

9th MEETING OF THE SCIENTIFIC COMMITTEE

Held virtually, 27 September to 2 October 2021

SC9-JM03

MSE Project Update

European Union

1. Development of an MSE framework for Jack mackerel

Summary

The present document reports of the progress of work towards the development of a simulation platform for the evaluation of candidate management procedures for the Chilean jack mackerel, *Trachurus murphyi*, stock in the South Pacific including areas under national jurisdiction. A platform has been developed and tested, based on the FLR libraries (Kell et al. 2007), that is able to condition operating models based on the current stock assessment model, apply a range of procedures that mimic current data sampling and stock assessment, and compute their performance according to a set of indicators.

A range of uncertainties are being incorporated, for example on stock structure and dynamics, future recruitment and data quality, but a complete set of them will have to be developed in agreement among interested scientists.

Test runs of the platform have been carried out, but no full evaluation of candidate procedures has yet been conducted. Discussion and agreement on a number of items, like sources and levels of observation and implementation error, or performance indicators and initial management objectives, is required before complete analyses can be performed.

Introduction

An important objective in the current Multi-annual workplan of the Scientific Committee (SC) of the South Pacific Regional Fisheries Management Organization (SPRFMO) is the 'MSE development to design alternative harvest control rule'. The objective is for this work to lead to the adoption of a management procedure to replace the current rebuilding plan which is currently used to provide catch advice on Chilean jack mackerel (CJM). The stock is considered to have recovered from the time-series low around 2010, as intended by the rebuilding plan, and is now around the proxy biomass reference levels. Management procedures should thus be explored and evaluated that focus on the long-term exploitation of the stock.

Management Strategy Evaluation (MSE) is considered here as the analysis by which a management procedure is simulation-tested. Simulations are to be carried out on a model that represents our best knowledge of the stock and fisheries past and future dynamics, but also recognizes and quantifies the uncertainties in that knowledge. Operating models are conditioned on the available data and, as it is the case here, are often based on the same population and fishery model used for stock assessment.

A management procedure follows three main steps to arrive at a decision to be applied to the fishery:

- An observation and sampling scheme, by which information from the stock (biology and surveys) and the fisheries (catch), is obtained. This process is replicated in MSE by the observation error model (OEM).
- An estimator of stock status or change in status. This could be model-based, for example the *jjms* stock assessment applied to Chilean jack mackerel, or model-free, based on trends in CPUE series or surveys.
- A Harvest Control Rule, as a function that compares the estimator output with some limits and targets, and provides a value for an output (catch) or input (effort) quantity to be followed by the fishery.

This decision can either be perfectly implemented in the system, or suffer from some level of implementation error, by which discrepancies between advice and the actual application of the management measure can be analysed. Additional processes and dynamics can also be included in MSE, for example technical measures on the fishing gear that alter the fisheries selectivity or catchability.

The results of the simulations of future stock and fishery dynamics under a particular candidate management procedure need to be assessed in comparison with a series of management objectives. A set of performance indicators need to be agreed that best measures how well those multiple objectives are being achieved.

Conditioning of Operating Models

Operating models are quantitative representations of the past and future dynamics of a stock, or set of stocks, and the fisheries operating on them. Although commonly based on the existing stock assessment model, the emphasis is on characterizing the productivity and time series dynamics, and the uncertainty in their estimation, rather than on obtaining precise values of past and current stock status.

A number of operating models have been developed that attempt to cover a range of important uncertainties previously identified. The OM's are conditioned on the available data using the latest version of the Joint Jack Mackerel Model, *jjms* (SPRFMO 2019). A number of changes and extensions have been made to the model for its use in the MSE work. They mostly relate to the generation of alternative model outputs or to optimize its performance during simulations, and do not affect the model dynamics.

Data

Data in the operating model conditioning is the same as used in the latest stock assessment (SPRFMO (2019), Annex 8), namely:

- Catch data (total landings) for the four fisheries.
- Mean weight at age or length by fishery.
- Catch at age for fisheries 1, 2 and 4.
- Catch at length for fishery 3.
- Three CPUE indices from fisheries 2, 3 and 4.
- Three acoustic indices and one DEPM-based index.

Model runs used for conditioning of the operating model used input files available at the SPRFMO github *jfm* repository, so no specific data preparation took place.

