# THE WORKSHOP FOR THE EVALUATION OF THE IBERIAN SARDINE HCR (WKSARHCR)

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# Contents

# i Executive summary

The Workshop for the evaluation of the Iberian sardine HCR (WKSARHCR) met to evaluate a new harvest control rule proposed by Portugal and Spain for the management of the Iberian sardine stock. Maximum Sustainable Yield (MSY) and Precautionary Approach (PA) reference points were re-examined. $F_{MSY}$ was recomputed using the management strategy evaluation (MSE) framework to be 0.092 $year^{-1}$. The proposed harvest control rule has three levels of fishing mortality and three levels of spawning–stock biomass. The request asked for the evaluation of the generic HCR with catches capped at 40–50 kt, but WKSARHCR also explored the generic HCR capped at 30 and 35 kt. The operating model of the MSE was based on the most recent stock assessment of the Iberian sardine. Future recruitment was generated according to a persistent low productivity for the basecase, based on the time-series 2006–2019. Two other recruitment scenarios were also considered: a transition from the low to a more productive regime, as observed in the time-series 1993–2019, and a wider dynamic recruitment, encompassing both productivity regimes. All HCRs are precautionary in the short and long term under a persistent low productivity and are robust to a potential future shift to a higher productivity state of the Iberian sardine. Among the precautionary harvest rates evaluated, the expected catches and interannual variability in catches are similar. Under a persistent low recruitment, the harvest control rule with a cap of 35 kt results in the highest annual catches in the long term, of 34 226 tonnes (fishing mortality in the range 0.094–0.11 $year^{-1}$), which is slightly higher than the ICES MSY advice rule expected catch, of 31 283 tonnes (fishing mortality in the range 0.101–0.115 $year^{-1}$).

# ii Expert group information

| Expert group name | The Workshop for the evaluation of the Iberian sardine (WKSARHCR) |
|---|---|
| Expert group cycle | Annual |
| Year cycle started | 2021 |
| Reporting year in cycle | 1/1 |
| Chair | Manuela Azevedo, Portugal |
| Invited Experts | Martin Dorn, US |
| | Sonia Sánchez-Maroño, Spain |
| | Peter Kuriyama, US |
| Meeting venue and dates | 12 April 2021, Online (14 participants) |
| | 27–30 April 2021, Online (10 participants) |

# 1 Introduction

## 1.1 Terms of Reference

The **Workshop for the evaluation of the Iberian sardine HCR (WKSARHCR)**, chaired by Manuela Azevedo, Portugal, and reviewed by Martin Dorn (US), Sonia Sánchez-Maroño (Spain) and Peter Kuriyama (US), will be established and will meet online on 12 April 2021 and 27–30 April 2021 to:

a) Re-examine and update (if necessary) MSY and PA reference points according to ICES guidelines (see Technical document on reference points);

b) Evaluate the proposed Harvest Control Rule (HCR) for the Iberian sardine stock (listed in the text table below) against precautionary criteria. The evaluation should consider:
   1. Whether the tools used (methods), and the model conditioning done (data), are appropriate for the stock;
   2. Whether the minimum requirements for simulation testing HCRs, as developed by WKGMSE process, are met;
   3. Analysis of the results of the HCR evaluation to develop conclusions on whether the proposed HCR can be considered precautionary;

c) Should the proposed HCR include elements that are in contradiction with ensuring that the stock is fished and maintained, also in the future, at levels which can produce MSY, comment specifically on such elements, and their consequences for ensuring MSY.

d) Deliver a report containing the key decisions and conclusions in relation to the ToRs.

e) Produce an initial draft of the advice.

WKSARHCR will report by 5 May 2021 for the attention of the Advisory Committee.

| Stock code | Stock | Stock leaders |
|---|---|---|
| pil.27.8c9a | Sardine (*Sardina pilchardus*) in divisions 8.c and 9.a (Cantabrian Sea and Atlantic Iberian waters) | Isabel Riveiro isabel.riveiro@ieo.es<br>Laura Wise lwise@ipma.pt |

## 1.2 The request

ICES received in February 2021 a Special Request from Portugal-Spain to evaluate a new generic harvest control rule (HCR) for the management of the Iberian sardine stock (Annex 1). ICES asked for an official document with the description of the HCR as well as further clarifications of the request content.

The new HCR is defined by three reference levels for fishing mortality, F = 0, F = 0.064 and F = 0.12 and, three reference levels for B1+, $B_{low}$ = 112 943 t, defined as the lowest biomass observed in the time-series according to the 2018 assessment (WGHANSA 2018), MSY $B_{trigger}$ = 252 523 t, under a Low productivity regime and MSY $B_{trigger}$ = 446 331 t, under a Medium productivity regime (Figure 1.1).

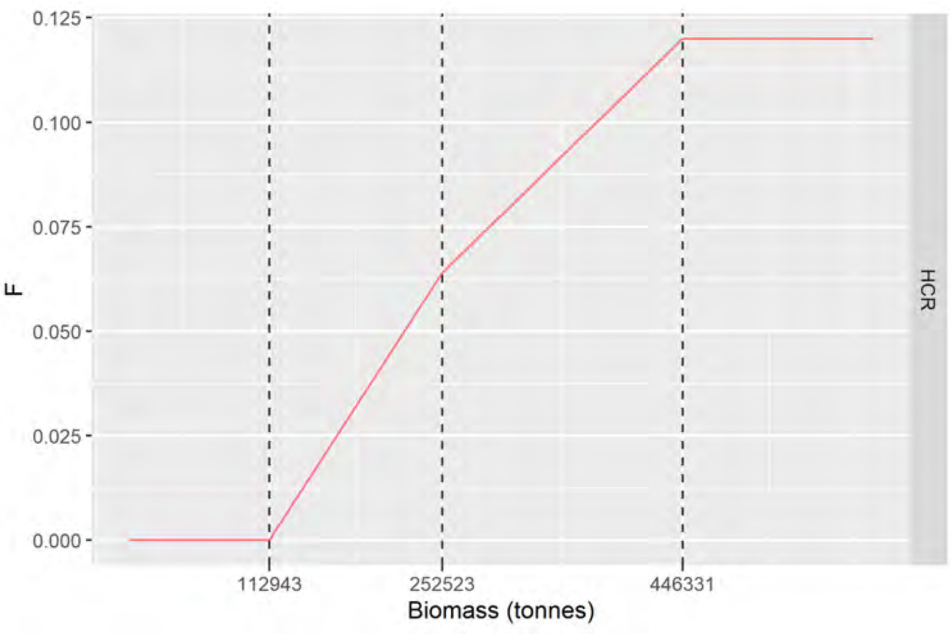


**Figure 1.1. Proposed HCR. The biomass reference levels (B1+) reported correspond to $B_{loss(2018)}$ = 112 943 t, MSY $B_{trigger\_low}$ = $B_{pa\_low}$ = 252 523 t and MSY $B_{trigger\_med}$ = $B_{pa\_med}$ = 446 331 t.**

The proposed HCR was described as follows:

i. If B1+ ≤ 112 943 t, then F = 0;
ii. If 112 943 t < B1+ ≤ 252 523 t, then F increases linearly from 0 to 0.064;
iii. If 252 523 t < B1+ ≤ 446 331 t, then F increases linearly from 0.064 to 0.12;
iv. If B1+ > 446 331 t, then F = 0.12.

Conditions ii) to iv) are overridden if the forecast catch in any given year exceeds the maximum allowed catches of 50 kt, 45 Kt and 40 kt.

The request asked ICES to evaluate if the new HCRs are precautionary, further specifying the following conditions for the evaluation of the HCRs:

i. Initial starting condition: latest assessment (WGHANSA, ICES, 2020);
ii. Catch in 2020: based on HCR12;
iii. Recruitment scenarios: given the recruitments in latest years, several recruitment scenarios can be considered in the evaluation if consistent.

The precautionary harvest rate HCR12 is described in WKSARMP (ICES, 2019a) and ICES (2019b).

## 1.3 Conduct of the Workshop

The list of participants and the meeting agenda are presented in Annex 2 and Annex 3, respectively.

To ensure credibility, salience, legitimacy, transparency and accountability in ICES work all contributors to ICES work are required to abide by the ICES Code of Conduct - CoI. The ICES CoI was brought to the attention of participants at the workshop and no CoI was reported.

A remote meeting took place on 12th April 2021 to present to the external experts the request and the management plan specifications, to discuss technical aspects related to the re-examination of Maximum Sustainable Yield (MSY) and Precautionary Approach (PA) reference points (ToR a) and to agree on the set of simulations to be carried out ahead of the workshop meeting. The work plan agreed among participants is summarized in Annex 4. A working document on the re-examination of $B_{lim}$ estimates for the Low and the Medium productivity regime scenarios was made available to reviewers prior to the meeting (Annex 7).

Given the demanding computational burden required for the re-examination of reference points and the simulation testing of the several HCRs, a lot of intersessional work took place ahead of the WKSARHCR meeting. This work was presented in the first two days of the workshop, making the basis for the plenary discussions and planning of sub-groups work in subsequent days.

The following presentations were made:

Laura Wise - Biological reference points (Section 2);

Leire Ibaibarriaga - Accuracy of risk estimates (Section 5);

Laura Wise - Simulation testing results for HCR50 and summary results for the other HCRs (Section 6);

Laura Wise - Assessment bias (Section 5).

The external reviewers provided feedback on the working document with the re-examination of $B_{lim}$ prior to the workshop meeting and fully participated during the workshop meeting. Section 8 presents the report of the external reviewers.

## 1.4 References

ICES. 2019a. Workshop on the Iberian Sardine Management and Recovery Plan (WKSARMP). ICES Scientific Reports. 1:18. 125 pp. https://doi.org/10.17895/ices.pub.5251.

ICES. 2019b. Request from Portugal and Spain to evaluate additional harvest control rules for the Iberian sardine stock in divisions 8.c and 9.a. In Report of the ICES Advisory Committee, 2019. ICES Advice 2019, sr.2019.26, https://doi.org/10.17895/ices.advice.5755.

ICES. 2020. Working Group on Southern Horse Mackerel, Anchovy and Sardine (WGHANSA). ICES Scientific Reports. 2:41. 655 pp. https://doi.org/10.17895/ices.pub.5977.

# 2 Biological Reference Points (ToR a)

## 2.1 Introduction

To answer the request, MSY and PA reference points for this stock were re-examined according to ICES guidelines (ICES, 2021a). The re-examination was based on the most recent assessment data (ICES, 2020a).

Current adopted reference points for this stock (Table 2.1) were estimated during Workshop on the Iberian Sardine Management and Recovery Plan (WKSARMP; ICES, 2019a). ICES adopted new reference points for the stock based on data from the period 2006–2017, which are considered representative of a low productivity state of the stock (ICES, 2019b). Reference points include $B_{lim}$ = 196 334 tonnes and $F_{MSY}$ = 0.032 year$^{-1}$.

The methodology used in 2019 for the estimation of the reference points followed the framework proposed in ICES guidelines for fisheries management reference points (ICES, 2017a). Therefore, simulations were conducted with ICES MSY R package 'msy' using the EqSim routines (https://github.com/ices-tools-prod/msy), a stochastic equilibrium reference point software that provides MSY reference points based on the equilibrium distribution of stochastic projections.

**Table 2.1. Summary of current Iberian sardine stock reference points (ICES, 2019a).**

| BRP | Value | Technical basis |
|---|---|---|
| $B_{lim}$ | 196 334 t | $B_{lim}$ = Hockey-stick change point |
| $B_{pa}$ | 252 523 t | $B_{pa} = B_{lim} * \exp(1.645 * \sigma)$,<br>$\sigma$ = 0.153 (ICES, 2018) |
| $F_{lim}$ | 0.156 | Stochastic long-term simulations performed with EqSim software (50% probability B1+ < $B_{lim}$) |
| $B_{trigger}$ | 252 523 t | $B_{trigger} = B_{pa}$ |
| $F_{pa}$ | 0.032 | Stochastic long-term simulations with ICES MSY AR (≤ 5% probability B1+ < $B_{lim}$), performed with EqSim software |
| $F_{MSY}$ | 0.224 | Median $F_{target}$ which maximizes yield without $B_{trigger}$ |
| Adopted $F_{MSY}$* | 0.032 | If $F_{pa} < F_{MSY}$ then $F_{MSY} = F_{pa}$ |

*** The F that maximizes long-term yield under the constraint that the long-term probability of B1+ < $B_{lim}$ is ≤ 5% when applying the ICES MSY advice rule (ICES, 2017a).**

## 2.2 Methodology

Within ICES different tools are used to estimate reference points. If we use the EqSim routines that are equivalent to a short cut approach we derive different reference points from those estimated within a full MSE approach. In the specific case of this stock, the large difference between the $F_{MSY}$ adopted ($F_{MSY} = F_{pa}$ = 0.032 year$^{-1}$) value obtained with the ICES MSY Advice Rule and estimated with EqSim and the maximum precautionary $F_{target}$ = 0.062 year$^{-1}$ obtained for the precautionary harvest control rule HCR12, evaluated in a full MSE during WKSARMP (ICES, 2019a), was in need of a close examination.

It is acknowledged that for stocks where an appropriate MSE methodology has already been developed, with careful consideration of the uncertainties involved for the stock, the MSE framework should be the preferred one to be used for the calculation of reference points (WKGMSE3, ICES, 2020b). Therefore, MSY and PA reference points were re-examined during WKSARHCR workshop with the MSE framework used to evaluate the HCR proposed by Portugal and Spain.

## 2.3 Results

### 2.3.1 Biomass reference points

#### 2.3.1.1 $B_{lim}$

Following ICES (2021) guidelines, the stock–recruitment (S–R) data of this stock (Figure 2.1) are consistent with a Type 2 pattern given the wide dynamic range of SSB and evidence that recruitment is impaired. In this case, $B_{lim}$ is equal to the change point of a Hockey-stick model fitted to S–R data. This was also the approach adopted in WKPELA 2017 (ICES, 2017b) and WKSARMP 2019 (ICES, 2019a) for the calculation of the $B_{lim}$ reference point.

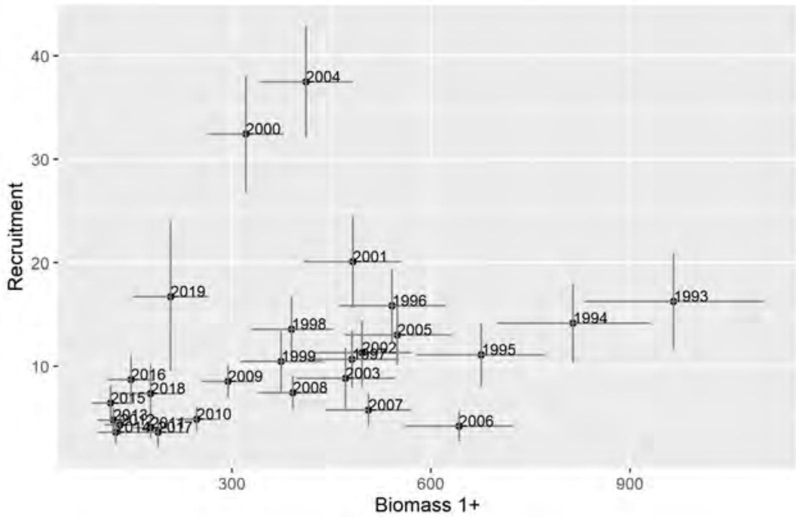


**Figure 2.1. Stock–recruitment pairs for the Iberian sardine stock (1993–2019). Horizontal bars represent the 95% confidence interval of Biomass 1+ (thousand tonnes) estimates and vertical bars represent the 95% confidence interval of Recruitment (billion) estimates.**

The updated estimates of $B_{lim}$ are within the 95% confidence interval (Figure 2.2) of the $B_{lim}$ estimated in WKPELA 2017 (ICES, 2017b) for the Medium productivity regime and in WKSARMP (ICES, 2019a) for the Low productivity regime. Therefore, WKSARHCR decided to keep $B_{lim}$ = 337 448 tonnes (ICES, 2017b) for the Medium productivity regime and the current adopted $B_{lim}$ = 196 334 tonnes (ICES, 2019a) for the Low productivity regime. A detailed analysis on changes of $B_{lim}$ estimates when new S–R data are added is presented in Wise, L. *et al*. (2021) (WD2021, Annex 7).

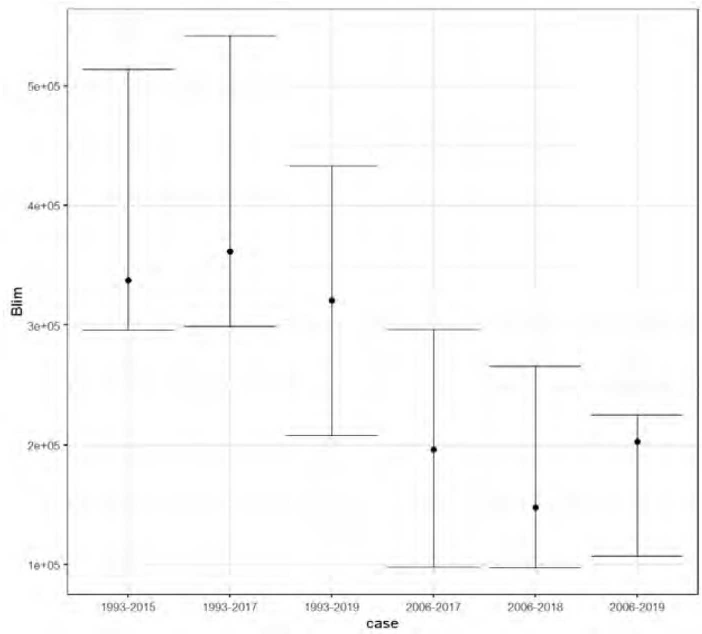


**Figure 2.2. Parameter b estimate (black dots) from deterministic fit of a Hockey-stick stock–recruitment relationship and the 2.5 and 97.5 quantiles from 1000 bootstrap re-samples of S–R pairs for the stock–recruitment models of the medium (since 1993) and low (since 2006) productivity regime.**

#### 2.3.1.2 $B_{pa}$ and MSY $B_{trigger}$

Following ICES guidelines (ICES, 2021), $B_{pa}$ was derived as $B_{pa} = B_{lim} * exp(1.645 * \sigma)$, where $\sigma$ is the coefficient of variation of B1+ from the stock assessment which was used to estimate $B_{lim}$ originally for each productivity regime. These values of $\sigma$ were 0.153 for the Low (WGHANSA, ICES, 2018; pg. 237) and 0.17 for the Medium (WKPELA, ICES, 2017b; pg. 45) productivity regimes. Since this stock has not been fished at $F_{MSY}$ for at least 5 years, MSY $B_{trigger}$ is set at $B_{pa}$ (ICES, 2021). Therefore, both reference points, $B_{lim}$ and MSY $B_{trigger}$ (=$B_{pa}$), remained unchanged from the previous estimates for their respective productivity regimes. The reason for not updating $B_{pa}$, and hence MSY $B_{trigger}$ (=$B_{pa}$), with the new sigma arising from the most recent assessment (0.158 for B1+ in 2020, WGHANSA, ICES, 2020a) was that as $B_{lim}$ remained unchanged keeping $B_{pa}$ also unchanged facilitates the comparability of the revised $F_{MSY}$ *versus* the former $F_{MSY}$ for the ICES MSY AR (Advice Rule), so that the actual influence of the new estimation procedure (MSE framework) and of the revised productivity of the stock would be more easily understood. A secondary reason is that the current re-examination of reference points (ToR a) is more related to revisit the actual $F_{MSY}$ value than to revisit all reference points since an inter-benchmark will take place during the second half of this year, when a revision of the assessment and of the biological reference points will take place.

### 2.3.2 Fishing mortality MSY and PA reference points

Simulations were conducted with the MSE framework to estimate the MSY and PA reference points for fishing mortality ($F$), namely $F_{lim}$, $F_{MSY}$ and $F_{pa}$ (ICES, 2021) for each productivity regime with recruitment generated from the hockey-stick S–R relationship with break points at the correspondent $B_{lim}$ reference points.

ICES defines $F_{lim}$ as the fishing mortality which in the long term will result in an average stock size at $B_{lim}$. Fishing at levels above $F_{lim}$ will result in a decline in the stock to levels below $B_{lim}$. $F_{MSY}$ is the fishing mortality that, in the long term, will generate the highest surplus production (MSY). ICES also defines $F_{pa}$, which is the fishing mortality that results in no more than 5%

probability of bringing the spawning stock to below $B_{lim}$ in the long term when applying the ICES MSY AR (ICES, 2021).

### 2.3.2.1 $F_{lim}$

$F_{lim}$ was derived from simulations conducted based on a fixed F (i.e. without the inclusion of a $B_{trigger}$) and without the inclusion of assessment and observation errors. $F_{lim}$ was estimated to be $F_{lim\_low}$ = 0.26 year$^{-1}$ in the Low productivity regime (Figure 2.3 and 2.4) and $F_{lim\_med}$ = 0.28 year$^{-1}$ in the Medium productivity regime (Figures 2.5 and 2.6).

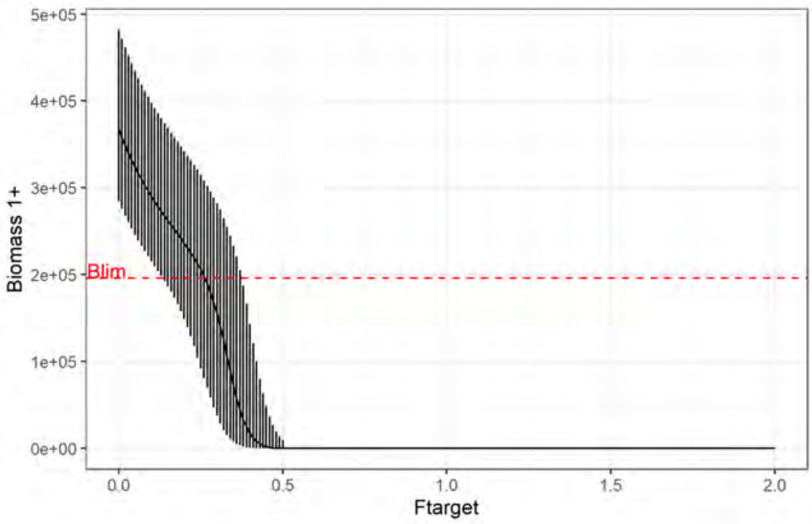


**Figure 2.3. Low productivity regime: Summary plot for Iberian Sardine SSB median (solid black line) and 95% intervals (shaded area) at fixed values of F. Simulations were run without assessment and observation errors and without $B_{trigger}$ to estimate $F_{lim}$. Horizontal dashed line represents $B_{lim}$ = 196 334 tonnes.**

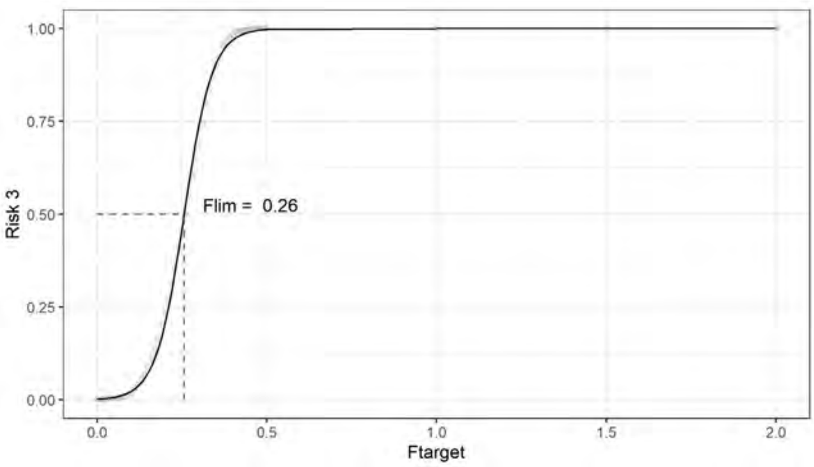


**Figure 2.4. Low productivity regime: Maximum probability of SSB < $B_{lim}$ (black) at fixed values of F. Simulations were run without assessment and observation errors and without $B_{trigger}$ to estimate $F_{lim}$. Horizontal dashed grey line indicates maximum probability of 50%. Vertical dashed grey line indicates the estimated F that leads to risk3 equal to 50% ($F_{lim}$).**

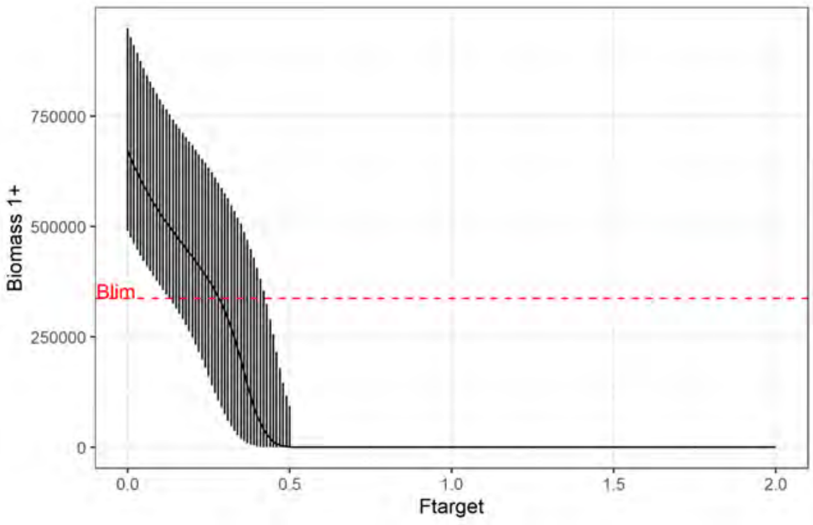


**Figure 2.5. Medium productivity regime: Summary plot for Iberian Sardine SSB median (solid black line) and 95% intervals (shaded area) at fixed values of F. Simulations were run without assessment and observation errors and without $B_{trigger}$ to estimate $F_{lim}$. Horizontal dashed red line represents $B_{lim}$ = 337 448 tonnes.**

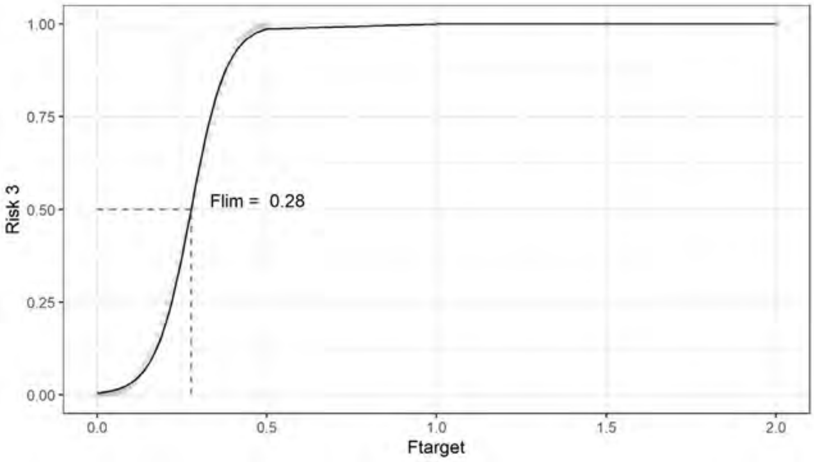


**Figure 2.6. Medium productivity regime: Maximum probability of SSB < $B_{lim}$ (black) at fixed values of F. Simulations were run without assessment and observation errors and without $B_{trigger}$ to estimate $F_{lim}$. Horizontal dashed grey line indicates maximum probability of 50%. Vertical dashed grey line indicates the estimated F that leads to risk3 equal to 50% ($F_{lim}$).**

### 2.3.2.2 $F_{MSY}$

$F_{MSY}$ was derived from simulations conducted based on a fixed F (i.e. without the inclusion of $B_{trigger}$) and with assessment and observation errors. $F_{MSY}$ was estimated to be $F_{MSY\_low}$ = 0.22 year$^{-1}$ with associated median catches of 45 364 tonnes in the Low productivity regime (Figures 2.7 to 2.9) and $F_{MSY\_med}$ = 0.24 year$^{-1}$ with associated median catches of 79 981 tonnes in the Medium productivity regime (Figures 2.10 to 2.12).

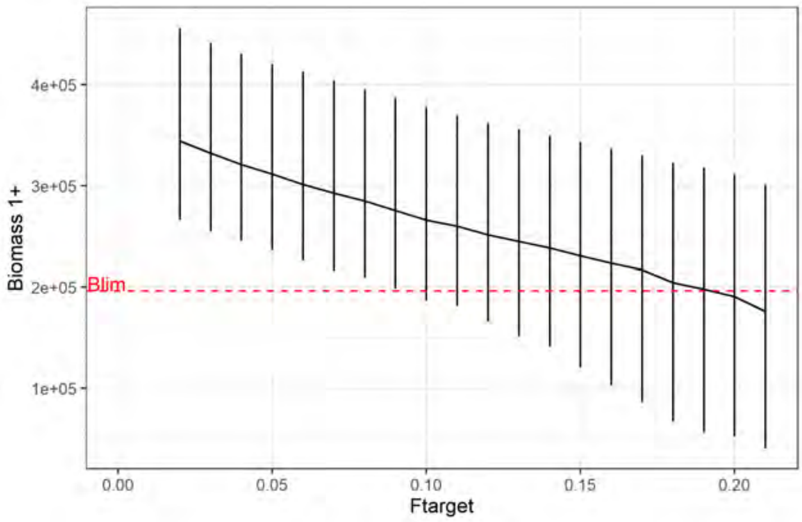


**Figure 2.7. Low productivity regime: Summary plot for Iberian Sardine SSB median (solid black line) and 95% intervals (vertical lines) at fixed values of F. Simulations were run with assessment and observation errors and without $B_{trigger}$ to estimate $F_{MSY}$. Horizontal dashed line represents $B_{lim}$ = 196 334 tonnes.**

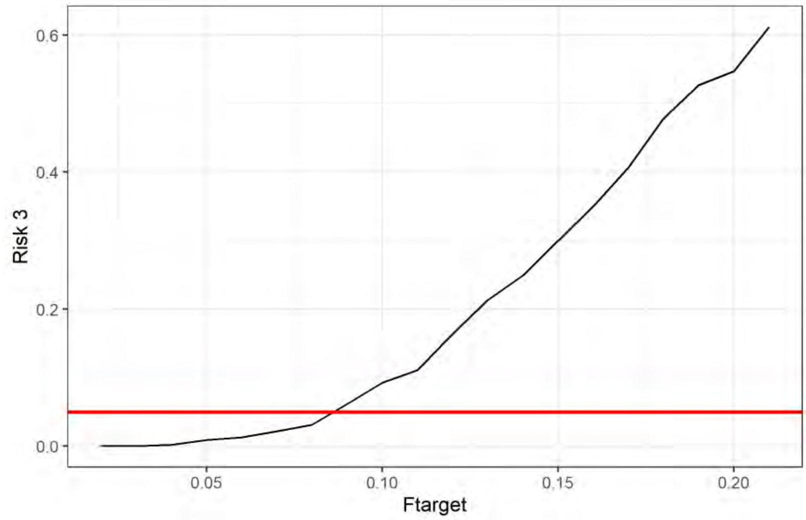


**Figure 2.8. Low productivity regime: Maximum probability of SSB < $B_{lim}$ (black) at fixed values of F. Simulations were run with assessment and observation errors and without $B_{trigger}$ to estimate $F_{MSY}$. Horizontal solid red line indicates probability of 5%.**

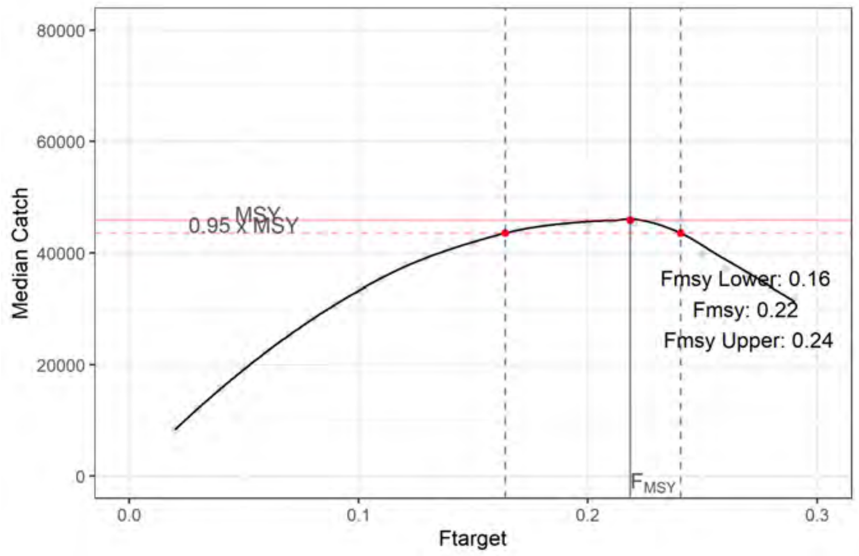


**Figure 2.9. Low productivity regime: Iberian sardine median catch yield curve with estimated $F_{MSY}$ reference point (without $B_{trigger}$). Vertical black lines: $F_{MSY}$ estimate (solid) and range at 95% of maximum yield (dashed). Horizontal red lines: maximum median catch estimate (solid) and 0.95 times maximum median catch estimates (dashed).**

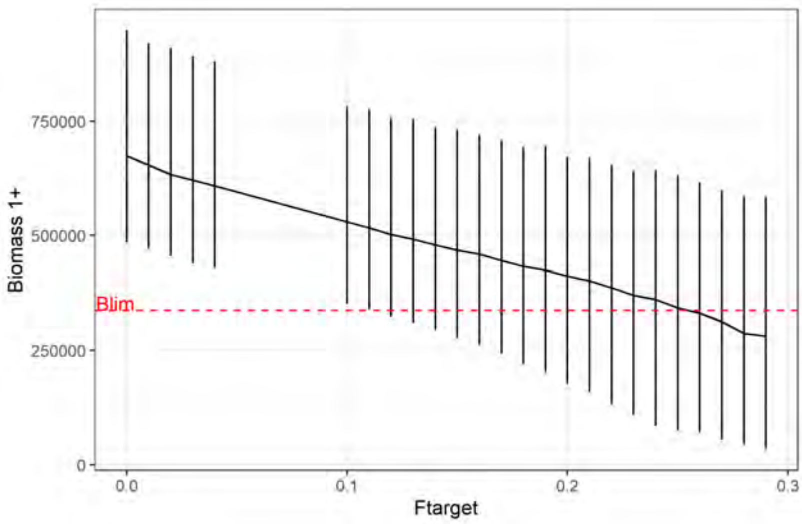


**Figure 2.10. Medium productivity regime: Summary plot for Iberian Sardine SSB median (solid black line) and 95% intervals (vertical lines) at fixed values of F. Simulations were run with assessment and observation errors and without $B_{trigger}$ to estimate $F_{MSY}$. Horizontal dashed line represents $B_{lim}$ = 337 448 tonnes.**

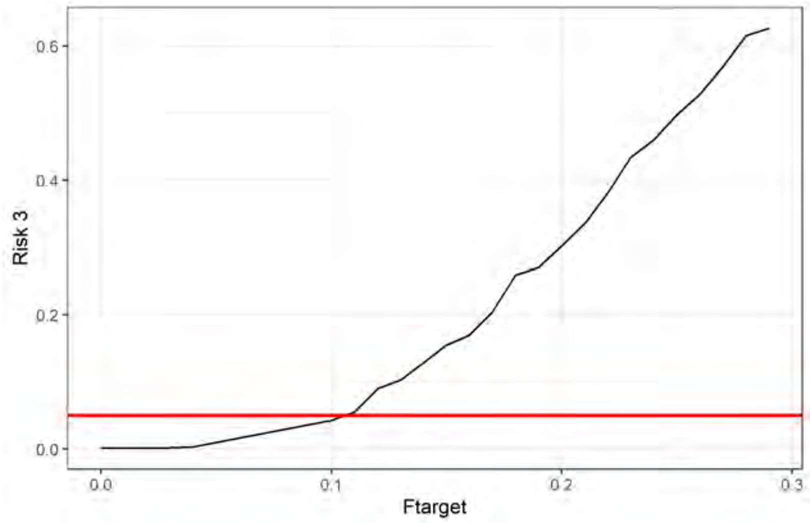


**Figure 2.11. Medium productivity regime: Maximum probability of SSB < $B_{lim}$ (black) at fixed values of F. Simulations were run with assessment and observation errors and without $B_{trigger}$ to estimate $F_{MSY}$. Horizontal solid red line indicates probability of 5%.**

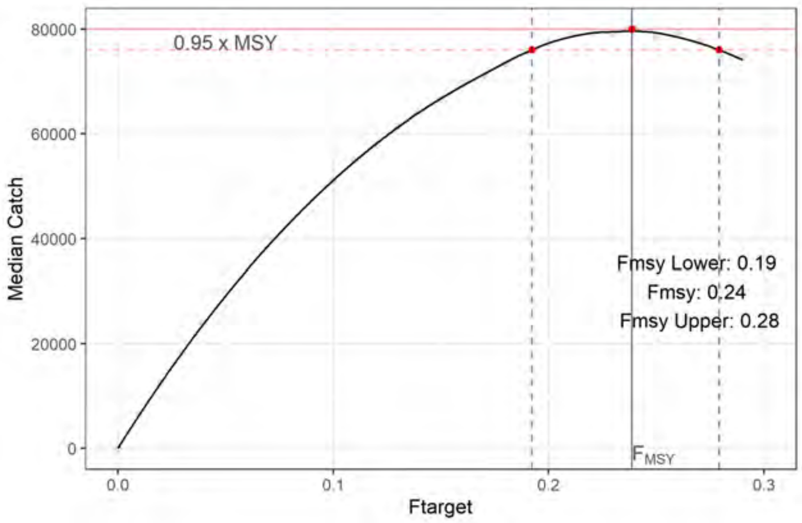


**Figure 2.12. Medium productivity regime: Iberian sardine median catch yield curve with estimated $F_{MSY}$ reference point (without $B_{trigger}$). Vertical black lines: $F_{MSY}$ estimate (solid) and range at 95% of maximum yield (dashed). Horizontal red lines: maximum median catch estimate (solid) and 0.95 times maximum median catch estimates (dashed).**

### 2.3.2.3 $F_{pa}$

$F_{pa}$ was derived from simulations conducted under ICES MSY AR (Advice Rule) (i.e. with the inclusion of a $B_{trigger}$) and with assessment and observation errors. $F_{pa}$ was estimated to be $F_{pa\_low}$ = 0.092 year$^{-1}$ with associated median catches of 31 283 tonnes in the Low productivity regime (Figures 2.13 and 2.14) and $F_{pa\_med}$ = 0.111 year$^{-1}$ with associated median catches of 55 037 tonnes in the Medium productivity regime (Figures 2.15 and 2.16).

