point to estimate the first TAC is the 2019 TAC =17500 (SP0). The studies of different values of the HCRs parameters should be continued once the final set of OMs has been selected to perform the MSE of the 3M cod.

Results of the Base Case under the HCRs with standard settings and the Base Case applying different HCRs settings:

HCR setting	Standard value	New value
HCR α parameter	1.0 (A10)	1.5 (A15)
Constraint on inter-annual TAC change	None (Cnone)	20% (C20)
Starting Point	TAC(2019)=17500 t (SP0)	75%TAC(2019)= 13125 t (SP25)

α parameter.

Figure 13 presents the median and percentiles (10,90) of the SSB/B_{lim} ratio, F, catches and the probability of SSB being below B_{lim} by year (2018-2037) for the Base Case scenario under the HCRs with different α parameter values. Changing the α parameter from 1.0 to 1.5 causes different results depending on HCR. In the case of the MFS, this change increases catches with similar low F values by slightly decreasing the SSB. This small decrease in SSB increases the risk of SSB being below B_{lim}, especially after 2025. While in the MFT, the α parameter change causes the SSB crash what is reflected in an increase of the risk of SSB below B_{lim} (> 60%).

Constraint on inter-annual TAC change.

Figure 14 shows the median and percentiles (10,90) of the SSB/B_{lim} ratio, F, catches and the probability of SSB being below B_{lim} by year (2018-2037) for the Base Case scenario under the HCRs with different inter-annual TAC change constraints. In the short term, the trajectories of biomass, catches and risks are very similar for the scenarios with and without constraint under the two HCRs. In the medium to long term, the scenarios with constraint show higher catches, higher F and lower levels of biomass. This causes in the medium - long term a considerable increase in the risk of SSB below B_{lim} in scenarios with HCRs with constraint compared with the scenarios without constrain.

Starting Point 25% reduction.

Figure 15 illustrates the median and percentiles (10, 90) of the SSB/B_{lim} ratio, F, catches and the probability of SSB being below B_{lim} by year (2018-2037) for the Base Case scenario under the HCRs with different starting point values. It was tested a starting point value of the 75% of the 2019 TAC (=13125 t). The application of the starting point reduction seems to have not much effect on the scenarios analyzed under the two HCRs. Of all the parameters analyzed, this seems to be the one that has the least impact on the analyzed results. In the short term, the starting point reduction has very small impact. In the medium-term the impact is quite small, with slightly higher biomass and catches and lower risk of SSB below B_{lim} in cases with a lower starting point.

Candidate Performance Statistic (PS).

The WG-RBMS of April 2019 established the Management Objectives as well as a draft of the possible PSs to be used to measure their achievement. Figures 16 through 20 show the results for PS1, PS2, PS3, PS4 and PS6.

Some Conclusions and Ideas

The results of all the fishing scenarios analyzed show in the very short term a high probability that the SSB will be lower than B_{lim}. This probability is very high even in scenarios without fishing (F = 0) with Low Recruitment (HR). This would imply the need to close the fishery in the very short term.

Biological Parameters OMs.

It was noted that in this stock biological parameters (weight and maturity at age) and recruitment have shown very high variability in the historical period. Projecting into the future without any obvious way of predicting how these variables will evolve in future years implies a very wide spectrum of possibilities for these variables in the future, which in turn results in very wide probability distributions and a high probability of failing the performance criteria.

The results of the scenarios where the biological parameters are estimated following density-dependent effects (DD) probably captures better the correlation of the different biological parameters. This OM has a much lower uncertainty than the average of the last three years (3Y) and the random walk (RW) cases. This uncertainty could be underestimated in the DD cases as it is at this moment. This OM could be improved in the future implementing a method to estimate natural mortality taking into account density-dependent effects and including errors in the logistic fit to estimate the maturity and/or considering the age in the logistic model.

Some of the scenarios with RW present great uncertainty in the estimates of the different variables. This may be due to the difficulty of capturing the variability observed in this OM. This OM takes into account the correlation between the biological parameters in the same year but ignores the correlation between them and abundance, which causes large variations in the final estimates. The need for an OM of this type should be studied, given that DD OM seems to capture better the observed variability.

The cases with 3Y OM can be considered as the most precautionary in this aspect since the values of the biological parameters of the last three years are the minimum observed in the historical series.

Recruitment OMs.

In the WG-RBMS April 2019 meeting, it was noted that, in the cases with BR recruitment, simulating future recruitment residuals by sampling historical recruitment residuals within SSB bins implied biased residuals within the SSB bins. Some possible alternatives to improve this OM could be incorporating time autocorrelation in the future recruitment simulation.

It is likely that the way in which the OM of low recruitment (HR) has been implemented is quite pessimistic by assuming a fairly long period of low recruitment in the future. It is also true that periods of that duration with low recruitments have been observed in the past. Other ways to implement this low recruitment scenarios could be studied, such as dividing the past into low and high productivity “regimes” and sampling from those two “regimes” separately.

The WG-RBMS April 2019 meeting agreed that further consideration of recruitment simulation was relevant and that alternative methods of generating recruitment values should be considered in future MSE work.

Natural Mortality OMs.

Three M options were approved to be tested in the 3M cod MSE: M estimated by the age-variable and time-constant model (MV), M obtained from an evaluation with GADGET taking into account the cannibalism (MG) and M estimated by the step model that allows variability in ages and time (MS).

The results of most of the scenarios with MS show a much greater variability than that present in the MG and MV scenarios. One of the scenarios that could be implemented in the future to improve this great variability could be weight-related natural mortality.

HCRs and parameters.

The results show that none of the HCRs tested so far meets the accepted risk levels for SSB below B_{lim} and F above F_{lim}. These HCRs need a reformulation and a much deeper study, both in their formulation and the values of the parameters. The new HCRs should allow the closure and opening of the fishery depending on the state of the resource (biomass levels, recruitments). The development of HCRs of this type is quite complicated and will take a lot of effort and time.

It would also be necessary to study how to vary the acceptable risk levels depending on the risk existing in cases with F = 0.

The results presented show that with the current formulation the MFS HCR gives better catch yields than the MFT HCR with lower risks that SSB below B_{lim} and that F above F_{lim}. This may be because some of the parameter values (B_{target}) used in the HCR target are not the most appropriate. A deeper study of these parameters would be necessary.

Due to the different difficulties encountered in the MSE process, there has been little time to investigate different values of the HCR parameters. Different Base Case scenarios have been run playing with different parameters values of the HCRs: with an alfa HCR parameter up to 1.5, with a maximum interannual TAC variation of 20% and with a starting point to estimate the first TAC of 25% less than approved. Within all the changes in the parameter values, the one that seems to have the least impact on the final results is a 25% reduction of the starting point. The increase in α and catch constraint parameters have a very limited effect in the short term (2018-2023). In the medium to long term, these changes produce an increase in catches, also increasing risks that the SSB below B_{lim} and that the F above F_{lim}.

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Table 1. Specifications of the scenarios. In bold, the base case OM.

	Variables	Scenarios		
HCR settings	HCR names	Model-Free Slope (MFS)	Model-Free Target (MFT)	
	alpha	1.0 (A10)	1.5 (A15)	
	Constraint on inter-annual TAC change	None (Cnone)	±20% (C20)	
	Starting Point*	TAC(2019)=17500 t (SP0)	TAC(2019)–25%=13125 t (SP25)	
OM settings	Natural Mortality (until year 2017)	**M vector (MV)**	M GADGET (MG)	M Steps (MS)
	Recruitment (2018 onwards)	**Bin Ricker (BR)**	Hockey Stick (HS)	Low Bin Ricker (LBR)
	Biological parameters (2018 onwards)	**Random walk (RW)**	3 Years Mean (3Y)	Denso Dependent (DD)
	Groups q	**Flat Shape (F)**	Dome Shape (D)	

* When the management strategy is applied for the first time (i.e. for year 2020 in the MSE simulation), the TAC obtained from the HCR is calculated starting from this value instead of starting from the TAC in the previous year.

Table 2. List of the approved scenarios with their specifications.

	HCR			alfa		Constraint		Starting Point		M			Q		R			BP			Presented
	MFS	MFT	F0	A10	A15	Cnone	C20	SP0	SP25	MV	MG	MS	QF	QD	BR	HS	HR	RW	3Y	DD	
1. MFS_A10_Cnone_SP0_MV_QF_BR_RW	X			X		X		X		X			X		X			X			WG-RBMS APRIL
2. MFS_A10_Cnone_SP0_MV_QF_BR_3Y	X			X		X		X		X			X		X				X		WG-RBMS APRIL
3. MFS_A10_Cnone_SP0_MV_QF_BR_DD	X			X		X		X		X			X		X					X	
4. MFS_A10_Cnone_SP0_MV_QF_HS_RW	X			X		X		X		X			X			X		X			WG-RBMS APRIL
5.MFS_A10_Cnone_SP0_MV_QF_HS_3Y	X			X		X		X		X			X			X			X		WG-RBMS APRIL
6. MFS_A10_Cnone_SP0_MV_QF_HS_DD	X			X		X		X		X			X			X				X	
7. MFS_A10_Cnone_SP0_MV_QF_HR_RW	X			X		X		X		X			X				X	X			SC JUNE
8.MFS_A10_Cnone_SP0_MV_QF_HR_3Y	X			X		X		X		X			X				X		X		SC JUNE
9. MFS_A10_Cnone_SP0_MV_QF_HR_DD	X			X		X		X		X			X				X			X	
10. MFS_A10_Cnone_SP0_MG_QF_BR_RW	X			X		X		X			X		X		X			X			WG-RBMS APRIL
11.MFS_A10_Cnone_SP0_MG_QF_BR_3Y	X			X		X		X			X		X		X				X		WG-RBMS APRIL
12. MFS_A10_Cnone_SP0_MG_QF_BR_DD	X			X		X		X			X		X		X					X	
13.MFS_A10_Cnone_SP0_MG_QF_HS_RW	X			X		X		X			X		X			X		X			WG-RBMS APRIL
14.MFS_A10_Cnone_SP0_MG_QF_HS_3Y	X			X		X		X			X		X			X			X		WG-RBMS APRIL
15. MFS_A10_Cnone_SP0_MG_QF_HS_DD	X			X		X		X			X		X			X				X	
16. MFS_A10_Cnone_SP0_MG_QF_HR_RW	X			X		X		X			X		X				X	X			SC JUNE
17.MFS_A10_Cnone_SP0_MG_QF_HR_3Y	X			X		X		X			X		X				X		X		SC JUNE
18. MFS_A10_Cnone_SP0_MG_QF_HR_DD	X			X		X		X			X		X				X			X	
19. MFS_A10_Cnone_SP0_MS_QF_BR_RW	X			X		X		X				X	X		X			X			
20.MFS_A10_Cnone_SP0_MS_QF_BR_3Y	X			X		X		X				X	X		X				X		
21. MFS_A10_Cnone_SP0_MS_QF_BR_DD	X			X		X		X				X	X		X					X	
22. MFS_A10_Cnone_SP0_MS_QF_HS_RW	X			X		X		X				X	X			X		X			
23.MFS_A10_Cnone_SP0_MS_QF_HS_3Y	X			X		X		X				X	X			X			X		
24. MFS_A10_Cnone_SP0_MS_QF_HS_DD	X			X		X		X				X	X			X				X	
25. MFS_A10_Cnone_SP0_MS_QF_HR_RW	X			X		X		X				X	X				X	X			
26.MFS_A10_Cnone_SP0_MS_QF_HR_3Y	X			X		X		X				X	X				X		X		
27. MFS_A10_Cnone_SP0_MS_QF_HR_DD	X			X		X		X				X	X				X			X	
28. MFT_A10_Cnone_SP0_MV_QF_BR_RW		X		X		X		X		X			X		X			X			WG-RBMS APRIL
29. MFT_A10_Cnone_SP0_MV_QF_BR_3Y		X		X		X		X		X			X		X				X		WG-RBMS APRIL