OM grid

A grid of alternative operating models was agreed during the various MSE meetings that attempts to incorporate major sources of uncertainty in the model for which reasonable hypotheses can be currently formulated:

- Single stock or two stock hypotheses (1s, 2s).
- Two values for the steepness of the Beverton & Holt stock-recruitment relationship: $h = 0.65$ or $h = 0.80$ (h06, h08).
- Alternative growth hypothesis, with corresponding changes in natural mortality and maturity schedules. Analyses are ongoing on this scenario, so no OM has yet been formulated including it.

A hypothesis is also considered that affects the future dynamics of the operating models for the 2 stocks scenario. Rather than a total isolation of both stocks, a degree of movement is incorporated. Movement is set to occur each year, according to the exchange rates at age contained in Table 2 of (Hintzen et al. 2015).

This movement scenario does not affect model conditioning, but is only applied in future projections. Movement is implemented by specifying a particular *projection* function to the OM, *fwdmov.om*, which takes the above movement matrix as input. These movement rates are currently constant, and not influenced by environmental factors, density-dependence or stock abundance.

Parameter uncertainty

For each of the models in the grid, a Markov chain Monte Carlo (MCMC) procedure was conducted using the no-U-turn (NUTS) sampler (Monnahan and Kristensen 2018) run in parallel along 12 chains, for 2,000 iterations each, and with a burn-in of 500 iterations. The depth of search by the NUTS algorithm, as controlled by the *max_treedepth* control argument, was set to 10, and increased to 12 for a single run. This run for the one stock, $h=0.65$ model, was also run for 10,000 iterations per core. The standard MCMC runs took approximately 15 hours to complete. The results presented are based on 500 iterations sampled at equal distances from the 20,000 parameter samples obtained.

OM projections and dynamics

Basic checks of the dynamics of the various operating models were carried out by projecting them from one year after the last year of conditioning, 2020, until 2040, and for a series of scenarios:

- $F_{2020-2040} = F_{2019}$
- $F_{2020-2040} = 0$
- $F_{2020-2040} = F_{MSY}$

where F refers here to the mean fishing mortality, F , computed across all ages (1-12).

Management Procedures

Observation Error Model (oem)

The observation error module in the FLR *mse* system replicates the data collection taking place on the fishery, and provides the necessary inputs to the estimation module, in this case the *jjms* model. Observations are generated from the operating model by the *cjm.oem* function on catches by fishery and the indices of abundance still active on the projection year. These observations are then appended to those available from the previous year, stored in the corresponding *jjms* input files.

Total landings for each fishery and the proportions at age for fisheries 1, 2 and 4 get generated directly by the projection of the operating model. Length-frequency in the catch for fishery 3, Far North, is generated from the observation of the operating model abundances at age available to that fishery and the following von Bertalanffy growth model: $L_{\infty} = 80.4$, $k = 0.16$, and $L_0 = 18$. Length samples are generated for a given Effective Sample Size (ESS) and coefficient of variation. The procedure borrows heavily from code developed for the length-based integrated mixed effects (LIME) model (Rudd and Thorson 2018)

Indices of abundance are generated according to the estimated selectivities and catchability coefficients, as

$$I_{sy} = \sum_a (N_{ya} W_{ya} S_{sa} \exp(-Z_{ya} t_s) Q_s)$$

where the index (I) for year y and survey s is calculated from the sum of the available biomass (from abundance N_a , weight W_a and selectivity at age S_a), the fraction of total mortality (from Z_a and survey timing t_s), and the survey catchability Q_s . The same variables are then used for the observations of the proportions at age in the catch associates with each of the indices. At the moment no changes in future selectivity or catchability are being considered, but the code allows for those values to be altered as required. For example, increases in catchability through technological improvements or changes in selectivity brought by environmental factors, could all be considered.

The *cjm.oem* function has been programmed with the ability to go back in time and create inputs to *jjms* from any point in the past. This feature would enable hindcasting analyses to be performed. The chosen management procedure would be applied starting at some point in the past, and the results of potential and actual management be compared. Currently only data inputs are altered when a stock assessment is specified in the past, but other parameters in the model might also need adjusting to the change in sample size and time series lengths. The reduced length of some indices of abundance, for example, might diminish the ability of the assessment model with the current setup to use their information. A full exploration of the consequences of this procedure on the model would have to be carried it if there is interest in a backtesting analysis for this stock.