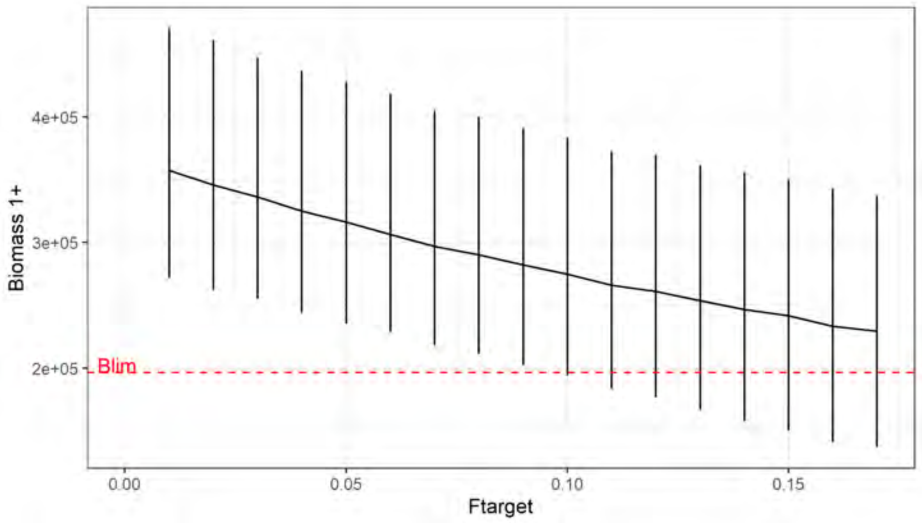


**Figure 2.13. Low productivity regime: Summary plot for Iberian Sardine SSB median (solid black line) and 95% intervals (vertical lines) with the ICES MSY AR. Simulations were run with assessment and observation errors and with $B_{trigger}$ to estimate $F_{pa}$. Horizontal dashed line represents $B_{lim\_low}$ = 196 334 tonnes.**

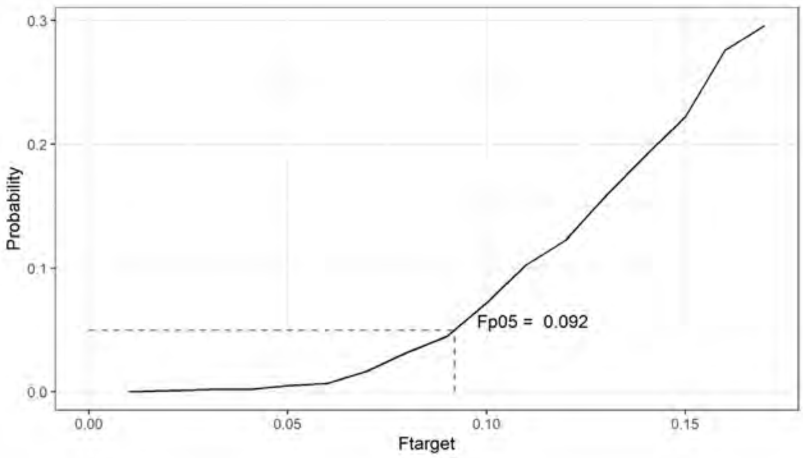


**Figure 2.14. Low productivity regime: Maximum probability of SSB < $B_{lim}$ (solid black line) with the ICES MSY AR. Simulations were run with assessment and observation errors and with $B_{trigger}$ to estimate $F_{pa}$. Horizontal dashed black line indicates probability of 5%.**

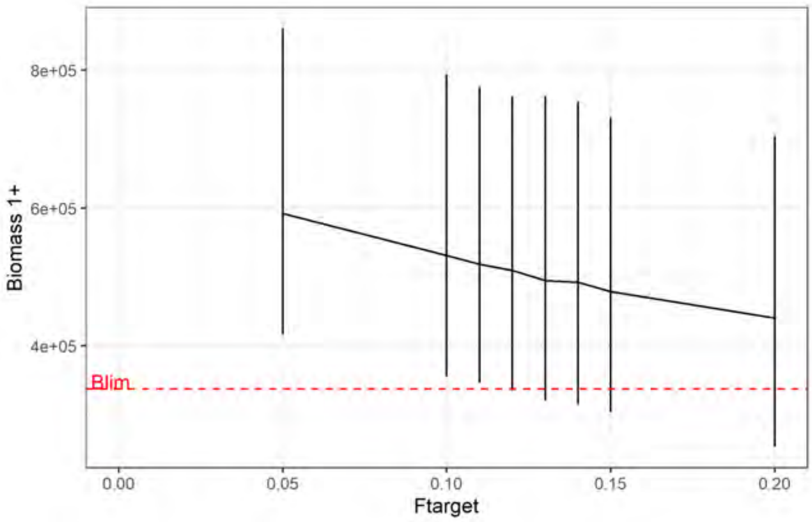


**Figure 2.15. Medium productivity regime: Summary plot for Iberian Sardine SSB median (solid black line) and 95% intervals (vertical lines) with the ICES MSY AR. Simulations were run with assessment and observation errors and with $B_{trigger}$ to estimate $F_{pa}$. Horizontal dashed line represents $B_{lim\_med}$ = 337 448 tonnes.**

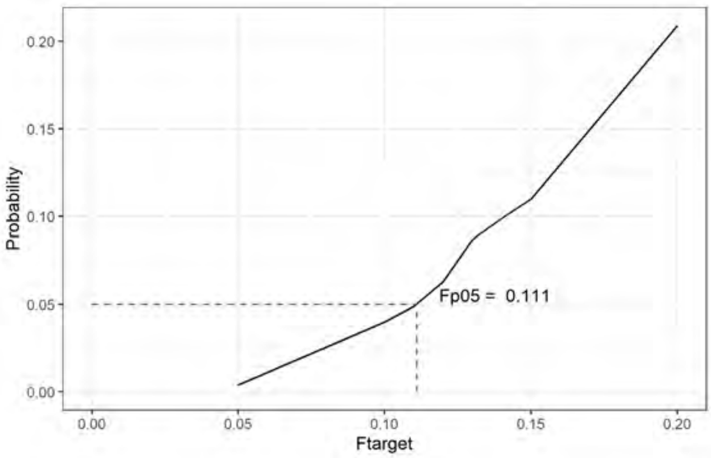


**Figure 2.16. Medium productivity regime: Maximum probability of SSB < $B_{lim}$ (solid black line) with the ICES MSY AR. Simulations were run with assessment and observation errors and with $B_{trigger}$ to estimate $F_{pa}$. Horizontal dashed black line indicates probability of 5%.**

## 2.4 Conclusions

Following ICES guidelines for the evaluation of management strategies, when calculating performance statistics in MSE, each Operating Model should have their own reference points. Therefore, WKSARHCR decided to adopt the references points presented in Table 2.2 for the simulation testing of the proposed HCRs.

**Table 2.2. Summary of Iberian sardine stock reference points for the low and medium productivity regimes.**

| BRP | Low productivity | Medium productivity | Technical basis |
|---|---|---|---|
| $B_{lim}$ | 196 334 t | 337 448 t | $B_{lim}$ = Hockey-stick change point |
| $B_{pa}$ | 252 523 t | 446 331 t | $B_{pa} = B_{lim} * \exp(1.645 * \sigma)$<br>σ = 0.153 for the low productivity<br>σ = 0.17 for the medium productivity |
| $F_{lim}$ | 0.26 | 0.28 | Stochastic long-term simulations within an MSE framework (50% probability B1+ < $B_{lim}$) |
| $B_{trigger}$ | 252 523 t | 446 331 t | $B_{trigger} = B_{pa}$ |
| $F_{pa}$ | 0.092 | 0.111 | Stochastic long-term simulations within an MSE framework with ICES MSY AR (≤ 5% probability B1+ < $B_{lim}$); |
| $F_{MSY}$ | 0.22 | 0.24 | Median $F_{target}$ which maximizes yield without $B_{trigger}$ from stochastic long-term simulations within an MSE framework |
| Adopted $F_{MSY}$* | 0.092 | 0.111 | If $F_{pa} < F_{MSY}$ then $F_{MSY} = F_{pa}$ |

*** The F that maximizes long-term yield under the constraint that the long-term probability of B1+ < $B_{lim}$ is ≤ 5% when applying the ICES MSY advice rule (ICES, 2021).**

## 2.5 References

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Wise, L., Ibaibarriaga, L., Uriarte, A., Riveiro, I and Azevedo, M. 2021. Changes in fit of stock–recruitment models with additional data and impact of stock–recruitment data pair from 2019. (WD2021, Annex 7).

# 3 Simulated scenarios and Harvest control rules

## 3.1 Introduction

Simulation of the performance of the proposed HCR by Portugal and Spain to manage the sardine fishery around the Iberian Peninsula was carried out for three scenarios of stock productivity: the default 'Low' productivity and two others which are the 'Low-to-medium' and the 'Mix' productivity regimes, as considered by ICES WKSARMP (ICES, 2019a) (see Section 3.2 below). The three scenarios try to encapsulate the most plausible uncertainties on the actual productivity regime affecting the sardine population around the Iberian Peninsula.

The proposed HCR by Portugal and Spain was tested for several variants of an upper ceiling to the total allowable catches (maximum TAC) and in comparison to the ICES MSY Advisory Rule and to the no fishing strategy (see Section 3.3).

Finally, the MSE was carried out including or excluding the application of the actual assessment based on SS3 between years throughout the projection period for each iteration, for the provision of B1+ forecasted at the beginning of the management year to set the catch opportunities according to the tested HCR.

## 3.2 Scenarios of productivity regime

In 2019, ICES concluded that the Iberian sardine stock was in a state of low productivity, which had resulted in low recruitment for the last decade (ICES, 2019a). For this reason, the default scenario for testing the performance of the HCR will be the low productivity regime (started in 2006 according to ICES, 2019b). However, the occurrence of a high recruitment during 2019, as assessed in 2020 (Figure 3.1), which had little chances of being produced at random in the low productivity regime, suggests that there are high uncertainties on the actual productivity affecting the sardine population around the Iberian Peninsula. This situation asks for a careful consideration of what might be the scenario(s) of productivity of this stock in the future as to test the performance of the proposed HCR in the long term, robust to the most likely future scenarios. To account for this uncertainty, it was decided to frame the testing of the proposed HCR for three scenarios of productivity: the default Low productivity regime, the Low-to-medium productivity regime and the Mix productivity regime as considered by ICES WKSARMP (ICES, 2019b).

A short description of each scenario of productivity as concerns the S–R relationships follows:

**'Low' productivity**

In the ICES Workshop on the Iberian Sardine Management and Recovery Plan (WKSARMP: ICES, 2019b) this was defined as the productivity corresponding to the last series of recruitments since 2006. As this is the scenario of productivity assumed by ICES, an update fitting of the S–R relationship was produced for the series of stock–recruitment pairs 2006–2019. The Hockey-stick fit is in Figure 3.2 and the parameters associated to this scenario of low productivity are in Table 3.1. In support of this scenario is the fact that since 2006 most of the recruitments were very poor and below the expected levels of recruitment of the Hockey-stick fitted to a medium productivity scenario for the series since 1993. However, as in 2019 there has been a high recruitment, inclusion of such new recruitment has changed the fitting compared to that produced in ICES WKSARMP (2019b) for the period 2006–2017. However, as explained in Section 2, as the break point did not differ statistically from the former one fitted for the series 2006–2017 in ICES WKSARMP (2019b), it was decided to force the updated fitting to have the same breakpoint as in the former fitting in WKSARMP, so that $B_{lim}$ which is set at 196 334 tonnes remains unchanged. Such fitting is presented in Figure 3.3 and in Figure 3.4.

In both fittings, the former and updated, the 2019 recruitment estimate lays out of the 95% confidence intervals. However, the slope and the sigma (variability) of the observations around the fitted Hockey-stick functions changed as a result of the inclusion of the most recent recruitment estimate (R2019). Therefore, the likelihood of observing the 2019 recruitment is increased when the R2019 is included in the fitting compared to when it is not. As an example, in Figure 3.4, the updated Hockey-stick fitting is compared with that excluding R2019; it is clear that the width of the 95% confidence intervals is increased when all datapoints are included. As a result of this, for the model that includes the 2019 data pair, the 2019 recruitment estimate corresponds with the 0.98 quantile, while in the model without the 2019 recruitment such value would correspond to the 0.996 quantile.

As indicated in WKSARMP (ICES, 2019b): "The selection of the year 2006 as the starting point of a change in the scenario of productivity is not statistically justified, and the actual duration of the scenario is uncertain, although, as seen in several ecosystems where small pelagic inhabit, it is unlikely that a low productivity scenario persists for several decades, if there is no overfishing. Moreover, the short time-series of years since 2006 (12 years – *now 14 years*) and the compatibility of those observations with the medium productivity fitted Hockey-stick model are indications to take care with this proposal and the applicability of this low productivity regime in the long term would have to be revisited in the next future if, as the juvenile survey indicates (Iberas acoustic survey- ICES, 2021 WGACEGG report), a new good recruitment might have occurred again in 2020.

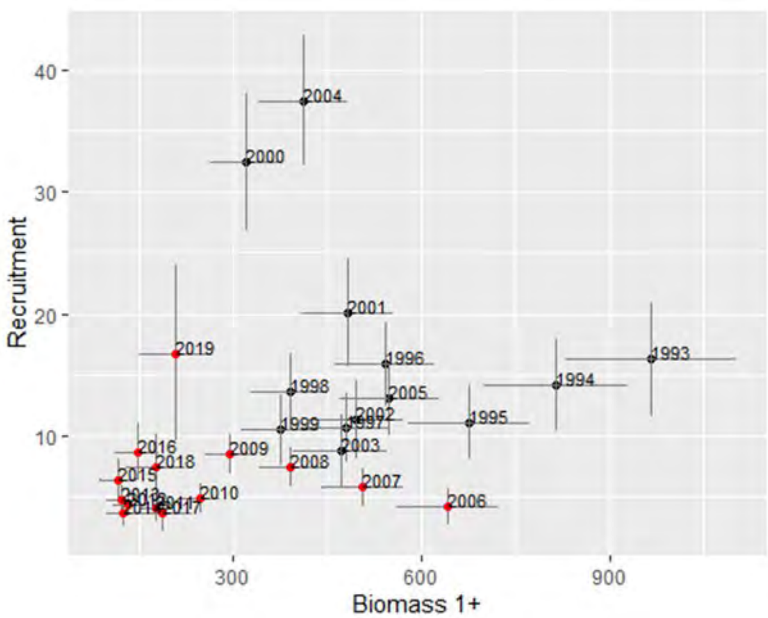



**Figure 3.1. Stock–recruitment pairs for the Iberian sardine stock (1993–2019). Horizontal bars represent the 95% confidence interval of Biomass 1+ estimates and vertical bars represent the 95% confidence interval of recruitment estimates. Points in color red evidence the period 2006–2019.**

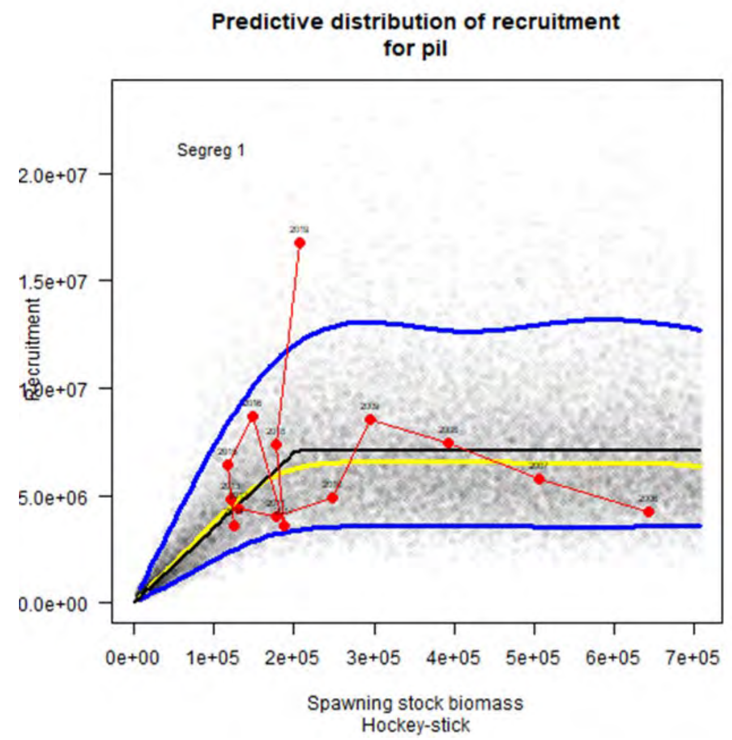



**Figure 3.2. Hockey-stick stock–recruitment function estimated with data from the 2020 assessment for the period 2006–2019, used to define the low productivity regime. The recent 2019 recruitment is outside the 90% confidence intervals defined by the blue lines.**

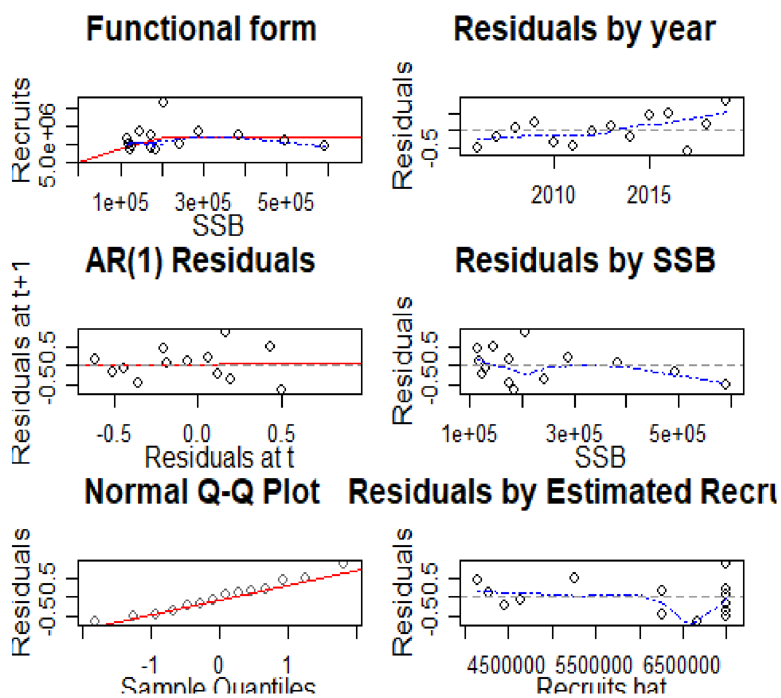
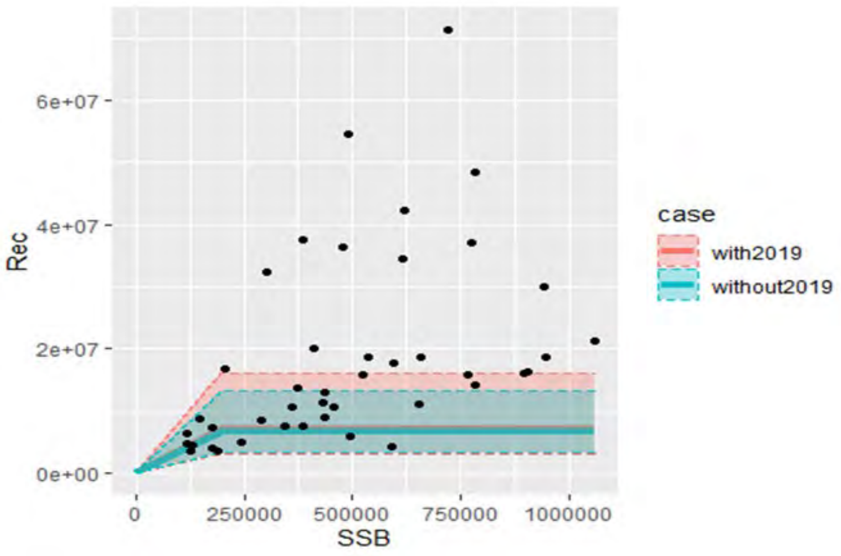



**Figure 3.3. Fit and residual plots of the Hockey-stick with the 2020 assessment data for the period 2006–2019, forcing the breakpoint to be equal to the formerly established $B_{lim}$ for the Low productivity regime ($B_{lim\_low}$ = 196 334 t) in ICES WKSARMP (ICES, 2019a).**




| Time-series | a | Fixed b | Sigma |
|---|---|---|---|
| 2006–2019 | 35.6 | 196 334 | 0.423 |
| 2006–2018 | 33.3 | 196 334 | 0.354 |

**Figure 3.4. Fitted (solid line) and 95% confidence intervals (dashed lines) for the Hockey-stick S–R relationship for the period 2006–2019 (red lines) and the period 2006–2018 (blue lines). Estimates of parameter a and recruitment standard deviation (sigma) are also provided.**

### "Low-to-Medium" productivity

Corresponds to a sequential application in time of the Low and Medium scenarios of productivity, so that as soon as the 'true' biomass in any trajectory (OM projections) is above $B_{lim}$ of the medium productivity ($B_{lim\_med}$=337 448 t) then the productivity will correspond to the Medium productivity since then onwards, until the end of the projection period. The Hockey-stick fitted for the Medium productivity scenario is the one fitted to the stock–recruit series 1993–2019 (Figure 3.5 and Table 3.1). The two hockey-stick functions (Low and Medium) which will be applied in the Low-to-Medium productivity are shown in Figure 3.6.

Although at current levels of sardine biomass in 2020 (as assessed by ICES), median biomass is above $B_{lim\_med}$, accounting for the variability on this starting population from the assessment uncertainties makes that some of the random starting populations would start from below $B_{lim\_med}$. This scenario incorporates the concern of a continuity of poor levels of recruitments for those starting population during the next years, until the population recovers above the $B_{lim\_med}$ of 337 448 tonnes. Once recovered above $B_{lim\_med}$, it is presumed that the Medium productivity will apply onwards for the rest of the simulation period. Here, two Hockey-stick models would exist sequentially if the starting population was below $B_{lim\_med}$, the first one is the "Low" productivity recruitment model, applicable over the recovery phase until the year $B_{lim\_med}$ is exceeded and then the "Medium" one is applied for the rest of the simulated years (Figure 3.5), even if the population occasionally falls below $B_{lim\_med}$. See the parameters in Table 3.1.

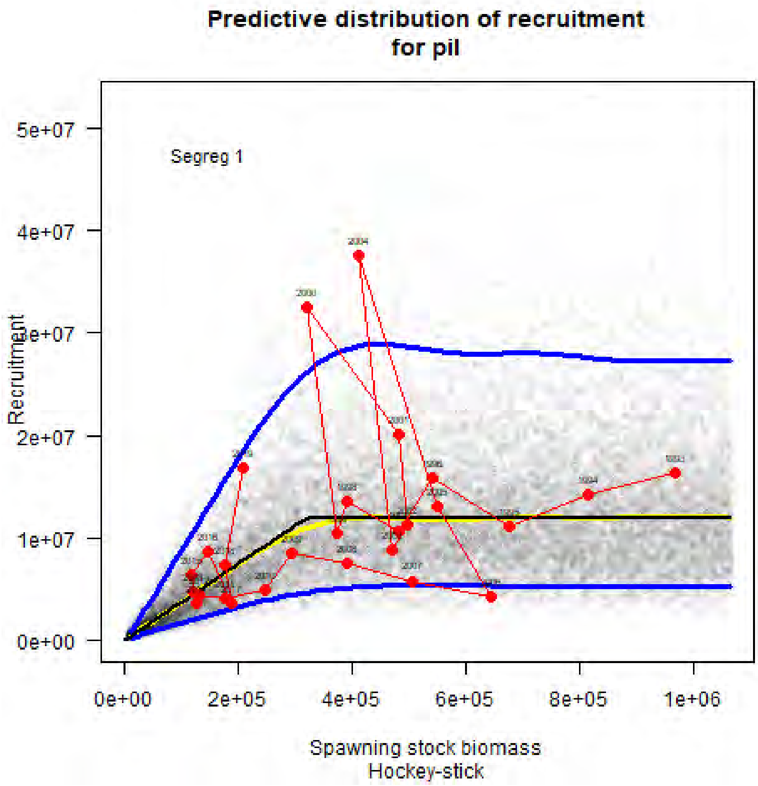



**Figure 3.5. Hockey-stick stock–recruitment function estimated with data from the 2020 assessment for the period 1993–2019 ($B_{lim\_med}$=337 448 t).**

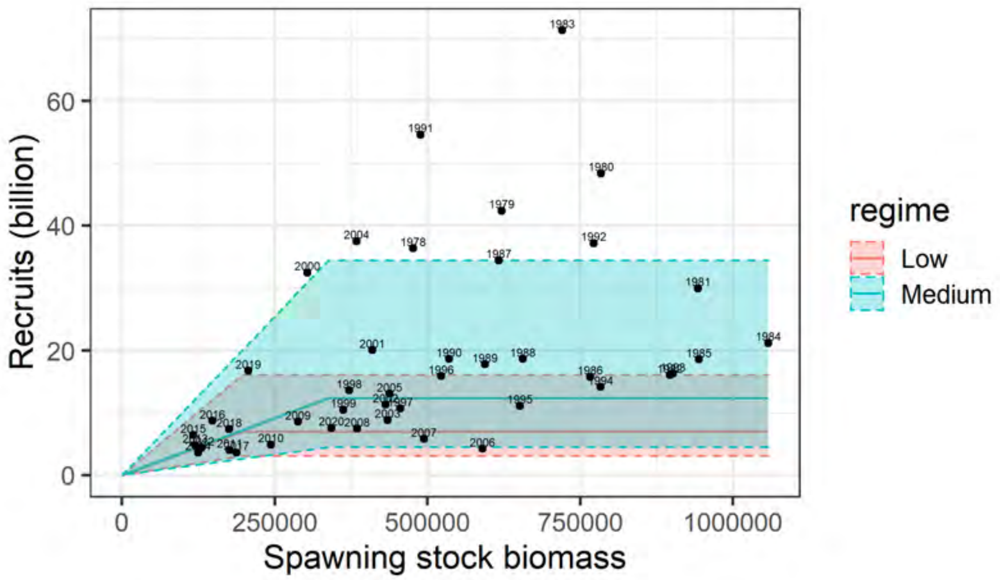



**Figure 3.6. Hockey-stick stock–recruitment functions and 95% confidence intervals, fitted for the Low (period 2006–2019; $B_{lim\_low}$=196 334 t) and for the Medium (period 1993–2019; $B_{lim\_med}$=337 448 t) productivity regimes.**

## 'Mix (Low & Medium)' productivity

This is a variant of the former scenario, corresponding to a combination of the Low and the Medium recruitment productivity scenarios (including their corresponding uncertainties), but in this case, after a recovery above $B_{lim\_med}$, if the biomass falls again below $B_{lim\_med}$, then the "Low" recruitment scenario would prevail again. Therefore, the actual 'Mix' model is the one in Figure

3.7 (parameters provided in Table 3.1), whereby recruitments of biomass above $B_{lim\_med}$ lay around the expected recruitments for the 'Medium' productivity scenario but the recruitments for biomass below $B_{lim\_med}$ will always correspond to the 'Low' productivity regime. This incorporates the concern and the difficulty that, for populations below $B_{lim\_med}$ (337 448 t), the actual dynamics of recruitment would be the Low recruitment productivity scenario. This makes the stock productivity unstable jumping from the Medium to the Low and vice versa depending on the actual biomass of the population. Although this feature renders very difficult the definition of a suitable $B_{lim}$ for such population dynamics, it was considered reasonable to take $B_{lim\_med}$ as the value of reference against which to judge the performance of HCRs in terms of risk (as in ICES, 2019b).

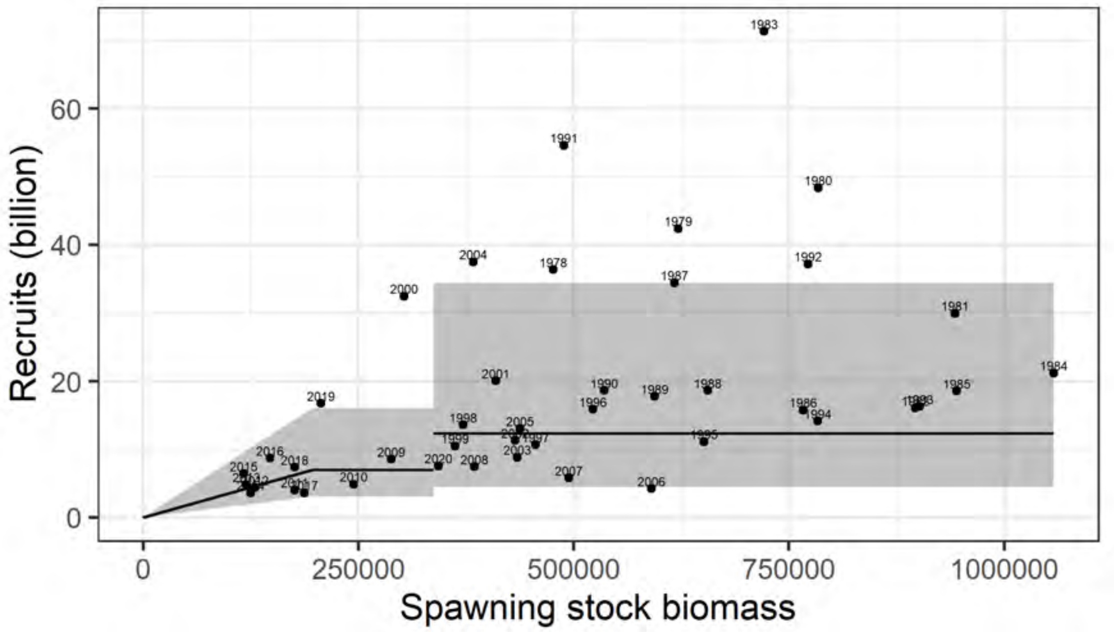



**Figure 3.7. Combined Hockey-stick models used to generate recruitment for the 'Mix' productivity scenario.**

**Table 3.1. Scenarios of productivity and fitted parameters for the Hockey-stick S–R relationships.**

| Scenario | Productivity | S–R model and parameters |
|---|---|---|
| Sc1 | 'Low':<br>whole simulation period (2020–2050) | Hockey-stick 'Low';<br>2006–2019;<br>a=35.6, b=196 334 tonnes; Sigma = 0.423 |
| Sc2 | 'Low–to-Medium':<br>If B1+$_{2020}$ is < $B_{lim\_med}$ (337 448 t) start with 'Low' in 2020<br>and while B1+$_{y-1}$<$B_{lim\_med}$ keep R='Low';<br><br>If B1+$_{2020}$ is > $B_{lim\_med}$ start with 'Medium' in 2020<br>All: Whenever B1+$_{y-1}$≥$B_{lim\_med}$ then R='Medium' and stays in the Medium productivity regardless of any future biomass value in B1+$_{y+1}$ | Hockey-stick 'Low';<br>2006–2019;<br>a=35.6, b=196 334 tonnes; Sigma= 0.423<br><br>Hockey-stick 'Medium';<br>1993–2019;<br>a=36.6, b=337 448 tonnes; Sigma = 0.522 |
| Sc3 | 'Mix':<br>If B1+$_{2020}$ is < $B_{lim\_med}$ (337 448 t) start with 'Low' in 2020<br>If B1+$_{y-1}$<$B_{lim\_med}$ then R='Low';<br><br>All: whenever B1+$_{y-1}$≥$B_{lim\_med}$ then R='Medium',<br>and whenever B1+$_{y-1}$<$B_{lim\_med}$ then R='Low' | Hockey-stick 'Low';<br>2006–2019;<br>a=35.6, b=196 334 tonnes; Sigma = 0.423<br><br>Hockey-stick 'Medium';<br>1993–2019;<br>a=36.6, b=337 448 tonnes; Sigma= 0.522 |

## 3.3 Harvest control rules and variants tested

According to the ToRs, the group decided to assess the performance of the following management options for the different productivity scenarios:

a) No Fishing (see Section 3.4).
This scenario is devised to serve as a reference of the natural state of the population without fishing (biomass and recruitment levels, variability, risks of falling below $B_{lim,}$ etc.) for comparison with the status under the different harvest strategies tested here.

In the Working Document (Wise *et al.*, 2021, Annex 7), simulations were run for a no fishing scenario for the three productivity regimes considered (Low, Low-to-medium and Mix). It is shown that the generation of recruitment for the Mix regime becomes in practice equal to that of the Low-to-medium regime after the first ten years of the projection period, where mean simulated recruitment equals the Mean R_med productivity (Annex 7, Figures 15 and 16). This means that under no fishing and for the starting conditions of these simulations (from the assessment in 2020) the Mix recruitment tends to the Medium productivity.

b) Management using the proposed Harvest Control Rule
The proposed HCR by Portugal and Spain was tested for several variants of an upper ceiling to the total allowable catches (maximum TAC) which covers the following range of values:

TACmax: 30 000 t / 35 000 t / 40 000 t / 45 000 t/ 50 000 t.

The request asked for the evaluation of catch rules with caps of 40 kt, 45 kt and 50 kt. WKSARHCR simulation tested two other rules with catch cap of 30 kt and 30 kt. The HCRs were named HCR30, HCR35, HCR40, HCR45 and HCR50.

c) ICES MSY Advisory Rule:
As a result of the revision of the $F_{MSY}$ values conditioned to the former $B_{lim}$ and MSY $B_{trigger}$ as defined in the former section (Section 2), two alternative ICES MSY AR were defined corresponding to the reference points established for the Low and the Medium productivity regimes of the stock. These are:

- ICES MSY AR Low: with $F_{MSY} = F_{pa} = 0.092$ year$^{-1}$, MSY $B_{trigger}$=252 523 t and $B_{lim}$=196 334 t
- ICES MSY AR Med: with $F_{MSY} = F_{pa} = 0.111$ year$^{-1}$, MSY $B_{trigger}$=446 331 t and $B_{lim}$=337 448 t

The ICES MSY AR rules were run for a projection period of 30 years to estimate the range of fishing mortality and median catches over the period. 'ICES MSY AR Low' was run under a Low productivity scenario and 'ICES MSY AR Med' assuming a Medium productivity scenario.

## 3.4 Variants of the MSE framework

In order to realise gradually the implications of adding uncertainties in the initial condition of the starting population and in the perception (observation) of the population to take decisions (through the assessment in the management procedure), several variants of the setting of the MSE framework were considered:

a) ASS: Inclusion of the Assessment (Stock Synthesis) in the loop or perfect observation of the population (none).
b) OER: Inclusion of observation error. The setting of the ASS was parallel to the inclusion or not of observation error: For the assessment (Stock Synthesis) observation errors were included in the numbers-at-age of both survey indexes and catches and in the catchability of the surveys (naq), while for the case with no assessment (none) no observation error was included (none).
c) INN: All simulations were run with variability in the starting population.

## 3.5 Summary of Productivity Scenarios, HCRs and setting of the MSE framework

Summary of the scenario options and Harvest Control Rules analysed during WKSARHCR:

| Options | ID | Alternatives |
|---|---|---|
| Recruitment Scenarios | REC | Low, Low-to-medium, Mix |
| Harvest control rule | HCR | No fishing, HCR50, HCR45, HCR40, HCR35, HCR30, ICES MSY AR Low, ICES MSY AR Med |
| Assessment | ASS | none, Stock Synthesis |
| Observation error | OER | none, naq (these correspond respectively to the two settings of Assessment modes above) |
| Initial numbers-at-age | INN | All simulation were run with variability. |

## 3.6 References

ICES 2019a. Request from Portugal and Spain to evaluate additional harvest control rules for the Iberian sardine stock in divisions 8.c and 9.a. ICES Special Request Advice (Published 13 December 2019). ICES Advice 2019 –sr.2019.26 – https://doi.org/10.17895/ices.advice.5755

ICES.2019b. Workshop on the Iberian Sardine Management and Recovery Plan (WKSARMP). ICES Scientific Reports. 1:18. 168 pp. http://doi.org/ 10.17895/ices.pub.5251

ICES. 2021. Working Group on Acoustic and Egg Surveys for small pelagic fish in NE Atlantic (WGACEGG; outputs from 2020 meeting). ICES Scientific Reports. In prep.

# 4 Management Strategy Evaluation (ToR b)

## 4.1 Introduction

The management strategy evaluation (MSE) of the proposed harvest control rule (HCR) was carried out using FLBEIA (García *et al.*, 2017). The methodology followed was the one used in WKSARMP (ICES, 2019a), but the dynamics of the stock and the fishery were updated according to the most recent stock assessment conducted by WGHANSA (ICES, 2020).

All the methodology is described in detail in WKSARMP (ICES, 2019a). Following ICES guidelines on MSE (ICES, 2019b) a summary of the methodology is presented in Annex 6.

## 4.2 Operating Model

The operating model (OM) is the mathematical representation of the best knowledge of the natural and fishery systems ('true' stock, fleets and any other covariate affecting the system). The operating model for the MSE to evaluate the proposed HCR for the Iberian sardine was based on the last stock assessment (ICES, 2020) conducted using Stock Synthesis (SS3, Methot and Wetzel, 2013). The population was considered age structured (from ages 0 to 6+) and exploited by a unique fleet (composed by one métier) and was projected forward in annual time-steps.

### 4.2.1 Initial conditions

The estimates of abundance in numbers-at-age (ages 0-6+) for the start of the projection period (2019) were created as a product of the estimate of numbers in this year from the last assessment (ICES, 2020) and a lognormal distribution with μ=0 and $\sigma=\sqrt{\mathbf{log}(\boldsymbol{cv}^2+\mathbf{1})}$ where cv is the coefficient of variation of the log-numbers-at-age of the population estimate of the SS3 assessment in year 2020 (Table 4.1).

**Table 4.1. Numbers-at-ages 0–6+ (in millions) in 2019 from last assessment (ICES, 2020) and coefficient of variance (cv) used for generating the initial 1000 populations.**

| **Age** | **0** | **1** | **2** | **3** | **4** | **5** | **6+** |
|---|---|---|---|---|---|---|---|
| Number | 16761 | 2743 | 692 | 929 | 394 | 128 | 183 |
| *CV* | 0.21 | 0.19 | 0.20 | 0.16 | 0.17 | 0.18 | 0.18 |

### 4.2.2 Biology

Natural mortality and proportion of mature individuals at-age were considered time-invariant during the projection period (Table 4.2). Natural mortality was age-dependent (higher for younger ages) and equal to the values used in the stock assessment. The proportion of mature individuals at-age followed a knife-edge ogive and all individuals of age 1+ were considered mature. As a result, spawning–stock biomass (SSB) and biomass 1+ (B1+) were equal during the projection period.

Assumptions about future mean weight-at-age of Iberian sardine followed the guidance of the short-term forecast described in the stock annex agreed on the last stock benchmark review (ICES, WKPELA 2017). Weights-at-age in the stock were calculated as the arithmetic mean value of the last six years of the assessment (2014–2019) while weight-at-age in the catch were calculated as the arithmetic mean value of the last three years of the assessment (2017–2019). As explained in the stock annex a six-year period is used to compute weights-at-age in the stock because these are based on data collected during the triennial DEPM surveys. No variability was considered for these variables, as there is no indication of significant trends in historical weight-at-age.

**Table 4.2. Natural mortality, proportion of mature individuals, mean weight-at-age in the stock and in the catch-at-age for ages 0–6+, used in the simulations.**

| Variable | Age | | | | | | |
|---|---|---|---|---|---|---|---|
| | **0** | **1** | **2** | **3** | **4** | **5** | **6+** |
| Natural Mortality (year$^{-1}$) | 0.98 | 0.61 | 0.47 | 0.40 | 0.36 | 0.35 | 0.32 |
| Maturity (prop) | 0 | 1 | 1 | 1 | 1 | 1 | 1 |
| Weight in the stock (kg) | 0 | 0.029 | 0.046 | 0.062 | 0.065 | 0.070 | 0.072 |
| Weight in the catch (kg) | 0.027 | 0.045 | 0.060 | 0.075 | 0.085 | 0.091 | 0.097 |

Recruits (numbers-at-age 0) were estimated from the spawning–stock biomass following a functional relationship:

$$R_t = N_{0,t} = f(SSB_t)\exp(\varepsilon_t).$$

The relationships used in the simulations to generate recruits depended on the productivity regime assumed for the true state of nature in each scenario (Section 3.2). Recruitment variability ($\varepsilon_t$) was introduced by generating random draws from a lognormal distribution with $\mu$=0 and $\sigma$ as estimated in the fitting of the stock–recruitment model.

### 4.2.3 Fishery

The fleet dynamics in FLBEIA is described by four submodels: the effort model, the catch model, the price model and the capital model. The effort model gives the effort exerted by each fleet and its distribution along métiers. In this case, the effort was allocated to the unique fleet and its unique métier along the projection period. In addition, no economic data were available and price and capital models were not considered. The catch model was given by the Cobb-Douglas production function (Cobb and Douglas, 1928; Clark, 1990) that relates the actual catch with the effort exerted and the stock size. The catchability-at-age parameters for the historic period were estimated as the ratio between catch and biomass (in weight) at-age in the middle of the year (Table 4.3). Catchability-at-age during the projection period was set as the average from the last six years of the assessment (2014–2019). These values mimicked the dome shape pattern estimated in the assessment with ages from 3 to 5 bound and a decline at the 6+ group.

**Table 4.3, Catchability-at-age estimated and assumed for the projection period.**

| Age | 0 | 1 | 2 | 3 | 4 | 5 | 6+ |
|---|---|---|---|---|---|---|---|
| Catchability | 0.023 | 0.081 | 0.132 | 0.141 | 0.141 | 0.141 | 0.115 |

### 4.2.4 Observation error model

Based on the operating model, the observation error model generated the data to be used as input of the assessment in the management procedure. Two types of data were generated: the catches and the abundance indices.