30. MFT_A10_Cnone_SP0_MV_QF_BR_DD		X		X		X		X		X			X		X					X	
31. MFT_A10_Cnone_SP0_MV_QF_HS_RW		X		X		X		X		X			X			X		X			WG-RBMS APRIL
32. MFT_A10_Cnone_SP0_MV_QF_HS_3Y		X		X		X		X		X			X			X			X		WG-RBMS APRIL
33. MFT_A10_Cnone_SP0_MV_QF_HS_DD		X		X		X		X		X			X			X				X	
34. MFT_A10_Cnone_SP0_MV_QF_HR_RW		X		X		X		X		X			X				X	X			SC JUNE
35. MFT_A10_Cnone_SP0_MV_QF_HR_3Y		X		X		X		X		X			X				X		X		SC JUNE
36. MFT_A10_Cnone_SP0_MV_QF_HR_DD		X		X		X		X		X			X				X			X	
37. MFT_A10_Cnone_SP0_MG_QF_BR_RW		X		X		X		X			X		X		X			X			WG-RBMS APRIL
38. MFT_A10_Cnone_SP0_MG_QF_BR_3Y		X		X		X		X			X		X		X				X		WG-RBMS APRIL
39. MFT_A10_Cnone_SP0_MG_QF_BR_DD		X		X		X		X			X		X		X					X	
40. MFT_A10_Cnone_SP0_MG_QF_HS_RW		X		X		X		X			X		X			X		X			WG-RBMS APRIL
41. MFT_A10_Cnone_SP0_MG_QF_HS_3Y		X		X		X		X			X		X			X			X		WG-RBMS APRIL
42. MFT_A10_Cnone_SP0_MG_QF_HS_DD		X		X		X		X			X		X			X				X	
43. MFT_A10_Cnone_SP0_MG_QF_HR_RW		X		X		X		X			X		X				X	X			SC JUNE
44. MFT_A10_Cnone_SP0_MG_QF_HR_3Y		X		X		X		X			X		X				X		X		SC JUNE
45. MFT_A10_Cnone_SP0_MG_QF_HR_DD		X		X		X		X			X		X				X			X	
46. MFT_A10_Cnone_SP0_MS_QF_BR_RW		X		X		X		X				X	X		X			X			
47. MFT_A10_Cnone_SP0_MS_QF_BR_3Y		X		X		X		X				X	X		X				X		
48. MFT_A10_Cnone_SP0_MS_QF_BR_DD		X		X		X		X				X	X		X					X	
49. MFT_A10_Cnone_SP0_MS_QF_HS_RW		X		X		X		X				X	X			X		X			
50. MFT_A10_Cnone_SP0_MS_QF_HS_3Y		X		X		X		X				X	X			X			X		
51. MFT_A10_Cnone_SP0_MS_QF_HS_DD		X		X		X		X				X	X			X				X	
52. MFT_A10_Cnone_SP0_MS_QF_HR_RW		X		X		X		X				X	X				X	X			
53. MFT_A10_Cnone_SP0_MS_QF_HR_3Y		X		X		X		X				X	X				X		X		
54. MFT_A10_Cnone_SP0_MS_QF_HR_DD		X		X		X		X				X	X				X			X	
55. F0_A10_Cnone_SP0_MV_QF_QF_BR_RW			X	X		X		X		X			X		X			X			WG-RBMS APRIL
56. F0_A10_Cnone_SP0_MV_QF_QF_BR_3Y			X	X		X		X		X			X		X				X		WG-RBMS APRIL
57. F0_A10_Cnone_SP0_MV_QF_QF_BR_DD			X	X		X		X		X			X		X					X	
58. F0_A10_Cnone_SP0_MV_QF_QF_HS_RW			X	X		X		X		X			X			X		X			WG-RBMS APRIL
59. F0_A10_Cnone_SP0_MV_QF_QF_HS_3Y			X	X		X		X		X			X			X			X		WG-RBMS APRIL
60. F0_A10_Cnone_SP0_MV_QF_QF_HS_DD			X	X		X		X		X			X			X				X	
61. F0_A10_Cnone_SP0_MV_QF_QF_HR_RW			X	X		X		X		X			X				X	X			SC JUNE
62. F0_A10_Cnone_SP0_MV_QF_QF_HR_3Y			X	X		X		X		X			X				X		X		SC JUNE

63. F0_A10_Cnone_SP0_MV_QF_QF_HR_DD			X	X		X		X		X			X				X			X	
64. F0_A10_Cnone_SP0_MG_QF_QF_BR_RW			X	X		X		X			X		X		X			X			WG-RBMS APRIL
65. F0_A10_Cnone_SP0_MG_QF_QF_BR_3Y			X	X		X		X			X		X		X				X		WG-RBMS APRIL
66. F0_A10_Cnone_SP0_MG_QF_QF_BR_DD			X	X		X		X			X		X		X					X	
67. F0_A10_Cnone_SP0_MG_QF_QF_HS_RW			X	X		X		X			X		X			X		X			WG-RBMS APRIL
68. F0_A10_Cnone_SP0_MG_QF_QF_HS_3Y			X	X		X		X			X		X			X			X		WG-RBMS APRIL
69. F0_A10_Cnone_SP0_MG_QF_QF_HS_DD			X	X		X		X			X		X			X				X	
70. F0_A10_Cnone_SP0_MG_QF_QF_HR_RW			X	X		X		X			X		X				X	X			SC JUNE
71. F0_A10_Cnone_SP0_MG_QF_QF_HR_3Y			X	X		X		X			X		X				X		X		SC JUNE
72. F0_A10_Cnone_SP0_MG_QF_QF_HR_DD			X	X		X		X			X		X				X			X	
73. F0_A10_Cnone_SP0_MS_QF_QF_BR_RW			X	X		X		X				X	X		X			X			
74. F0_A10_Cnone_SP0_MS_QF_QF_BR_3Y			X	X		X		X				X	X		X				X		
75. F0_A10_Cnone_SP0_MS_QF_QF_BR_DD			X	X		X		X				X	X		X					X	
76. F0_A10_Cnone_SP0_MS_QF_QF_HS_RW			X	X		X		X				X	X			X		X			
77. F0_A10_Cnone_SP0_MS_QF_QF_HS_3Y			X	X		X		X				X	X			X			X		
78. F0_A10_Cnone_SP0_MS_QF_QF_HS_DD			X	X		X		X				X	X			X				X	
79. F0_A10_Cnone_SP0_MS_QF_QF_HR_RW			X	X		X		X				X	X				X	X			
80. F0_A10_Cnone_SP0_MS_QF_QF_HR_3Y			X	X		X		X				X	X				X		X		
81. F0_A10_Cnone_SP0_MS_QF_QF_HR_DD			X			X		X				X	X				X			X	
82. MFS_A15_Cnone_SP0_MV_QF_BR_RW	X				X	X		X		X			X		X			X			WG-RBMS APRIL
83. MFS_A10_C20_SP0_MV_QF_BR_RW	X			X			X	X		X			X		X			X			WG-RBMS APRIL
84. MFS_A10_Cnone_SP25_MV_QF_BR_RW	X			X		X			X	X			X		X			X			WG-RBMS APRIL
85. MFT_A15_Cnone_SP0_MV_QF_BR_RW		X			X	X		X		X			X		X			X			WG-RBMS APRIL
86. MFT_A10_C20_SP0_MV_QF_BR_RW		X		X			X	X		X			X		X			X			WG-RBMS APRIL
87. MFT_A10_Cnone_SP25_MV_QF_BR_RW		X		X		X			X	X			X		X			X			WG-RBMS APRIL
88. F0_A10_Cnone_SP25_MV_QF_QF_BR_RW			X	X		X			X	X			X		X			X			WG-RBMS APRIL
89. MFS_A10_Cnone_SP0_MV_QD_BR_RW	X			X		X		X		X				X	X			X			