Estimation method (est)

The estimation method in a management procedure is tasked with providing an estimate or calculation of current stock status, or of the change of status between previous and current time steps. Both model-based or model-free estimators can be used, and the FLR *mse* platform allows modules to be defined for either of the two. The initial estimator being applied for Chilean jack mackerel is the current stock assessment model, *jjms*.

A series of R functions have been written that enable running *jjms* in R from the two lists holding the contents of the *dat* and *ctl* files used by the model executable. These lists can be created through a call to the functions available in the *jjmR* package. For example, the 'runjjms' function requires only an object of class *jjm.output* to execute

a model run. A full description of the functions developed around the *jjms* model will be available inside the *FLjjm* package.

Harvest Control Rules (hcr)

Two harvest control rules have so far been developed for testing purposes. Both require an estimate of stock abundance in terms of either spawning or total biomass (\hat{B}). They are of the hockey-stick type, with either a catch or fishing mortality target level (Ctarget or Ftarget), a biomass level below which catch or F is reduced (Btrigger), a minimum catch or F value (Cmin or Fmin) and a level of biomass below which catch or F are reduced to this minimum (Blim). They are both implemented as functions in the *FLjjm* package, respectively called *catchHockey.hcr* and *fHockey.hcr*. This type of harvest control rule is commonly employed in multiple advice bodies (e.g. ICES or IOTC) when an absolute estimate of abundance is available.

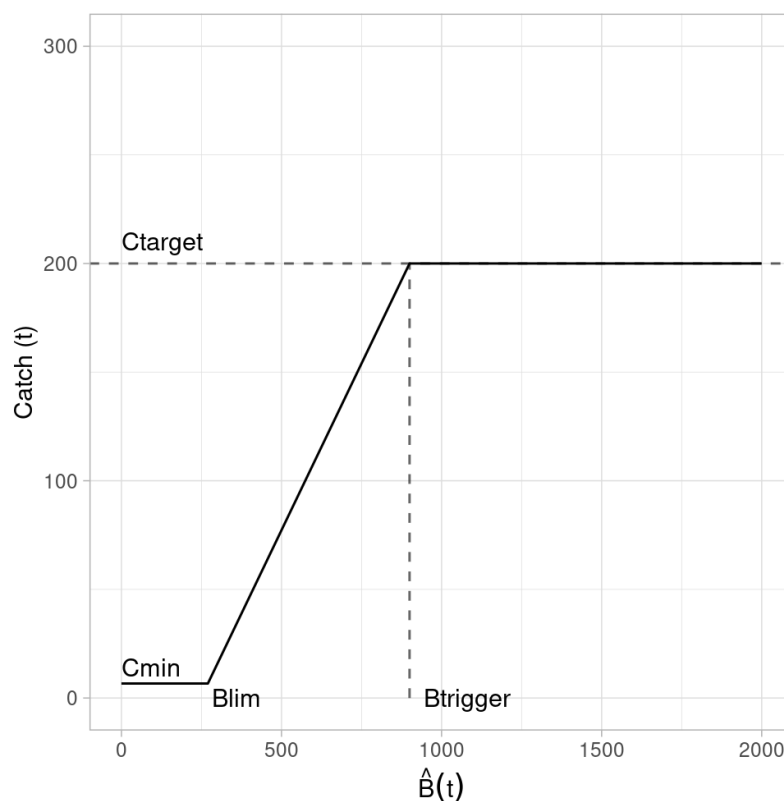


Figure 1. Diagrammatic representation of the catch-based hockey stick harvest control rule (*catchHockey.hcr*).

The standard ICES control rule returns a proposed level of fishing mortality, as *fHockey.hcr* does. Its application would require that forecasting be conducted for the selected F level to obtain the corresponding catch levels. The precise methodology to be applied in the forecast would have to be agreed and would then for an implementation system step in the management procedure.