The abundance indices used as input to each assessment cycle were generated from the "true" population with lognormal distributed errors. For the DEPM survey the estimated catchability value in the last assessment was used ($q$ =1.1906) and a lognormal distribution with μ=0 and σ=$\sqrt{\log(cv^2+1)}$ where $cv$ is the coefficient of variance of the parameter assumed fixed, and equal to 0.25, from the SS3 assessment. Catchability-at-age ($q_{a,t}$) of the acoustic survey was estimated as the mean of $\frac{Nas_{a,1996:2019}}{Npop_{a,1996:2019}}$, where $N_{as}$ is the number-at-age observed in the acoustic survey and $N_{pop}$ is the number-at-age estimated by the assessment (Figure 4.1). Number-at-age for the acoustic survey were then estimated as the product of catchability-at-age by the number-at-age in the 'true' stock and error was introduced as a lognormal distribution with μ=$\log\frac{Nas_{a,1996:2019}}{Npop_{a,1996:2019}}$and σ equal to the standard deviation of $\log\frac{Nas_{a,1996:2019}}{Npop_{a,1996:2019}}$ (Table 4.4).

**Table 4.4. Mean catchability and standard deviation (sd) for the acoustic numbers-at-age.**

| Age | 0 | 1 | 2 | 3 | 4 | 5 | 6+ |
|---|---|---|---|---|---|---|---|
| Catchability (log scale) | 0 | 0.015 | -0.089 | -0.049 | 0.145 | 0.286 | -0.146 |
| *sd* | 0 | 0.532 | 0.513 | 0.447 | 0.518 | 0.681 | 0.772 |


**Figure 4.1. Catchability-at-age from the acoustic survey estimated as the ratio between the number-at-age observed in the acoustic survey and the number-at-age estimated by the assessment.**

Observation error was also introduced in the numbers-at-age in the catch as a multiplicative error by means of a lognormal distribution with μ and σ of the logarithmic residuals in the catch from the SS3 assessment model (Table 4.5, Figure 4.2).

**Table 4.5. Mean observation error and standard deviation (sd) for the catch-at-age.**

| Age | 0 | 1 | 2 | 3 | 4 | 5 | 6+ |
|---|---|---|---|---|---|---|---|
| Mean (log scale) | -0.060 | -0.022 | -0.059 | 0.002 | 0.127 | 0.165 | -0.070 |
| *sd* | 0.519 | 0.217 | 0.168 | 0.192 | 0.359 | 0.402 | 0.245 |

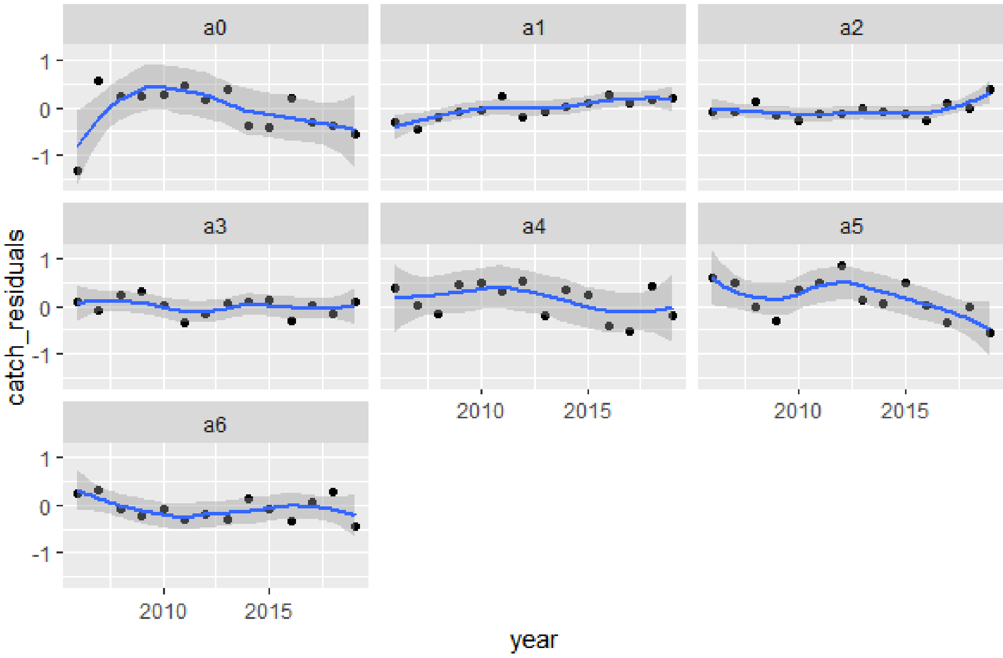



**Figure 4.1. Residuals of the catch-at-age estimated as the ratio between the observed catch-at-age and the catch-at-age estimated by the assessment.**

These observations were then used as input to the stock assessment model.

## 4.3 Management procedure

The management procedure (MP) includes the stock assessment ('perceived' stock), the short-term forecast and advice for fisheries management following the application of the management strategy (Harvest Control Rules or Decision Rules), and the management process to implement the scientific advice. In this case a full-feedback MSE was used, which means that the assessment model was applied yearly in the simulation.

### 4.3.1 Stock assessment

The model used to assess the Iberian sardine is Stock Synthesis 3 (SS3, Methot and Wetzel, 2013), version 3.24f (Methot, 2012). The sardine assessment is an age-based assessment assuming a single area, a single fishery, a yearly season and genders combined. Input data include catch (in biomass), age composition of the catch, total abundance (in numbers) and age composition from an annual acoustic survey and spawning–stock biomass (SSB) from a triennial DEPM survey. Considering the current assessment calendar (annual assessment WG in November) in year (*y*), the assessment includes fishery data up to year *y-1* and acoustic data up to year *y*.

To include the SS3 stock assessment model within the MSE simulations running in FLBEIA, a function named 'ss32flbeia' originally developed to mimic the stock assessment of the Bay of Biscay sardine was adapted for the Iberian sardine case study during WKSARMP (Citores, L. WD2019, Annex5). A detailed description is provided in WKSARMP (ICES, 2019a).

### 4.3.2 Short-term forecast

Regarding the short-term forecast the same procedure as described in the stock annex with small deviations was used. The initial stock size corresponded to the assessment estimates for ages 1–6+ at the final year of the assessment. The maturity ogive corresponded to a knife-edge ogive. The proportion of F and M before spawning were set at zero, which corresponded to the beginning of the year when the SSB is estimated by the model. Weights-at-age in the stock are calculated as the arithmetic mean value of the last six years of the assessment (to account for the weights-at-age estimated from two triennial DEPM surveys) but in this case were calculated as the arithmetic mean value of the last three years of the assessment. Weights-at-age in the catch were calculated as the arithmetic mean value of the last three years of the assessment. The exploitation pattern was equal to the last year of the assessment. For the intermediate year assumptions, predictions were carried out assuming no implementation error and therefore they were made with a catch constraint for the assessment year equal to the TAC advised for that year. Recruitment in the interim year and forecast year was set equal to the geometric mean of the last five years.

### 4.3.3 Decision rule

The forecast B1+ at spawning time of year *y+1* was used to apply the TAC setting procedures according to the HCRs described in Section 3.3.

### 4.3.4 Implementation error

The present MSE was run without implementation error, i.e. assuming perfect implementation of the Total Allowable Catch (TAC) advice, which may include zero catch.

## 4.4 Simulations

The FLBEIA MSE simulation carried out to analyse the performance of the proposed HCR was based on 1000 populations (*iters*), each projected from 2021 to 2050 for the Low and Low-to-medium recruitment regimes and from 2021 to 2070 for the Mix recruitment regime. Therefore, the full-feedback MSE performed simulations for *nt*= 30 or 50 future years resulting in 30 000 or 50 000 assessment cycles for each scenario depending on the recruitment regime. For comparison, the same MSE simulations were carried out for the case in which no observation and assessment errors were included. Given the computational burden, all the simulations were carried out in the computation cluster located in AZTI. Simulations were carried out using the FLR packages FLCore (version 2.6.13), FLBEIA (version 1.15.6.5) and FLash (version 2.5.11; used for short-term projections). The results were examined using the package FLBEIAshiny (1.0.0).

## 4.5 Performance statistics

Table 4.7 summarizes the performance statistics used. They include the median average biomass of fish age 1 and older (B1+), fishing mortality and catch. The interannual variation (IAV) of the catch (absolute values) was also estimated (average across years and then across iterations) as well as the probability of the fishery being closed (i.e. TAC equal to zero).

The probability of B1+ falling below $B_{lim}$ was also computed. Currently ICES uses the Risk3 ≤0.05 criterion as the basis for defining a multiannual plan as precautionary. Risk3 is defined as the maximum probability that B1+ is below $B_{lim}$, where the maximum (of the annual probabilities) is taken over *nt* years. Finally, the first year in which B1+ would be above or equal to $B_{lim}$ with 95% probability was computed.

All these metrics were estimated for three time periods:

- Initial (2021–2026): an initial time period starting in the first projection year 2021 and ending in 2026, covering the first six years of the duration of the management plan as indicated in the request;
- Short (2021–2030): a short time period corresponding to the first ten years of the projection period;
- Long (2041–2050): corresponding to the last ten years of the 30 years in the projection period which corresponds to the period when the 'true' stock has reached equilibrium for the Low and Low-to-medium recruitment regimes.

In the case of the Mix recruitment regime, for which the simulations were conducted over a longer period (2021–2070), the designated 'Long' period corresponds to the last ten years of the 50 years of the projection period, which corresponds to the period when the 'true' stock has reached equilibrium for the Mix recruitment regime.

**Table 4.7. Statistics used to summarize the performance of the proposed HCRs.**

| | Indicator |
|---|---|
| Yield | Median catch |
| | IAV $= Mean\lvert Catch_{t-1} - Catch_t \rvert$ |
| Fishing Mortality | Median $F_{bar}$, 5th and 95th percentiles |
| B1+ | Median B1+, 5th and 95th percentiles |
| First year B1+ reaches 196 kt | Year in which $P(B1+ \geq B_{lim\_low}) \geq 0.95$ |
| First year B1+ reaches 337 kt | Year in which $P(B1+ \geq B_{lim\_med}) \geq 0.95$ |
| Precautionary considerations | $Risk\ 3 = max(P(B1+ < B_{lim}))$ |

## 4.6 Code and software

FLBEIA is a generic tool to conduct Bio-Economic Impact Assessment of fisheries management strategies in a management strategy evaluation framework (Garcia *et al.*, 2017). FLBEIA can be categorized as a 'Models of Intermediate Complexity for Ecosystem assessments' or MICE (Plagányi *et al.*, 2014) focused on fishing activity in a multistock and multifleet context. It has been built using R-FLR packages (Kell *et al.*, 2007) and can automatically benefit from new developments in those packages.

The model documentation is extensive. There is a research paper describing the model (Garcia *et al.*, 2017). A manual that describes in detail all the models available is provided within the R library. And there is a set of dedicated tutorials in the FLR website http://www.flr-project.org/. The source code can be downloaded from GitHub (https://github.com/flr/FLBEIA) and the compiled package from the FLR website (http://www.flr-project.org/). There is a support mailing list flbeia@azti.es.

## 4.7 References

Citores, L. 2019. SS2flbeia function and analysis of convergence issues. WD presented to the ICES Workshop on the Iberian sardine management and recovery plan (WKSARMP).

Clark, C. W. 1990. Mathematical Bioeconomics: The optimal management of renewable resources. John Wiley and Sons.

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# 5 Additional test runs

## 5.1 Effect of the assessment

To better understand the inclusion of the assessment in the full-MSE, all the simulations were repeated without observation and assessment errors. This means that the true population was used in the short-term forecast to obtain B1+ at the beginning of the management year, to which the HCR was applied. In this section we analyse in detail the effect of the inclusion of the observation and assessment errors in the HCRs. Overall, the assessment produces positively biased recruitment and B1+ estimates and negatively biased fishing mortality estimates, i.e. the recruitment and B1+ estimates from the assessment are larger than in the true population, whereas the fishing mortality estimates are smaller than the actual values (Figures 5.1 and 5.2). The bias is larger in the Low recruitment regime (Figure 5.1) than in the Low-to-medium recruitment regime (Figure 5.2). Along the projection period other parameters estimated in the assessment also change. For instance, the acoustic and DEPM surveys catchabilities decrease along the projection period (Figure 5.3), with larger changes for the Low recruitment regime than for the Low-to-medium recruitment regime. Other parameters, like selectivity-at-age do not show any systematic pattern (Figure 5.4).

The overestimation of B1+ when observation and assessment errors are implemented, leads to larger fishing mortalities and, therefore, lower B1+ in the population in comparison to the simulations without observation and assessment errors (Figure 5.5). The differences increase along the projection period. The largest differences correspond to the Low recruitment regime, followed by the Mix and finally by the Low-to-medium recruitment regimes. In addition, the differences between the simulations without and with observation and assessment errors increase as the maximum TAC of the proposed HCR increases. In contrast, for the no fishing catch rule, the relative change of estimates of B1+ of runs with assessment and observation error in relation to runs without assessment and no observation error are around 1 with no systematic pattern and no major differences between the recruitment regimes (Figure 5.6). The assessment bias conditions the performance of any HCR, and in this case was substantial, particularly for the scenario of low productivity regime. Due to time constraints it was not possible to investigate the origin of the bias. If bias persists in future evaluations of HCRs, sensitivity analysis should be undertaken to identify the origin of the bias.

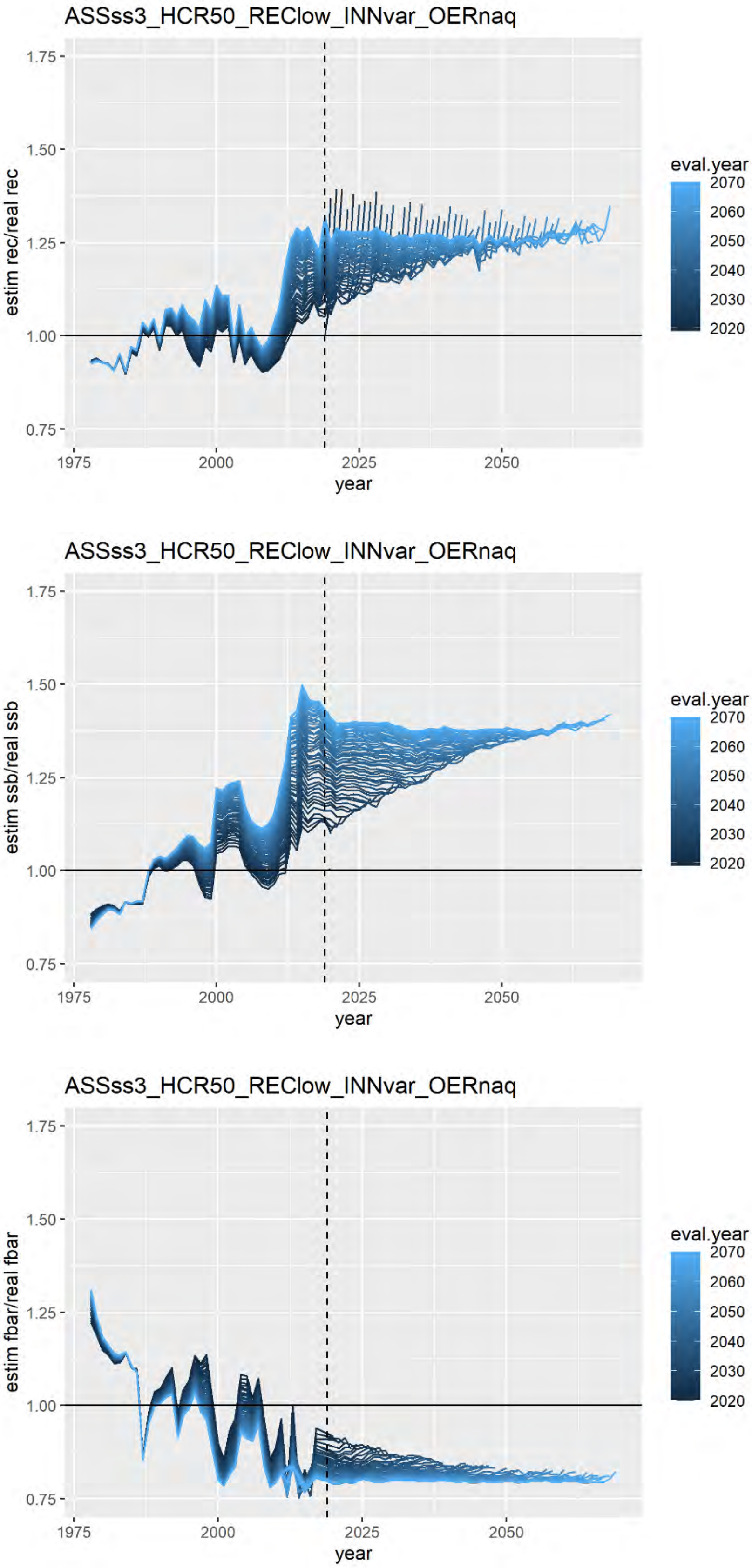



**Figure 5.1 From top to bottom relative values of recruitment, B1+ and fishing mortality estimated from the assessment with respect to the true values of the population for HCR50 under a Low recruitment regime. The colours indicate the evaluation year and the vertical dashed line is the beginning of the projection period.**

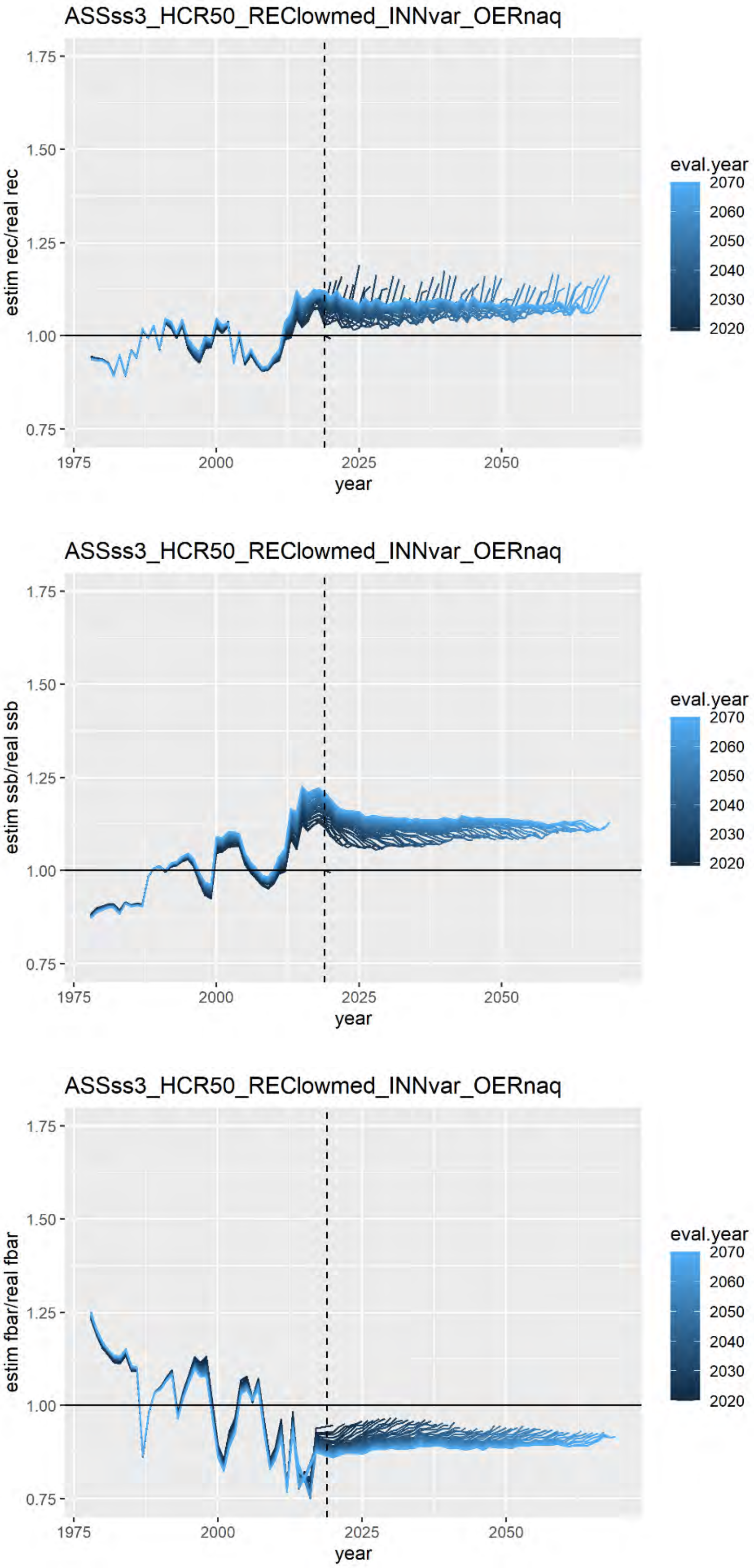



**Figure 5.2. From top to bottom relative values of recruitment, B1+ and fishing mortality estimated from the assessment with respect to the true values of the population for HCR50 under a Low-to-medium recruitment regime. The colours indicate the evaluation year and the vertical dashed line is the beginning of the projection period.**

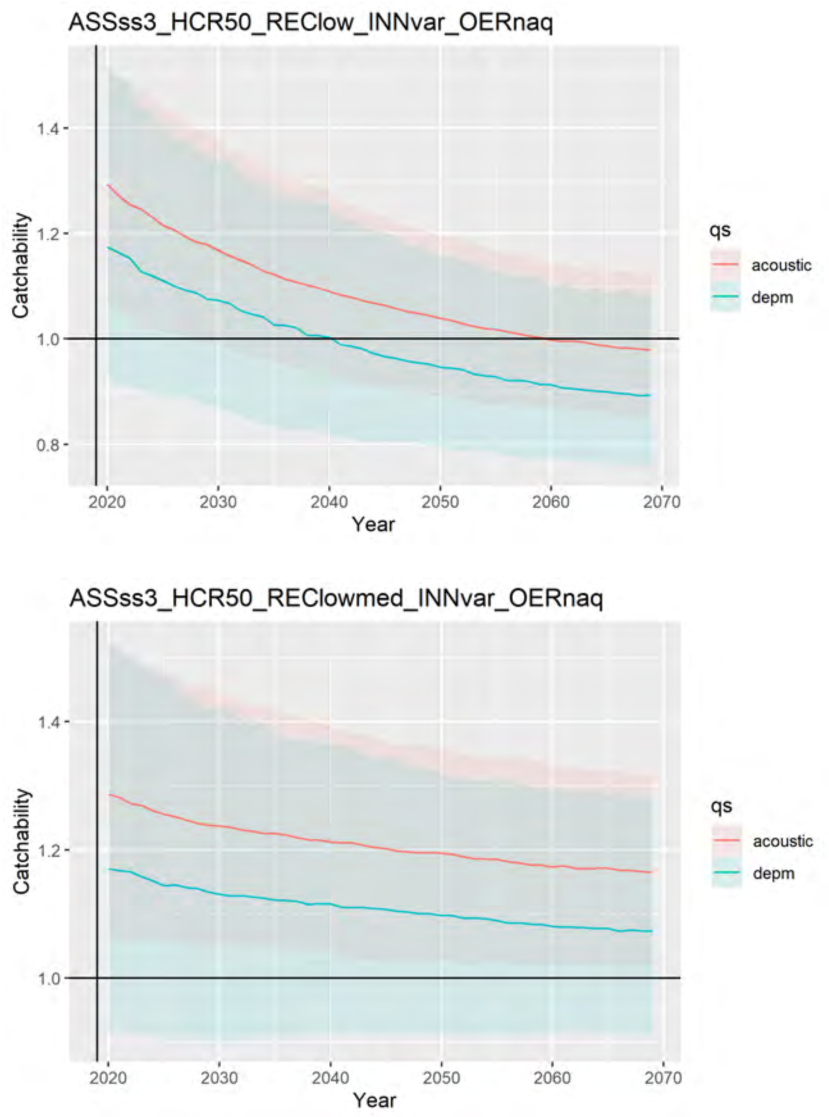



**Figure 5.3. Catchability estimates from the assessment model in the simulations for HCR50 under a Low recruitment regime (top panel) and a Low-to-medium recruitment regime (bottom panel).**

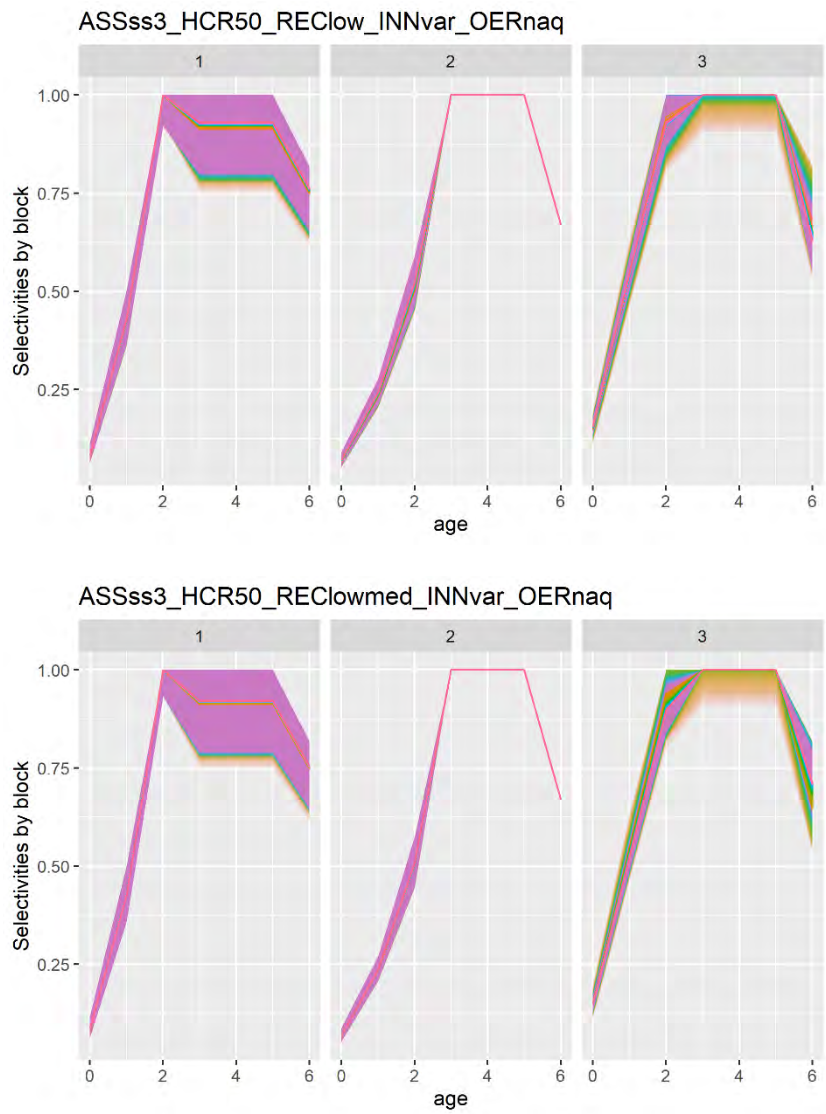



**Figure 5.4. Selectivity-at-age estimates per time-block (in columns) from the assessment model in the simulations for HCR50 under a Low recruitment regime (top panel) and a Low-to-medium recruitment regime (bottom panel).**


**Figure 5.5. Relative change of estimates of B1+ (upper panels) and $F_{bar2\text{-}5}$ (lower panels) of runs with assessment and observation error in relation to runs without assessment and no observation error for HCR30, HCR35, HCR40, HCR45 and HCR50 (in columns) for scenarios assuming Low, Low–to-medium and Mix productivity for the 'true' stock, from 2020 to 2070.**

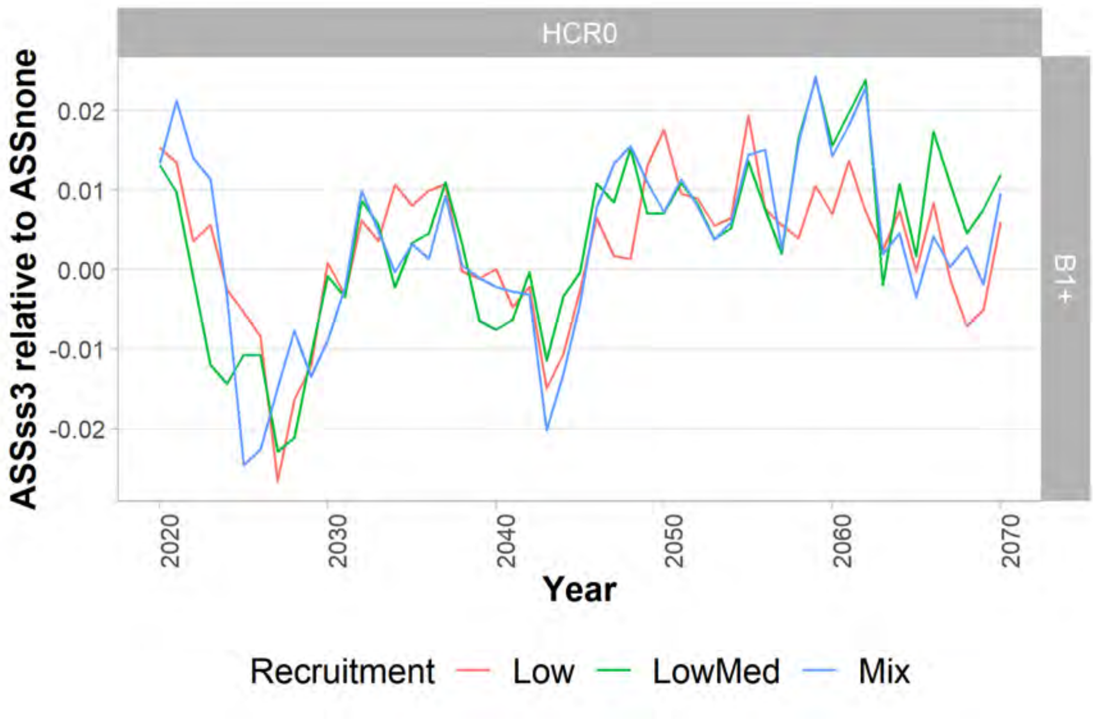



**Figure 5.6. Relative change of estimates of B1+ of runs with assessment and observation error in relation to runs without assessment and no observation error for no fishing HCR for scenarios assuming Low, Low–to-medium and Mix productivity for the 'true' stock, from 2020 to 2070.**

## 5.2 Number of iterations

ICES establishes that a HCR is precautionary when Risk3 ≤ 0.05. For a proper evaluation of this criterion, it's necessary that the number of iterations in the simulations are large enough to obtain accurate and robust estimates of risk. This is especially relevant for Risk3 that depends on the tails of the biomass distributions. In this section, we analyse the bias, precision and accuracy of Risk1 and Risk3 estimates depending on the number of iterations.

For three selected cases without and with observation and assessment error (Table 5.1) the simulations were run with 10 000 iterations. The Low recruitment with HCR40 and HCR45 catch rules were selected because Risk1 and Risk3 estimates based on 1000 iterations were close to 0.05, whereas the Low-to-medium recruitment with HCR50 was selected as a case of interest before the risk estimate for 1000 iterations was available.

**Table 5.1. Selected cases to run 10 000 iterations. Risk1 and Risk3 are the estimates for 1000 iterations.**

| Observation/ Assessment error | Recruitment | HCR | Risk1 | Risk3 |
|---|---|---|---|---|
| No | Low | HCR40 | 0.0041 | 0.008 |
| No | Low | HCR45 | 0.0041 | 0.008 |
| No | Low-to-medium | HCR50 | 0.0246 | 0.03 |
| Yes | Low | HCR40 | 0.0347 | 0.047 |
| Yes | Low | HCR45 | 0.0395 | 0.051 |
| Yes | Low-to-medium | HCR50 | 0.0301 | 0.038 |

From the 10 000 iterations, we sampled randomly without replacement 100 samples of different sizes that ranged from 500 to 10 000 in steps of 500. For each of these samples we computed Risk1 and Risk3 and we compared them with the Risk1 and Risk3 estimates of the 10 000 iterations, that were considered the best possible estimates (Figure 5.7).

Bias, precision and accuracy of Risk1 and Risk3 estimates as a function of the number of iterations were evaluated in terms of the mean error (Figure 5.8), the coefficient of variation (Figure 5.9) and the root mean squared error (Walther and Moore, 2005) (Figure 5.10). In all cases, Risk1 estimates were unbiased regardless the number of iterations (Figure 5.8). On the contrary, Risk3 estimates were positively biased, and the bias decreased as the number of iterations increased (Figure 5.8). The precision of both Risk1 and Risk3 improved as the number of iterations increased (Figure 5.9). As a consequence of the bias and precision results, Risk1 was more accurate than Risk3 and in both cases accuracy improved with the number of iterations. Nevertheless, the exact levels of bias, precision and accuracy varied depending on the recruitment regime, the HCR and the inclusion or not of the observation and assessment errors.

In all the cases, and even for the 10 000 iterations, Risk3 tended to be larger than Risk1, suggesting that the biomass distributions might not be fully stationary. A close inspection of the biomass distributions along the projection period, revealed that this was more relevant for the Mix recruitment regime, that needed a longer projection period to converge, and when the observation and assessment errors were included as the bias in the assessment estimates in the Low recruitment regime produced a continuous decreasing trend in the population biomass.

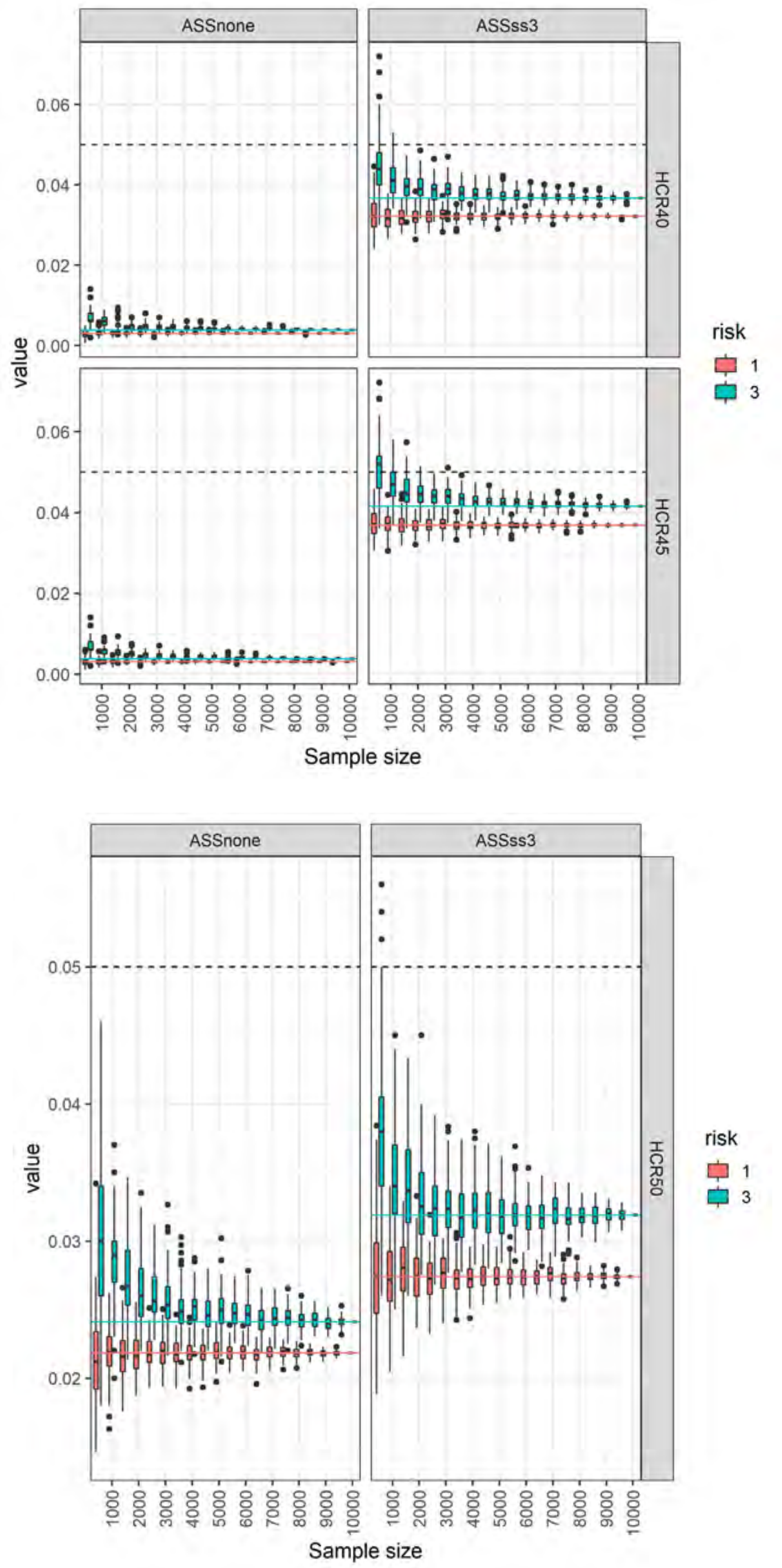



**Figure 5.7. Boxplots of Risk1 (in red) and Risk3 (in blue) estimates depending on the number of iterations (in the x-axis) for the Low recruitment regime (in the top, HCR40 and HCR45) and the Low-to-medium recruitment regime (in the bottom, HCR50). The columns correspond to the without/with observation and assessment error. The horizontal solid red and blue lines represent Risk1 and Risk3 estimates for the 10 000 iterations. The horizontal grey dashed line represent value of 0.05.**

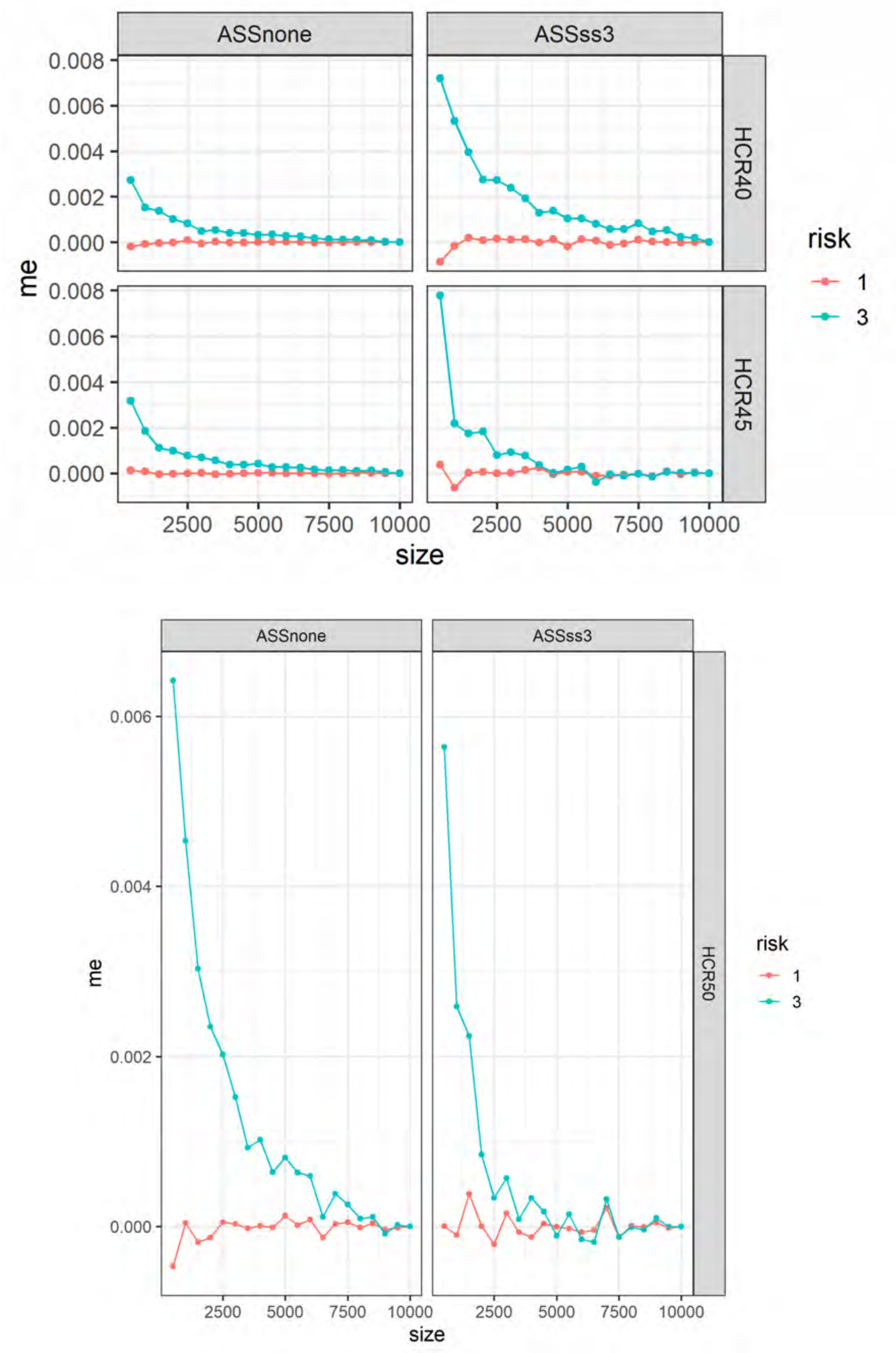



**Figure 5.8. Mean error of Risk1 (in red) and Risk3 (in blue) estimates depending on the number of iterations (in the x-axis) for the Low recruitment regime (in the top, HCR40 and HCR45) and the Low-to-medium recruitment regime (in the bottom, HCR50). ASSnone and ASSss3 correspond to the without/with observation and assessment error.**