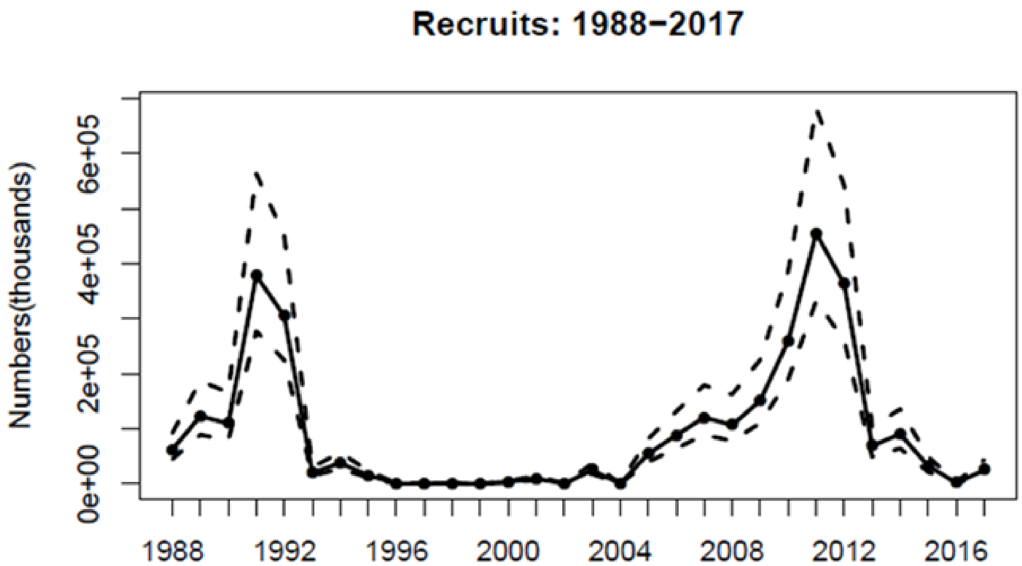

Figure 1. Results of the recruitment at age 1 in the 3M cod assessment approved in 2018 (Base Case OM). The black line is the median and the dash lines are the 5 and 95 % percentiles.

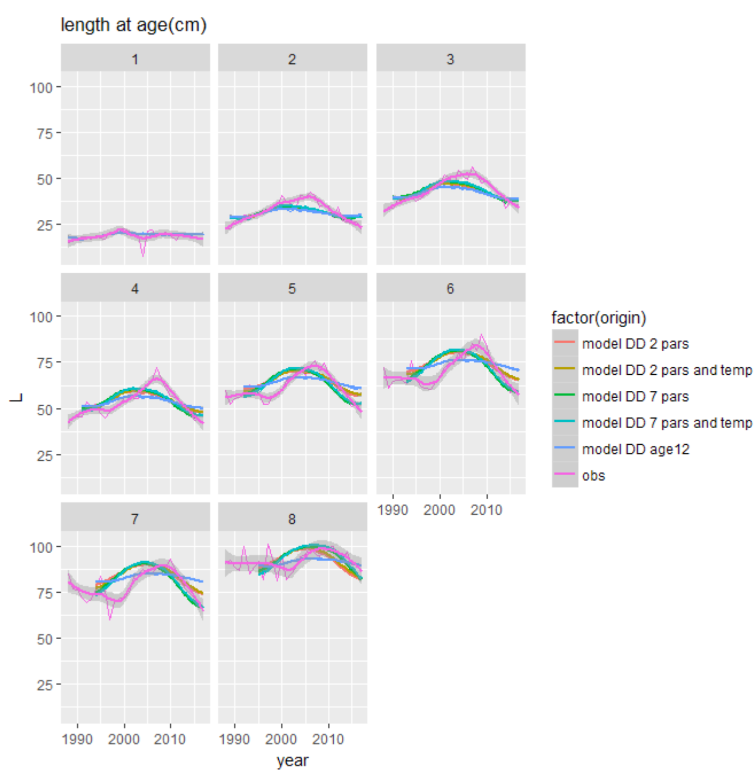

Figure 2. Historical performance of the density-dependent growth model: observed (obs) vs. predicted (3 different models) weight-at-age. The final SC approved model was DD 7 pars.

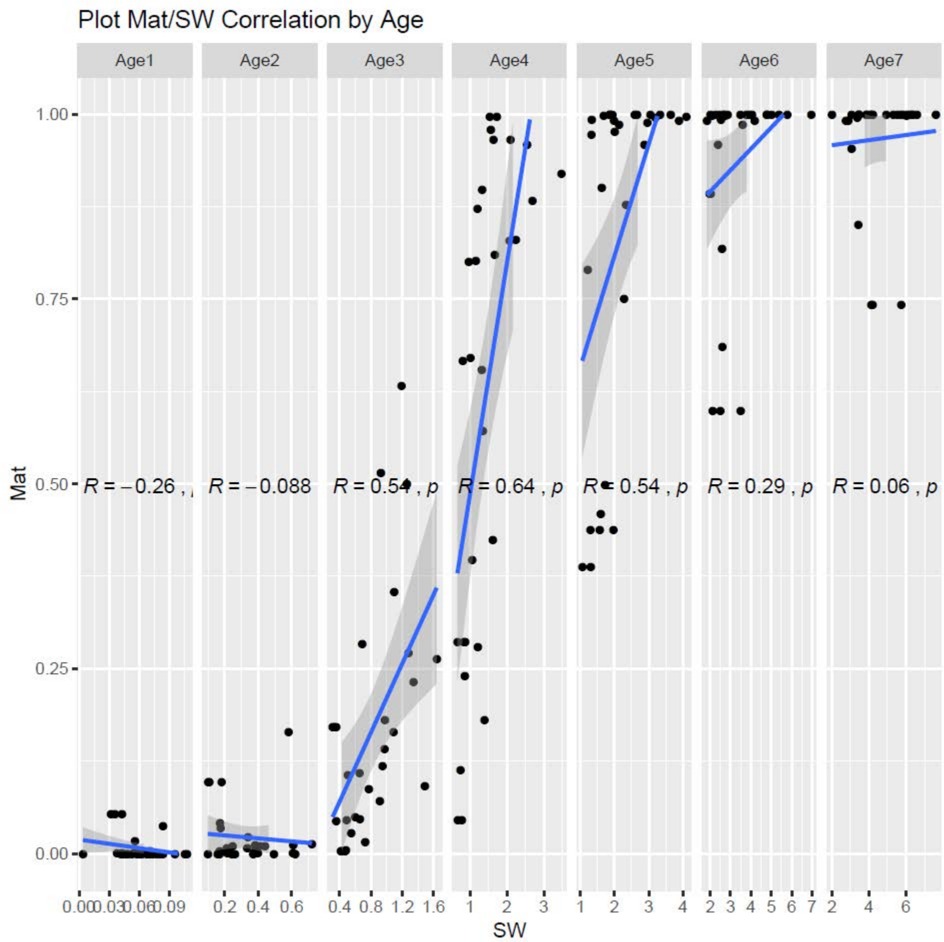

Figure 3. 3M cod median maturity/weight correlation by age (1988-2017).

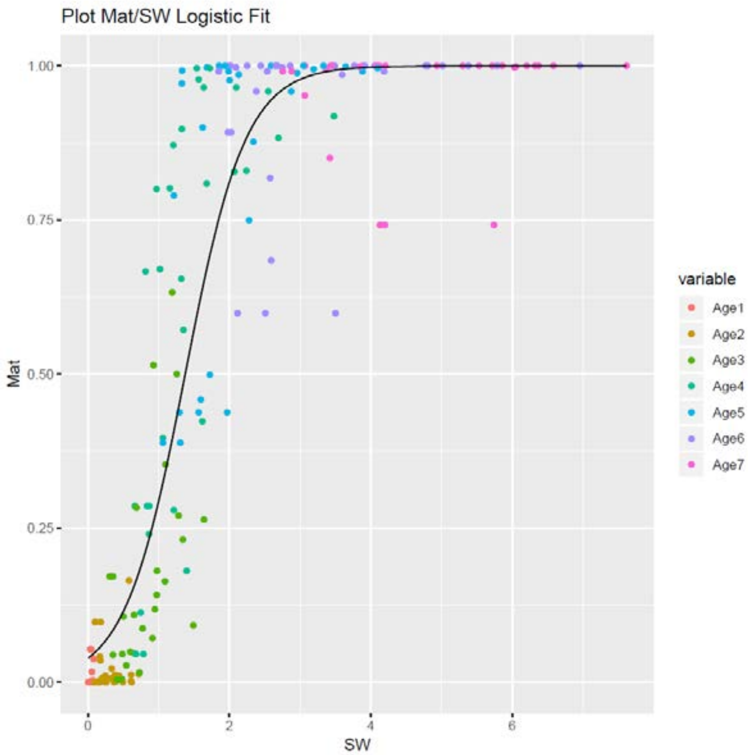

Figure 4. 3M cod median maturity at weight by age and the median maturity/weight fit (line) to a logistic function.

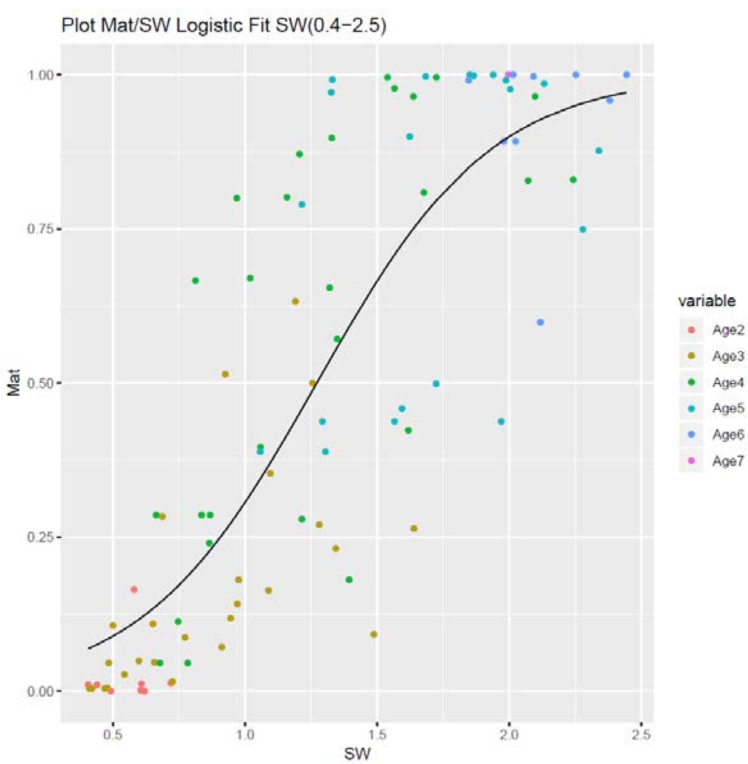

Figure 5. 3M cod median maturity at weight for the range (0.4-2.5 kg) by age and median maturity/weight fit (line) to a logistic function.