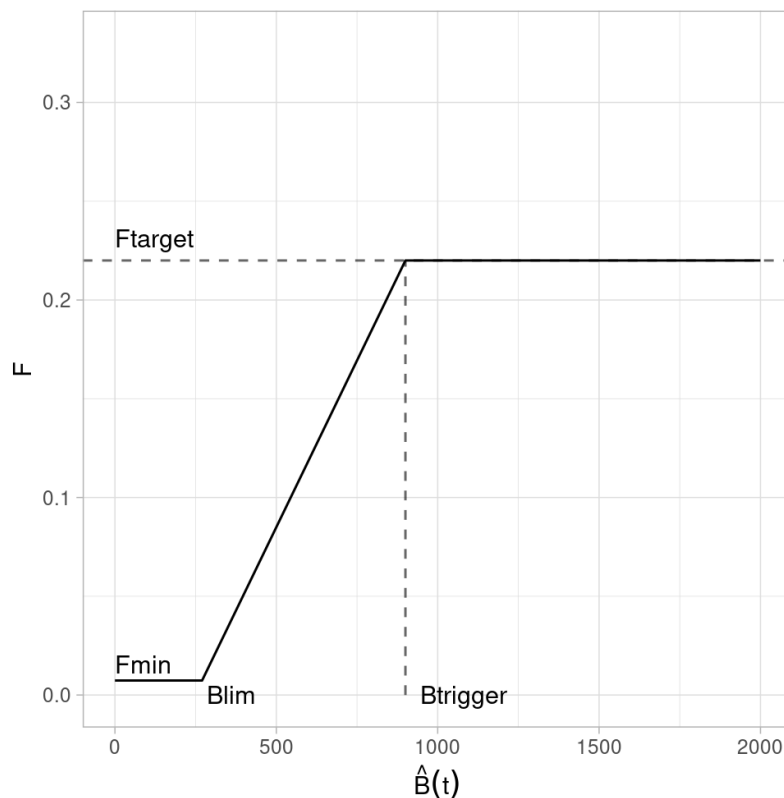


Figure 2. Diagrammatic representation of the fishing mortality-based hockey stick harvest control rule (*fHockey.hcr*).

Implementation error model (iem)

Implementation error is an essential element to consider when evaluating the likely performance of a management procedure, and should reflect how management regulations are expected to be applied in practice (Punt et al. 2014). In the platform presented here, implementation error is set up as a module by which the catch or fishing mortality level applied to the operating model would deviate from what was determined by the harvest control rule. The patterns of that deviation would need to be considered and adopted in dialogue between scientists and managers, so at this point no attempt has been made to introduce it in the analysis.

Performance indicators

The choice of performance indicators is largely determined by the management objectives that managers would like to explore for this fishery. For the development work on this platform, a minimal set of objectives has been defined. They are intended to provide input to the various functions in the code that require performance calculations. For example, testing of the tuning algorithm was carried out as if the primary desired objective was for the probability of the stock biomass being at the corresponding MSY level (B/B_{MSY}) to be 50%.

The current list includes the following indicators:

- Mean spawner biomass relative to unfished
- Mean spawner biomass relative to SB_{MSY}
- Mean fishing mortality relative to F_{MSY}
- Probability of SB greater or equal to SB_{MSY}
- Probability that spawner biomass is above B_{lim}
- Mean catch over years
- Catch variability

- Probability of fishery shutdown

where SB_{MSY} and F_{MSY} are the spawning biomass and fishing mortality at MSY reference points, unfished refers to the estimated initial biomass, and B_{lim} has been arbitrarily set at 20% of SB_{MSY} . Catch computed for performance purposes refers to overall catch, across all fleets, while fishery shutdown refers to any year or iteration in which catch is set to the minimum level in the harvest control rule.

In the tests conducted so far, indicators were computed over the second half of the projection period (2030-2039), as averages across years. Short, medium and long-term indicators can also be easily computed and could prove useful when presenting the implications and trade-offs of alternative procedures.

Software platform

The developed platform is based around the tools for Management Strategy Evaluation available in the FLR platform (Kell et al. 2007). Information on the structure, capabilities and features of FLR can be found in the FLR Project website, <https://flr-project.org>.

A specific R package, *FLjm*, has been created that contains all code that is specific to the CJM MSE. Functions dealing with *jjms* inputs and outputs are based around the functions already available on the *jjmR* package. From a *jjm.output* object, a whole range of FLR classes can be created. They represent the various elements in the simulation of the fishery system built in MSE, including the natural population(s) and their estimated reference points, fisheries, indices of abundance, and stock-recruitment relationships.