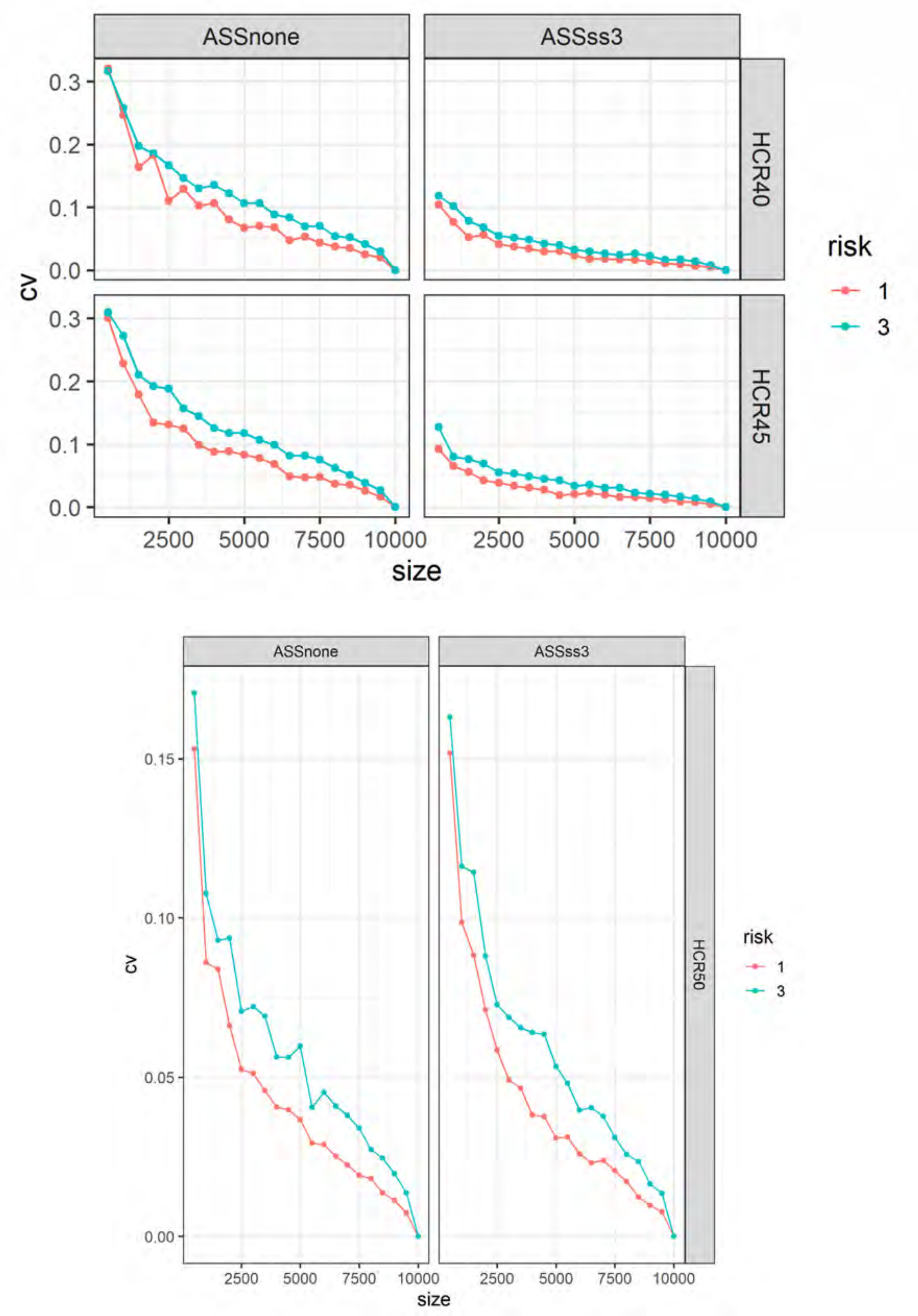



**Figure 5.9. Coefficient of variation of Risk1 (in red) and Risk3 (in blue) estimates depending on the number of iterations (in the x-axis) for the Low recruitment regime (in the top, HCR40 and HCR45) and the Low-to-medium recruitment regime (in the bottom, HCR50). ASSnone and ASSss3 correspond to the without/with observation and assessment error.**

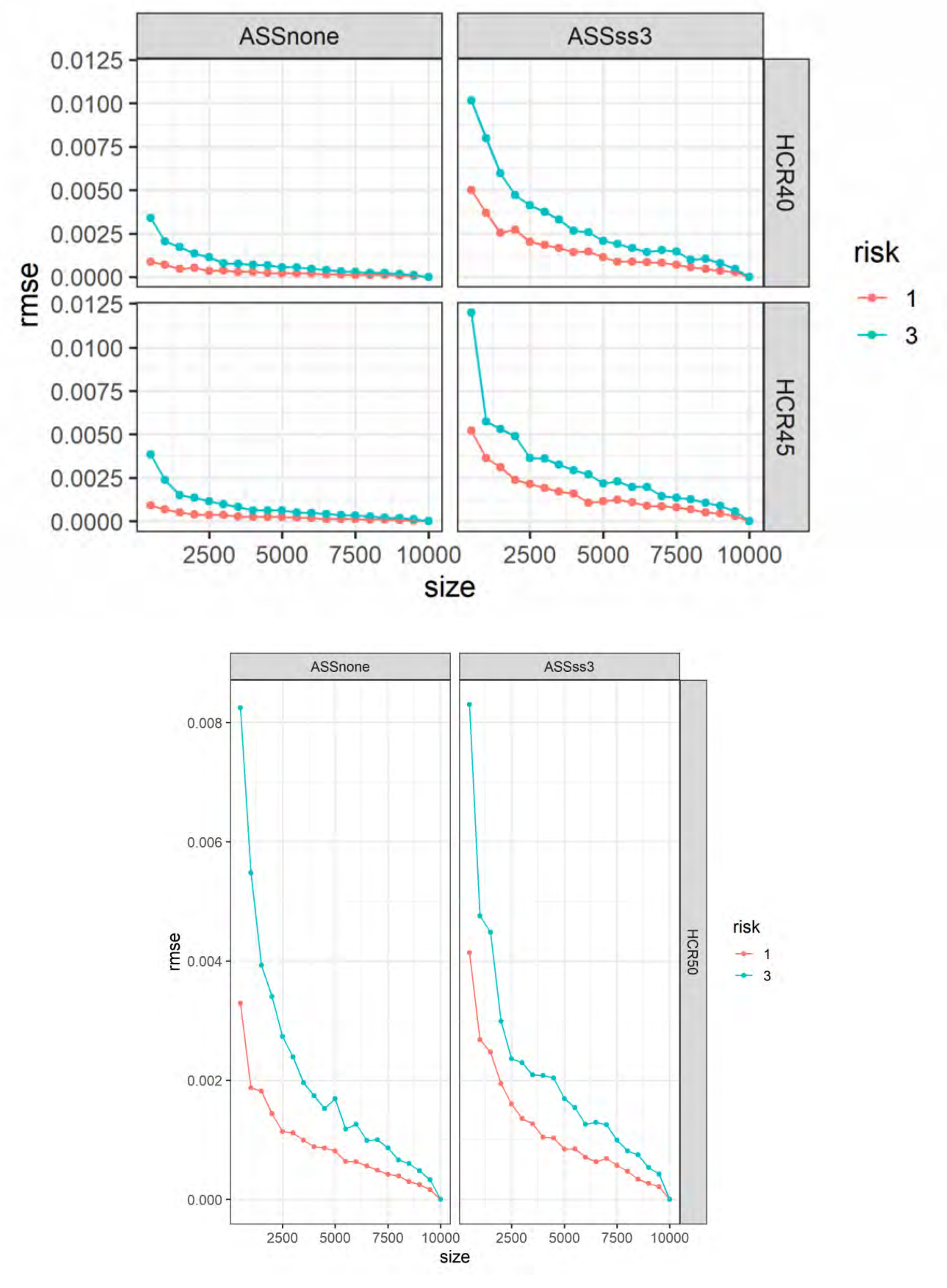



**Figure 5.10. Root Mean Squared Error of Risk1 (in red) and Risk3 (in blue) estimates depending on the number of iterations (in the x-axis) for the Low recruitment regime (in the top, HCR40 and HCR45) and the Low-to-medium recruitment regime (in the bottom, HCR50). ASSnone and ASSss3 correspond to the without/with observation and assessment error.**

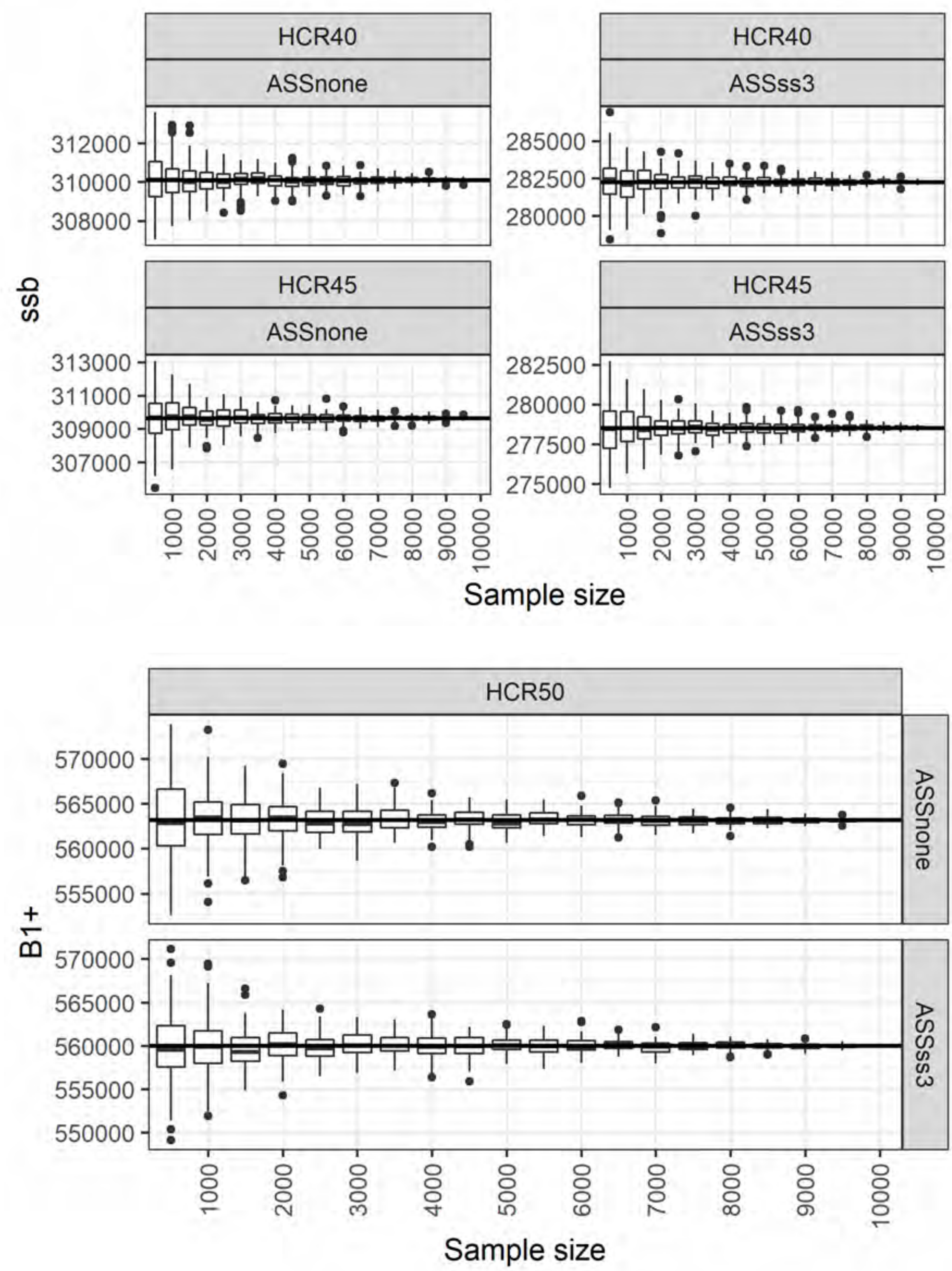
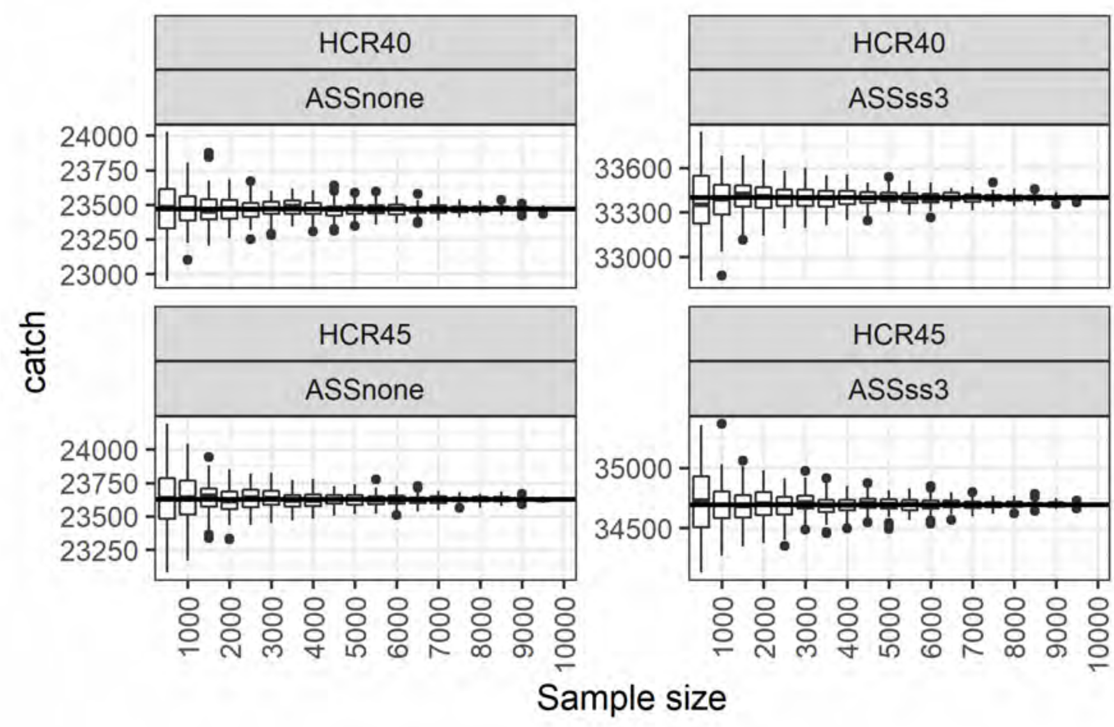



**Figure 5.11. Average B1+ estimates depending on the number of iterations (in the x-axis) for the Low recruitment regime (in the top, HCR40 and HCR45) and the Low-to-medium recruitment regime (in the bottom, HCR50). ASSnone and ASSss3 correspond to the without/with observation and assessment error.**



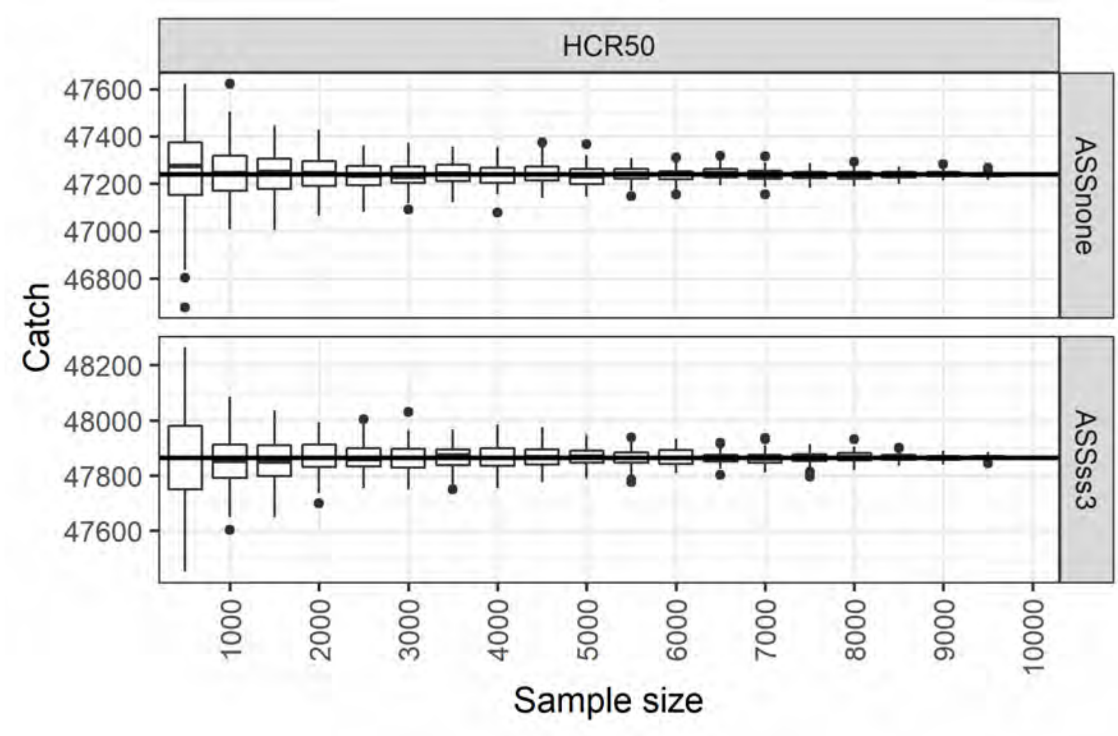




**Figure 5.12. Average catch estimates depending on the number of iterations (in the x-axis) for the Low recruitment regime (in the top, HCR40 and HCR45) and the Low-to-medium recruitment regime (in the bottom, HCR50). ASSnone and ASSss3 correspond to the without/with observation and assessment error.**

## 5.3 References

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# 6 Results and Discussion (ToR b)

Simulation testing of the performance of the proposed HCR and the ICES MSY AR was carried out with full feedback MSE for three productivity scenarios (Section 3.2). HCRs were evaluated in relation to the 0.05 threshold value used by ICES for Risk3, which is the maximum probability that B1+ is below $B_{lim}$, where the maximum of the annual probabilities is taken over the long-term period. Risk3 was computed from 1000 iterations, unless the estimated value was at the very border of the 5% threshold. In this case, given the bias in Risk3 (Section 5), the precautionarity of the HCR was considered inconclusive. Since the bias in Risk3 decreases with increasing number of iterations, the precautionarity of the HCR was evaluated based on Risk3 computed from 10 000 iterations.

## 6.1 MSE testing of HCR50

The catch rule proposed in the special request was first tested with maximum allowed catches of 50 kt and assuming three productivity scenarios for the 'true' stock (Figures 6.1-6.3), corresponding to Low, Low–to-medium and Mix productivity.

### 6.1.1 Simulated recruitment, spawning–stock biomass (B1+), fishing mortality and catch

The trajectories of the key parameters R, B1+, $F_{bar}$2–5 and catch under Low, Low-to-medium and Mix productivity are shown in Figures 6.1–6.3.

In the long term, Low productivity true stock leads to a median R around 6.8 billion individuals and a decrease of median B1+ to 278 thousand tonnes. The lower confidence limit of B1+ is below the corresponding $B_{lim}$ = 196 thousand tonnes (Figure 6.1).

If the true stock has Low-to-medium productivity, median R will increase to maximum values around 12 billion individuals, and the median B1+ increases to around 540 thousand tonnes (Figure 6.2). The lower confidence limit of B1+ is above $B_{lim\_med}$ = 337 thousand tonnes in the long term.

For the Mix productivity scenario, the long-term median R and B1+ are closer to those of the Low-to-medium productivity than to those of the Low productivity, although the confidence intervals are much wider (Figure 6.3).

In the short term, higher catches correspond to the Low-to-medium productivity. Catches reach the maximum allowable catch of the HCR in the medium and long term for both Low-to-Medium and Mix productivity scenarios. If the 'true' stock is under Low productivity, this level is not reached in any of the periods, and the median of long-term catches is 32 kt.

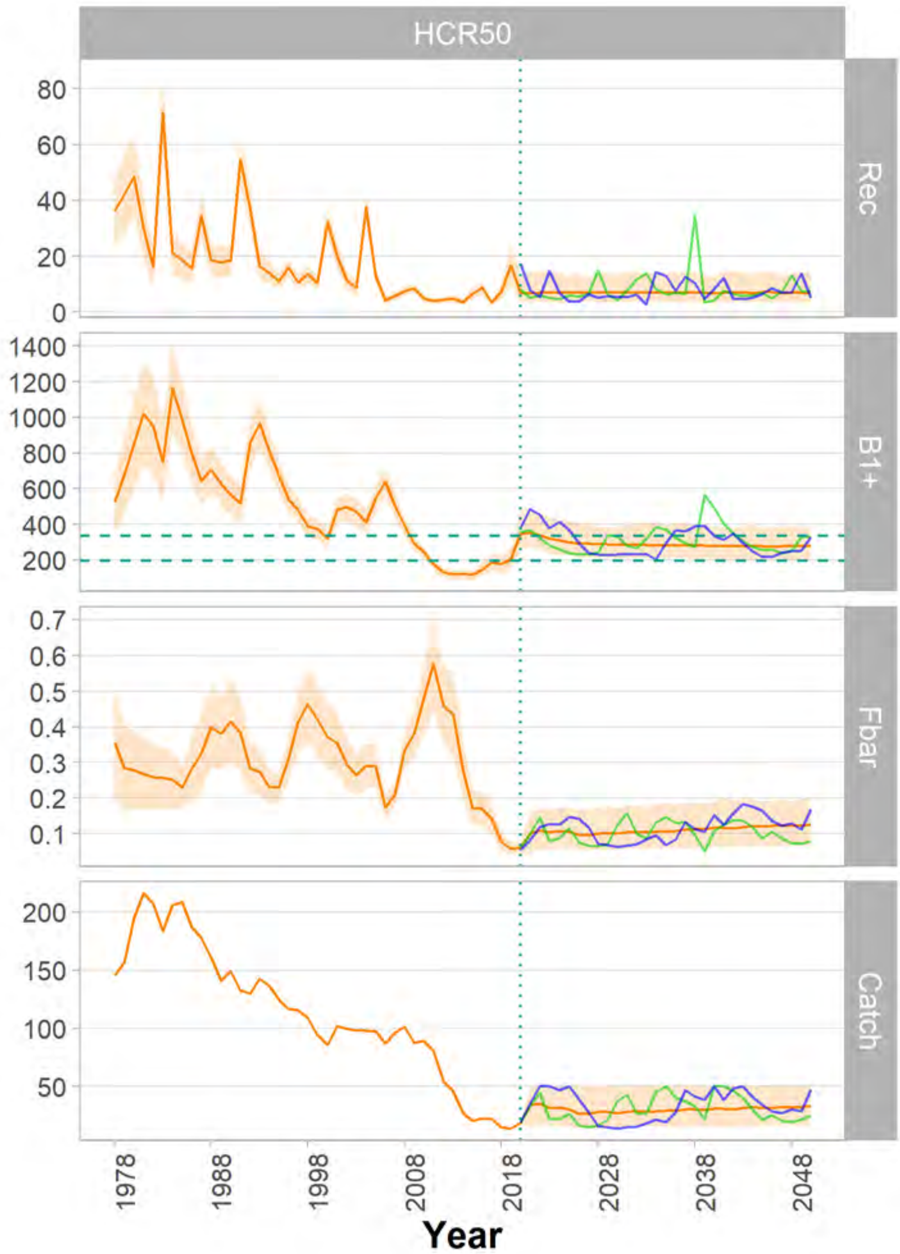


**Figure 6.1. HCR50 under Low productivity. Recruitment (Rec, billion individuals), biomass of fish age 1 and older (B1+, thousand tonnes), fishing mortality ($F_{bar}$2–5, year$^{-1}$) and catch (thousand tonnes) for the assessment period (1978–2019) and during the projected period (2020–2050) for HCR50 under 'true' stock of Low productivity. Shaded area represents 90% confidence intervals. Horizontal dashed lines in B1+ show $B_{lim}$ of Low productivity (196 thousand tonnes) and of Medium productivity (337 thousand tonnes). Vertical long dashed lines separate the historical from the projected period. The blue and green lines show the results from two simulated iterations selected randomly.**

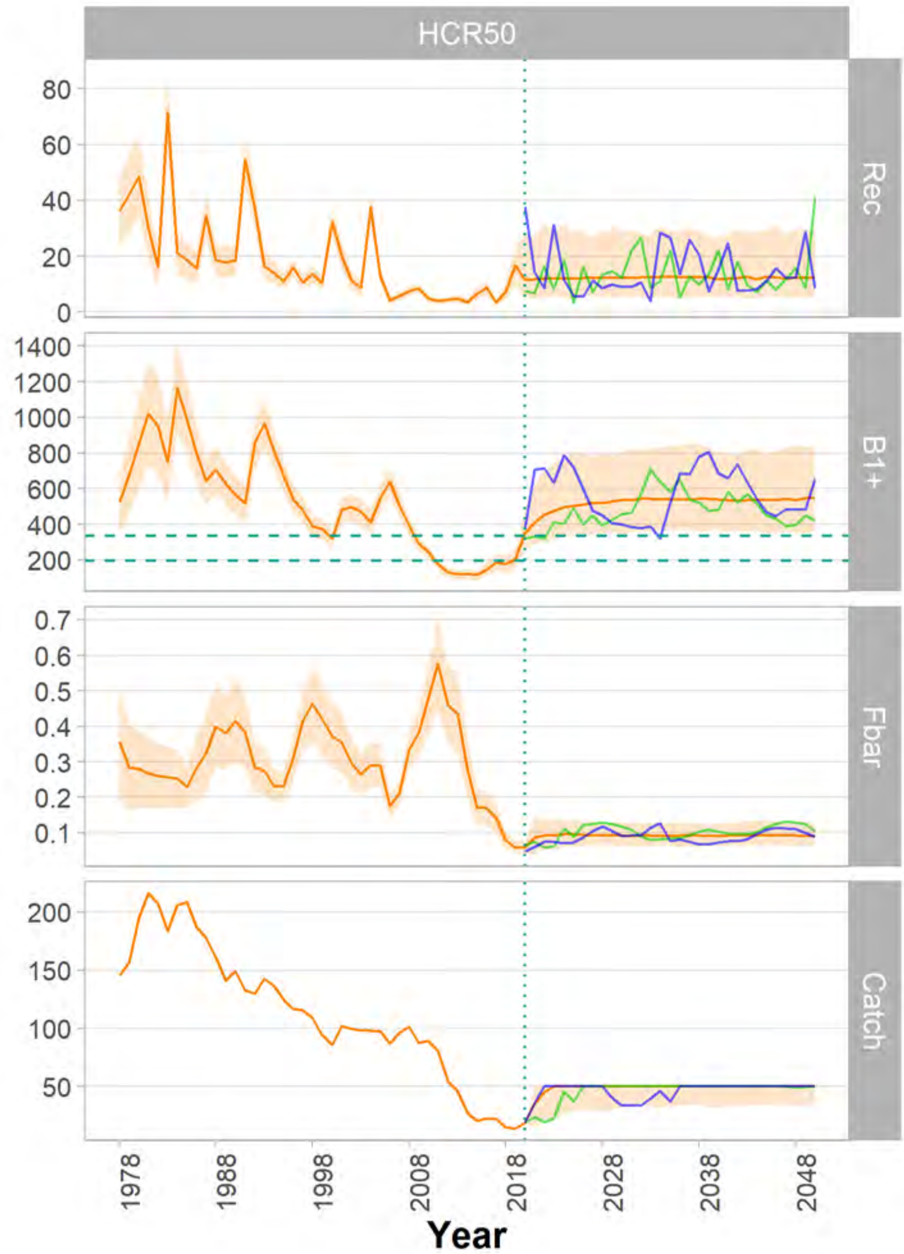


**Figure 6.2. HCR50 under Low-to-medium productivity. Recruitment (Rec, billion individuals), biomass of fish age 1 and older (B1+, thousand tonnes), fishing mortality ($F_{bar}$2–5, year-1) and catch (thousand tonnes) for the assessment period (1978–2019) and during the projected period (2020–2050) for HCR50 under 'true' stock of Low-to-medium productivity. Shaded area represents 90% confidence intervals. Horizontal dashed lines in B1+ show $B_{lim}$ of Low productivity (196 thousand tonnes) and of Medium productivity (337 thousand tonnes). Vertical long dashed lines separate the historical from the projected period. The blue and green lines show the results from two simulated iterations selected randomly.**

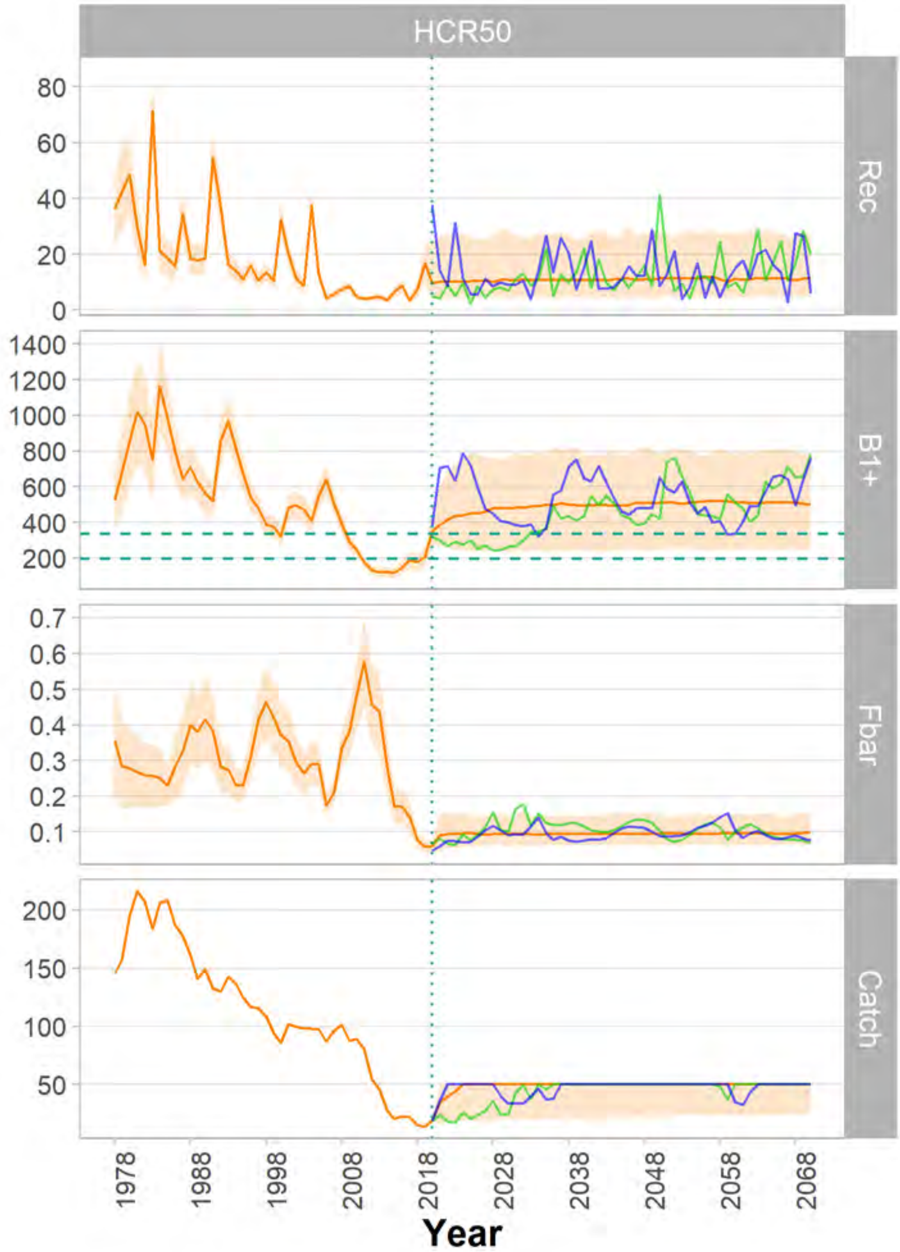


**Figure 6.3. HCR50 under Mix productivity. Recruitment (Rec, billion individuals), biomass of fish age 1 and older (B1+, thousand tonnes), fishing mortality ($F_{bar}$2–5, year-1) and catch (thousand tonnes) for the assessment period (1978–2019) and during the projected period (2020–2070) for HCR50 under 'true' stock of Mix productivity. Shaded area represents 90% confidence intervals. Horizontal dashed lines in B1+ show $B_{lim}$ of Low productivity (196 thousand tonnes) and of Medium productivity (337 thousand tonnes). Vertical long dashed lines separate the historical from the projected period. The blue and green lines show the results from two simulated iterations selected randomly.**

## 6.1.2 Performance statistics

During the first six years of the projection period (2021–2026, initial period) the estimated median biomass of fish age 1 and older (B1+) varied between 319 and 475 thousand tonnes, depending on the assumed productivity for the 'true' stock (Table 6.1). For the same period, the catches vary between 32 and 50 thousand tonnes. Catches are higher in the Low-to-medium scenario, while $F_{bar2–5}$ values are above, and around 0.10 year$^{-1}$ in the Low productivity scenario. Interannual variation of catches is around 7 thousand tones in the long term for the Low productivity and 2 kt for the Low-to-medium and for Mix scenarios.

Simulation testing of HCR50 in a Low productivity scenario with 1000 iterations was inconclusive regarding the precautionary criterion (Risk 3 = 5.1, Table 6.1.). Therefore, conclusions on the precautionary level of this rule in the Low productivity scenario were based on 10 000 iterations. For 10 000 iterations, Risk 3 was estimated to be 4.2 and therefore the rule is considered precautionary. HRC50 is also considered precautionary under the Low-to-medium scenario (Risk 3 <5%; Table 6.1), which is not the case under the Mix scenario (Risk 3 = 17.8, Table 6.1).

**Table 6.1. Summary of performance statistics for HCR50. Reported Risk 3 were calculated in the last ten years of a 30-year projection period (2041:2050) for the Low and Low-to-medium recruitment regimes and in the last ten years of a 50-year projection period (2061:2070) for the Mix recruitment regime. Reported Risk 3 for the Low recruitment regime uses $B_{lim}$ = 196 kt as a reference point while for the Low-to-medium and Mix recruitment regimes uses $B_{lim}$ = 337 kt as a reference point.**

| Period | Recruitment | | |
|---|---|---|---|
| | Low | Low-to-medium | Mix |
| **B1+** | | | |
| initial | 319 | 475 | 425 |
| short | 307 | 496 | 444 |
| long | 278 | 541 | 510 |
| **Catch** | | | |
| initial | 32 | 50 | 45 |
| short | 30 | 50 | 49 |
| long | 32 | 50 | 50 |
| **F** | | | |
| initial | 0.104 | 0.093 | 0.094 |
| short | 0.103 | 0.093 | 0.094 |
| long | 0.121 | 0.092 | 0.095 |
| **IAV** | | | |
| initial | 7 | 5 | 5 |
| short | 7 | 4 | 4 |
| long | 7 | 2 | 2 |
| **First year Blim = 196 kt** | | | |
| all | 2021 | 2021 | 2021 |
| **First year Blim = 337 kt** | | | |
| all | — | 2025 | — |
| **Risk 3** | | | |
| long | 5.1 (4.2*) | 3.8 | 17.8 |

***Risk 3 was estimated with 10 000 iterations.**

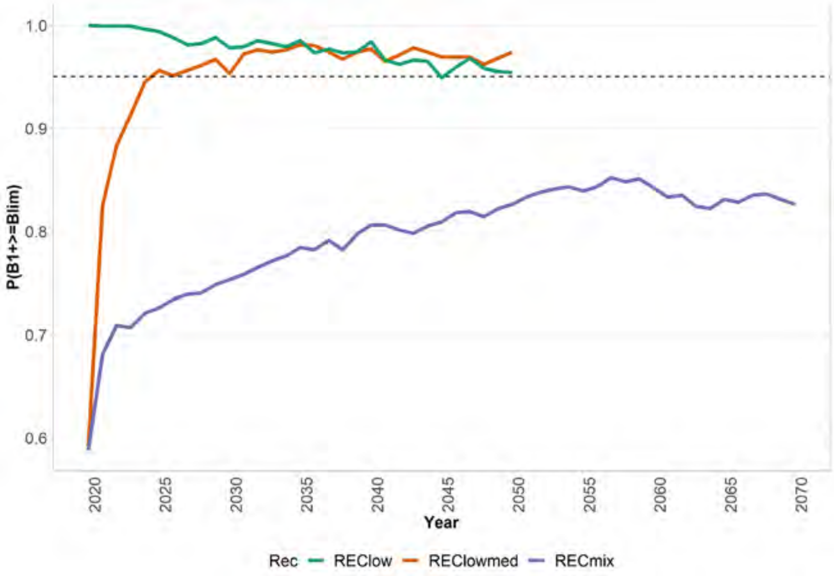


**Figure 6.4. Probability profile of P(B1+≥$B_{lim}$) for catch rule HCR50 for the three productivity regimes Low (REClow, green line; $B_{lim}$ = 196 thousand tonnes), Low-to-medium (REClowmed, orange line; $B_{lim}$ = 337 thousand tonnes) and Mix (RECmix, purple line; $B_{lim}$ = 337 thousand tonnes) from 2020 to 2070. Horizontal dashed line represents 95% probability.**

## 6.2 MSE testing of HCR45

The catch rule proposed in the special request was also tested with maximum allowed catches of 45 kt and assuming three productivity scenarios for the 'true' stock (Figures 6.5–6.8), corresponding to Low, Low-to-medium and Mix productivity.

### 6.2.1 Simulated recruitment, spawning–stock biomass (B1+), fishing mortality and catch

The trajectories of the key parameters R, B1+, $F_{bar2\text{-}5}$ and catch under Low, Low-to-medium and Mix productivity are shown in Figures 6.5–6.7.

In the long term, Low productivity true stock leads to a median R to around 6.8 billion individuals and a decrease of median B1+ to 281 thousand tonnes. The lower confidence limit of B1+ is above to the corresponding $B_{lim}$ = 196 thousand tonnes (Figure 6.5).

If the true stock has Low-to-medium productivity, median R will increase to maximum values around 12.5 billion individuals, and the median B1+ increases to around 540 thousand tonnes (Figure 6.6). The lower confidence limit of B1+ is well above $B_{lim}$ = 196 thousand tonnes and $B_{lim}$ = 337 thousand tonnes in the long term.

For the Mix productivity scenario, the long-term median R and B1+ are closer to those of the Low-to-medium productivity than to those of the Low productivity, although the confidence intervals are much wider (Figure 6.7).

In the short term, higher catches correspond to the Low-to-Medium and Mix productivity scenarios, which reach the maximum allowable catch of the HCR. If the 'true' stock is under Low productivity, this level is not reached in any of the periods, and the median of long-term catches is 32 kt, the same catches as for HCR50.