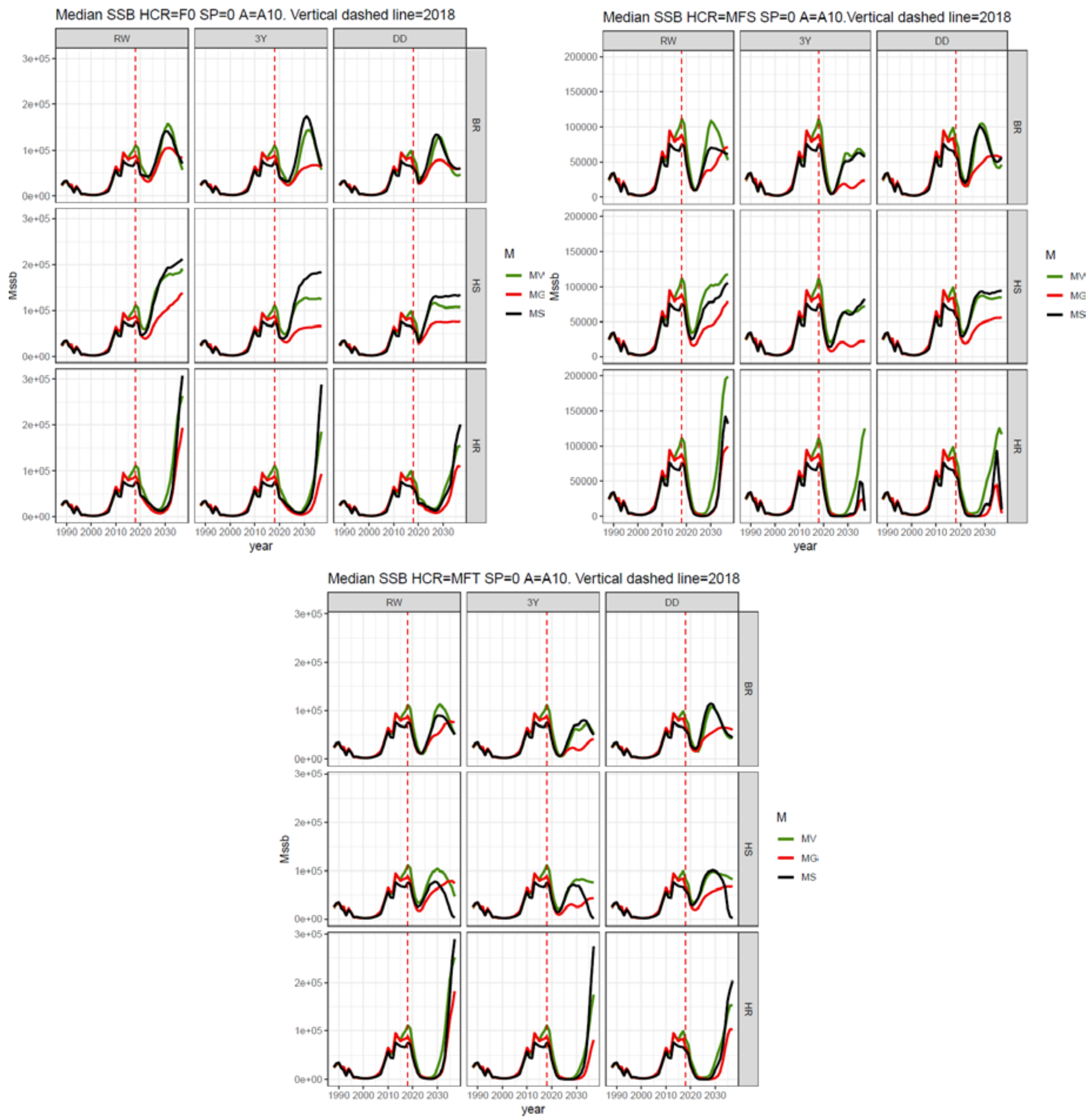

Figure 6. 3M cod median SSB by year (1988-2037) for the different OMs under the three different standard HCRs. Each panel of graphics presents the results for one HCR (F=0 up left, MFS up right and MFT down). Within each panel of graphs, the columns present the different OMS for the biological parameters (random walk = RW), mean of the last 3 years = 3Y and density-dependent = DD. The rows show the results of the different recruitment OMs (Bin Ricker = BR, segmented regression = HS and low recruitment = HR). The colors represent the different OMs of natural mortality (age vector constant over time = MV, estimated mortality by GADGET = MG and estimated mortality by steps = MS).

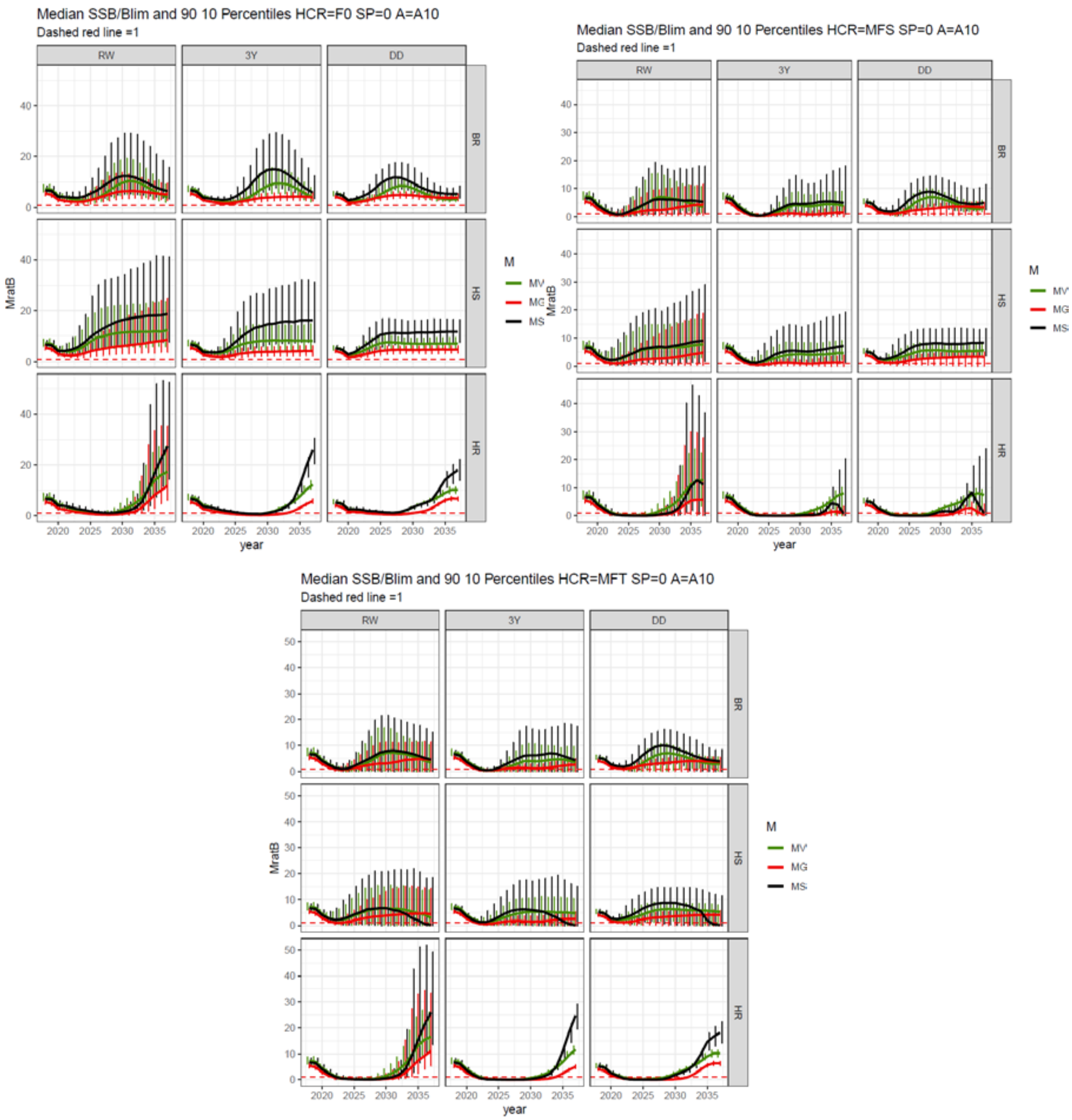

Figure 7. 3M cod median SSB/B_{lim} and percentiles (10,90) ratio by year (2018-2037) for the different OMs under the three different standard HCRs. Each panel of graphics presents the results for one HCR (F=0 up left, MFS up right and MFT down). Within each panel of graphs, the columns present the different OMS for the biological parameters (random walk = RW), mean of the last 3 years = 3Y and density-dependent = DD. The rows show the results of the different recruitment OMs (Bin Ricker = BR, segmented regression = HS and low recruitment = HR). The colors represent the different OMs of natural mortality (age vector constant over time = MV, estimated mortality by GADGET = MG and estimated mortality by steps = MS).