A significant extension of some FLR packages has been carried out to accommodate the nature of the Chilean jack mackerel operating model: one or two stock and multiple fisheries operating on them. Many MSE analyses include an operating model that is based on a stock assessment model that considers a single stock and an aggregated fishery.

A trial of the accessibility of the platform to other scientists was carried out during one of the MSE online meetings. Most participants were able to install the necessary packages and dependencies, and run some example code. A great effort is being made in making the platform as accessible as possible to all interested parties. Usage of this platform still requires a certain familiarity with the R language, and any user willing to extend or modify the provided analyses would also benefit from some experience with the FLR toolset. But the code has been built with transparency and readability in mind, so as to help as much as possible scientists reviewing and engaging with the tools.

All development has taken place in a SPRFMO-owned github-hosted source code repository (<https://github.com/SPRFMO/hcr>), which includes the right version of the necessary FLR packages, as well as instructions for installation.

Initial results

The platform has been able to evaluate candidate management procedures during its development, but only some initial results are available. They are intended as proof of the platform working status and possibilities. Interpretation of these results should be made with great caution.

Conditioned Operating Models

A total of three operating models from the grid have so far been fully conditioned, although issues remain to be solved on quality of the output from the Markov chain Monte Carlo, as indicated by the diagnostics reported below. These tentative runs

have provided a test of the suitability of the McMC methodology employed by the *adnuts* package to obtain a solid evaluation of the parameter uncertainty for the *jjms* model. They have also been used as a realistic test bed for the development of the functions and methods specific to the analysis presented here. The following outputs should be interpreted with caution as they might not reflect the real uncertainties in estimation for these models (Figures 3-6). Future work will be necessary to obtain more robust output from the McMC sampler, possibly including a reformulation of some of the model processes so they are more amenable to the methods employed by this sampler.

McMC diagnostics

Basic diagnostics for the McMC output indicate at this point that the sampler is not able to obtain a robust set of samples from these models. The reported minimum Effective Sample Size is 7 (0.04%), the maximum $\hat{R} = 2.012$. The algorithm reported a large number of divergences, an indication that some part of the posterior is not being explored.

The trajectories and uncertainty obtained from these initial operating model conditioning attempts can be found in Figures 3 to 6. The spawning biomass trajectory, together with the ratio of SSB to SSB at MSY and F over F at MSY, are shown for the one stock operating model, with either low or high steepness, and for the two stocks model with low steepness.

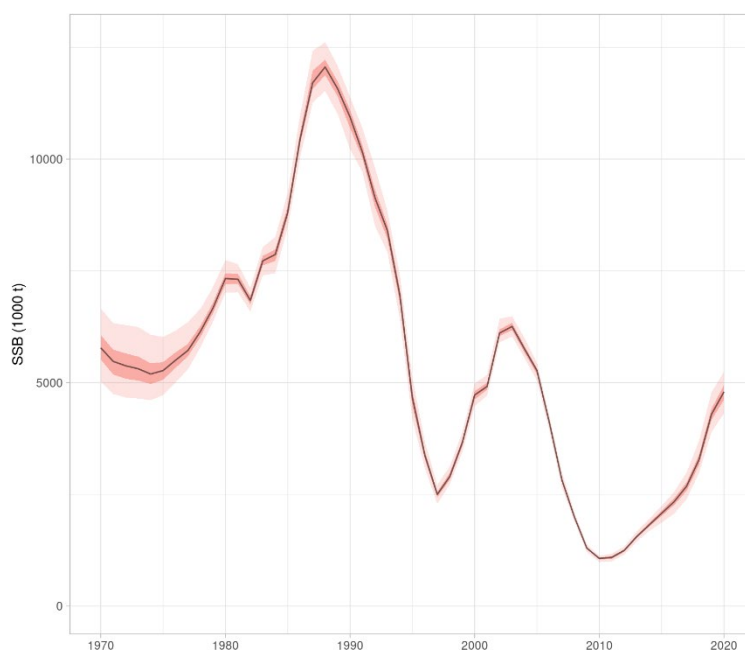


Figure 3. Spawning biomass of Chilean jack mackerel (1970-2019) as determined by the output of the McMC sampler on operating model 1 (one stock, $h=0.65$). Black line shows the median value, while the darker and lighter bands show the 65% and 33% probabilities.