**Figure 6.5. HCR45 under Low productivity. Recruitment (Rec, billion individuals), biomass of fish age 1 and older (B1+, thousand tonnes), fishing mortality ($F_{bar}$2–5, year-1) and catch (thousand tonnes) for the assessment period (1978–2019) and during the projected period (2020–2050) for HCR45 under 'true' stock of Low productivity. Shaded area represents 90% confidence intervals. Horizontal dashed lines in B1+ show Blim of Low productivity (196 thousand tonnes) and of Medium productivity (337 thousand tonnes). Vertical long dashed lines separate the historical from the projected period. The blue and green lines show the results from two simulated iterations selected randomly.**


**Figure 6.6. HCR45 under Low-to-medium productivity. Recruitment (Rec, billion individuals), biomass of fish age 1 and older (B1+, thousand tonnes), fishing mortality ($F_{bar}$2–5, year-1) and catch (thousand tonnes) for the assessment period (1978–2019) and during the projected period (2020–2050) for HCR45 under 'true' stock of Low-to-medium productivity. Shaded area represents 90% confidence intervals. Horizontal dashed lines in B1+ show Blim of Low productivity (196 thousand tonnes) and of Medium productivity (337 thousand tonnes). Vertical long dashed lines separate the historical from the projected period. The blue and green lines show the results from two simulated iterations selected randomly.**

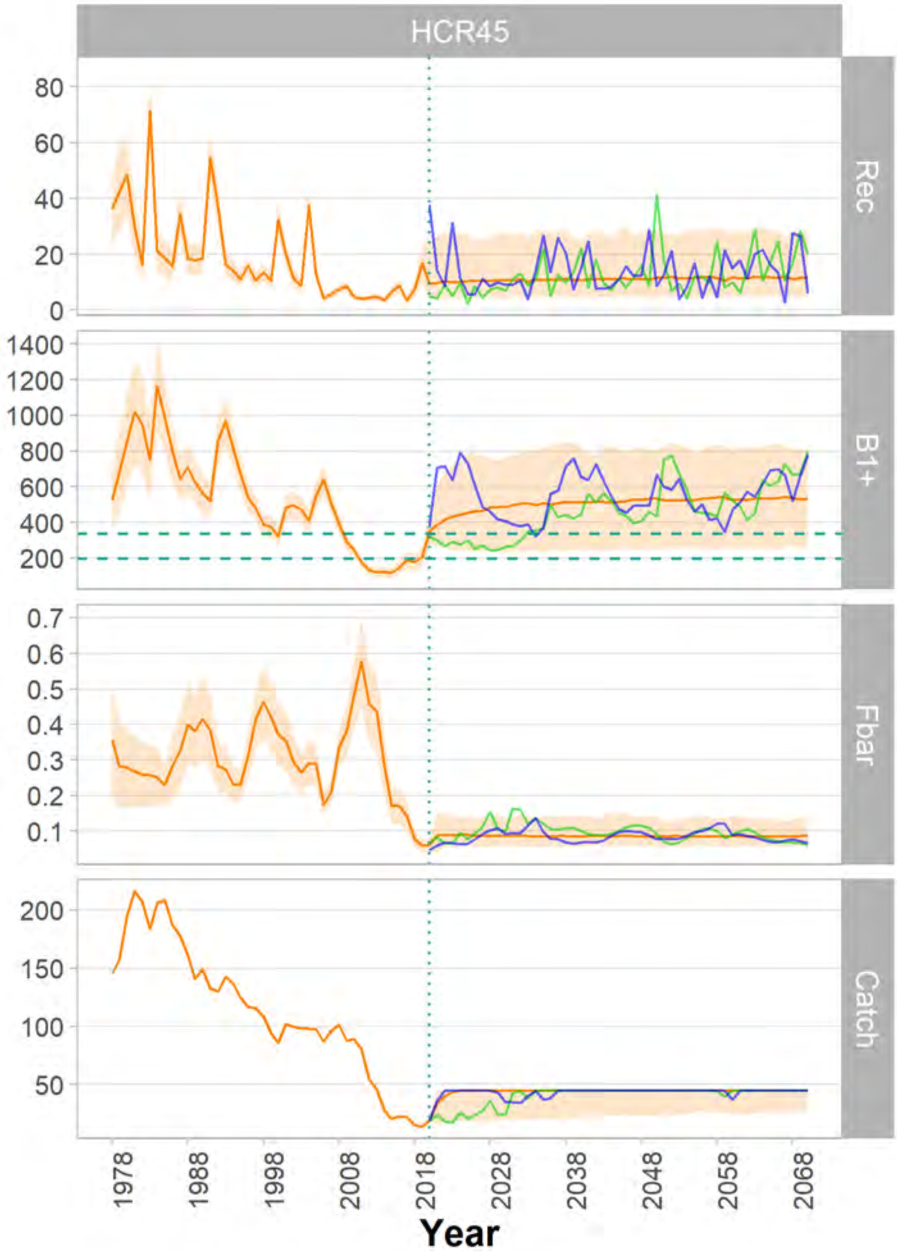


**Figure 6.7. HCR45 under Mix productivity. Recruitment (Rec, billion individuals), biomass of fish age 1 and older (B1+, thousand tonnes), fishing mortality ($F_{bar2–5}$, year$^{-1}$) and catch (thousand tonnes) for the assessment period (1978–2019) and during the projected period (2020–2070) for HCR45 under 'true' stock of Mix productivity. Shaded area represents 90% confidence intervals. Horizontal dashed lines in B1+ show $B_{lim}$ of Low productivity (196 thousand tonnes) and of Medium productivity (337 thousand tonnes). Vertical long dashed lines separate the historical from the projected period. The blue and green lines show the results from two simulated iterations selected randomly.**

## 6.2.2 Performance statistics

During the first six years of the projection period (2021–2026, initial period) the estimated median biomass of fish age 1 and older (B1+) varied between 320 and 472 thousand tonnes, depending on the assumed productivity for the 'true' stock (Table 6.2). For the same period, the catches vary between 32 and 45 thousand tonnes. Catches achieve the maximum allowed values in the Low-to-medium and Mix scenarios with corresponding values of $F_{bar2–5}$ = 0.087 year$^{-1}$ and $F_{bar2–5}$ = 0.088 year$^{-1}$, below $F_{MSY}$ of the Low productivity scenario ($F_{MSY}$ = 0.092 year$^{-1}$).

Interannual variation of catches is around 6 thousand tonnes in the long term for the Low productivity and 1 thousand tonnes for the Low-to-medium and Mix scenarios.

Simulation testing of HCR45 in a Low productivity scenario with 1000 iterations was inconclusive regarding the precautionary criterion (Risk 3 = 5.1, Table 6.2). Therefore, conclusions on the precautionary level of this rule in the Low productivity scenario were based on 10 000 iterations. For 10 000 iterations, Risk 3 was estimated to be 4.2 and therefore the rule is considered precautionary. HRC45 is also considered precautionary under the Low-to-medium scenario (Risk 3 <5%; Table 6.2), which is not the case under the Mix scenario (Risk 3 = 14%, Table 6.2).

**Table 6.2. Summary of performance statistics for HCR45. Reported Risk 3 were calculated in the last ten years of a 30-year projection period (2041:2050) for the Low and Low-to-medium recruitment regimes and in the last ten years of a 50-year projection period (2061:2070) for the Mix recruitment regime. Reported Risk 3 for the Low recruitment regime uses $B_{lim}$ = 196 kt as a reference point while for the Low-to-medium and Mix recruitment regimes uses $B_{lim}$ = 337 kt as a reference point.**

| Period | Recruitment | | |
|---|---|---|---|
| | Low | Low-to-medium | Mix |
| **B1+** | | | |
| initial | 320 | 472 | 427 |
| short | 308 | 496 | 447 |
| long | 281 | 551 | 534 |
| **Catch** | | | |
| initial | 32 | 45 | 45 |
| short | 30 | 45 | 45 |
| long | 32 | 45 | 45 |
| **F** | | | |
| initial | 0.103 | 0.087 | 0.088 |
| short | 0.102 | 0.085 | 0.087 |
| long | 0.121 | 0.083 | 0.084 |
| **IAV** | | | |
| initial | 6 | 4 | 4 |
| short | 6 | 3 | 4 |
| long | 6 | 1 | 1 |
| **First year Blim = 196 kt** | | | |
| all | 2021 | 2021 | 2021 |
| **First year Blim = 337 kt** | | | |
| all | — | 2025 | — |
| **Risk 3 Blim** | | | |
| long | 5.1 (4.2*) | 2.7 | 14 |

***Risk 3 was estimated with 10 000 iterations.**

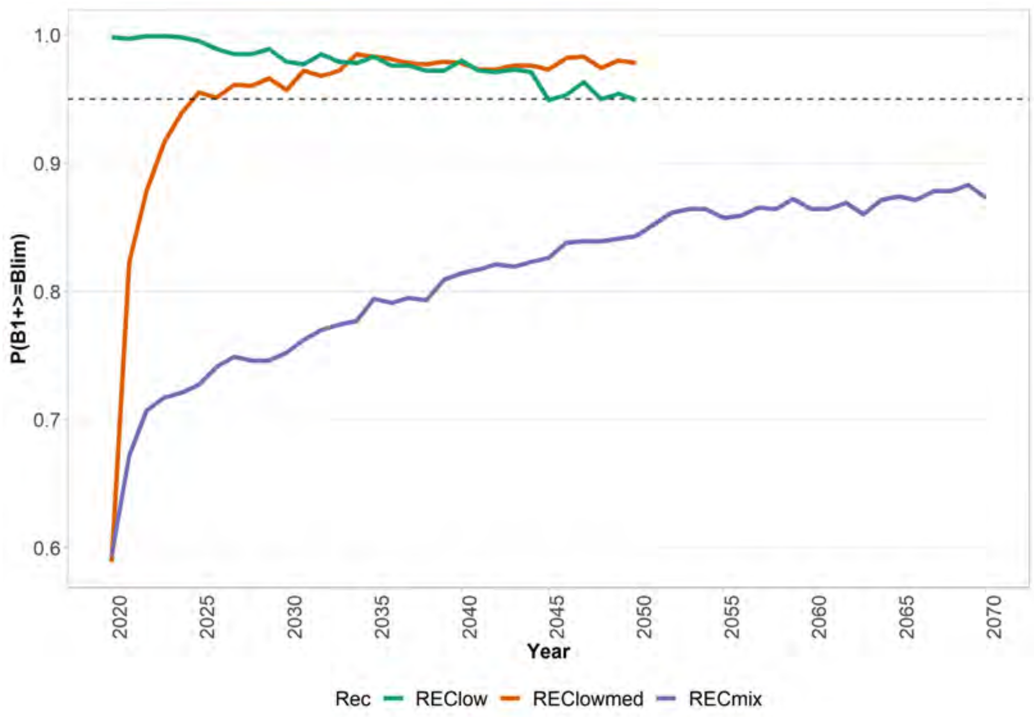


**Figure 6.8. Probability profile of P(B1+≥$B_{lim}$) for catch rule HCR45 for the three productivity regimes Low (REClow, green line; $B_{lim}$ = 196 thousand tonnes), Low-to-medium (REClowmed, orange line; $B_{lim}$ = 337 thousand tonnes) and Mix (RECmix, purple line; $B_{lim}$ = 337 thousand tonnes) from 2020 to 2070. Horizontal dashed line represents 95% probability.**

## 6.3 MSE testing of catch rule HCR40

The catch rule proposed in the special request was also tested with maximum allowed catches of 40 kt and assuming three productivity scenarios for the 'true' stock (Figures 6.9–6.12), corresponding to Low, Low-to-medium and Mix productivity.

### 6.3.1 Simulated recruitment, spawning–stock biomass (B1+), fishing mortality and catch

The trajectories of the key parameters R, B1+, $F_{bar2-5}$ and catch under Low, Low-to-medium and Mix productivity are shown in Figures 6.9–6.11.

In the long term, Low productivity true stock leads to a median R around 6.7 billion individuals and a decrease of median B1+ to 283 thousand tonnes. The lower confidence limit of B1+ is above to the corresponding $B_{lim\_low}$ = 196 thousand tonnes (Figure 6.9).

If the true stock has Low-to-medium productivity, median R will increase to maximum values around 12.6 billion individuals, and the median B1+ increases to around 563 thousand tonnes (Figure 6.10). The lower confidence limit of B1+ is well above $B_{lim\_low}$ = 196 thousand tonnes and $B_{lim\_med}$ = 337 thousand tonnes in the long term.

For the Mix productivity scenario, the long-term median R and B1+ are closer to those of the Low-to-medium productivity than to those of the Low productivity, although the confidence intervals are much wider (Figure 6.11).

In the short term, for both Low-to-medium and Mix productivity scenarios, the maximum catches allowed by the rule are achieved, while the Low productivity scenario provides smaller catches of around 32 thousand tonnes.


**Figure 6.9. HCR40 under Low productivity. Recruitment (Rec, billion individuals), biomass of fish age 1 and older (B1+, thousand tonnes), fishing mortality ($F_{bar2-5}$, year$^{-1}$) and catch (thousand tonnes) for the assessment period (1978–2019) and during the projected period (2020–2050) for HCR40 under 'true' stock of Low productivity. Shaded area represents 90% confidence intervals. Horizontal dashed lines in B1+ show $B_{lim}$ of Low productivity (196 thousand tonnes) and of Medium productivity (337 thousand tonnes). Vertical long dashed lines separate the historical from the projected period. The blue and green lines show the results from two simulated iterations selected randomly.**


**Figure 6.10. HCR40 under Low-to-medium productivity. Recruitment (Rec, billion individuals), biomass of fish age 1 and older (B1+, thousand tonnes), fishing mortality ($F_{bar}$2–5, year-1) and catch (thousand tonnes) for the assessment period (1978–2019) and during the projected period (2020–2050) for HCR40 under 'true' stock of Low-to-medium productivity. Shaded area represents 90% confidence intervals. Horizontal dashed lines in B1+ show $B_{lim}$ of Low productivity (196 thousand tonnes) and of Medium productivity (337 thousand tonnes). Vertical long dashed lines separate the historical from the projected period. The blue and green lines show the results from two simulated iterations selected randomly.**

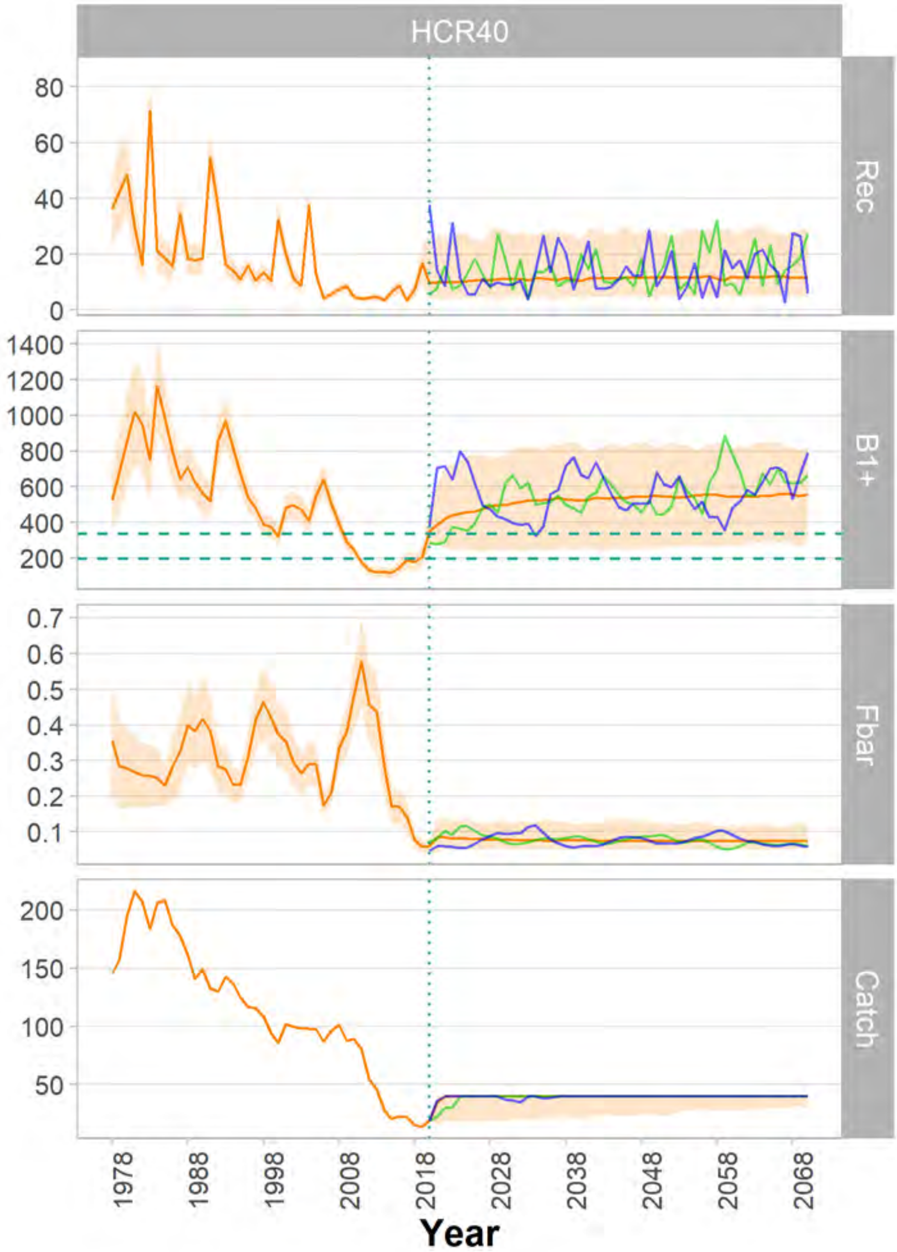


**Figure 6.11. HCR40 under Mix productivity. Recruitment (Rec, billion individuals), biomass of fish age 1 and older (B1+, thousand tonnes), fishing mortality ($F_{bar2\text{-}5}$, year$^{-1}$) and catch (thousand tonnes) for the assessment period (1978–2019) and during the projected period (2020–2070) for HCR40 under 'true' stock of Mix productivity. Shaded area represents 90% confidence intervals. Horizontal dashed lines in B1+ show $B_{lim}$ of Low productivity (196 thousand tonnes) and of Medium productivity (337 thousand tonnes). Vertical long dashed lines separate the historical from the projected period. The blue and green lines show the results from two simulated iterations selected randomly.**

## 6.3.2 Performance statistics

During the first six years of the projection period (2021–2026, initial period) the estimated median biomass of fish age 1 and older (B1+) varied between 322 and 477 thousand tonnes, depending on the assumed productivity for the 'true' stock (Table 6.3). For the same period, the catches vary between 32 and 40 thousand tons. The maximum catches, which are obtained in the Low-to-medium and Mix scenarios, correspond to the maximum allowed by the rule, 40 kt.

Interannual variation of catches is around 5 thousand tones in the long term for the Low productivity and 1 kt for both the Low-to-medium and Mix scenarios.

HCR40 is considered precautionary in both the Low and the Low-to-medium productivity scenarios (Risk 3 < 5%; Table 6.3) but not under the Mix scenario (Risk 3 = 9.4%, Table 6.3).

**Table 6.3. Summary of performance statistics forHCR40. Reported Risk 3 were calculated in the last ten years of a 30-year projection period (2041:2050) for the Low and Low-to-medium recruitment regimes and in the last ten years of a 50-year projection period (2061:2070) for the Mix recruitment regime. Reported Risk 3 for the Low recruitment regime uses $B_{lim}$ = 196 kt as a reference point while for the Low-to-medium and Mix recruitment regimes uses $B_{lim}$ = 337 kt as a reference point.**

| Period | Recruitment | | |
|---|---|---|---|
| | Low | Low-to-medium | Mix |
| **B1+** | | | |
| initial | 322 | 477 | 433 |
| short | 311 | 502 | 455 |
| long | 283 | 563 | 551 |
| **Catch** | | | |
| initial | 32 | 40 | 40 |
| short | 31 | 40 | 40 |
| long | 33 | 40 | 40 |
| **F** | | | |
| initial | 0.099 | 0.079 | 0.082 |
| short | 0.1 | 0.077 | 0.08 |
| long | 0.117 | 0.072 | 0.074 |
| **IAV** | | | |
| initial | 5 | 3 | 3 |
| short | 5 | 2 | 3 |
| long | 5 | 1 | 1 |
| **First year $B_{lim}$ = 196 kt** | | | |
| All | 2021 | 2021 | 2021 |
| **First year $B_{lim}$ = 337 kt** | | | |
| all | — | 2025 | — |
| **Risk 3** | | | |
| long | 4.7 | 2.3 | 9.4 |

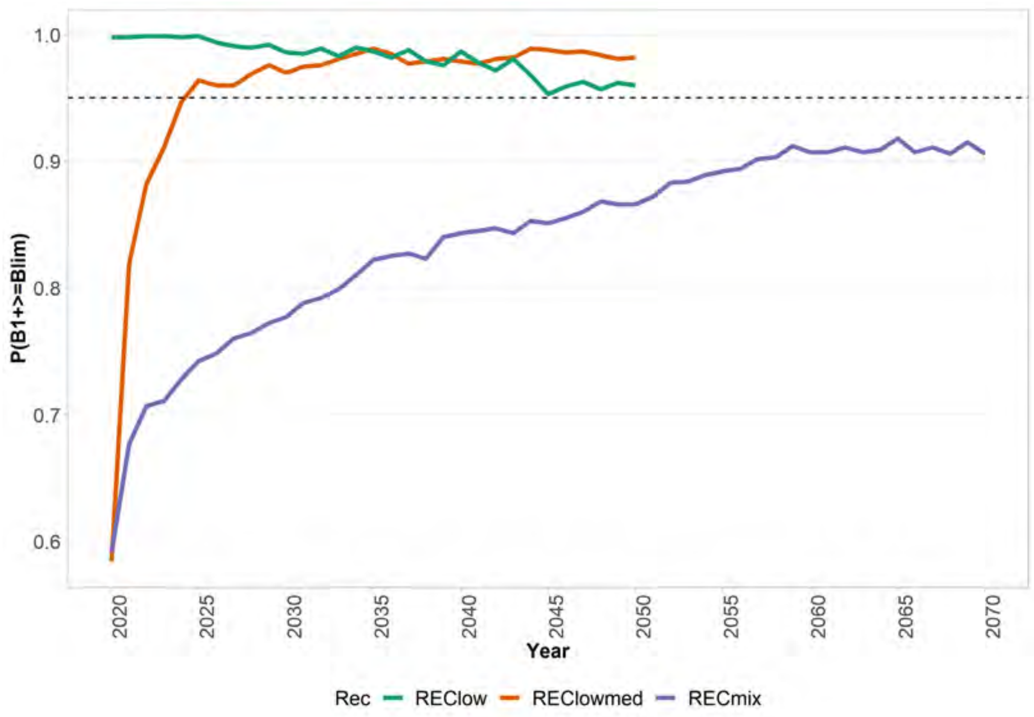


**Figure 6.12. Probability profile of P(B1+≥$B_{lim}$) for catch rule HCR40 for the three productivity regimes Low (REClow, green line; $B_{lim}$ = 196 thousand tonnes), Low-to-medium (REClowmed, orange line; $B_{lim}$ = 337 thousand tonnes) and Mix (RECmix, purple line; $B_{lim}$ = 337 thousand tonnes) from 2020 to 2070. Horizontal dashed line represents 95% probability.**

## 6.4 MSE testing of catch rule HCR35

The catch rule proposed in the special request was also tested with maximum allowed catches of 35 kt and assuming three productivity scenarios for the 'true' stock (Figures 6.13–6.16.), corresponding to Low, Low-to-medium and Mix productivity.

### 6.4.1 Simulated recruitment, spawning–stock biomass (B1+), fishing mortality and catch

The trajectories of the key parameters R, B1+, $F_{bar2-5}$ and catch under Low, Low-to-medium and Mix productivity are shown in Figures 6.13–6.15.

In the long term, Low productivity true stock leads to a median R to around 6.8 billion individuals and a decrease of median B1+ to 287 thousand tonnes. The lower confidence limit of B1+ is above to the corresponding $B_{lim}$ = 196 thousand tonnes (Figure 6.13).

If the true stock has Low-to-medium productivity, median R will increase to maximum values around 12.2 billion individuals, and the median B1+ increases to around 578 thousand tonnes (Figure 6.14). The lower confidence limit of B1+ is well above $B_{lim\_low}$ = 196 thousand tonnes and $B_{lim\_med}$ = 337 thousand tonnes in the long term.

For the Mix productivity scenario, the long-term median R and B1+ are closer to those of the Low-to-medium productivity than to those of the Low productivity, although the confidence intervals are much wider (Figure 6.15).

In the short term, for both Low-to-medium and Mix productivity scenarios, the maximum catches allowed by the rule are achieved, while the Low productivity scenario provides fewer catches, of around 33 thousand tonnes. The maximum catches of the HCR35 are not obtained in the long term projected period, under a situation of 'true' low productivity, but they are higher than those provided by rules HCR40 and HCR45.

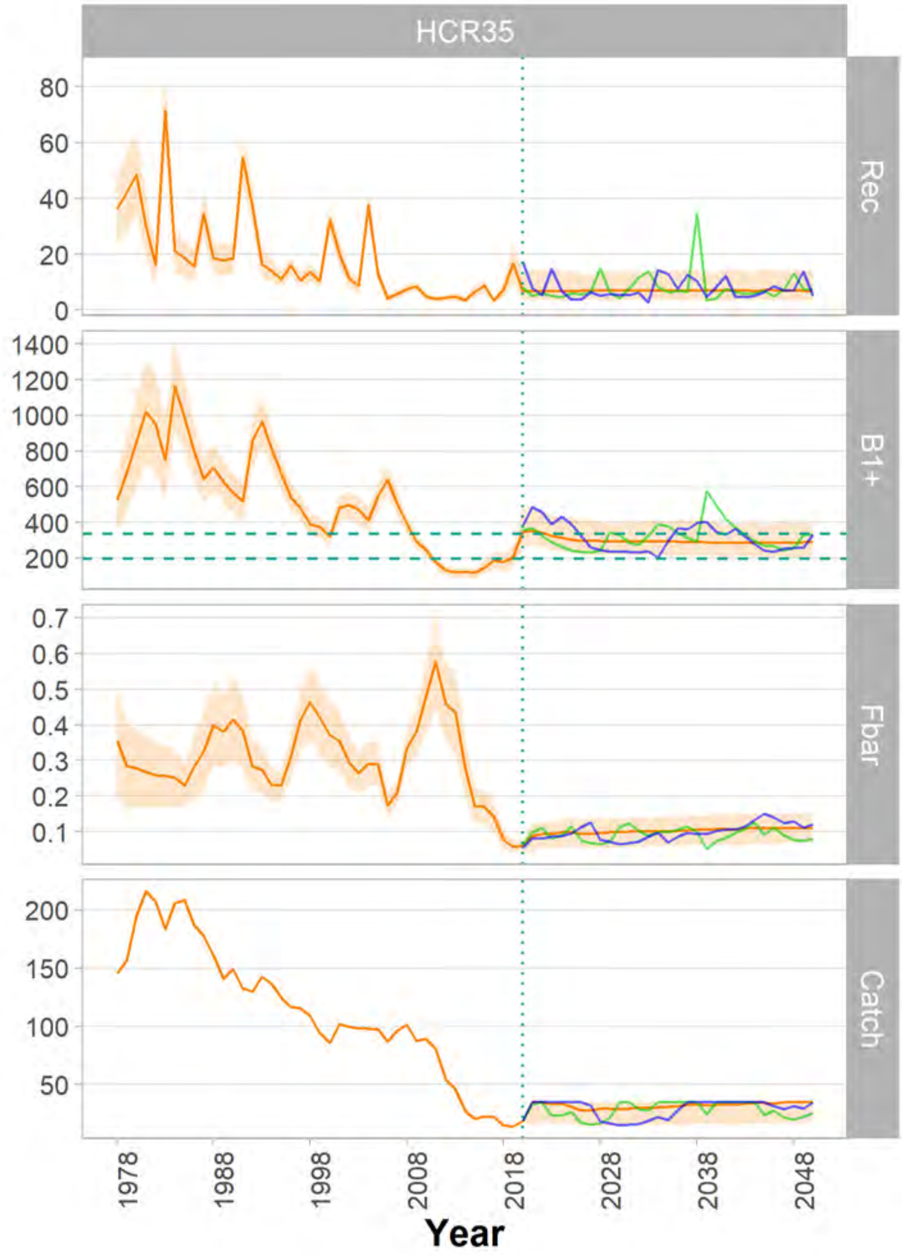


**Figure 6.13. HCR35 under Low productivity. Recruitment (Rec, billion individuals), biomass of fish age 1 and older (B1+, thousand tonnes), fishing mortality ($F_{bar2\text{-}5}$, year$^{-1}$) and catch (thousand tonnes) for the assessment period (1978–2019) and during the projected period (2020–2050) for HCR35 under 'true' stock of Low productivity. Shaded area represents 90% confidence intervals. Horizontal dashed lines in B1+ show $B_{lim}$ of Low productivity (196 thousand tonnes) and of Medium productivity (337 thousand tonnes). Vertical long dashed lines separate the historical from the projected period. The blue and green lines show the results from two simulated iterations selected randomly.**


**Figure 6.14. HCR35 under Low-to-medium productivity. Recruitment (Rec, billion individuals), biomass of fish age 1 and older (B1+, thousand tonnes), fishing mortality ($F_{bar}$2–5, year-1) and catch (thousand tonnes) for the assessment period (1978–2019) and during the projected period (2020–2050) for HCR35 under 'true' stock of Low-to-medium productivity. Shaded area represents 90% confidence intervals. Horizontal dashed lines in B1+ show Blim of Low productivity (196 thousand tonnes) and of Medium productivity (337 thousand tonnes). Vertical long dashed lines separate the historical from the projected period. The blue and green lines show the results from two simulated iterations selected randomly.**

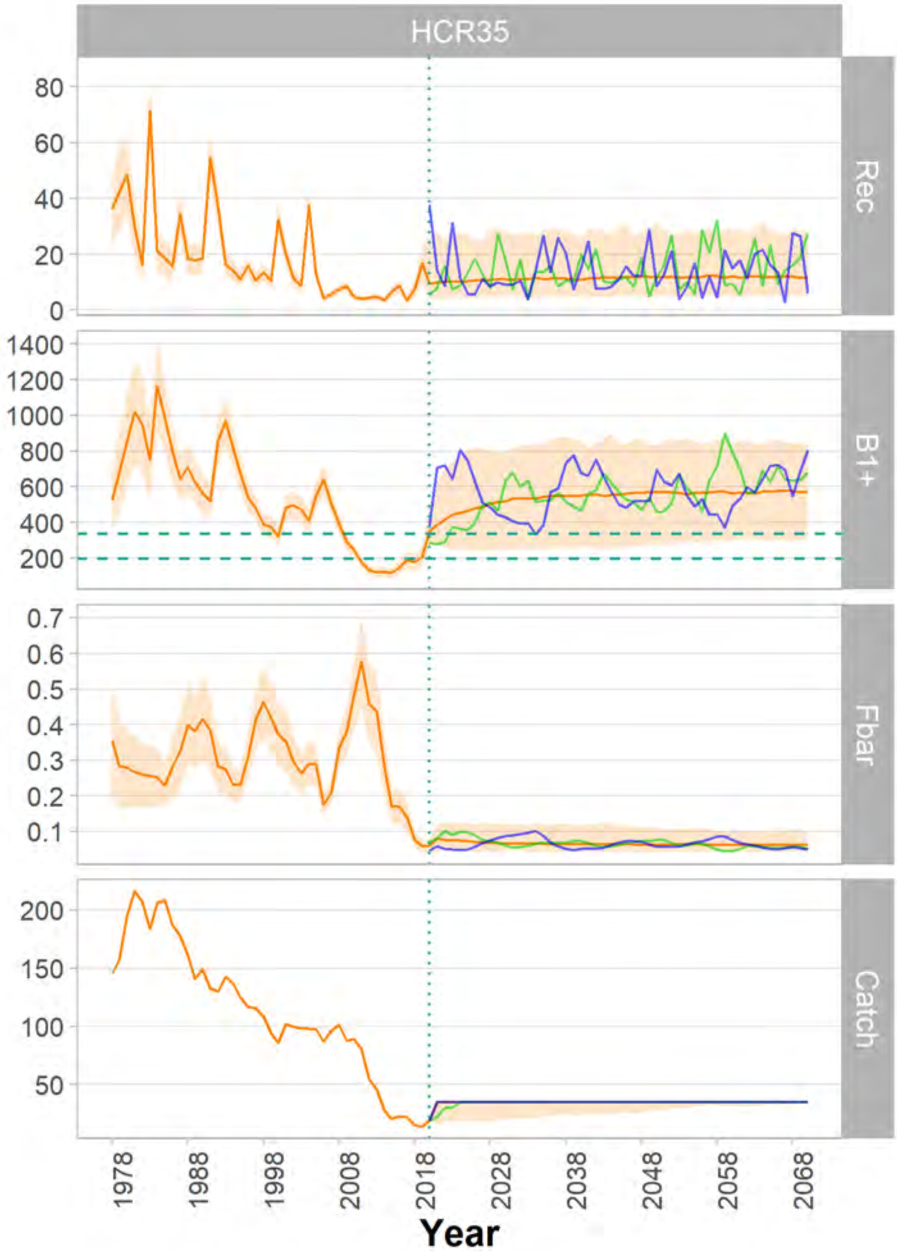


**Figure 6.15. HCR35 under Mix productivity. Recruitment (Rec, billion individuals), biomass of fish age 1 and older (B1+, thousand tonnes), fishing mortality ($F_{bar2–5}$, year$^{-1}$) and catch (thousand tonnes) for the assessment period (1978–2019) and during the projected period (2020–2070) for HCR35 under 'true' stock of Mix productivity. Shaded area represents 90% confidence intervals. Horizontal dashed lines in B1+ show $B_{lim}$ of Low productivity (196 thousand tonnes) and of Medium productivity (337 thousand tonnes). Vertical long dashed lines separate the historical from the projected period. The blue and green lines show the results from two simulated iterations selected randomly.**

## 6.4.2 Performance statistics

During the first six years of the projection period (2021–2026, initial period) the estimated median biomass of fish age 1 and older (B1+) varied between 323 and 482 thousand tonnes, depending on the assumed productivity for the 'true' stock (Table 6.4). For the same period, maximum catches are obtained in the Low-to-medium and Mix scenarios and correspond to the maximum allowed by the rule, 35 kt.

Interannual variation of catches is around 3 thousand tonnes in the long term for the low productivity and constant over time in the Low-to-medium and Mix scenarios.

HRC35 can be considered precautionary under the Low and the Low-to-medium productivity scenario, since Risk 3 is below 5% in the long term but is not precautionary under the Mix scenario since Risk 3 = 7.3 (Table 6.4 and Figure 6.16).

**Table 6.4. Summary of performance statistics for HCR35. Reported Risk 3 were calculated in the last ten years of a 30-year projection period (2041:2050) for the Low and Low-to-medium recruitment regimes and in the last ten years of a 50-year projection period (2061:2070) for the Mix recruitment regime. Reported Risk 3 for the Low recruitment regime uses $B_{lim}$ = 196 kt as a reference point while for the Low-to-medium and Mix recruitment regimes uses $B_{lim}$ = 337 kt as a reference point.**

| Period | Recruitment | | |
|---|---|---|---|
| | Low | Low-to-medium | Mix |
| **B1+** | | | |
| initial | 323 | 482 | 436 |
| short | 312 | 513 | 463 |
| long | 287 | 579 | 572 |
| **Catch** | | | |
| initial | 33 | 35 | 35 |
| short | 31 | 35 | 35 |
| long | 34 | 35 | 35 |
| **F** | | | |
| initial | 0.094 | 0.07 | 0.074 |
| short | 0.096 | 0.067 | 0.071 |
| long | 0.11 | 0.062 | 0.063 |
| **IAV** | | | |
| initial | 3 | 2 | 2 |
| short | 4 | 1 | 2 |
| long | 3 | 0 | 0 |
| **First year Blim = 196 kt** | | | |
| all | 2021 | 2021 | 2021 |
| **First year Blim = 337 kt** | | | |
| all | — | 2025 | — |
| **Risk 3** | | | |
| long | 4 | 1.5 | 7.3 |

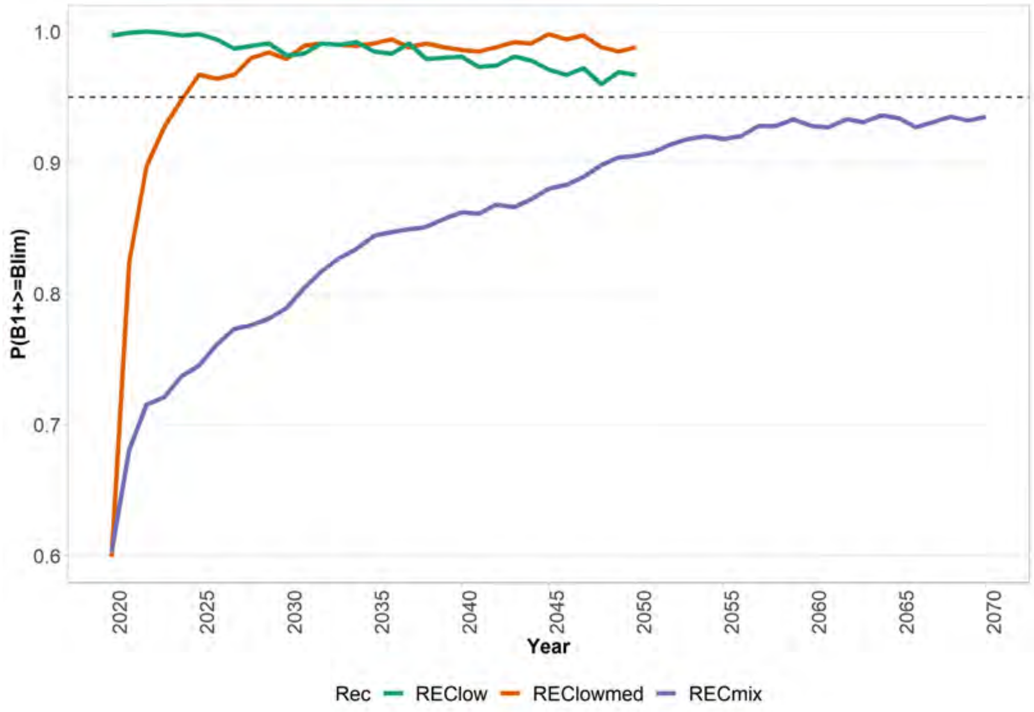


**Figure 6.16. Probability profile of P(B1+≥$B_{lim}$) for catch rule HCR35 for the three productivity regimes Low (REClow, green line; $B_{lim}$ = 196 thousand tonnes), Low-to-medium (REClowmed, orange line; $B_{lim}$ = 337 thousand tonnes) and Mix (RECmix, purple line; $B_{lim}$ = 337 thousand tonnes) from 2020 to 2070. Horizontal dashed line represents 95% probability.**

## 6.5 MSE testing of catch rule HCR30

The catch rule proposed in the special request was also tested with maximum allowed catches of 30 kt and assuming three productivity scenarios for the 'true' stock (Figures 6.17–6.20), corresponding to Low, Low-to-medium and Mix productivity.

### 6.5.1 Simulated recruitment, spawning–stock biomass (B1+), fishing mortality and catch

The trajectories of the key parameters R, B1+, $F_{bar2-5}$ and catch under Low, Low-to-medium and Mix productivity are shown in Figures 6.17–6.19.

In the long term, Low productivity true stock leads to a median R to around 6.8 billion individuals and a decrease of median B1+ to 295 thousand tonnes. The lower confidence limit of B1+ is above the corresponding $B_{lim}$ = 196 thousand tonnes (Figure 6.17).

If the true stock has Low-to-medium productivity, median R will increase to maximum values around 12.4 billion individuals, and the median B1+ increases to around 590 thousand tonnes (Figure 6.18). The lower confidence limit of B1+ is well above $B_{lim}$ = 196 thousand tonnes and $B_{lim}$ = 337 thousand tonnes in the long term.

For the Mix productivity scenario, the long-term median R and B1+ are closer to those of the Low-to-medium productivity than to those of the Low productivity, although the confidence intervals are much wider (Figure 6.19).

In the case of application of this HCR30, the catches are constant and equal to the maximum allowed catch (30 kt) during the entire projected period, regardless of the scenario.