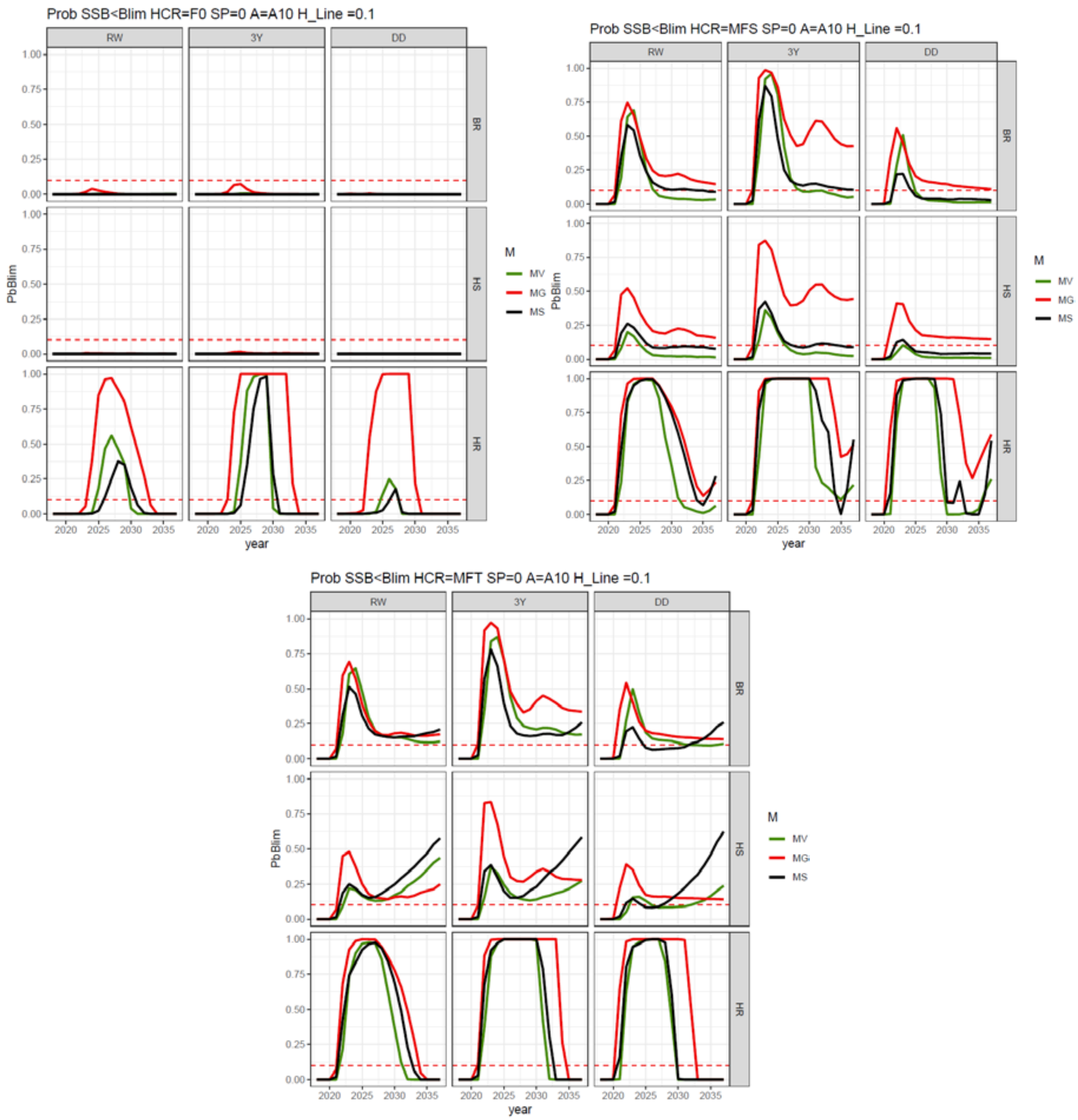

Figure 8. 3M cod probability SSB<B_{lim} by year (2018-2037) for the different OMs under the three different standard HCRs. Each panel of graphics presents the results for one HCR (F=0 up left, MFS up right and MFT down). Within each panel of graphs, the columns present the different OMS for the biological parameters (random walk = RW), mean of the last 3 years = 3Y and density-dependent = DD. The rows show the results of the different recruitment OMs (Bin Ricker = BR, segmented regression = HS and low recruitment = HR). The colors represent the different OMs of natural mortality (age vector constant over time = MV, estimated mortality by GADGET = MG and estimated mortality by steps = MS).

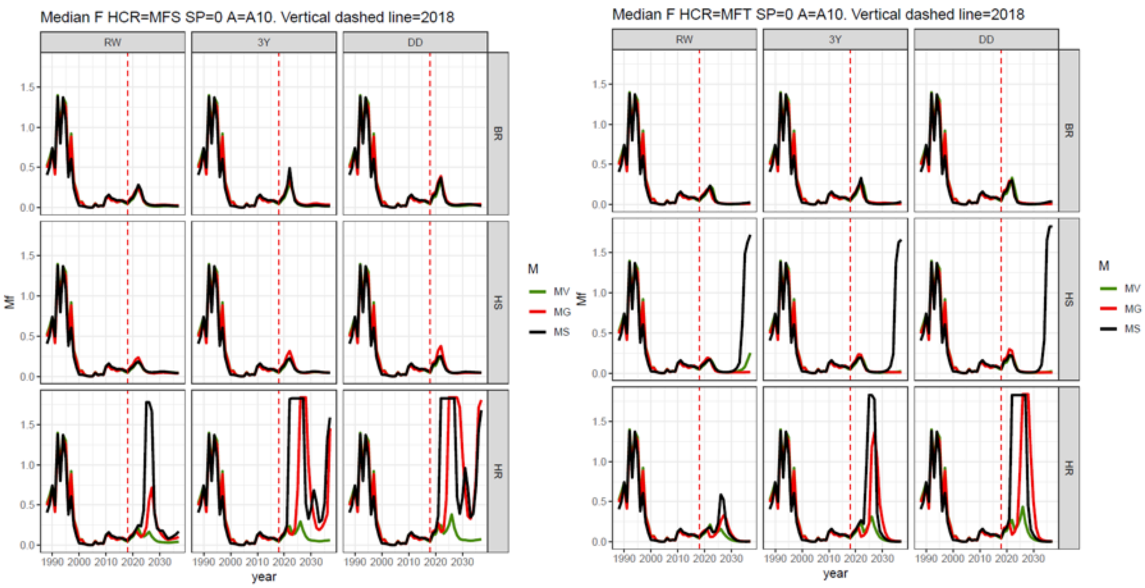

Figure 9. 3M cod median F by year (1988-2037) for the different OMs under the two different standard HCRs. Each panel of graphics presents the results for one HCR (MFS left and MFT right Within each panel of graphs, the columns present the different OMS for the biological parameters (random walk = RW), mean of the last 3 years = 3Y and density-dependent = DD. The rows show the results of the different recruitment OMs (Bin Ricker = BR, segmented regression = HS and low recruitment = HR). The colors represent the different OMs of natural mortality (age vector constant over time = MV, estimated mortality by GADGET = MG and estimated mortality by steps = MS).

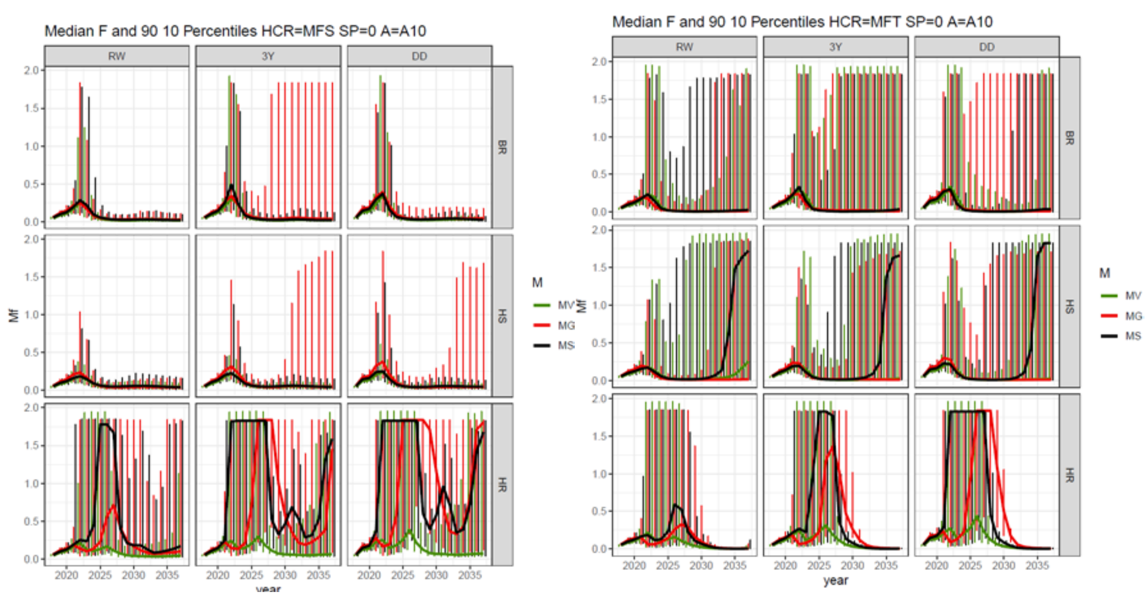

Figure 10. 3M cod median F and percentiles (10,90) by year (2018-2037) for the different OMs under the two different standard HCRs. Each panel of graphics presents the results for one HCR (MFS left and MFT right). Within each panel of graphs, the columns present the different OMS for the biological parameters (random walk = RW), mean of the last 3 years = 3Y and density-dependent = DD. The rows show the results of the different recruitment OMs (Bin Ricker = BR, segmented regression = HS and low recruitment = HR). The colors represent the different OMs of natural mortality (age vector constant over time = MV, estimated mortality by GADGET = MG and estimated mortality by steps = MS).