**Figure 6.17. HCR30 under Low productivity. Recruitment (Rec, billion individuals), biomass of fish age 1 and older (B1+, thousand tonnes), fishing mortality ($F_{bar2–5}$, year$^{-1}$) and catch (thousand tonnes) for the assessment period (1978–2019) and during the projected period (2020–2070) for HCR30 under 'true' stock of Low productivity. Shaded area represents 90% confidence intervals. Horizontal dashed lines in B1+ show $B_{lim}$ of Low productivity (196 thousand tonnes) and of Medium productivity (337 thousand tonnes). Vertical long dashed lines separate the historical from the projected period. The blue and green lines show the results from two simulated iterations selected randomly.**

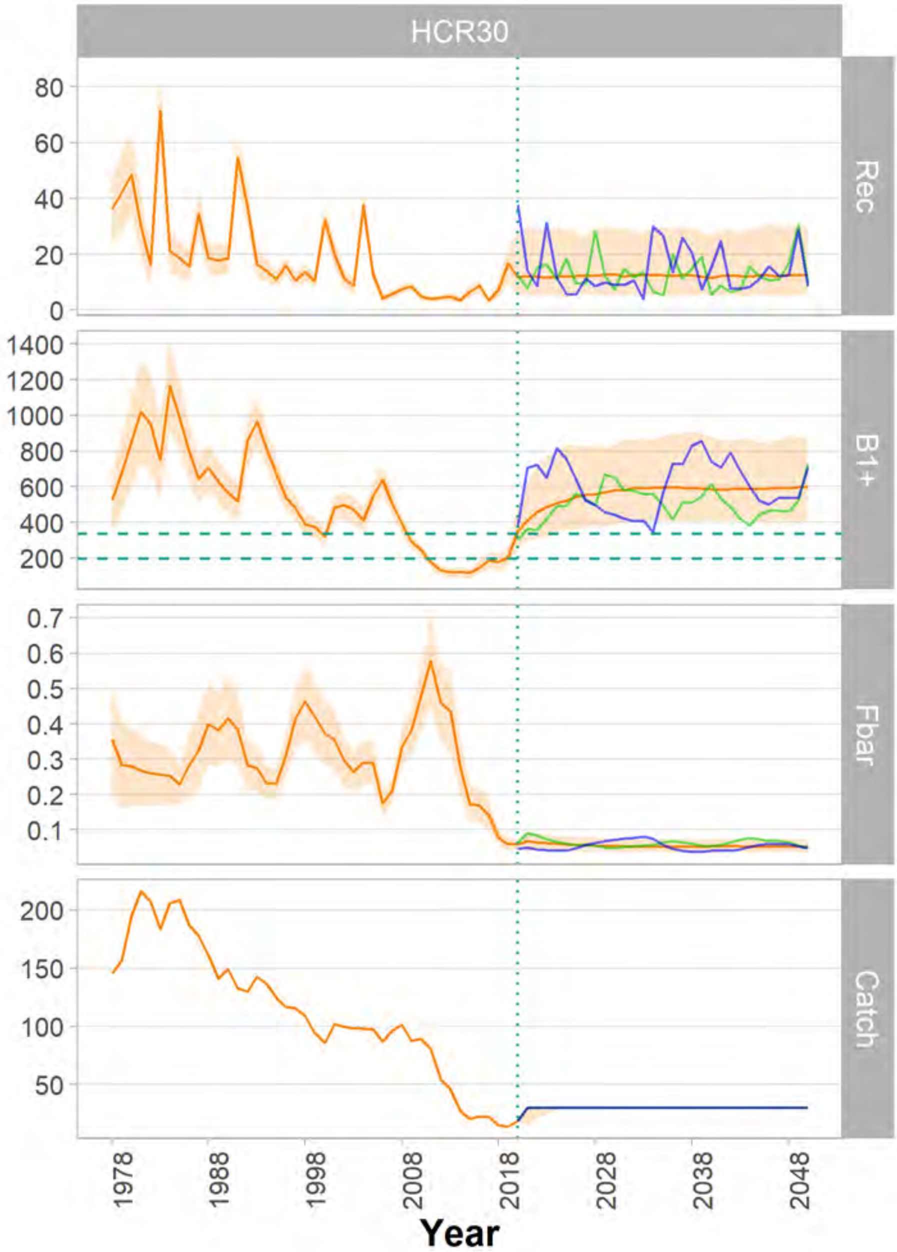


**Figure 6.18. HCR30 under Low-to-medium productivity. Recruitment (Rec, billion individuals), biomass of fish age 1 and older (B1+, thousand tonnes), fishing mortality ($F_{bar}$2–5, year-1) and catch (thousand tonnes) for the assessment period (1978–2019) and during the projected period (2020–2050) for HCR30 under 'true' stock of Low-to-medium productivity. Shaded area represents 90% confidence intervals. Horizontal dashed lines in B1+ show $B_{lim}$ of Low productivity (196 thousand tonnes) and of Medium productivity (337 thousand tonnes). Vertical long dashed lines separate the historical from the projected period. The blue and green lines show the results from two simulated iterations selected randomly.**

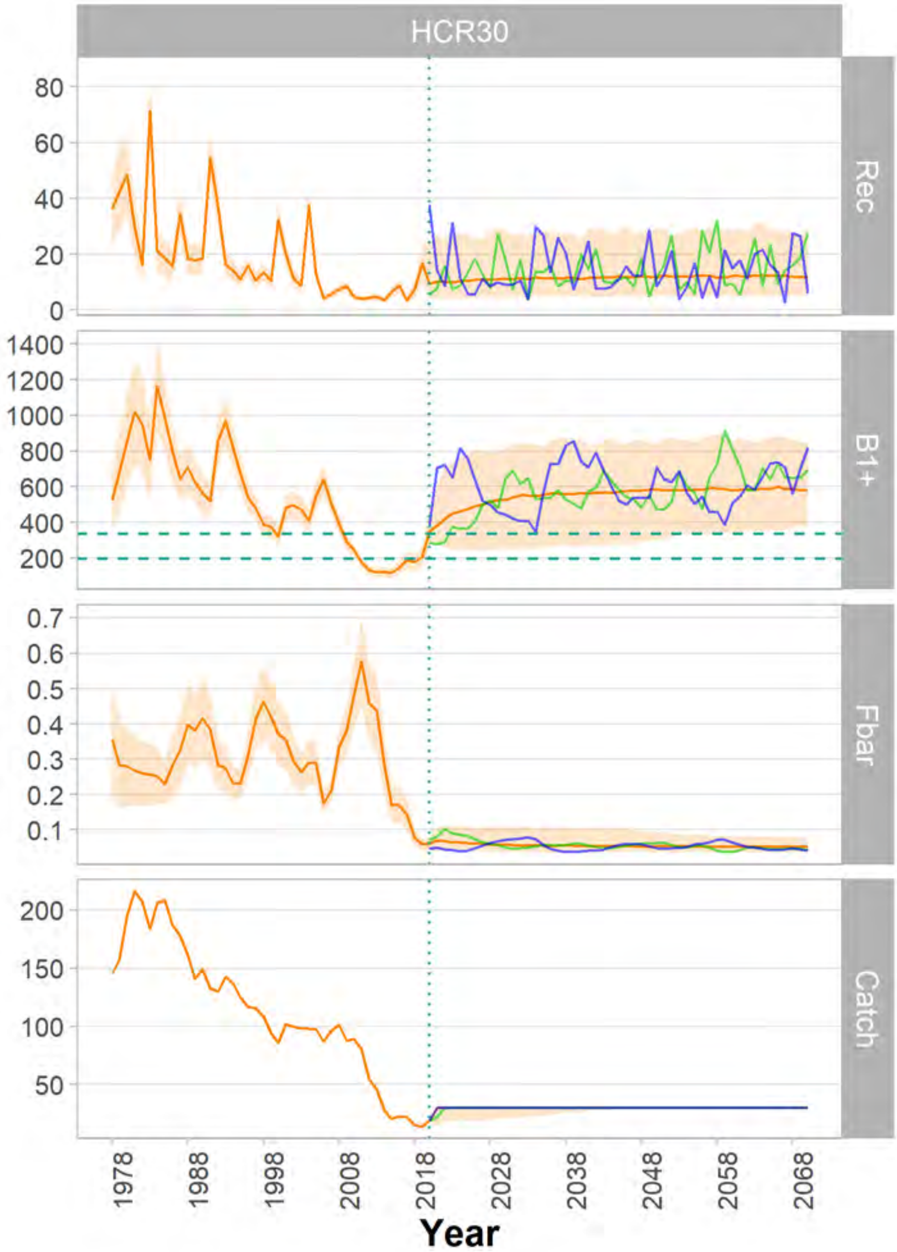


**Figure 6.19. HCR30 under Mix productivity. Recruitment (Rec, billion individuals), biomass of fish age 1 and older (B1+, thousand tonnes), fishing mortality ($F_{bar2-5}$, year$^{-1}$) and catch (thousand tonnes) for the assessment period (1978–2019) and during the projected period (2020–2070) for HCR30 under 'true' stock of Mix productivity. Shaded area represents 90% confidence intervals. Horizontal dashed lines in B1+ show $B_{lim}$ of Low productivity (196 thousand tonnes) and of Medium productivity (337 thousand tonnes). Vertical long dashed lines separate the historical from the projected period. The blue and green lines show the results from two simulated iterations selected randomly.**

### 6.5.2 Performance statistics

During the first six years of the projection period (2021–2026, initial period) the estimated median biomass of fish age 1 and older (B1+) varied between 326 and 487 thousand tonnes, depending on the assumed productivity for the 'true' stock (Table 6.5). For the same period, the catches are constant between scenarios and equal to 30kt (maximum allowed by the rule).

Interannual variation of catches is around 2 thousand tones in the long term for the Low productivity and constant over time for the Mix and the Low-to-medium scenarios.

HRC30 is the only rule that can be considered precautionary for all productivity scenarios, since risk 3 is below 5% in the long term (Table 6.5 and Figure 6.20).

**Table 6.5. Summary of performance statistics forHCR30. Reported Risk 3 were calculated in the last ten years of a 30-year projection period (2041:2050) for the Low and Low-to-medium recruitment regimes and in the last ten years of a 50-year projection period (2061:2070) for the Mix recruitment regime. Reported Risk 3 for the Low recruitment regime uses $B_{lim}$ = 196 kt as a reference point while for the Low-to-medium and Mix recruitment regimes uses $B_{lim}$ = 337 kt as a reference point.**

| Period | Recruitment | | |
|---|---|---|---|
| | Low | Low-to-Medium | Mix |
| **B1+** | | | |
| initial | 326 | 487 | 444 |
| short | 315 | 518 | 472 |
| long | 295 | 590 | 589 |
| **Catch** | | | |
| initial | 30 | 30 | 30 |
| short | 30 | 30 | 30 |
| long | 30 | 30 | 30 |
| **F** | | | |
| initial | 0.085 | 0.061 | 0.065 |
| short | 0.087 | 0.058 | 0.062 |
| long | 0.098 | 0.052 | 0.052 |
| **First year $B_{lim}$ = 196 kt** | | | |
| | 2021 | 2021 | 2021 |
| **First year $B_{lim}$ = 337 kt** | | | |
| | — | 2024 | 2054 |
| **IAV** | | | |
| initial | 2 | 1 | 1 |
| short | 2 | 1 | 1 |
| long | 2 | 0 | 0 |
| **Risk 3** | | | |
| long | 2.8 | 1 | 4.9 |

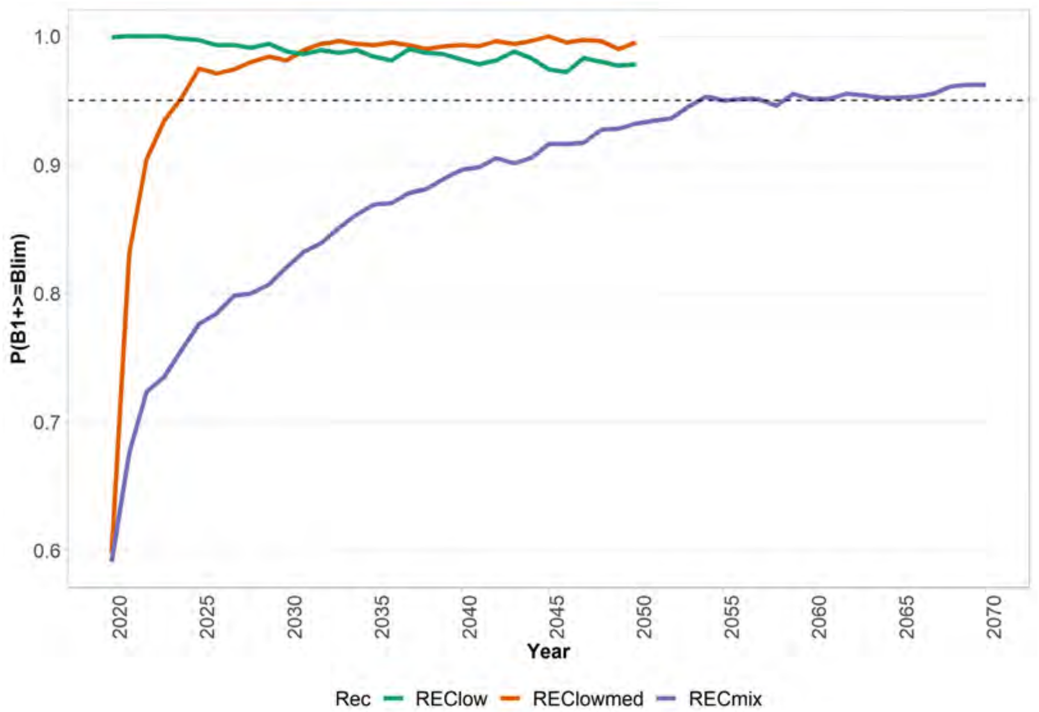


**Figure 6.20 Probability profile of P(B1+≥$B_{lim}$) for catch rule HCR30 for the three productivity regimes Low (REClow, green line; $B_{lim}$ = 196 thousand tonnes), Low-to-medium (REClowmed, orange line; $B_{lim}$ = 337 thousand tonnes) and Mix (RECmix, purple line; $B_{lim}$ = 337 thousand tonnes) from 2020 to 2070. Horizontal dashed line represents 95% probability.**

## 6.6 Simulated productivity scenarios under no fishing

Table 6.6 presents summary statistics for the simulations performed for no fishing (HCR0). During the first six years of the projection period (2021–2026, initial period) the estimated median biomass of fish age 1 and older (B1+) varied between 363 and 528 thousand tonnes, depending on the assumed productivity for the 'true' stock (Table 6.6). In the short term, for the low productivity scenario, with $F_{bar2–5}$ = 0, B1+ presents a 11% increase regarding HCR30, 12% in reference to HCR35 and 13% to HCR40 and HCR45.

Throughout the projected period without fishing, the biomass of the population remains stable, with an estimated B1+ of 367 thousand tons in the long term under the Low recruitment, which represents an increase of 24% in reference to HCR30, 28% to HCR35 and 30% to HCR40 and HCR45.

This scenario can be considered precautionary since Risk 3 is well below 5% and close to zero in the long term (Table 6.6, Figure 6.21).

**Table 6.6. Summary of performance statistics for scenario with no fishing. Reported Risk 3 were calculated in the last ten years of a 30-years projection period (2041:2050) for the Low and Low-to-medium recruitment regimes and in the last ten years of a 50-year projection period (2061:2070) for the Mix recruitment regime. Reported Risk 3 for the Low recruitment regime uses $B_{lim}$ = 196 kt as a reference point while for the Low-to-medium and Mix recruitment regimes uses $B_{lim}$ = 337 kt as a reference point.**

| Period | Recruitment | | |
|---|---|---|---|
| | Low | Low-to-medium | Mix |
| **B1+** | | | |
| initial | 363 | 528 | 494 |
| short | 363 | 578 | 546 |
| long | 367 | 674 | 676 |
| **Catch** | | | |
| initial | 0 | 0 | 0 |
| short | 0 | 0 | 0 |
| long | 0 | 0 | 0 |
| **F** | | | |
| initial | 0 | 0 | 0 |
| short | 0 | 0 | 0 |
| long | 0 | 0 | 0 |
| **IAV** | | | |
| initial | 0 | 0 | 0 |
| short | 0 | 0 | 0 |
| long | 0 | 0 | 0 |
| **First year Blim = 196 kt** | | | |
| all | 2021 | 2021 | 2021 |
| **First year Blim = 337 kt** | | | |
| all | — | 2023 | 2028 |
| **Risk 3** | | | |
| long | 0 | 0.1 | 0 |

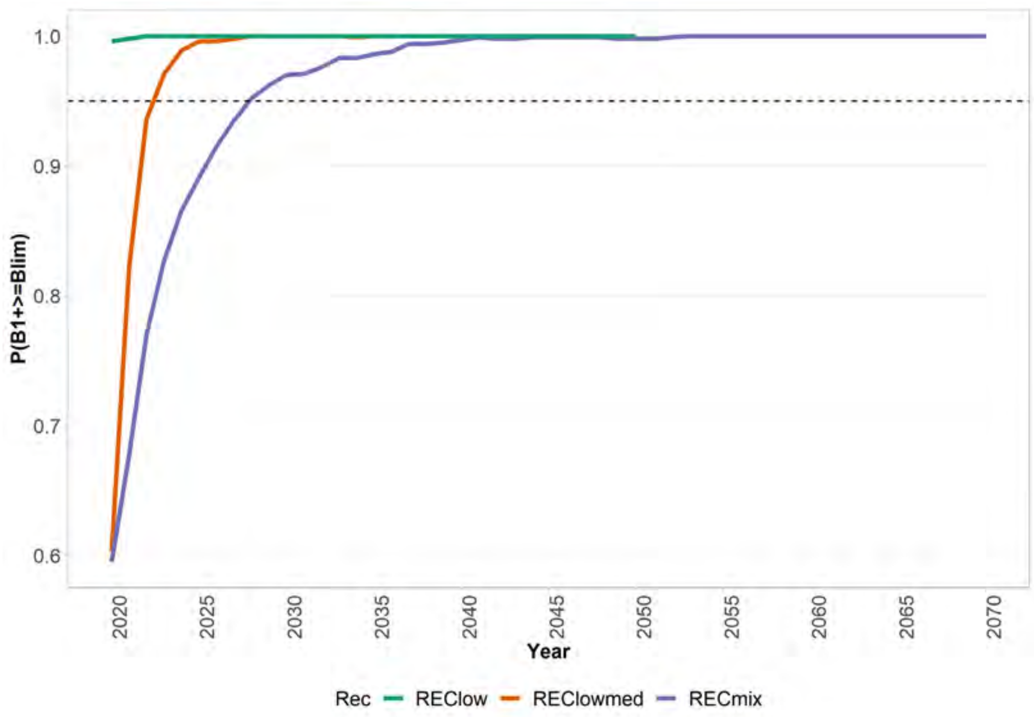


**Figure 6.21. Probability profile of P(B1+≥$B_{lim}$) in the no fishing scenario for the three productivity regimes Low (REClow, green line; $B_{lim}$ = 196 thousand tonnes), Low-to-medium (REClowmed, orange line; $B_{lim}$ = 337 thousand tonnes) and Mix (RECmix, purple line; $B_{lim}$ = 337 thousand tonnes) from 2020 to 2070. Horizontal dashed line represents 95% probability.**

## 6.7 ICES MSY AR in a Low productivity scenario

To estimate reference points for the Low productivity scenario simulations were run with MSY $B_{trigger}$ (see Section 2). In this section we present the trajectories of the key parameters R, B1+, $F_{bar2-5}$ and catch with the ICES MSY AR with estimated $F_{MSY} = F_{pa} = 0.092$ year$^{-1}$.

### 6.7.1 Simulated recruitment, spawning–stock biomass (B1+), fishing mortality and catch

The trajectories of the key parameters R, B1+, $F_{bar2-5}$ and catch under Low productivity regime are shown in Figure 6.22.

In the long term, Low productivity true stock leads to a median R to around 7.6 billion individuals and a decrease of median B1+ to 282 thousand tonnes. The lower confidence limit of B1+ is above to the corresponding $B_{lim}$ = 196 thousand tonnes (Figure 6.22).

In the case of application of the ICES MSY AR, median catches are similar during the entire period, between 30 and 31 kt.

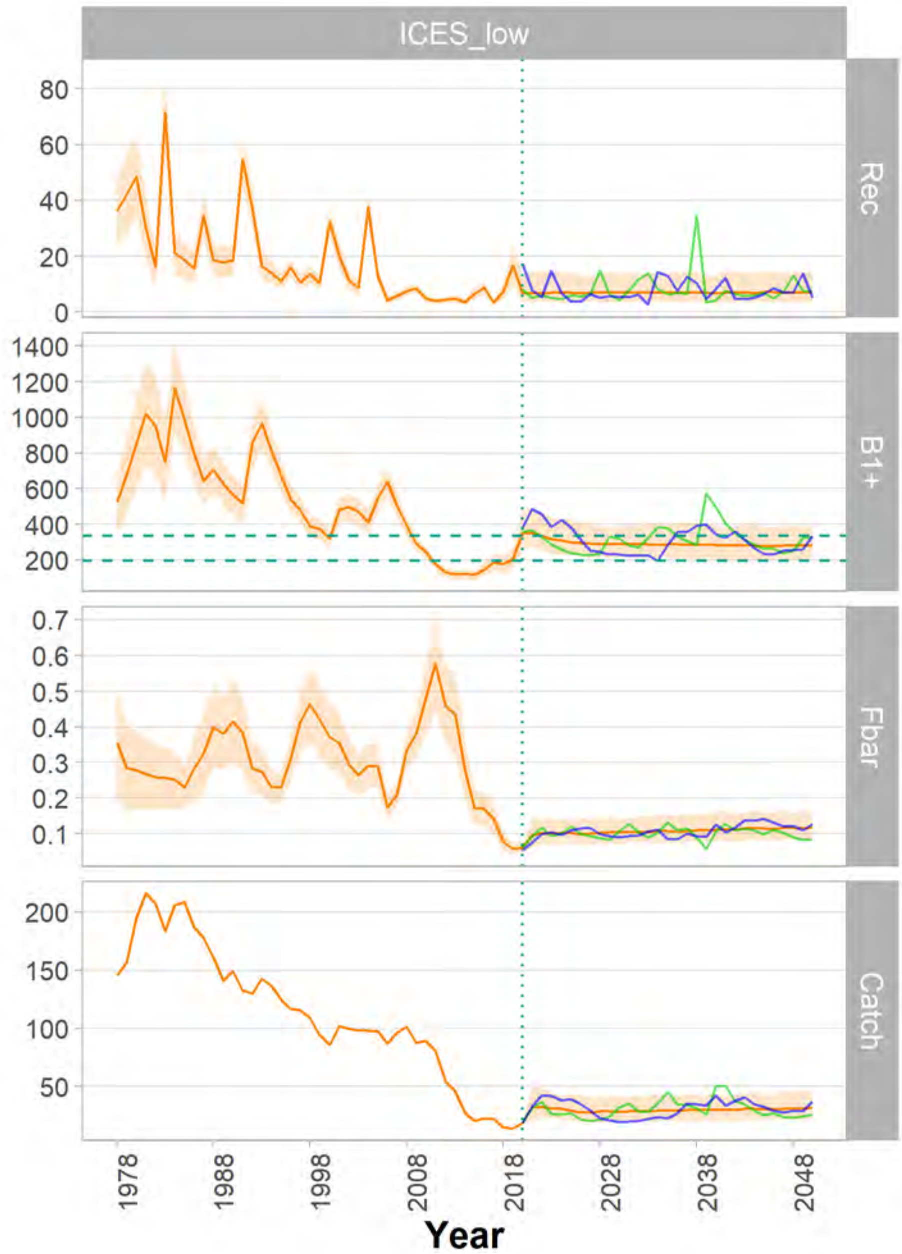


**Figure 6.22. ICES AR under Low productivity. Recruitment (Rec, billion individuals), biomass of fish age 1 and older (B1+, thousand tonnes), fishing mortality ($F_{bar2–5}$, year$^{-1}$) and catch (thousand tonnes) for the assessment period (1978–2019) and during the projected period (2020–2050) for ICES AR under 'true' stock of Low productivity. Shaded area represents 90% confidence intervals. Horizontal dashed lines in B1+ show $B_{lim}$ of Low productivity (196 thousand tonnes) and of Medium productivity (337 thousand tonnes). Vertical long dashed lines separate the historical from the projected period. The blue and green lines show the results from two simulated iterations selected randomly.**

## 6.7.2 Performance statistics

During the first six years of the projection period (2021–2026, initial period) the estimated median biomass of fish age 1 and older (B1+) is 320 thousand tones (Table 6.7). For the same period, the catches are equal to 31 kt.

Interannual variation of catches is around 4 thousand tones in all the time frames considered.

The ICES MSY AR is considered precautionary, since risk 3 is equal to 5% in the long term (Table 6.7 and Figure 6.23). This ICES MSY AR has $F_{MSY} = F_{pa} = 0.092$ year$^{-1}$ and MSY $B_{trigger}$ = 252 thousand tonnes.

**Table 6.7. Summary of performance statistics for ICES MSY AR under Low productivity. Reported Risk 3 were calculated in the last ten years of a 30-years projection period (2041:2050). Reported Risk 3 for the Low recruitment regime uses $B_{lim}$ = 196 kt as a reference point.**

| Period | Recruitment |
|---|---|
| | Low |
| **B1+** | |
| initial | 320 |
| short | 307 |
| long | 282 |
| **Catch** | |
| initial | 31 |
| short | 30 |
| long | 31 |
| **F** | |
| initial | 0.101 |
| short | 0.101 |
| long | 0.115 |
| **First year $B_{lim}$ = 196 kt** | |
| | 2021 |
| **First year $B_{lim}$ = 337 kt** | |
| | — |
| **IAV** | |
| initial | 4 |
| short | 4 |
| long | 4 |
| **Risk 3** | |
| long | 5 |

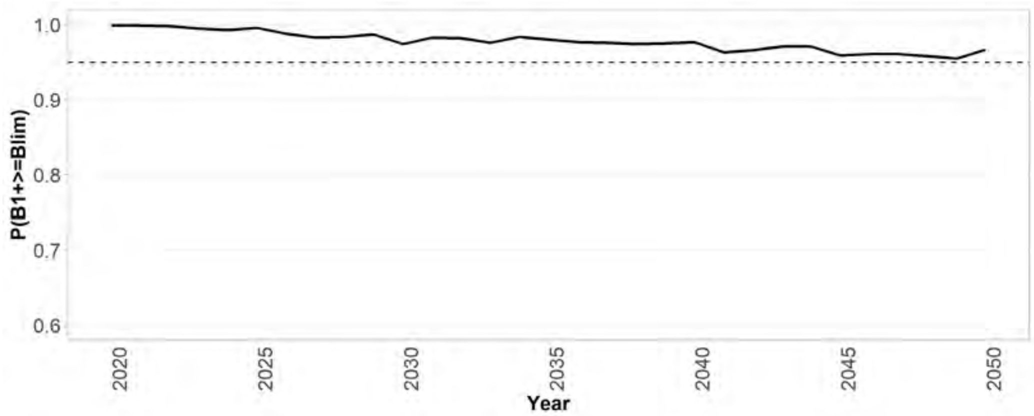


**Figure 6.23. Probability profile of P(B1+≥$B_{lim}$) for ICES MSY AR for the Low productivity regime ($B_{lim}$ = 196 thousand tonnes) from 2020 to 2050. Horizontal dashed line represents 95% probability.**

## 6.8 ICES MSY AR in a Medium productivity scenario

To estimate reference points for the Medium productivity scenario simulations were run with MSY $B_{trigger}$ (see Section 2). In this section we present the trajectories of the key parameters R, B1+, $F_{bar2–5}$ and catch with the ICES MSY AR with estimated $F_{MSY} = F_{pa} = 0.111$ year$^{-1}$.

### 6.8.1 Simulated recruitment, spawning–stock biomass (B1+), fishing mortality and catch

The trajectories of the key parameters R, B1+, $F_{bar2-5}$ and catch under Medium productivity are shown in Figure 6.24.

In the long term, Medium productivity true stock leads to a median R to around 7.6 billion individuals and an increase of median B1+ to 519 thousand tonnes. The lower confidence limit of B1+ is above the corresponding $B_{lim}$ = 337 thousand tonnes (Figure 6.24).

In the case of application of ICES MSY AR, median catches vary from 47 kt in the initial period to 55 kt in the long term.

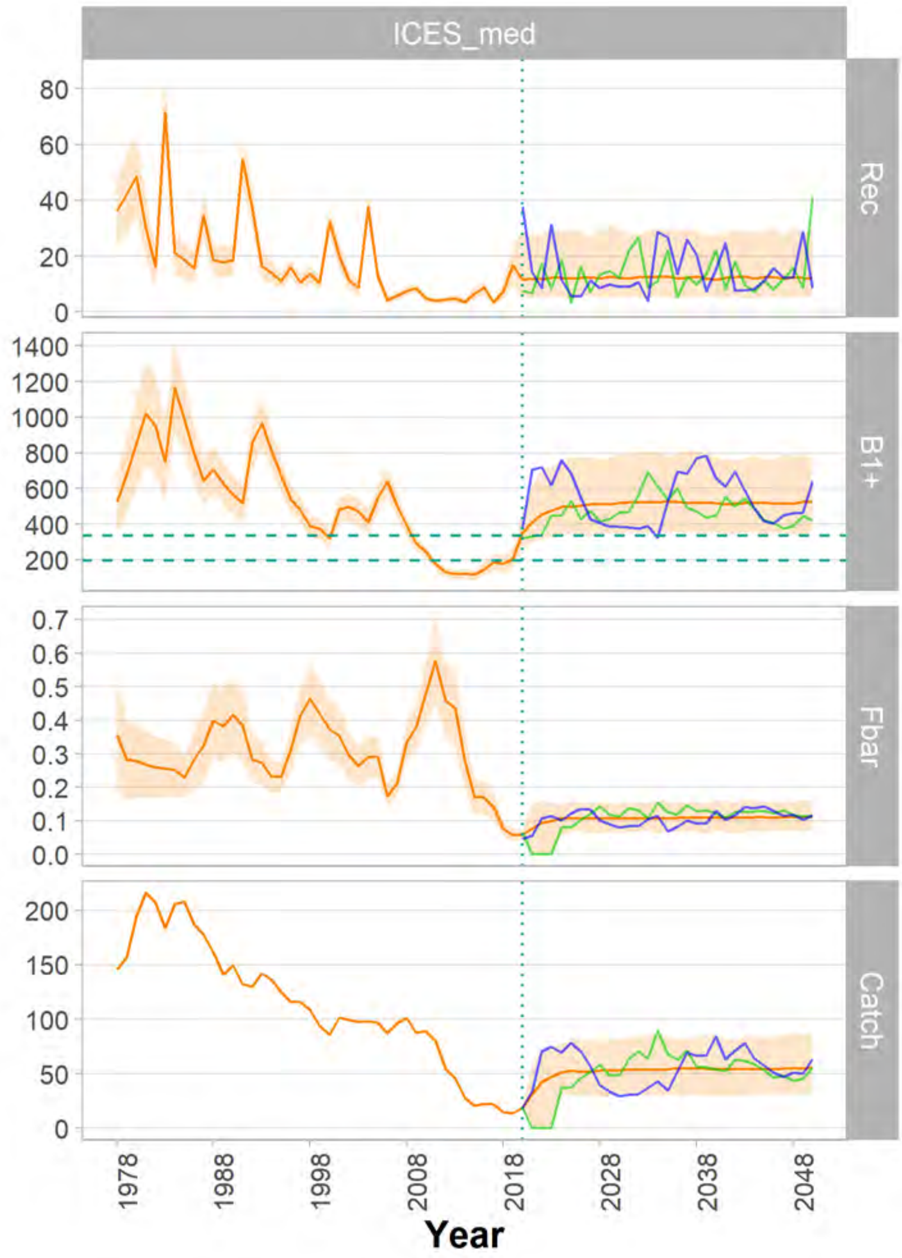


**Figure 6.24. ICES MSY AR under Medium productivity. Recruitment (Rec, billion individuals), biomass of fish age 1 and older (B1+, thousand tonnes), fishing mortality ($F_{bar}$2–5, year-1) and catch (thousand tonnes) for the assessment period (1978–2019) and during the projected period (2020–2050) for ICES MSY AR under 'true' stock of Medium productivity. Shaded area represents 90% confidence intervals. Horizontal dashed lines in B1+ show $B_{lim}$ of Low productivity (196 thousand tonnes) and of Medium productivity (337 thousand tonnes). Vertical long dashed lines separate the historical from the projected period. The blue and green lines show the results from two simulated iterations selected randomly.**

### 6.8.2 Performance statistics

During the first six years of the projection period (2021–2026, initial period) the estimated median biomass of fish age 1 and older (B1+) is 470 thousand tonnes (Table 6.8). For the same period, the catches are equal to 47 kt.

Interannual variation of catches are estimated to be between 13 thousand tonnes in the initial period and 10 thousand tonnes in the long term.

The ICES MSY AR is considered precautionary, since risk 3 is equal to 5% in the long term (Table 6.8 and Figure 6.25). Due to time constraints, the performance of the harvest rule could not be evaluated for the low-to-medium or mix productivity scenarios. This ICES MSY AR has $F_{MSY}$ = $F_{pa}$ = 0.111 year$^{-1}$ and MSY $B_{trigger}$ = 443 thousand tonnes.

**Table 6.8. Summary of performance statistics for ICES MSY AR under Medium productivity. Reported Risk 3 were calculated in the last ten years of a 30-years projection period (2041:2050). Reported Risk 3 for the Medium recruitment regime uses $B_{lim}$ = 337 kt as a reference point.**

| **Period** | **Recruitment** |
|---|---|
| | Medium |
| **B1+** | |
| initial | 470 |
| short | 488 |
| long | 519 |
| **Catch** | |
| initial | 47 |
| short | 50 |
| long | 55 |
| **F** | |
| initial | 0.101 |
| short | 0.104 |
| long | 0.111 |
| **IAV** | |
| initial | 13 |
| short | 11 |
| long | 10 |
| **First year $B_{lim}$ = 196 kt** | |
| 2021 | |
| **First year $B_{lim}$ = 337 kt** | |
| 2024 | |
| **Risk 3** | |
| long | 5 |

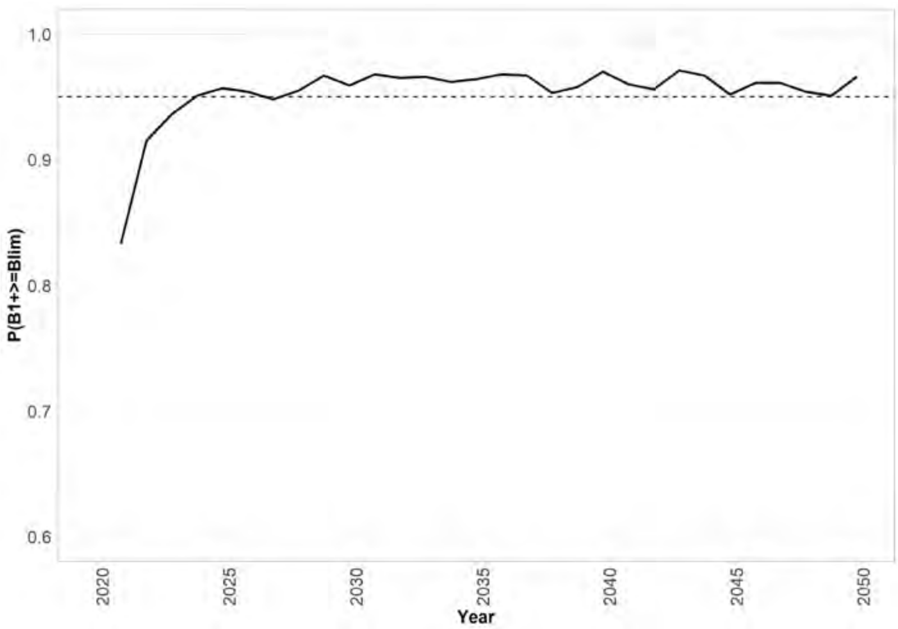


**Figure 6.25. Probability profile of P(B1+≥$B_{lim}$) for ICES MSY AR for the Medium productivity regime ($B_{lim}$ = 337 thousand tonnes) from 2020 to 2050. Horizontal dashed line represents 95% probability.**

# 6.9 Summary Results and Conclusions

In the Low productivity regimes, all HCR can be considered precautionary according to ICES criterion of no more than 5% probability of the spawning–stock biomass (B1+) falling below $B_{lim}$ of 196 kt in the long term (Figure 6.26). These conclusions are robust to a potential future shift to a higher productivity scenario (Low-to-medium). In the Mix productivity scenario only HCR30 can be considered precautionary.

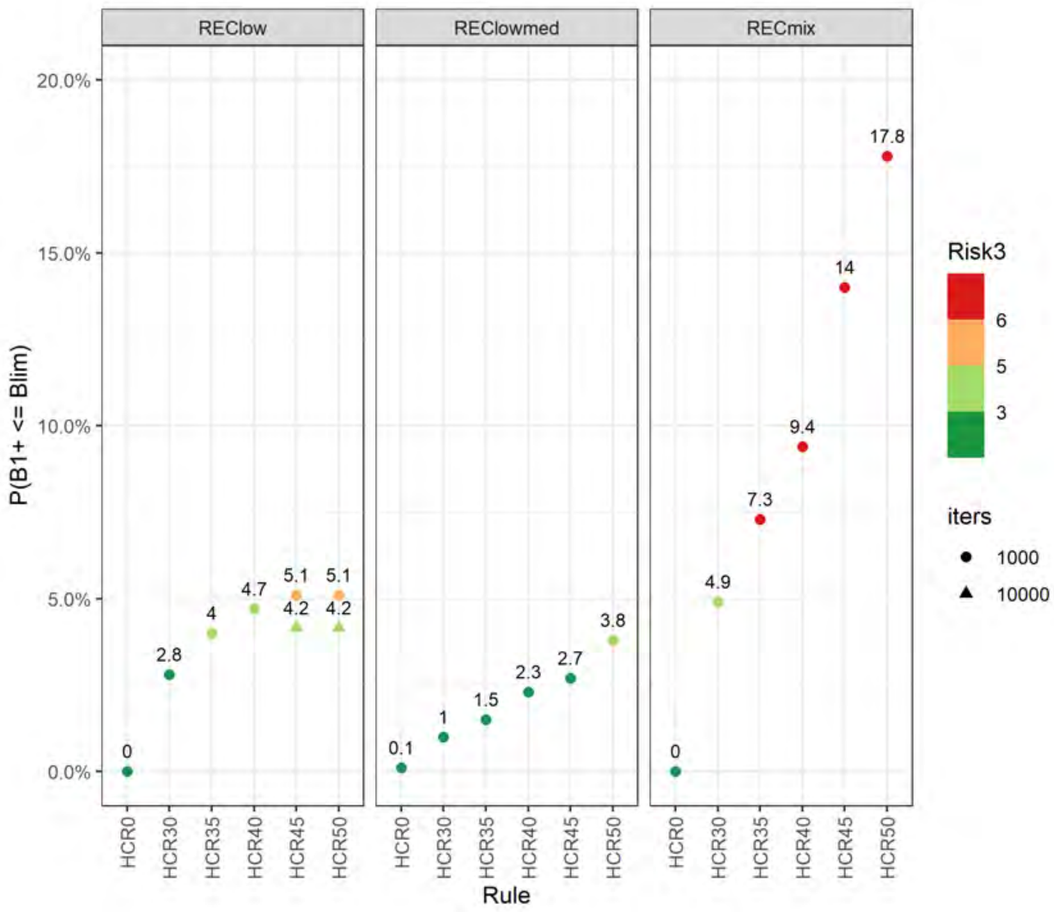


**Figure 6.26. Risk 3 in the long term for the three productivity regimes: Low ($REC_{Low}$; $B_{lim\_low}$ = 196 thousand tonnes), Low-to-medium ($REC_{Low\text{-}to\text{-}medium}$; $B_{lim\_med}$ = 337 thousand tonnes) and Mix ($REC_{mix}$; $B_{lim\_med}$ = 337 thousand tonnes) for all the HCR tested. Number of iterations: circle= 1000 iterations, triangle= 10 000 iterations.**

For all productivity scenarios and catch rules tested, the probability of closure of the fishery is 0.

The highest long-term yield for the Low productivity scenario is around 34 kt and is associated with HCR35 (Table 6.9). This HCR35 also produces the highest short-term yield, with an associated $F_{bar2\text{–}5}$ of 0.094 year$^{-1}$, very close to the value of $F_{MSY}$ = 0.092 year$^{-1}$ estimated during the workshop. Differences in expected catches are in any case relatively small among rules, between 30–33 thousand tonnes in the initial period (2021–2026) and between 30–34 thousand tonnes in the long term (Table 6.9).

**Table 6.9. Summary of the performance statistics for the simulation tested harvest control rules under a persistent Low productivity of the Iberian sardine stock ($B_{lim\_low}$ = 196 334 t), including the ICES MSY AR (Advice Rule).**

| Metrics | Periods | Harvest control rules | | | | | |
|---|---|---|---|---|---|---|---|
| | | HCR30 | HCR35 | HCR40 | HCR45 | HCR50 | ICES MSY AR |
| B1+ (thousand tonnes) | 2021-2026 | 326 | 323 | 322 | 320 | 319 | 320 |
| | 2021-2030 | 315 | 312 | 311 | 308 | 307 | 307 |
| | 2041-2050 | 295 | 287 | 283 | 281 | 278 | 282 |
| Catch (thousand tonnes) | 2021-2026 | 30 | 33 | 32 | 32 | 32 | 31 |
| | 2021-2030 | 30 | 31 | 31 | 30 | 30 | 30 |
| | 2041-2050 | 30 | 34 | 33 | 32 | 32 | 31 |
| F ($year^{-1}$) | 2021-2026 | 0.085 | 0.094 | 0.099 | 0.103 | 0.104 | 0.101 |
| | 2021-2030 | 0.087 | 0.096 | 0.1 | 0.102 | 0.103 | 0.101 |
| | 2041-2050 | 0.098 | 0.11 | 0.117 | 0.121 | 0.121 | 0.115 |
| IAV (thousand tonnes) | 2021-2026 | 2 | 3 | 5 | 6 | 7 | 4 |
| | 2021-2030 | 2 | 4 | 5 | 6 | 7 | 4 |
| | 2041-2050 | 2 | 3 | 5 | 6 | 7 | 4 |
| First year $B_{lim}$= 196 kt | 2021-2050 | 2021 | 2021 | 2021 | 2021 | 2021 | 2021 |
| First year $B_{lim}$= 337 kt | 2021-2050 | - | - | - | - | - | - |

In case it is confirmed a transition of the stock to a medium productivity state in the short term, all the tested rules would allow B1+ to increase above $B_{lim}$ of 337 kt by 2024 for HCR30 and by 2025 for HCR35, HCR40, HCR45 and HCR50 (Table 6.10).

**Table 6.10. Summary of the performance statistics for a Low-to-medium productivity scenario of the Iberian sardine stock for the simulation tested harvest control rules.**

| Metrics | Periods | Harvest control rules | | | | |
|---|---|---|---|---|---|---|
| | | HCR30 | HCR35 | HCR40 | HCR45 | HCR50 |
| B1+ (thousand tonnes) | 2021-2026 | 487 | 482 | 477 | 472 | 475 |
| | 2021-2030 | 518 | 513 | 502 | 496 | 496 |
| | 2041-2050 | 590 | 579 | 563 | 551 | 541 |
| Catch (thousand tonnes) | 2021-2026 | 30 | 35 | 40 | 45 | 50 |
| | 2021-2030 | 30 | 35 | 40 | 45 | 50 |
| | 2041-2050 | 30 | 35 | 40 | 45 | 50 |
| F ($year^{-1}$) | 2021-2026 | 0.061 | 0.07 | 0.079 | 0.087 | 0.093 |
| | 2021-2030 | 0.058 | 0.067 | 0.077 | 0.085 | 0.093 |
| | 2041-2050 | 0.052 | 0.062 | 0.072 | 0.083 | 0.092 |
| IAV (thousand tonnes) | 2021-2026 | 1 | 2 | 3 | 4 | 5 |
| | 2021-2030 | 1 | 1 | 2 | 3 | 4 |
| | 2041-2050 | 0 | 0 | 1 | 1 | 2 |
| First year $B_{lim}$= 196 kt | 2021-2050 | 2021 | 2021 | 2021 | 2021 | 2021 |
| First year $B_{lim}$= 337 kt | 2021-2050 | 2024 | 2025 | 2025 | 2025 | 2025 |

**Table 6.11. Summary of the performance statistics for a Mixed productivity scenario of the Iberian sardine stock for the simulation tested harvest control rules.**

| Metrics | Periods | Harvest control rules | | | | |
|---|---|---|---|---|---|---|
| | | HCR30 | HCR35 | HCR40 | HCR45 | HCR50 |
| B1+ (thousand tonnes) | 2021-2026 | 444 | 436 | 433 | 427 | 425 |
| | 2021-2030 | 472 | 463 | 455 | 447 | 444 |
| | 2061-2070 | 589 | 572 | 551 | 534 | 510 |
| Catch (thousand tonnes) | 2021-2026 | 30 | 35 | 40 | 45 | 45 |
| | 2021-2030 | 30 | 35 | 40 | 45 | 49 |
| | 2061-2070 | 30 | 35 | 40 | 45 | 50 |
| F ($year^{-1}$) | 2021-2026 | 0.065 | 0.074 | 0.082 | 0.088 | 0.094 |
| | 2021-2030 | 0.062 | 0.071 | 0.08 | 0.087 | 0.094 |
| | 2061-2070 | 0.052 | 0.063 | 0.074 | 0.084 | 0.095 |
| IAV (thousand tonnes) | 2021-2026 | 1 | 2 | 3 | 4 | 5 |
| | 2021-2030 | 1 | 2 | 3 | 4 | 4 |
| | 2061-2070 | 0 | 0 | 1 | 1 | 2 |
| First year $B_{lim}$= 196 kt | 2061-2070 | 2021 | 2021 | 2021 | 2021 | 2021 |
| First year $B_{lim}$= 337 kt | 2061-2070 | 2054 | - | - | - | - |

Table 6.12 presents the probability that under a persistent Low productivity the 'real' fishing mortality is above $F_{MSY}$ = 0.092 $year^{-1}$ in the initial, short- and long-term periods and also over the 30-years projection period (2021: 2050). Because of the assessment bias observed in the MSE (Section 5), the probability that the 'real' fishing mortality is above $F_{MSY}$ = 0.092 $year^{-1}$ is higher than 50% for the majority of the HCRs and including the ICES MSY AR (Table 6.12). Exceptions are for HCR30 in the initial and short-term periods and for HCR35 in the initial period (Table 6.12). Imposing a catch constraint, as in the proposed HCRs, reduces fishing mortality and minimises the potential overexploitation due to the overestimation of biomass in the assessment.

**Table 6.12. Low productivity scenario: Probability that the 'real' fishing mortality is above $F_{MSY}$ = 0.092 $year^{-1}$.**

| Rule | ICES MSY AR | HCR0 | HCR30 | HCR35 | HCR40 | HCR45 | HCR50 |
|---|---|---|---|---|---|---|---|
| 2021:2026 | 0.568 | 0 | 0.299 | 0.464 | 0.511 | 0.531 | 0.534 |
| 2021:2030 | 0.616 | 0 | 0.357 | 0.507 | 0.546 | 0.555 | 0.555 |
| 2041:2050 | 0.861 | 0 | 0.62 | 0.759 | 0.776 | 0.773 | 0.766 |
| 2021:2050 | 0.747 | 0 | 0.496 | 0.636 | 0.663 | 0.662 | 0.658 |

# 7 General conclusions

During WKSARHCR, the MSY and PA reference points were re-examined. The hockey-stick stock–recruitment model was fitted to the time-series 1993–2019, corresponding to a Medium productivity and to the time-series 2006–2019, corresponding to the current assumed Low productivity regime for the Iberian sardine. $B_{lim}$ estimates were not significantly different from those previously estimated and WKSARHCR kept the same values as used in the last evaluation of HCRs: $B_{lim}$=196 334 tonnes for the Low productivity and $B_{lim}$=337 448 tonnes for the Medium productivity regimes. Subsequently, $B_{pa}$ and MSY $B_{trigger}$ reference points were also kept the same.

The current $F_{MSY}$, of 0.032 year$^{-1}$ (ICES, 2019), was estimated using the EqSim software which estimates reference points based on the equilibrium distribution of stochastic projections. However, this approach is not consistent with the MSE framework used to evaluate the harvest control rules, which includes an annual stock assessment cycle and short-term projections. WKSARHCR has, therefore, recomputed $F_{MSY}$ using the MSE framework. $F_{MSY}$, which was constrained by $F_{pa}$, was revised upwards to 0.092 year$^{-1}$. This significant upward revision is due to various factors, including the different estimation methodology used and a higher expectation of future recruitment levels given the recent observations of stronger year classes. $F_{MSY}$ under a Medium productivity scenario was slightly revised from 0.12 year$^{-1}$ (ICES, 2019) to 0.111 year$^{-1}$.

The request asked for the evaluation of a generic HCR with catch caps of 50 kt (HCR50), of 45 kt (HCR45) and of 40 kt (HCR40). WKSARHCR decided to evaluate two additional HCRs, with caps of 35 kt (HCR35) and of 30 kt (HCR30) in the event that the proposed HCR was not precautionary with the initial caps. In both Low and Low-to-medium productivity regimes, all HCRs are precautionary in the short- and long term. HCR35 results in slightly higher catches and slightly lower interannual variability in the catches than the other HCRs. HCR35, with fishing mortality in the range 0.094–0.11 year$^{-1}$, results in long term catches of 34 226 tonnes and an interannual variability in the initial period (2021–2026) of 2 thousand tonnes. The ICES MSY AR, with fishing mortality in the range 0.101–0.115 year$^{-1}$, results in slightly lower long-term catches, of 31 283 tonnes, and slightly higher interannual variability in catches, of 4 thousand tonnes.

There are indications that the stock may have begun a transition to a new productivity regime as evidenced by the stronger year class in 2019 and indications from the juvenile survey of an equally high recruitment in 2020. At this point, the evidence is still inconclusive and information on incoming year classes is crucial to confirm if the stock has shifted to a more productive state. If this turns to be the case, then allowable catches following the HCRs would increase, while remaining precautionary (Low-to-medium productivity regime). Under the Mix scenario catches would also increase, but it cannot be concluded that the HCRs would be precautionary in this scenario, as the likelihood of dropping below $B_{lim\_med}$ would be higher than 5%, though always below 20% (and for HCR40 and HCR35 below 10%).

Because the evaluation of Risk type 3 depends on estimates obtained at the tails of the biomass distributions, a proper evaluation of this criterion requires that the number of iterations in the simulation is large enough to obtain accurate and robust estimates of risk. WKSARHCR evaluated the precision and accuracy of Risk type 1 and Risk type 3 for three of the proposed control rules (HCR40, HCR45 and HCR50). In all cases, Risk type 1 was more accurate than Risk type 3. Risk type 3 estimates were positively biased, and the bias decreased with increasing number of iterations. This aspect was particularly important for the precautionary evaluation of HCR50 and HCR45, under the Low recruitment scenario, because these HCRs presented Risk type 3 at the border of the 5% threshold for 1000 iterations. Risk type 3 tended to be larger than Risk type 1 and the lack of convergence was more relevant for the Mix recruitment regime, which needed a longer projection period to converge. This feature may also lead to some underestimation of $F_{MSY}$.

ICES. 2019. Workshop on the Iberian Sardine Management and Recovery Plan (WKSARMP). ICES Scientific Reports. 1:18. 153 pp. http://doi.org/10.17895/ices.pub.5251.

# 8 Reviewers' report

Martin Dorn, Sonia Sánchez-Maroño, and Peter Kuriyama acted as the external experts for the WKSARHCR. Martin Dorn and Sonia Sánchez-Maroño were external experts for the workshop on the management and recovery plan for Iberian sardine (WKSARMP) and previously reviewed and approved of the Management Strategy Evaluation (MSE) modelling framework applied in this workshop. The two primary goals of the workshop were to re-examine reference points according to ICES guidelines, update if considered necessary, and to evaluate several proposed harvest control rules against precautionary criteria. A harvest control rule was considered to be precautionary if the maximum probability of the age 1+ biomass (B1+) being below $B_{lim}$ was 0.05 during the last ten years of the projection (2041–2050) (known as Risk 3 in ICES terminology). This is a measure of long-term risk after the stock has rebuilt, and corresponds to the ICES standard for multi-annual management plans.

WKSARHCR used the same methods that had been developed in WKSARMP for a full feedback management strategy evaluation (MSE) using FLBEIA and the stock synthesis assessment model. The performance of each candidate harvest control rule was evaluated with 1000 iterations for the thirty-year period 2021–2050. Some harvest control rule scenarios were run with up to 10 000 iterations to evaluate convergence in the results, and harvest control rule performance was also evaluated at the end of a fifty-year period to check for stability. These checks were particularly important for harvest control rules that had ICES Risk 3 probabilities near the 5% threshold. Since the MSE was done according to previously reviewed and approved methods, and was done to a high scientific standard, we therefore support the findings of WKSARHCR with respect to the proposed harvest controls as being suitable for the management of the Iberian sardine stock according to ICES standards. We also support the working group's recommendations on biomass and fishing mortality reference points. It is important to note that this is a highly variable stock that will require close monitoring for rebuilding progress, and checking for changes in stock productivity and reference points.

Below we provide additional specific comments on the reference point evaluation and the MSE testing of alternative rules for the Iberian sardine. This report reflects solely the views of the external experts.

## 8.1 Specific comments

The 2019 recruitment estimate, from the most recent stock assessment, was higher than recruitment estimates from 2006–2018. Re-estimation of the hockey-stick stock–recruit relationship with the 2019 recruitment estimate did not result in significantly different biomass reference points than used previously. Therefore, the $B_{lim}$ reference points were kept the same as in the last management strategy evaluation. This decision was supported by external reviewers.

Stock–recruit relationship used in the MSE was a re-estimated segmented regression in which the $B_{lim}$ value was fixed at the previously estimated value. There is some rationale for this approach, since the decision was made not to change the $B_{lim}$ reference point. It is important to distinguish the use of $B_{lim}$ as a reference point, and as a parameter in the stock–recruit relationship. It would have perhaps been better to use a stock–recruitment relationship in the MSE in which the full set of parameters was re-estimated to better represent current understanding of stock dynamics, however this approach probably would not have altered the recommendations substantially.

Precautionary advice was based on the final ten years of a 30-year projection time frame (2041–2050) for the low and low–medium productivity regimes. The advice in both productivity regimes was evaluated relative to the $B_{lim}$ value for the respective regimes. The 30-year projection time frame was consistent with the approach that was used to provide previous advice. The working group also projected the models for 50 years (up to 2070), but decided to not provide precautionary advice based on the longer time period. The argument for evaluating the longer time period is that the simulation models better achieve a stochastic equilibrium, a desired outcome in MSEs. The period extension was motivated in particular by the apparent lack of stability under the mixed productivity regime. However, Iberian sardine is a highly variable stock, and 50-year projections are unlikely to realistically represent stock dynamics. ICES will also be conducting stock assessments and re-evaluating the harvest control rules multiple times for Iberian sardine in the next 50 years.

The stock synthesis assessment model in the MSE produced positively biased biomass estimates relative to true stock size in the operating model. This resulted in some simulations not reaching a stochastic equilibrium, with low productivity regime seeming to be most affected by the positive bias. Addressing this issue was not feasible in the working group’s time but should be investigated before future management strategy evaluations. Although in this case the bias results in a risk averse evaluation of harvest control rules, it could result in underestimation of the fishing opportunities, of still unknown magnitude.

Given increased use of MSE to evaluate harvest policies, ICES may want to consider whether it is possible to provide guidelines on the number of simulations required to evaluate whether a harvest control rule is precautionary. The ICES Risk 3 evaluation requires estimation of the tail of the distribution of stock biomass, which is likely to require more iterations than estimating mean properties. Results presented during the working group meeting suggested that use of 1000 iterations, which is common practice, is not sufficient to achieve convergence. The use of 1000 iterations does give a precautionary result in that Risk 3 estimates tend to be higher than for a Risk 3 estimates using a greater number of iterations. It may also be good to recommend that in borderline cases additional iterations should be run to ensure converged results.

ICES may also want to consider whether it is possible to provide guidance on the number of years to run the MSE when evaluating the performance of harvest control rules. Intuitively, the number of years required for the MSE to stabilize should be related to the generation time of the stock, but for the Iberian sardine MSE, there seem to be issues with lack of stability even at the end of the projection period, mostly likely due to a continuing bias in the stock assessment model. This may be especially important for short-lived stocks (consequently, highly variable stocks) that have the potential to not reach stability (and consequently Risk1 not converging to Risk3).

In general, when MSEs are conducted there is an expectation that adopted harvest control rule will be kept in place for a number of years before there is a need to revisit the MSE and re-evaluate the harvest control. The typical range may be between three to six years, but we have seen no review papers dealing with this specific issue. The ICES standard for precautionary harvest control rules is based on their long-term properties, so frequent revision of harvest control rules may prevent that standard from being achieved. Several of us have now participated in reviews of multiple revisions to the harvest control rule for Iberian sardine over the past three years, and consequently we suggest that there may be some benefit to restricting frequency of revisions to harvest control rules, for example, to no more than once every three years (or five years).

Another concern regarding harvest control rule revisions concerns the use of a cap on harvest. There may be good reasons for capping harvests, such as market demand, or an objective to stabilize employment in the fishing industry. However, when the objective of the harvest control rule is to restrict the probability of low stock size, as with the ICES precautionary standard, a harvest control rule with a cap will generally allow for a higher harvest rate in periods when the cap is not limiting. Therefore, there may be some potential to game the MSE to obtain higher short-term harvests by setting caps that will only be limiting far into the future, with the understanding that the MSE can always be revised before the caps are imposed.

The MSE makes the assumption that there is no implementation error, i.e. the catch amounts generated by the harvest control rule are caught exactly in all cases. It would be good to examine the management history of Iberian sardine for examples of catches higher and lower than the target that was set by managers. This documentation would provide the basis for modelling implementation error (and potentially bias) in the MSE.

An inter-benchmark assessment of Iberian sardine is planned after summer 2021, when results from surveys conducted this year will be available. It is not possible to anticipate how the new assessment results would affect results from WKSARHCR. If there are important changes to stock status or if new reference points are adopted, there could be a need to reanalyse the results for the selected rule to check if it is still precautionary and ensure that the stock is harvested sustainably in the future.

# Annex 1: The request

MINISTERIO
DE AGRICULTURA, PESCA
Y ALIMENTACION

REPÚBLICA
PORTUGUESA

05 th February 2021

To

Anne Christine Brusendorff

General Secretary ICES

H. C. Andersen

Boulevard 44-46, DK 1553

Copenhagen V, Denmark

Dear General Secretary of ICES,

Portugal and Spain updated the 2019 Management Plan (MP) for the Iberian sardine (*Sardina pilchardus*) in ICES waters zones 8c and 9a for the period 2021-2026. to be evaluated by ICES and submitted to the Commission for consideration.

For this reason, we kindly ask to ICES to evaluate the fulfillment of the precautionary criteria of the Harvest Control Rules in the annex MP 2021-2026. The HCR from this updated MP was previously tested by our research institutes as attached in annex 1 and the summary of the methodology used in this evaluation in annex 2.

We hope that next June advice is using these updated HCR rules. We also request ICES to revise the advice for 2021 and 2022 on the Iberian sardine in June to be issued at the same time as Anchovy and Horse-mackerel advice in ICES 9a.

Yours sincerely,

José Carlos Simão

Director General for

Natural Resources

Safety and Maritime Services

PORTUGAL

Isabel Artime Garcia

Director General for Sustainable Fisheries

SPAIN

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Portugal and Spain updated the 2019 Management Plan (MP) for the Iberian sardine (*Sardina pilchardus*) in ICES waters zones 8c and 9a for the period 2021–2026, to be evaluated by ICES and submitted to the Commission for consideration. For this reason, we kindly ask to ICES to evaluate the fulfilment of the precautionary criteria of the Harvest Control Rules in the annex MP 2021–2026.

# Management plan for the Iberian sardine stock

## Harvest control rule

The proposed HCR (Figure 1) has:

i. three levels for fishing mortality (F = 0, F = 0.064 and F = 0.12);

ii. three reference levels for B1+ (Blow (defined as the lowest observed time-series Biomass according to the 2018 assessment - WGHANSA 2018) = 112 943 t; $B_{trigger}$ (under the low productivity regime) = 252 523 t and $B_{trigger}$ (under a medium productivity regime) = 443 331 t).

The proposed HCR can be described as follows:

i. If B1+ ≤ 112 943 t then F=0;

ii. If 112 943 t < B1+ ≤ 252523 t then F increases linearly from 0 to 0.064;

iii. If 252 523 t < B1+ ≤ 446 331 t then F increases linearly from 0.064 to 0.12;

iv. If B1+ > 446 331 t then F = 0.12.

Conditions ii) to iv) are overridden if the forecast catch in any given year exceeds the maximum allowed catches of 50 kt, 45 Kt and 40 kt.

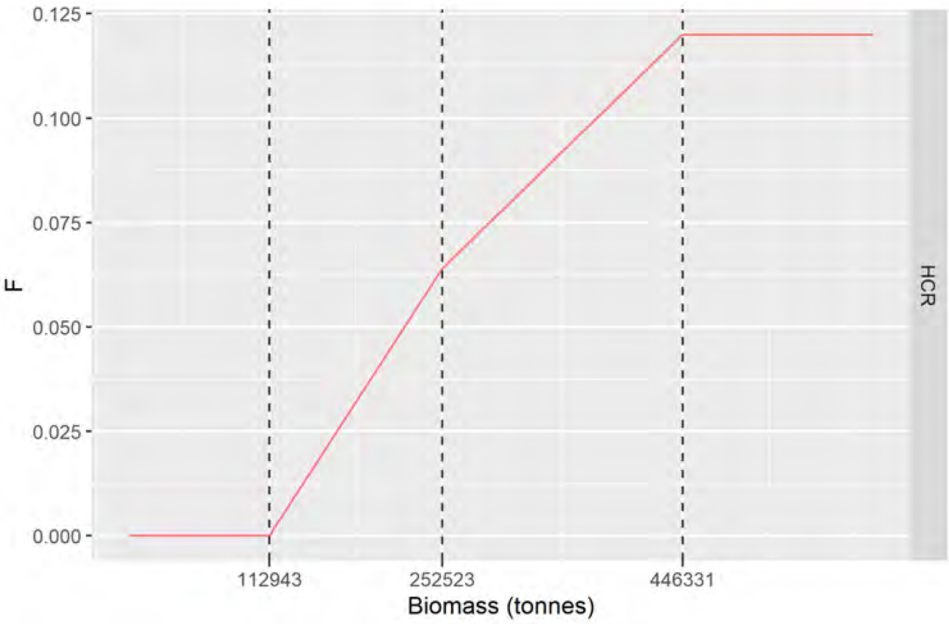



**Figure 1. Proposed HCR. The biomass reference levels of B1+ reported correspond to $B_{loss}$(2018)=112 943 t, $B_{trigger}$_low = $B_{pa}$_low = 252 523 t and $B_{trigger}$_medium = $B_{pa}$_medium = 446 331 t.**

i. If B1+ ≤ 112 943 t, then F=0;

ii. If 112 943 t < B1+ ≤ 252 523 t, then F increases linearly from 0 to 0.064;

iii. If 252 523 t < B1+ ≤ 446 331 t, then F increases linearly from 0.064 to 0.12;

iv. If B1+ > 446 331 t, then F = 0.12.

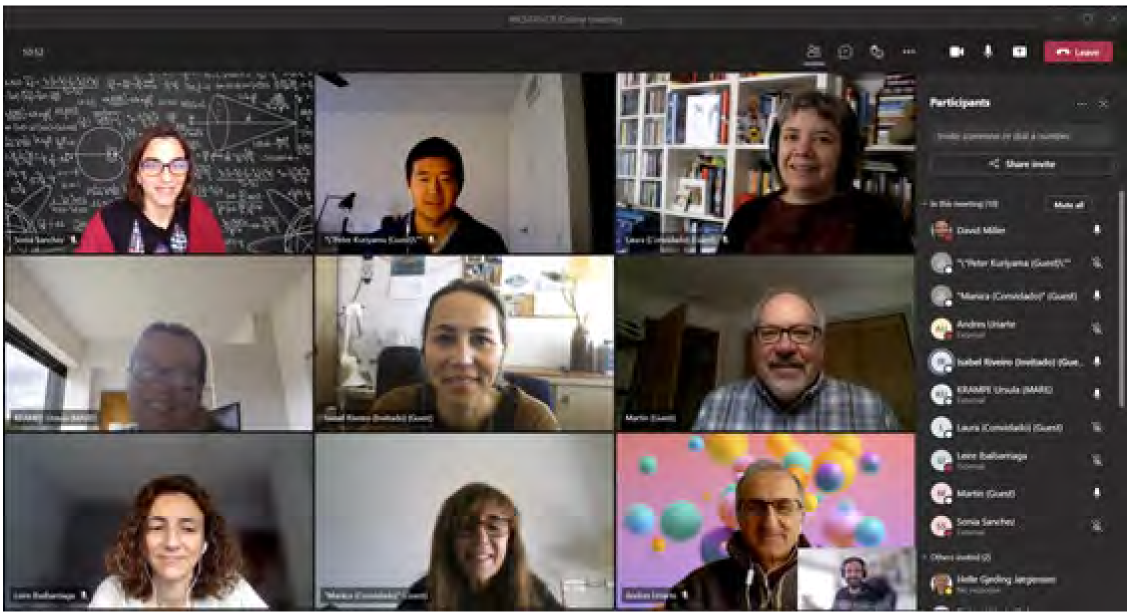
Conditions ii) to iv) are overridden if the forecast catch in any given year exceeds the maximum allowed catches of 50 kt, 45 Kt and 40 kt.

ICES is requested to evaluate the MP under the following conditions:

i. Initial starting condition: latest assessment (WGHANSA 2020);
ii. Catch in 2020: based on HCR 12;
iii. Recruitment scenarios: given the recruitments in latest years, several recruitment scenarios can be considered in the evaluation if consistent.

# Annex 2: List of participants

| Name | Institute | Country (of institute) | Email |
|---|---|---|---|
| Manuela Azevedo<br>Chair | IPMA | Portugal | mazevedo@ipma.pt |
| Martin Dorn<br>Invited Expert | NOAA | US | martin.dorn@noaa.gov |
| Leire Ibaibarriaga | AZTI | Spain | libaibarriaga@azti.es |
| Ursula Krampe | DGMare | Belgium | Ursula.Krampe@ec.europa.eu |
| Peter Kuriyama<br>Invited Expert | NOAA | US | peter.kuriyama@noaa.gov |
| David Miller | ICES | Denmark | david.miller@ices.dk |
| Isabel Riveiro | IEO | Spain | isabel.riveiro@ieo.es |
| Sonia Sánchez-Maroño<br>Invited Expert | AZTI | Spain | ssanchez@azti.es |
| Andrés Uriarte | AZTI | Spain | auriarte@azti.es |
| Laura Wise | IPMA | Portugal | lwise@ipma.pt |



# Annex 3: Workshop agenda

## 27 April (Tuesday)

16:00–16:20

Introductions, CoC, meeting ToRs, adoption of draft agenda.

Summary of the analysis carried out following the work plan agreed during the remote meeting (12 April)

16:20–20:00 (17:00–17:10 – short health break)

Presentations & plenary discussions and conclusions:

Biological reference points (ToR a) – Laura Wise

Accuracy of risk estimates (ToR b) – Leire Ibaibarriaga

HCR50_MSE simulations and summary results for HCR0-HCR30-HCR35-HCR40-HCR45-HCR50-ICES_med & ICES_low, under Low, Low-med and Mix productivity regime scenarios (ToR b & c) – Laura Wise

Planning of subgroup work

## 28 April (Wednesday)

09:00–15:00

Subgroup work.

16:00–19:00 (17:00–17:10 – short health break)

Discussion on accuracy of risk estimates, part II

Presentations & plenary discussions and conclusions:

Stationarity on SSB – Leire Ibaibarriaga

Assessment bias – Laura Wise

Adoption of report structure

Planning of subgroup work

## 29 April (Thursday)

09:00–15:00

Subgroup work.

Report writing and collation

16:00–18:30 (17:00–17:10 – short health break)

Plenary discussions and conclusions

Report writing and collation

## 30 April (Friday)

09:00–15:00

Report writing and collation; advice drafting (ToR e).

16:00–19:00

Adoption of the report (overall conclusions & recommendations) and of the initial draft of the advice.

# Annex 4: Summary of remote meeting (12 April 2021)

Participants: Manuela Azevedo (PT), Laura Wise (PT), Leire Ibaibarriaga (SP), Andres Uriarte (SP), Isabel Riveiro (SP), Fernando Ramos (SP), Gersom Costas (SP), Susana Garrido (PT), Richard Nash (UK), Rosana Ourens (UK), David Miller (ICES secretariat), Martin Dorn (US), Sonia Sánchez-Maroño (SP), Peter Kuryiama (US).

Working plan following LW presentation, discussion with external reviewers and PK comments by email

### BRPs (ToR a)

- Fit segmented S–R for the time-series 1993–2019 and 2006–2019 to check if the estimated $B_{lim}$ (breakpoint) is outside the 95%CI of previous estimates for 'medium' 1993–2015 and 'low' 2006–2017 productivity scenarios;
- Fit segmented S–R for the time-series 2006–2019, with fixed $B_{lim}$, to check if the upper CI changes and the effect on R;
- Send WD (latest 19 April) to reviewers with the BRPs analysis and proposal for the approach to be used in the evaluation of the HCRs, for their agreement;
- Estimate $F_{MSY}$ (=$F_{p0.5}$), $F_{lim}$ and $F_{pa}$ with the ICES AR using MSE approach for each of the 'low' and 'medium' productivity scenarios.

## Simulation testing of the HCRs (ToR b)

- Agreed to use the MSE approach/methodology applied in WKSARMP 2019 (full-feedback MSE using FLBEIA)
- Agreed to conditioning OM with the 2020 sardine stock assessment and MP with SS3 assessment, short-term catch forecast as stock Annex, no implementation error
- Projection period: 50 years (2021–2070) and metrics computed for

  Initial-period (2021–2026)

  Short-period (2021–2030)

  Long-period=last ten years

- Scenarios:
  - set as the basecase the 'Low' productivity scenario, which is currently the R scenario assumed by ICES;
  - productivity scenarios:
  - 'Low'
  - 'Low-to-medium': there is some evidence for a transition from Low to Medium R given the high R observed in 2019 and also a strong YC as measured by the Autumn 2020 survey
  - 'Mix' (to ensure a dynamic trajectory)
  - Without/with observation and assessment errors
  - Fishing:

    'no fishing'

    'HCR50'

    'HCR45'

    'HCR40'

'HCR35'

or 'HCR_without cap' (catch cap)

ICES AR

- Precision in risk

  Run 10 000 iterations for:

  'HCR40' & 'HCR45' with 'Low' productivity scenario

  'HCR50' & 'ICES MSY AR' for 'Low-to-medium' scenario

risk 1 and risk 3 computed following approach indicated in LW presentation.

# Annex 5: Recommendations

The results from the evaluation of the HCRs are contingent on recent data and assessment performance. Therefore, in case the perception of recruitment, biological characteristics, or exploitation change, the simulation tested HCRs should be re-evaluated. An inter-benchmark of the Iberian sardine stock will take place during the second half of this year, prior to WGHANSA meeting in November. The inter-benchmark will investigate the inclusion in the assessment of a new survey carried out in the fall (IBERAS), which provides estimates of recruitment for the interim year. This may result in a revised stock assessment (SS3) configuration and reference points.

The estimation of fishing mortality reference points for two productivity scenarios and the simulation testing of the several HCRs for three operating models (stock productivity scenarios), carried out during WKSARHCR with full-feedback MSE, represented a high computational burden. Simulations were run in the AZTI computing cluster and took around one month, using 180 cores, which is likely to be an unsustainable situation in future management plans evaluation. Therefore, WKSARHCR recommends ICES to explore the possibility of making available its own computing capacity for this type of analysis or to explore an agreement among ICES member countries to create a 'computational time bank'.

The Reviewers´report also includes recommendations and suggestions (see Section 8).

# Annex 6: MSE template

Summary of the methodology used in the evaluation of the Management Plan for sardine in divisions 8c and 9a.

| | |
|---|---|
| **Background** | |
| Motive/initiative/background | ICES received a Special Request from Portugal-Spain to evaluate a management plan (MP) for the Iberian sardine under a Harvest Control Rule (HCR) with maximum allowed catches ranging from 40 000 to 50 000 tonnes. Scientists of IPMA, AZTI and IEO and external experts carried out the performance analysis during the WGSARHCR workshop and online meetings. |
| Main objectives | The main objective of the MP is not specified in the request. |
| Formal framework | The performance of the MP was analysed during the WGSARHCR workshop with scientists from Portugal and Spain and three external reviewers |
| Evaluation work | The WKSARHCR performance analysis is evaluated by ICES ACOM. |
| **Method** | |
| Software | MSE framework implemented in FLBEIA (García *et al*., 2017) using R-FLR packages (Kell *et al*., 2007). |
| Name, brief outline | The performance of the proposed HCR, as well as the ICES MSY AR, were analysed with a full-feedback MSE under several scenarios with different OMs and different MPs (i.e. advice assumptions on the BRP or 'perceived' BRP's). Age-structured operating model based on the last stock assessment and assessment model (Stock Synthesis) with catches-at-age, annual acoustic survey (PELAGO and PELACUS) and triennial DEPM survey as input. Assessment is performed in each simulation loop and the abundance indices are generated from the "true population" with lognormal distributed errors to simulate observation error. Observation error was also introduced in the numbers-at-age in the catch as a multiplicative lognormal error. The MSE was run without implementation error. |
| Reference or documentation | Documentation for the FLBEIA available in García *et al*., 2017 and for the stock assessment model in Methot and Wetzel, 2013. Code used for the simulation testing available in GitHub ( https://github.com/ices-eg/wk_WKSARHCR-2021 available with limited access). |
| Type of stock | Medium–short life span (6+), pelagic, high socio-economic importance at the regional level. |
| Knowledge base | ICES category 1 stock. |
| Type of regulation | Annual catch limits and seasonal closures regulated by Portugal and Spain. |

| Operating model (Biology and Fishery Model) | Function, source of data | Stochastic? – how (distribution, source of variability) |
|---|---|---|
| Base case | The Base Case corresponds to the representation of reality considered "most plausible" among the set of models considered in the study. For ICES stocks that have a stock assessment agreed in a benchmark, the default would be the stock assessment agreed at the benchmark.<br>All settings for future years (recruitment, growth, M, maturity, fishery selectivity) should be congruent with the historical past, but reflect what is considered to be more likely for the upcoming period of application of the management strategy. No obvious disconnect should occur between recent past and near future. When variability in the above-mentioned variables has been observed in the past, it is desirable to account for it in the upcoming period. This refers not only to variance, but also to autocorrelation or time trends. However, recruitment is the variable that definitely needs to be modelled as stochastically varying from year to year. | |
| Recruitment | Hockey-stick model according to three scenarios of productivity: low and two scenarios with a persistent or non-persistent transition between the low and medium productivity dependent on the biomass level. | Modelled as stochastic, variability introduced from a lognormal distribution with μ=0 and σ as the estimated in each productivity fit of the stock–recruitment model. The low productivity regime uses data pairs from historical years of 2006–2019 and transition regime uses data pairs from 1993–2019. |
| Growth | Stock weight-at-age as the arithmetic mean of the last six years of the assessment (2014–2019). Catch weight-at-age as the arithmetic mean value of the last three years of the assessment (2017–2019). | Stochasticity not included as no significant trends are found in historical weight-at-age. Age-dependent and time-invariant |
| Maturity | Knife-edge, with 0 for age 0 and assumed to fully mature at-age 1+ | No evidence to support added stochasticity in maturity. The knife-edge ogive is time-invariant resulting in SSB=B1+ during the projection period. |
| Natural mortality | As in last assessment (WGHANSA, 2020) | No evidence that support including variability in the natural mortality pattern. Natural mortality is age-dependent and time-invariant. |
| Fishery selectivity | Age-dependent and set as the average from the last six years of the assessment (2014–2019). | No. These values mimic the recent dome-shaped pattern estimated in the last assessment with ages from 3 to 5 bound and a decline at the 6+ group. |
| Initial stock numbers | The estimates of abundance (ages 0–6+) in 2019 from the last assessment (WGHANSA, 2020) | Variability in the initial populations implemented with a lognormal distribution error with μ=0 and σ=$\sqrt{\log(cv^2+1)}$) with coefficient of variation (cv) derived from the estimated log-numbers-at-age for the year 2020. |
| Technical interactions | Majority of sardine catches and landings are made by the purse-seine fleet in clean and single species hauls. No significant technical interactions are expected with other gears. | N/A |

| | | |
|---|---|---|
| Biological interactions | Asynchronous dynamics of sardines and the pair anchovy and chub mackerel in the area are documented. Conditions that favour these two species were reported to be opposite to those favouring sardines, but a direct causality was not shown yet, with the available data. Therefore, it is not clear yet if they are a consequence of a modification of the ecosystem or the result of a direct impact of these species on sardine distribution and abundance. For the purposes of the MSE, these biological interactions were believed not to be significant drivers of Iberian sardine stock development. | N/A |
| Decision basis | Catch in the advice year, t, based on B1+ at the beginning of year t | N/A |
| Number of populations | 1000; 10 000 used to estimate risk accuracy for some HCRs | N/A |
| Projection time | 2021 to 2050 (30 years) for the Low and Low-to-medium scenarios; 2021 to 2070 (50 years) for the Mix scenario | N/A |
| **Observation and implementation models** | | |
| With assessment | | |
| Input data | Catches, annual acoustic survey (PELAGO and PELACUS) and triennial DEPM survey | Catch: errors lognormally distributed with μ and σ from the logarithmic residuals in the observed catch-at-age<br>Surveys: error coefficients lognormally distributed to simulate observation error, where:<br>i) Acoustic survey: μ=log $\frac{Nas_{a,1996:2019}}{Npop_{a,1996:2019}}$ and σ = sd(log $\log \frac{Nas_{a,1996:2019}}{Npop_{a,1996:2019}}$)<br>ii) DEPM survey: μ=0 and σ= $\sqrt{\log(0.25^2 + 1)}$ |
| Comparison with ordinary assessment? | Yes | Full feedback MSE runs show similar bias when compared to the current assessment in scenarios assuming low-to-medium productivity. In other scenarios (mainly low productivity), this bias tends to aggravate and diverge from the level observed in the assessment. |
| Deviations from WG practice? | Yes | The SS3 bounds settings for the fishery selectivity-at-age 6+ were changed to minimize convergence issues in the projection years. |

| **Harvest rule** | |
|---|---|
| Harvest rule design | HCR:<br><br>i) If B1+ ≤ 112943 t then F=0<br><br>ii) If 112943 t < B1+ ≤ 252523 t then F increases linearly from 0 to 0.064<br><br>iii) If 252523 t < B1+ ≤ 446331 t then F increases linearly from 0.064 to 0.12<br><br>iv) If B1+ > 446331 t then F = 0.12<br><br>v) Conditions ii) to iv) are overridden if the forecast catch in any given year exceeds the maximum allowed catches of 40 000–50 000t. |
| Stabilizers | No stabilizers |
| Duration of decisions | TAC annually |
| Revision clause | After five years or before if any of the following situations are identified: i) If the performance of the stock assessment deteriorates substantially relative to what was assumed in the MSE; ii) If the observed conditions of the stock and/or fishery depart considerably from what was assumed in the MSE. |

| **Presentation of results** | |
|---|---|
| Interest parame-ters | Computed in the initial-term (2021:2026), first ten years (short-term; 2021:2030), and long-term (2041:2050 for the Low and Low-to-medium scenarios; 2061:2070 for the Mix scenario):<br>$P(B1+ < B_{lim})$<br>Probability of fishery closure, average number of years with fishery closure.<br>Median catch, 5th and 95th percentiles, and interannual variation (IAV); Median $F_{bar}$, 5th and 95th percentiles; Median B1+, 5th and 95th percentiles.<br>First year that ($B1+ \geq B_{lim}$) with≥95% probability |
| Risk type and time interval | Risk3 = maximum probability that B1+ is below $B_{lim}$, where the maximum of the annual probabilities is taken over the long-term period. |
| Precautionary risk level | Risk3 <= 5% in the long term |

# Annex 7: BRP Working document for WKSARHCR

## Changes in fit of stock–recruitment models with additional data and impact of stock–recruitment data pair from 2019

Wise, L., Ibaibarriaga, L., Uriarte, A., Riveiro, I and Azevedo, M.