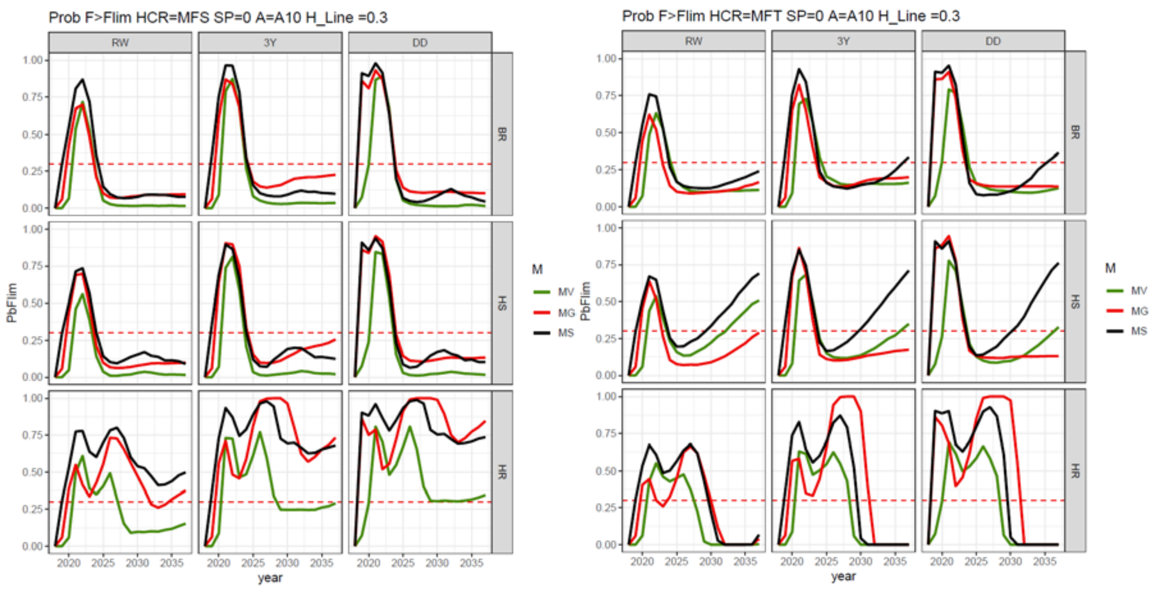

Figure 11. 3M cod probability F>F_{lim} by year (2018-2037) for the different OMs under the two different standard HCRs. Each panel of graphics presents the results for one HCR (MFS left and MFT right). Within each panel of graphs, the columns present the different OMS for the biological parameters (random walk = RW), mean of the last 3 years = 3Y and density-dependent = DD. The rows show the results of the different recruitment OMs (Bin Ricker = BR, segmented regression = HS and low recruitment = HR). The colors represent the different OMs of natural mortality (age vector constant over time = MV, estimated mortality by GADGET = MG and estimated mortality by steps = MS).

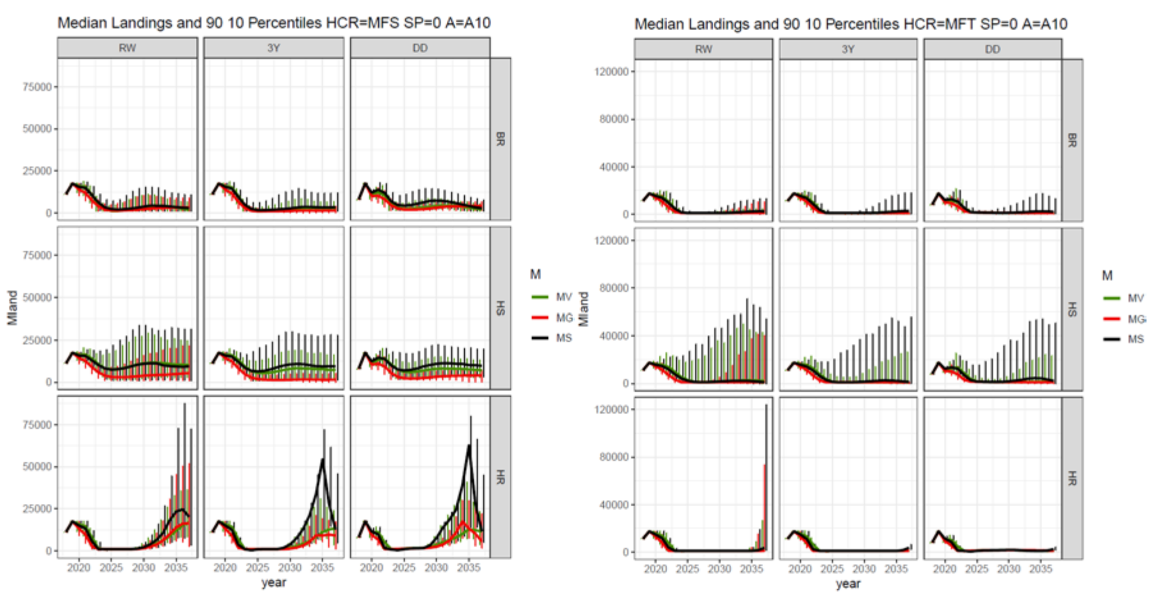

Figure 12. 3M cod median catches and percentiles (10,90) by year (2018-2037) for the different OMs under the two different standard HCRs. Each panel of graphics presents the results for one HCR (MFS left and MFT right). Within each panel of graphs, the columns present the different OMS for the biological parameters (random walk = RW), mean of the last 3 years = 3Y and density-dependent = DD. The rows show the results of the different recruitment OMs (Bin Ricker = BR, segmented regression = HS and low recruitment = HR). The colors represent the different OMs of natural mortality (age vector constant over time = MV, estimated mortality by GADGET = MG and estimated mortality by steps = MS).

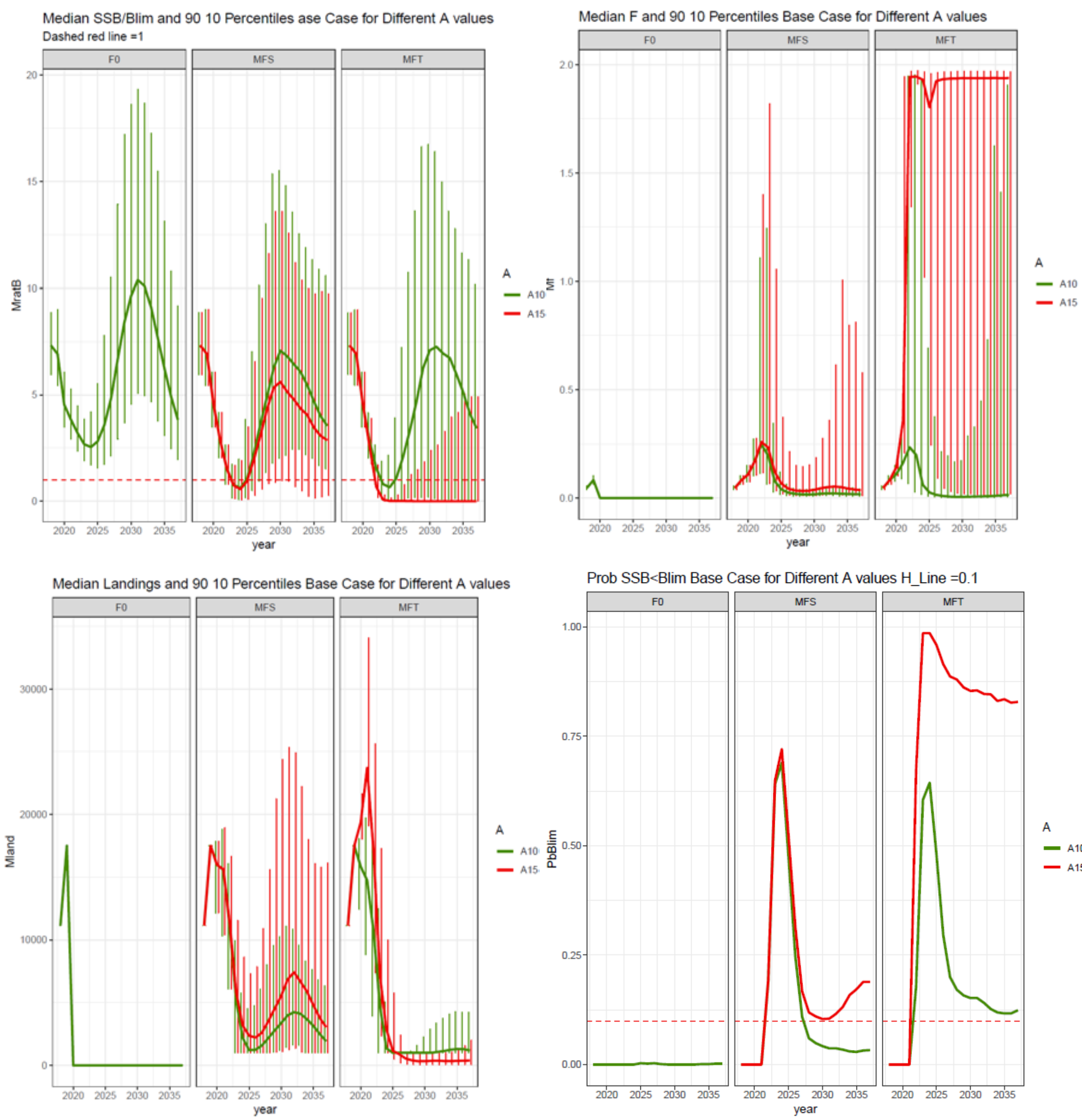

Figure 13. 3M cod median and percentiles (10,90) SSB/B_{lim} ratio (upper left), F (upper right), catches (bottom left) and probability of SSB<B_{lim} (bottom right) by year (2018-2037) for the Base Case OM under the three standard HCRs and under the HCR changing the A standard value 1.0 (A10 green) for 1.5 (A15 red). Within each graph, the columns present the different HCRs results (F=0, slope HCR=MFS and target HCR=MFT). The Base Case has the following configuration: random walk parameters (RW), M age vector constant over time (MV), Bin Ricker recruitment (BR). The standard HCR has the following configuration: α parameter equal to 1.0 (A10), there is not limited for TAC variation between years (Cnone) and the starting point to estimate the first TAC is 2019 TAC =17500 (SP0).

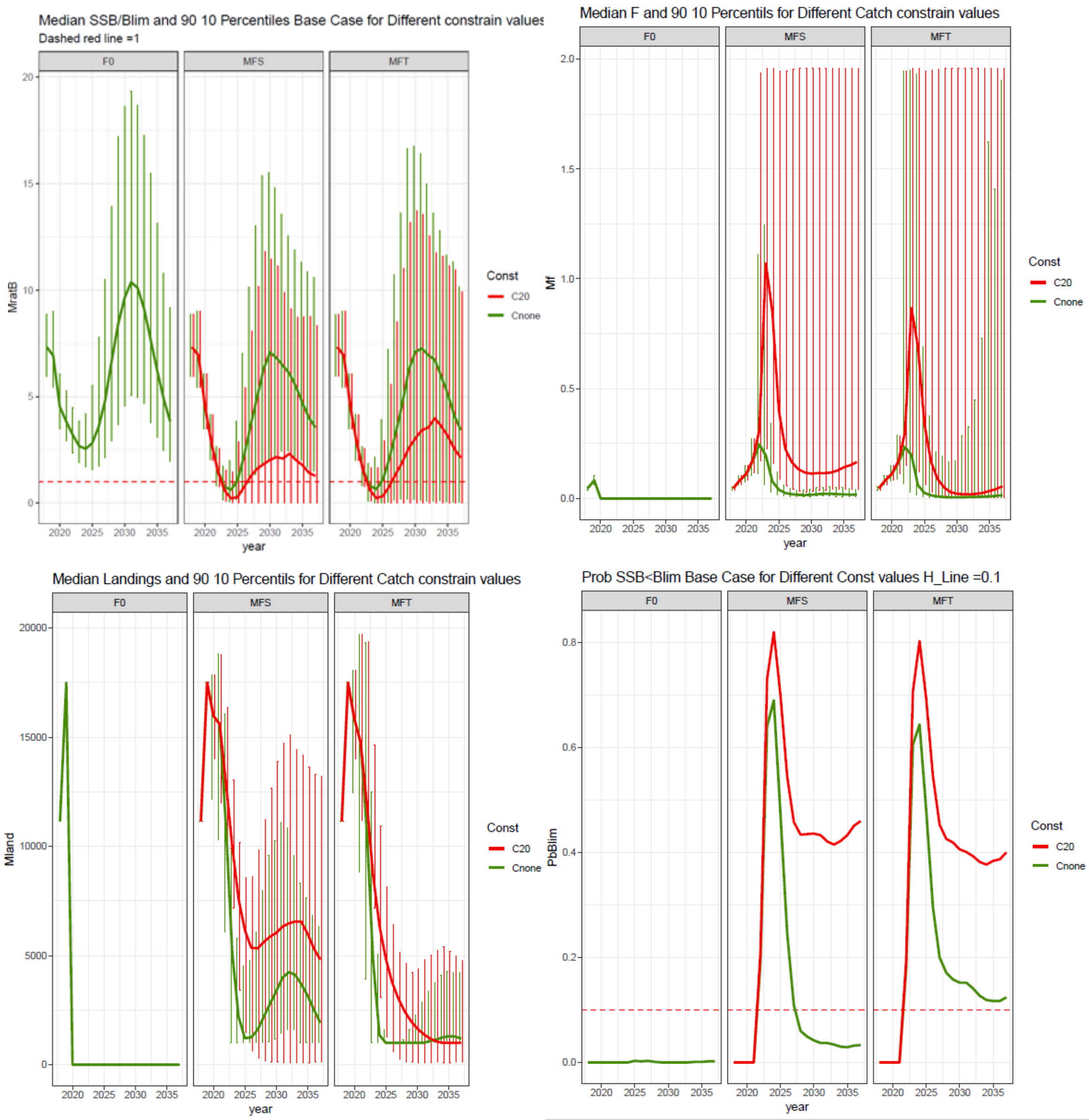

Figure 14. 3M cod median and percentiles (10,90) SSB/B_{lim} ratio (upper left), F (upper right), catches (bottom left) and probability of SSB<B_{lim} (bottom right) by year (2018-2037) for the Base Case OM under the three standard HCRs and under the HCR changing the TAC constrain standard value (not constraint=**Cnone** green) to a constraint of maximum of 20% TAC change between years (C20) (red). Within each graph, the columns present the different HCRs results (F=0, slope HCR=MFS and target HCR=MFT). The Base Case has the following configuration: random walk parameters (RW), M age vector constant over time (MV), Bin Ricker recruitment (BR). The standard HCR has the following configuration: α parameter equal to 1.0 (A10), there is not limited for TAC variation between years (Cnone) and the starting point to estimate the first TAC is the 2019 TAC=17500 (SP0).

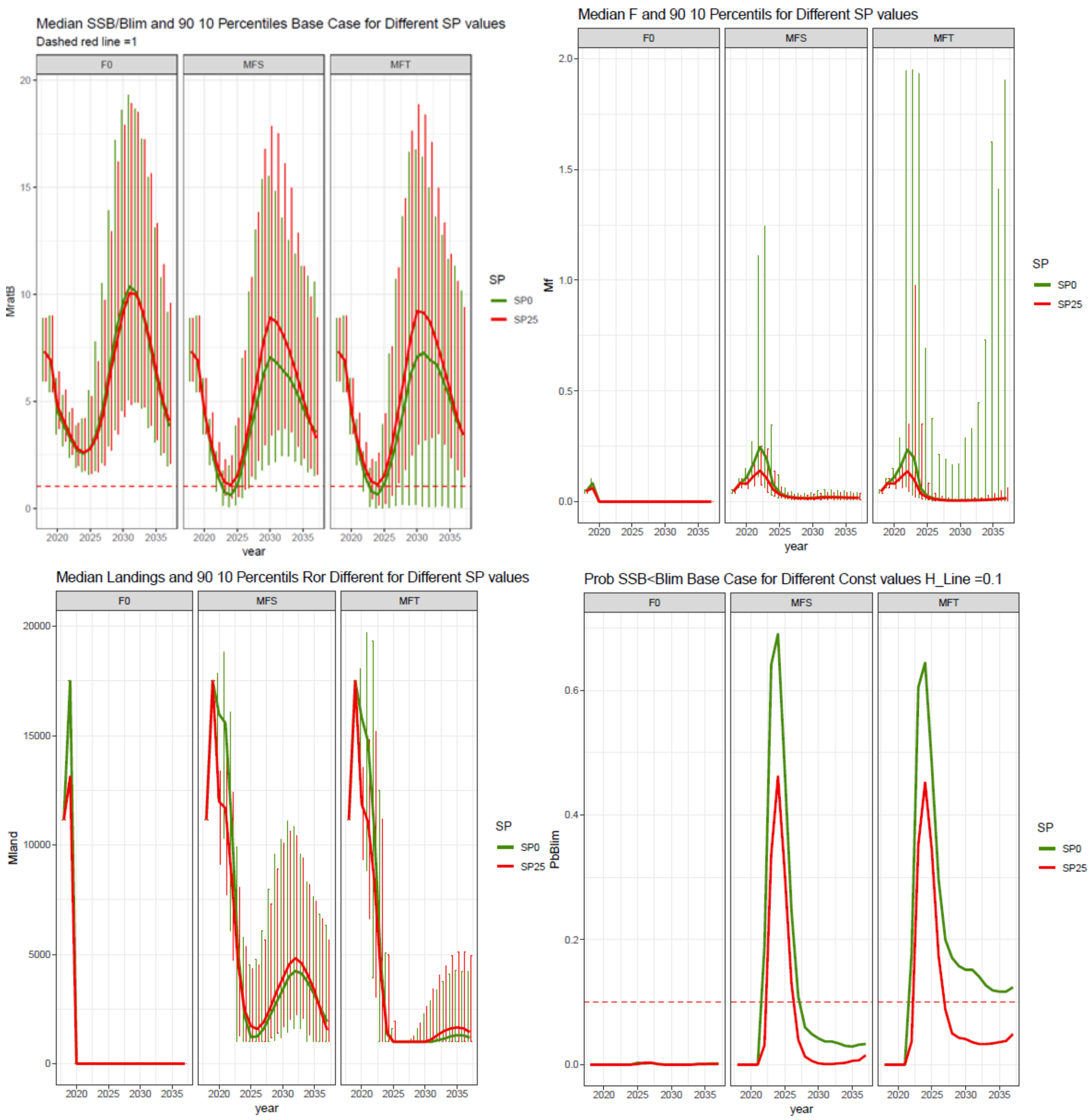

Figure 15. 3M cod median and percentiles (10,90) SSB/B_{lim} ratio (upper left), F (upper right), catches (bottom left) and probability of SSB<B_{lim} (bottom right) by year (2018-2037) for the Base Case OM under the three standard HCRs and under the HCR changing the starting point to estimate the first TAC standard value (17500 t) in green to a 25% reduction (13125 t) in red. Within each graph, the columns present the different HCRs results (F=0, slope HCR=MFS and target HCR=MFT). The Base Case has the following configuration: random walk parameters (RW), M age vector constant over time (MV), Bin Ricker recruitment (BR). The standard HCR has the following configuration: α parameter equal to 1.0 (A10), there is not limited for TAC variation between years (Cnone) and the starting point to estimate the first TAC is the 2019 TAC=17500 (SP0).

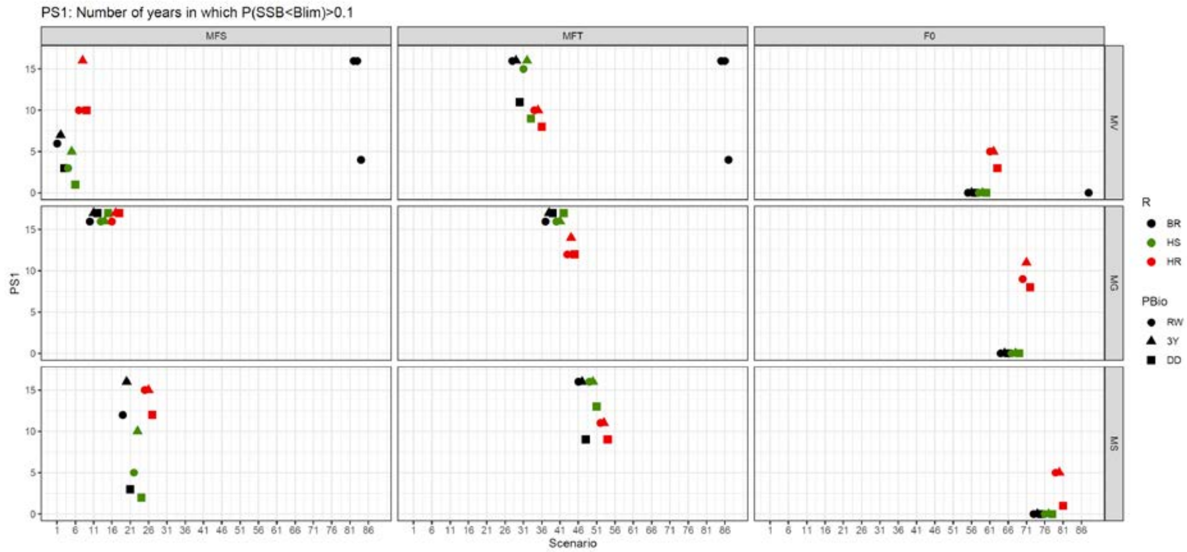

Figure 16. Candidate PS1. Number of years in which P(SSB<B_{lim})>0.1 by scenario (Table 2).