1. Introduction

The evaluation of an HCR proposed by the Portuguese and Spanish Administration during WKSARHCR will consider three scenarios of productivity: low, low-to-medium and mix. Figure 1 shows the stock–recruitment pairs estimates for the Iberian sardine and their estimated 95% confidence interval (time-series 1993–2019) according to the most recent assessment of the stock (ICES, 2020). First, Hockey-stick stock–recruitment models were fitted for the time-series 1993–2019 and 2006–2019 to check if the estimated $B_{lim}$ (breakpoint of the segmented regression) are within the 95% confidence interval of the previous estimates for $B_{lim}$ representative of the medium (time-series 1993–2015) and low (time-series 2006–2017) productivity scenarios. Then Hockey-stick stock–recruitment models were fitted for the low productivity regime by fixing parameter b at the previous estimate of $B_{lim} = 1.96334 \times 10^5$ tonnes, to check differences in mean recruitment and $\sigma R$ with and without the stock–recruitment data pair of 2019.

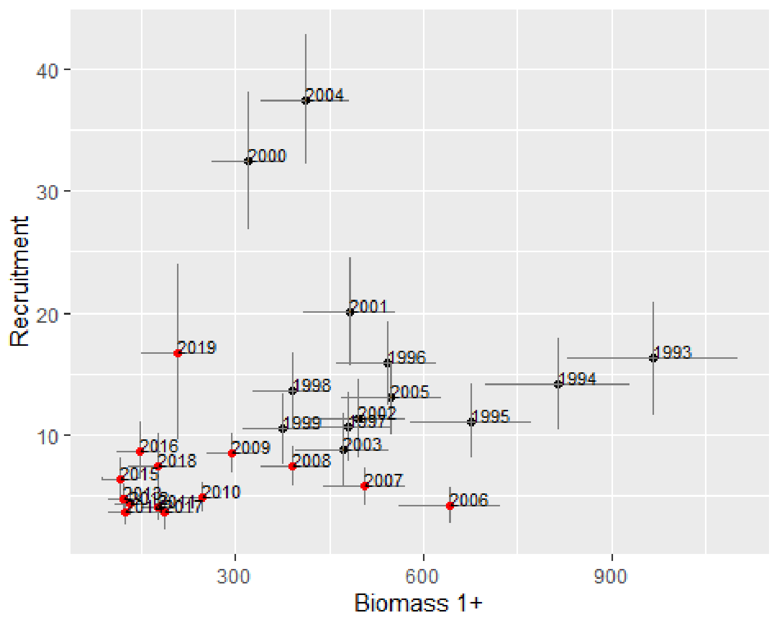



**Figure 1. Stock–recruitment pairs for the Iberian sardine stock (1993–2019). Horizontal bars represent the 95% confidence interval of Biomass 1+ estimates and vertical bars represent the 95% confidence interval of Recruitment estimates. Points in color red evidence the period 2006–2019.**

2. Fit of stock–recruitment models (Hockey-stick) to the time-series 1993–2019 and 2006–2019

Biological reference points for the Iberian sardine stock were estimated and accepted for the first time during WKPELA (ICES, 2017a) using assessment results for the period 1993–2015. The methodology used to estimate biological reference points followed the framework proposed in ICES guidelines for fisheries management reference points (ICES, 2017b). All statistical analyses were carried out in R environment and simulations analyses were conducted with the package “MSY” using the EqSim routines (ICES, 2016), a stochastic equilibrium reference point software that provides MSY reference points based on the equilibrium distribution of stochastic projections. Figure 2 shows the fit of a Hockey-stick model to data from the 2016 assessment (ICES, 2017c) for the period 1993–2015.

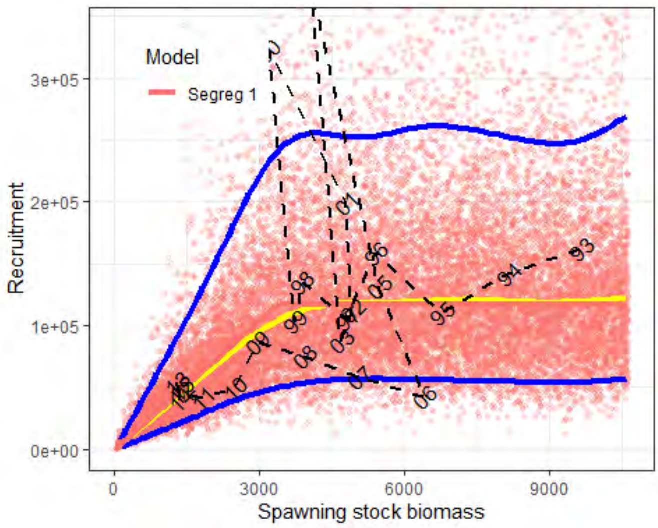



**Figure 2. Hockey-stick stock–recruitment function estimated with data from the 2016 assessment for the period 1993–2015.**

During WKSARMP (ICES, 2019), biological reference points were re-examined to account for (i) the possibility that a low productivity of the stock (since 2006) might continue in the future and (ii) the retrospective bias in the assessment estimates. The re-examination was based on the assessment data of 2018 (ICES, 2018) and the analysis followed the same procedure as in WKPELA 2017. For the medium productivity regime, the biological reference points were kept the same as the ones adopted during WKPELA 2017 because the breakpoint of the new estimated Hockey-stick recruitment model was within the 95% confidence interval (296 057, 514 150 tonnes) of the breakpoint of the Hockey-stick recruitment model estimated during WKPELA 2017 (Table 1). Figure 3 shows the Hockey-stick stock–recruitment function fitted to estimates from the 2018 assessment (ICES, 2018) for the period 1993–2017.

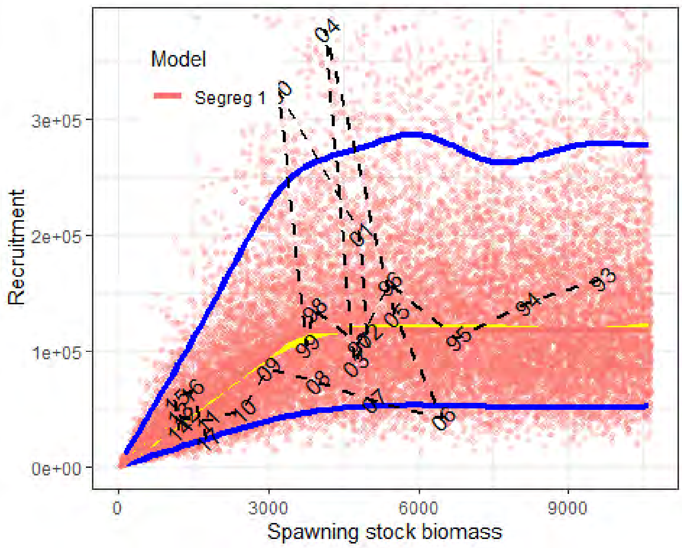



**Figure 3. Hockey-stick stock–recruitment function estimated with data from the 2018 assessment for the period 1993–2017.**

Biological reference points were also estimated for a low productivity regime. Data used were from 2006 up to 2017. Figure 4 shows the Hockey-stick stock–recruitment function fitted to data from the 2018 assessment (ICES, 2018) for the period 2006–2017.

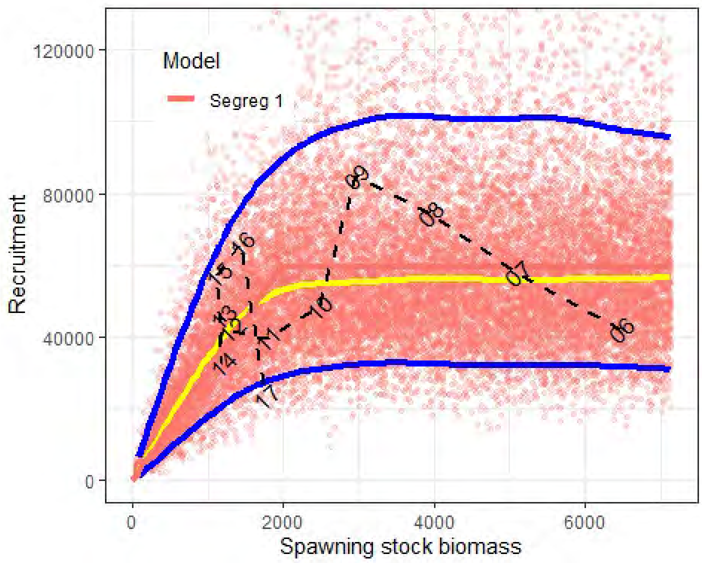



**Figure 4. Hockey-stick stock–recruitment function estimated with data from the 2018 assessment for the period 2006–2017.**

Finally, stock–recruitment models were fitted to data from the most recent assessment (ICES, 2020). Figure 5 and 6 show the Hockey-stick stock–recruitment functions fitted to data for the periods 1993–2019 and 2006–2019, respectively. To check the effect of the 2019 data pair on the low productivity scenario, a stock–recruitment model was also fitted to data from 2006 up to 2018 (Figure 7).

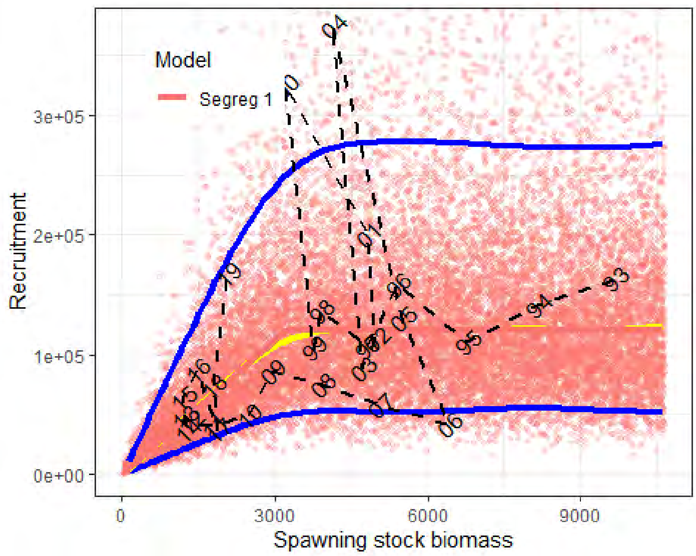



**Figure 5. Hockey-stick stock–recruitment function estimated with data from the 2020 assessment for the period 1993–2019.**

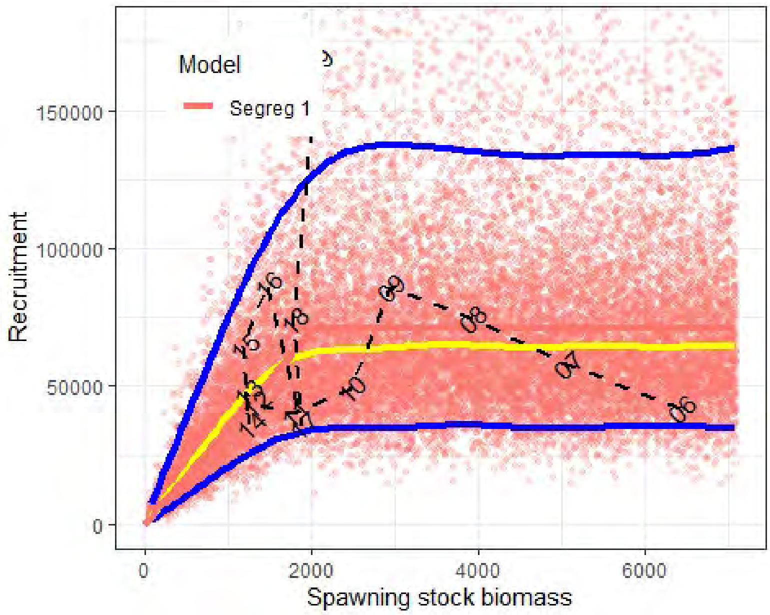



**Figure 6. Hockey-stick stock–recruitment function estimated with data from the 2020 assessment for the period 2006–2019.**

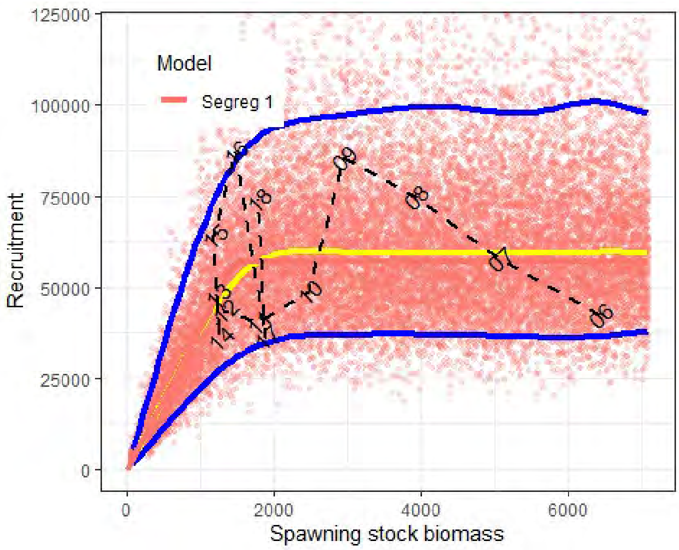



**Figure 7. Hockey-stick stock–recruitment function for data 2006–2018.**

Table 1 summarizes information for all the previous fits, namely the estimated parameters a and b, CV and the 95% confidence intervals of parameter b. Differences between parameter b deterministic fit and its 95% confidence interval can be observed in Figure 8.

**Table 1. Parameters estimates (a,b) from deterministic fit, coefficient of variation of the fit and 2.5 and 97.5 quantiles from 1000 bootstrap resamples of S–R pairs for the different stock–recruitment models.**

| a | b | CV | Conf. Int. param b | Time-series |
|---|---|---|---|---|
| 34.7 | 337 448 | 0.49 | 296 057–514 150 | 1993–2015 |
| 32.5 | 361 639 | 0.52 | 299 149–541 822 | 1993–2017 |
| 37.4 | 320 952 | 0.51 | 208 305–433 013 | 1993–2019 |
| 30.3 | 196 334 | 0.37 | 98 389–296 557 | 2006–2017 |
| 35.0 | 202 815 | 0.41 | 107 168–225 194 | 2006–2019 |
| 38.7 | 147 564 | 0.30 | 97 410–266 105 | 2006–2018 |

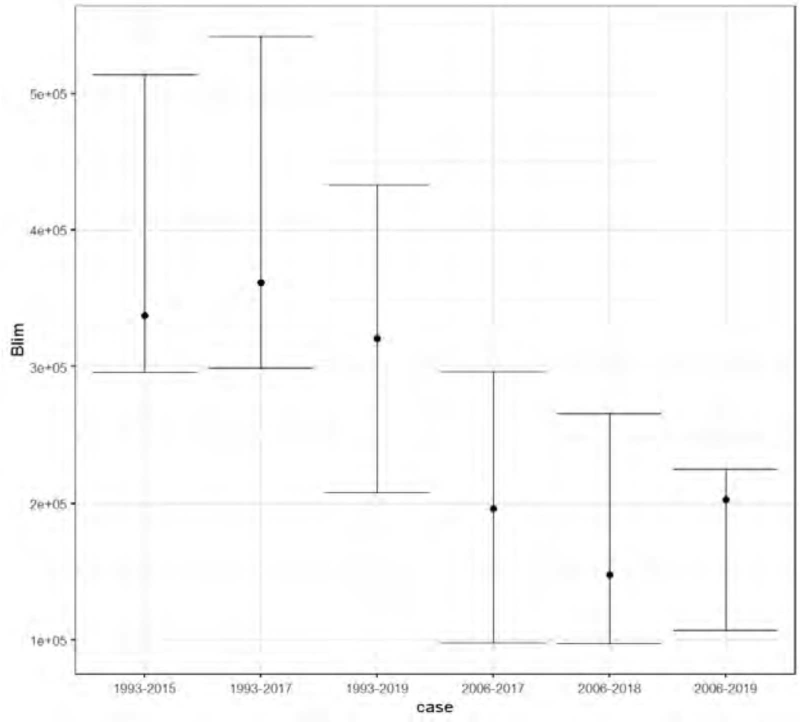



**Figure 8. Parameter estimate b from deterministic fit and 2.5 and 97.5 quantiles from 1000 bootstrap resamples of S–R pairs for the different stock–recruitment models.**

Within productivity regimes, point estimates of $B_{lim}$ are similar when new stock–recruitment data are added to the series (Figure 8). In addition, the corresponding confidence intervals overlap (Figure 8). Therefore, we propose to use the same $B_{lim}$ estimates that were adopted during WKSARMP (ICES, 2019) for each productivity regime.

3. Fit of the Hockey-stick S–R model for the time-series 2006–2019, with fixed $\boldsymbol{B_{lim}}$

In this section, Hockey-stick stock–recruitment models were fitted for the low productivity regime by fixing parameter b at the previous estimate of $B_{lim} = 1.96334 \times 10^5$tonnes, to check differences in mean recruitment and $\sigma R$ with and without the stock–recruitment data pair of 2019.

## Stock–recruitment function

In the MSE, recruits (numbers-at-age 0) are estimated from the spawning–stock biomass following a functional relationship. In this particular case, we use a Hockey-stick model. For each productivity scenario a Hockey-stick model is fitted. The low productivity scenario uses data from 2006 to 2019.

Figure 9 shows the fit of the Hockey-stick to data from 2006 to 2019. The model is fitted by fixing parameter b to be $B_{lim}$ estimated for the low productivity regime during WKSARMP (ICES, 2019). This is the current adopted $B_{lim}$ for the stock ($B_{lim} = 1.96334 \times 10^5$ t).

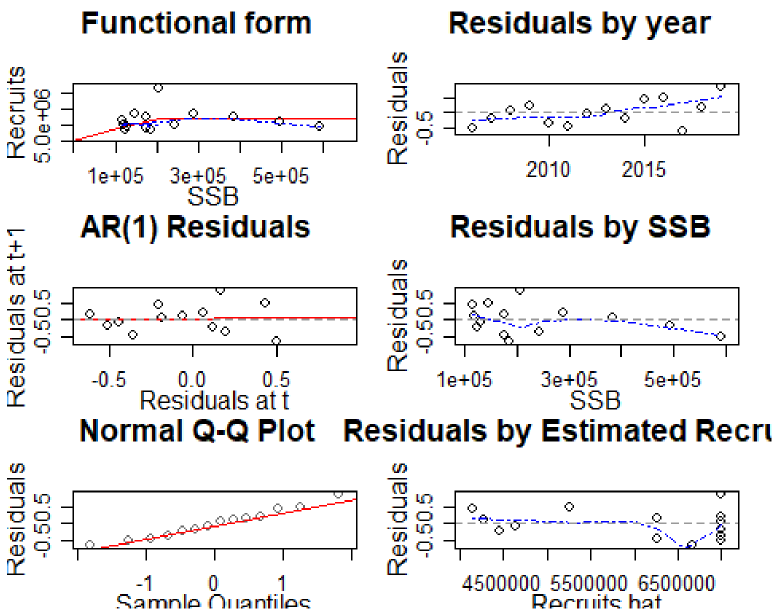



**Figure 9. Fit of the Hockey-stick with the 2020 assessment data for the period 2006–2019.**

Figure 10 shows the fit of the Hockey-stick without the 2019 stock–recruitment data pair.

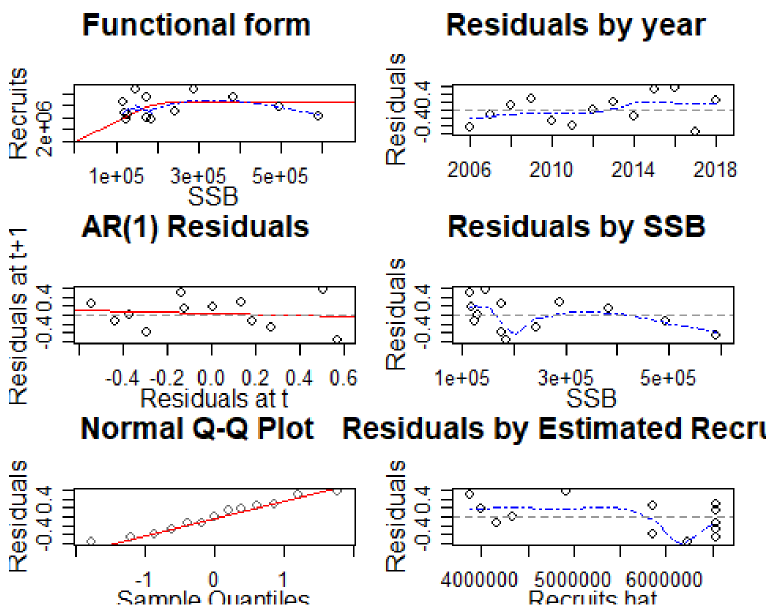



**Figure 10. Fit of the Hockey-stick with the 2020 assessment data for the period 2006–2018.**

Table 2 shows the deterministic fit of the Hockey-stick model with data from the 2020 assessment model for the period 2006–2019 and 2006–2018.

**Table 2. Parameters estimates (a, b) from deterministic fit of the Hockey-stick model with data from the 2020 assessment model when $B_{lim}$ is fixed.**

| Time-series | Fixed Parameter | Parameter a | Parameter b |
|---|---|---|---|
| 2006–2019 | Yes, b | 36 | 196 334 |
| 2006–2018 | Yes, b | 33 | 196 334 |

In the MSE, the relationships used in the simulations to generate recruits depend on the productivity regime assumed for the true state of nature in each scenario. Recruits (numbers-at-age 0) are generated from the spawning–stock biomass following a functional relationship:

$$N_{a,t} = f(SSB)exp(\varepsilon_t)$$

Recruitment variability $\varepsilon_t$ was introduced by generating random draws from a lognormal distribution with $\mu = 0$ and $\sigma$ as estimated in the fitting of the stock–recruitment model.

The stock–recruitment model estimated for the period 2006–2019 has $\sigma = 0.423$ and the stock–recruitment model estimated for the period 2006–2018 has $\sigma = 0.354$. Figure 11 shows the 95% confidence intervals for the two stock–recruitment models.

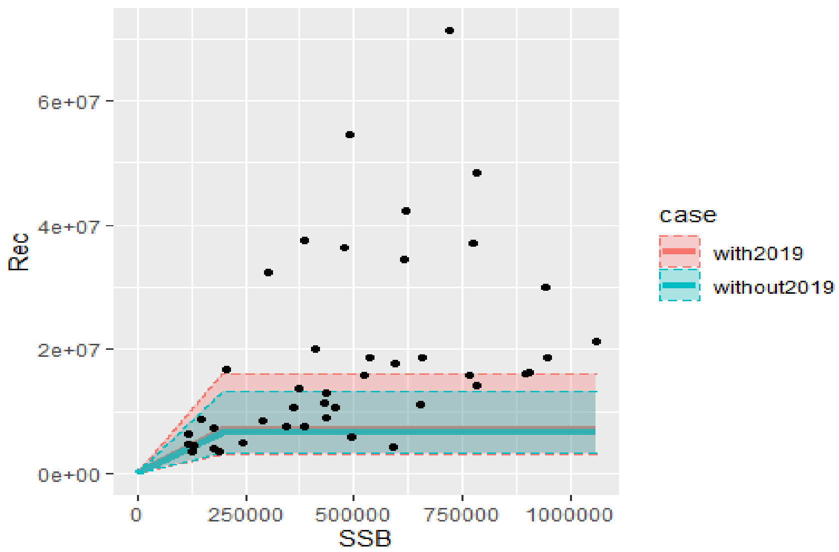



**Figure 11. Fitted (solid line) and 95% confidence intervals (dashed lines) for Hockey-stick for the period 2006–2019 (red lines) and the period 2006–2018 (blue lines).**

In Figure 12 and 13 we can see the Recruitment density distribution for the 2019 biomass from the Hockey-stick for the time-series 2006–2019 and 2006–2018 respectively.

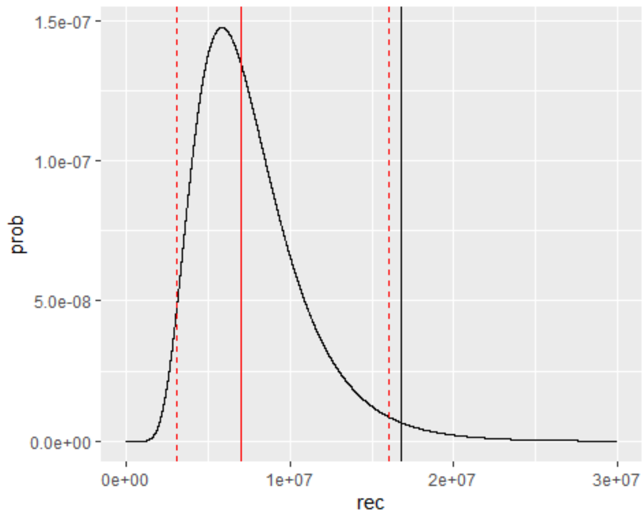



**Figure 12. Recruitment density distribution for the 2019 biomass from the Hockey-stick model for the period 2006–2019. Black vertical line is the 2019 recruitment estimate. Solid red vertical line is the predicted 2019 recruitment. Dashed red vertical lines represents the 95% confidence interval of the predicted 2019 recruitment.**

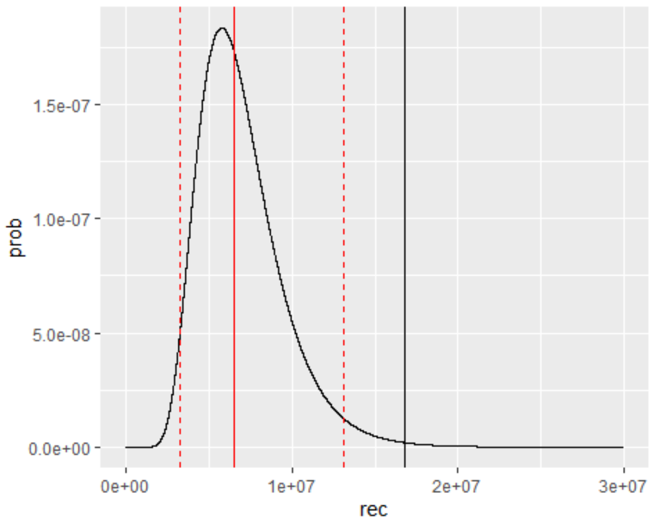



**Figure 13. Recruitment density distribution for the 2019 biomass from the Hockey-stick for the period 2006–2018. Black vertical line is the 2019 recruitment estimate. Solid red vertical line is the predicted 2019 recruitment. Dashed red vertical lines represents the 95% confidence interval of the predicted 2019 recruitment.**

None of the models are good to estimate the 2019 recruitment. For the model that includes the 2019 data pair, the 2019 estimate is equivalent to the 0.98 quantile while in the model without the 2019 data pair it is equivalent to the 0.996 quantile.

The fit of the stock–recruitment model with the data pair 2019 has a mean recruitment (6 993 117) which is above the mean recruitment (6 538 306) of the fit of the stock–recruitment model without it, but differences are small. The upper bound of the 95% confidence interval is also higher, but the 2019 observed recruitment is not included in it.

4. Recruitment distribution in a no fishing scenario

Simulations were run for a no fishing scenario for the three productivity regimes considered (low, low-to-medium and mix). The recruitment models used to simulate recruitment were fit with the 2019 data pair. Figures 14, 15 and 16 show the recruitment distribution for each of the productivity regimes considered.

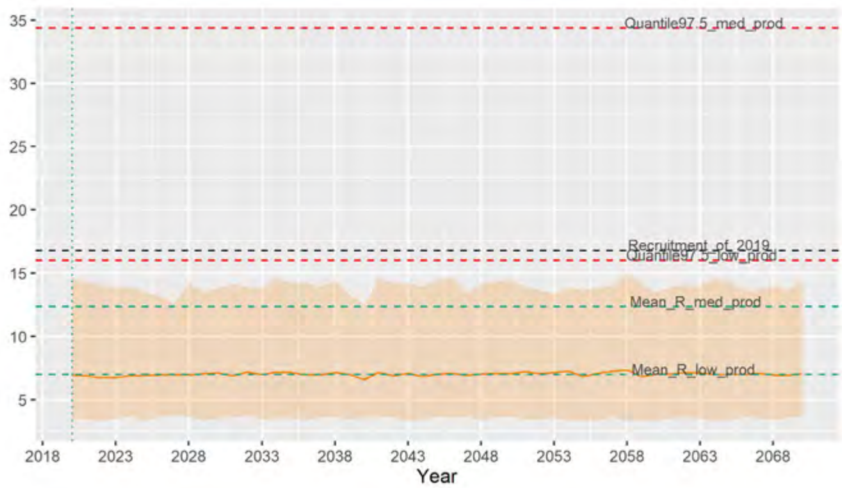



**Figure 14. Recruitment (Rec, million individuals) during the projected period (2021–2070) for a no fishing scenario under the low productivity scenario. Shaded area represents 90% confidence intervals. Horizontal blue dashed lines represent the mean recruitment of the low (Mean_R_low_prod) and the medium (Mean_R_med_prod) productivity. Horizontal red dashed lines represent the upper bound of the 95% confidence interval of the low (Quantile97.5_low_prod) and the medium (Quantile97.5_med_prod) productivity. Horizontal black dashed line represents the recruitment observed in 2019.**


**Figure 15. Recruitment (Rec, million individuals) during the projected period (2021–2070) for a no fishing scenario under the low-to-med productivity scenario. Shaded area represents 90% confidence intervals. Horizontal blue dashed lines represent the mean recruitment of the low (Mean_R_low_prod) and the medium (Mean_R_med_prod) productivity. Horizontal red dashed lines represent the upper bound of the 95% confidence interval of the low (Quantile97.5_low_prod) and the medium (Quantile97.5_med_prod) productivity. Horizontal black dashed line represents the recruitment observed in 2019.**

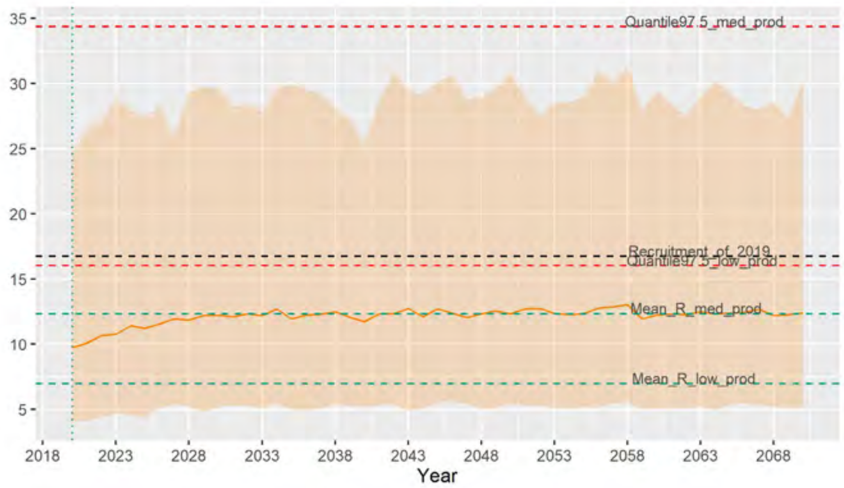



**Figure 16. Recruitment (Rec, million individuals) during the projected period (2021–2070) for a no fishing scenario under the mix productivity scenario. Shaded area represents 90% confidence intervals. Horizontal blue dashed lines represent the mean recruitment of the low (Mean_R_low_prod) and the medium (Mean_R_med_prod) productivity. Horizontal red dashed lines represent the upper bound of the 95% confidence interval of the low (Quantile97.5_low_prod) and the medium (Quantile97.5_med_prod) productivity. Horizontal black dashed line represents the recruitment observed in 2019.**

Figure 17 shows a summary of the 2.5, 50 and 97.5 quantiles, the mean recruitment and the median recruitment observed in the last year for the three different productivity regimes considering different time periods. Initial corresponds to the first five years, short represents the first ten years, med represents the last ten years of a 30-year projection period, last represents the last ten years of a 50-year projection period and all represents the whole projection period.

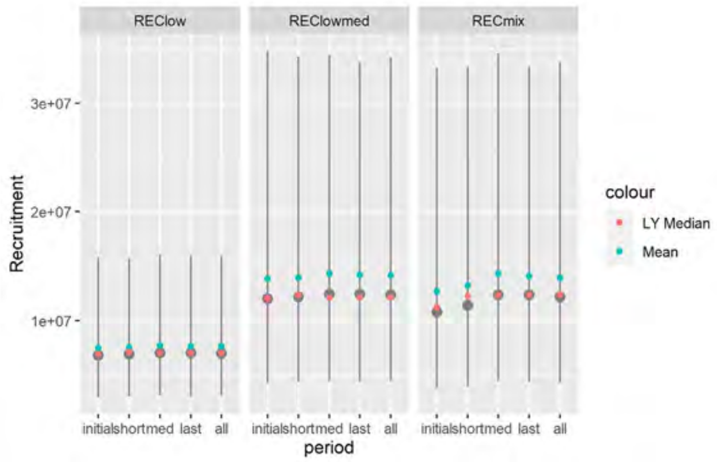



**Figure 17. The 2.5, 50 and 97.5 quantiles (point and line range in grey), mean recruitment (blue dots) and the median recruitment observed in the last year (red dots) for the three different productivity regimes simulated for different time periods. Initial corresponds to the first five years, short represents the first ten years, med represents the last ten years of a 30-year projection period, last represents the last ten years of a 50-year projection period and all represents the whole projection period (50 years).**

Figure 18 shows a summary of risk type 1 (mean probability of ssb being below $B_{lim}$), type 2 (probability of at least once ssb is below $B_{lim}$) and type 3 (max probability that ssb is below $B_{lim}$) of SSB for the different time periods and productivity regimes. $B_{lim}$of the low ( $B_{lim}$ = $1.96334 \times 10^5$ tonnes) and medium productivity ($B_{lim}$ = $3.37448 X 10^5$ tonnes) regime where considered.

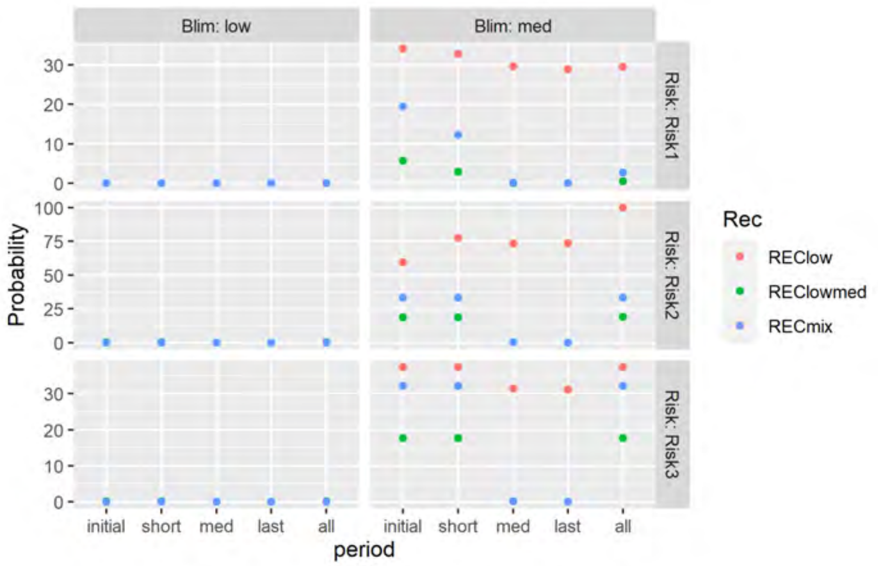



**Figure 18. Average probability that SSB is below $B_{lim}$ (top panels, Risk: Risk1), probability that SSB is below $B_{lim}$ at least once (middle panels, Risk: Risk2) and maximum probability that SSB is below $B_{lim}$ (bottom panel, Risk: Risk3) for the three different productivity regimes simulated (low productivity in red, low-to-medium productivity in green and mix productivity in blue) for different time periods. Average and maximum risk are taken across ny years. Probabilities are estimated considering $B_{lim}$ of the low productivity regime (left panels, $B_{lim}$: low = $1.96334 \times 10^5$ *tonnes*) and $B_{lim}$ of the medium productivity ($B_{lim}$: med = 3.37448 X $10^5$ tonnes). In the x-axis we have the different periods (ny years) considered in the analysis. Initial corresponds to the first five years, short represents the first ten years, med represents the last ten years of a 30-year projection period, last represents the last ten years of a 50-year projection period and all represents the whole projection period.**

Figure 19 shows a summary of risk type 1 of recruitment for the different time periods and productivity regimes. Risk 1 (mean probability of recruitment being above a specific value) was assessed to check when recruitment is above mean recruitment, the 97.5 quantile of the low and medium stock–recruitment models estimated and also the recruitment of 2019.

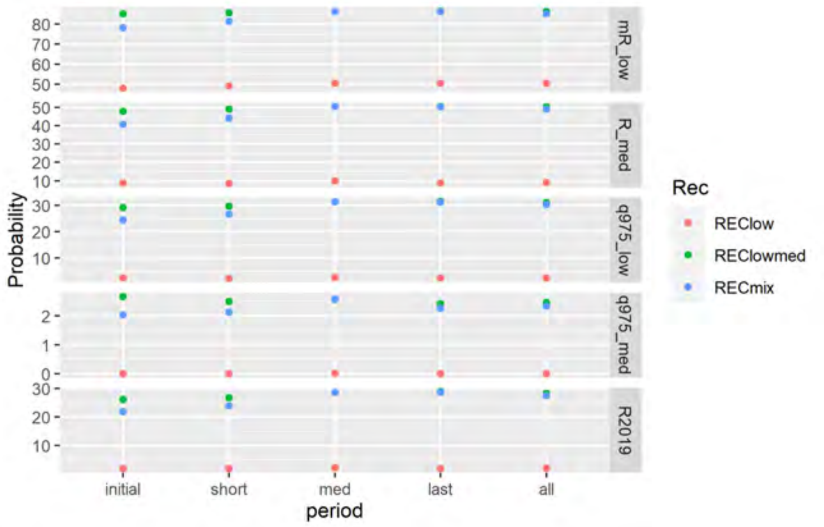



**Figure 19. Average probability that recruitment is above mean recruitment of the low (top panel, 'mR_low') and medium (second panel from top, 'R_med') productivity, above the 97.5 quantile of recruitment in the low (third panel from top, 'q975_low') and medium (forth panel from top, 'q975_med') productivity, and above recruitment observed in 2019 (bottom panel, 'R2019') for the three productivity scenarios simulated (low productivity in red, low-to-medium productivity in green and mix productivity in blue). Average is taken across ny years. In the x-axis we have the different periods (ny years) considered in the analysis. Initial corresponds to the first five years, short represents the first ten years, med represents the last ten years of a 30-year projection period, last represents the last ten years of a 50-year projection period and all represents the whole (50 years) projection period.**

Results show that when we include the 2019 data pair in the fit of the stock–recruitment models the probability of a recruitment of that magnitude to occur in the projection period is low (maximum of 2%). The probability of a recruitment to be higher than the 97.5 quantile of the recruitment model is also low (maximum of 2.6%).

## 5. Conclusion

Within productivity regimes, point estimates of $B_{lim}$ are similar when new stock–recruitment are added to the series (Figure 8). In addition, the corresponding confidence intervals overlap (Figure 8). Therefore, we propose to use the same $B_{lim}$ estimates that were adopted during WKSARMP (ICES, 2019).

When we fix $B_{lim}$, the fit of the stock–recruitment model with the data pair 2019 the mean recruitment is rather similar to the mean recruitment of the fit of the stock–recruitment model without it. Differences are higher when we consider the upper bound of the 95% confidence interval.

However, results from a no fishing scenario including the 2019 data pair show that the probability of a recruitment to be higher than the 97.5 quantile of recruitment or the 2019 recruitment is very low.

The 2019 recruitment estimate is a model result that comes from data and assessment and despite the fact that we know that the 2020 recruitment may also be a strong year class, there is also uncertainty on how long the low productivity scenario will continue for. Therefore, we consider that we should include the 2019 data pair in the estimation of the stock–recruitment models used to generate recruitments for both the medium and the low productivity regimes.