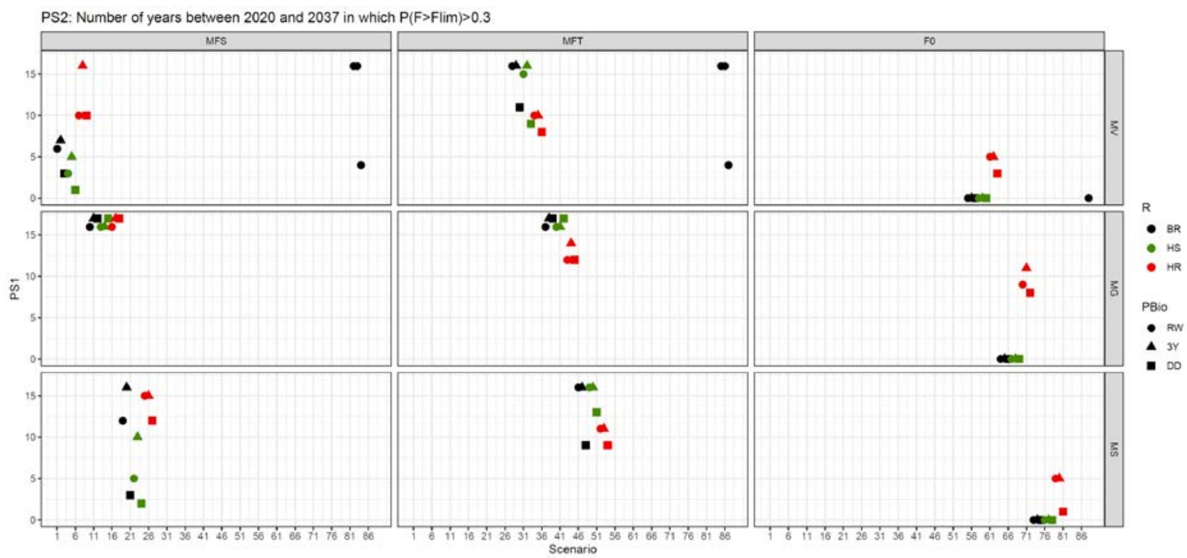

Figure 17. Candidate PS2. Number of years in which P(F>F_{lim})>0.3 by scenario (Table 2).

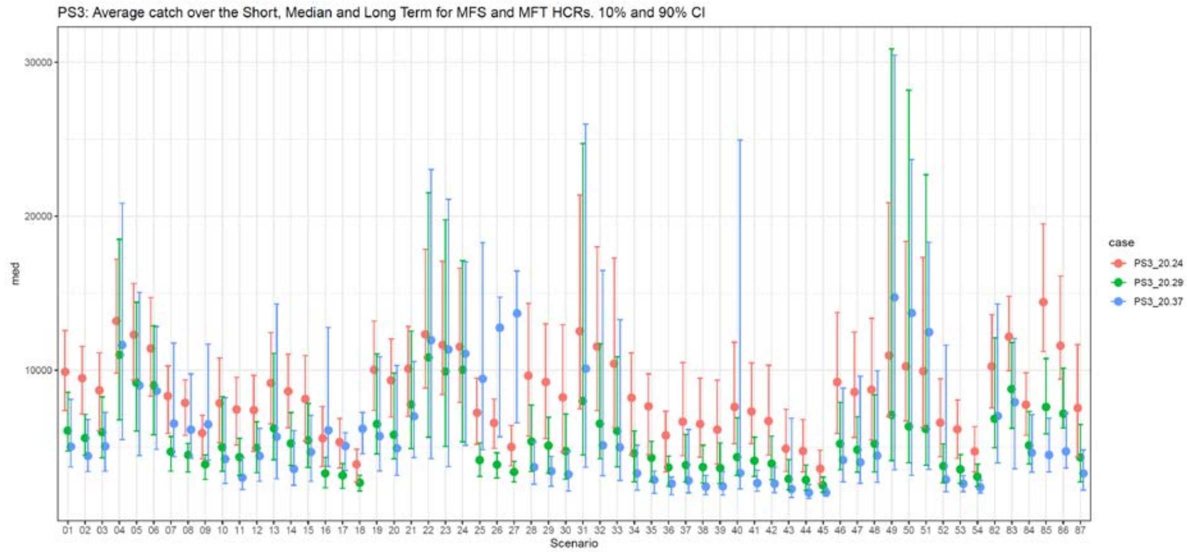

Figure 18. Candidate PS3. Average catch over the short (5 years), medium (10 years) and long term (20 years) by scenario, except the scenarios with HCR=F0 (scenarios 55-81 and 88, Table 2). Vertical lines are the percentiles (10,90).

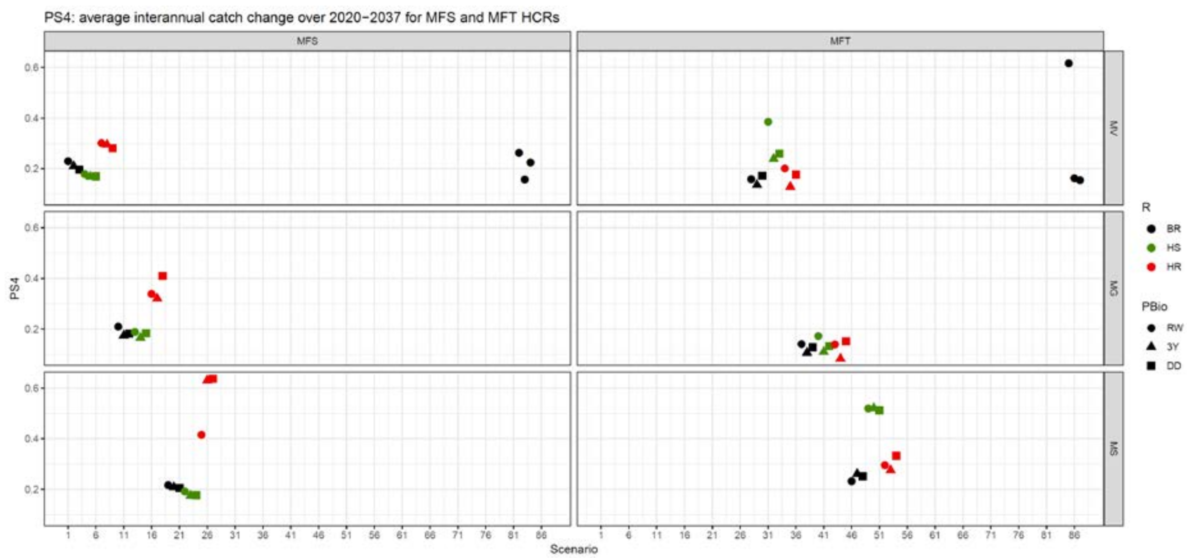

Figure 19. Candidate PS4. Average interannual catch change over 2020-2037 by scenario, except the scenarios with HCR=F0 (scenarios 55-81 and 88, Table 2).

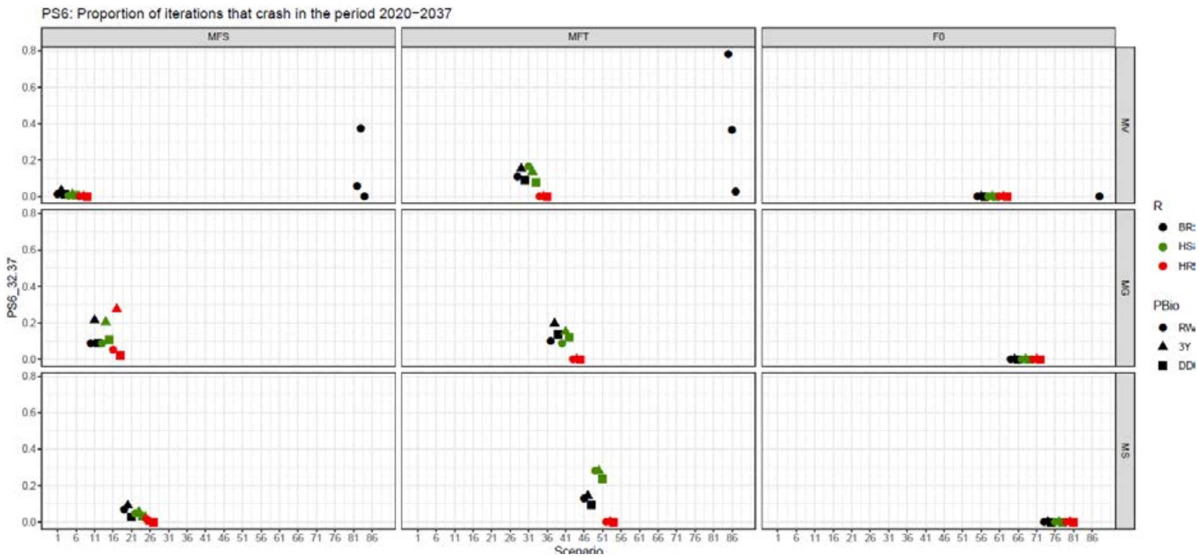

Figure 20. Candidate PS6. Proportion of crash iterations in the period 2020-2037 by scenario (Table2).