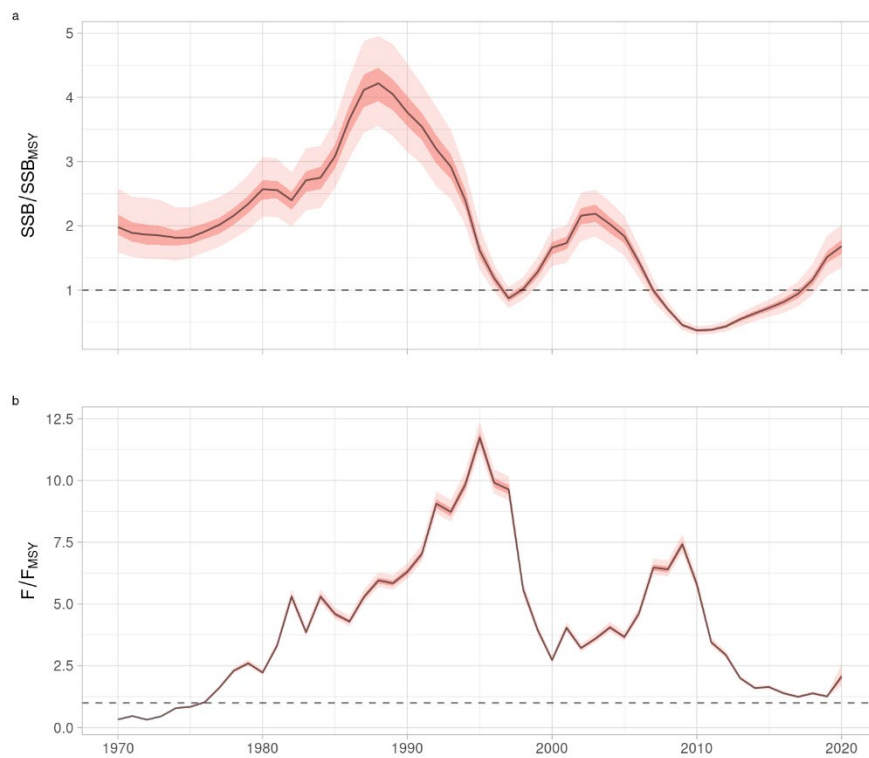


Figure 4. SSB and mean F (ages 1-12) relative to the MSY reference points of Chilean jack mackerel (1970-2019) as determined by the output of the MCMC sampler on operating model 1 (one stock, $h=0.65$).

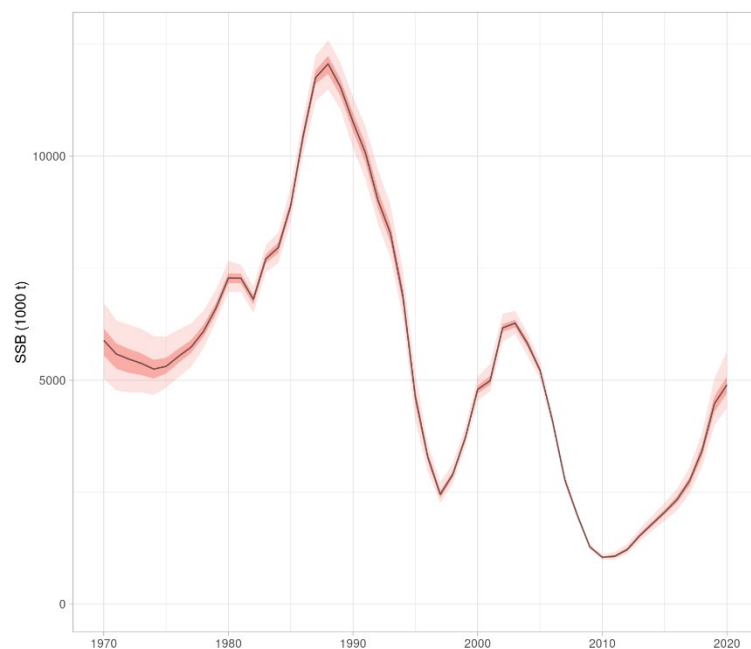


Figure 5. Spawning biomass of Chilean jack mackerel (1970-2019) as determined by the output of the MCMC sampler on operating model 2 (one stock, $h=0.80$). Black line shows the median value, while the darker and lighter bands show the 65% and 33% probabilities.

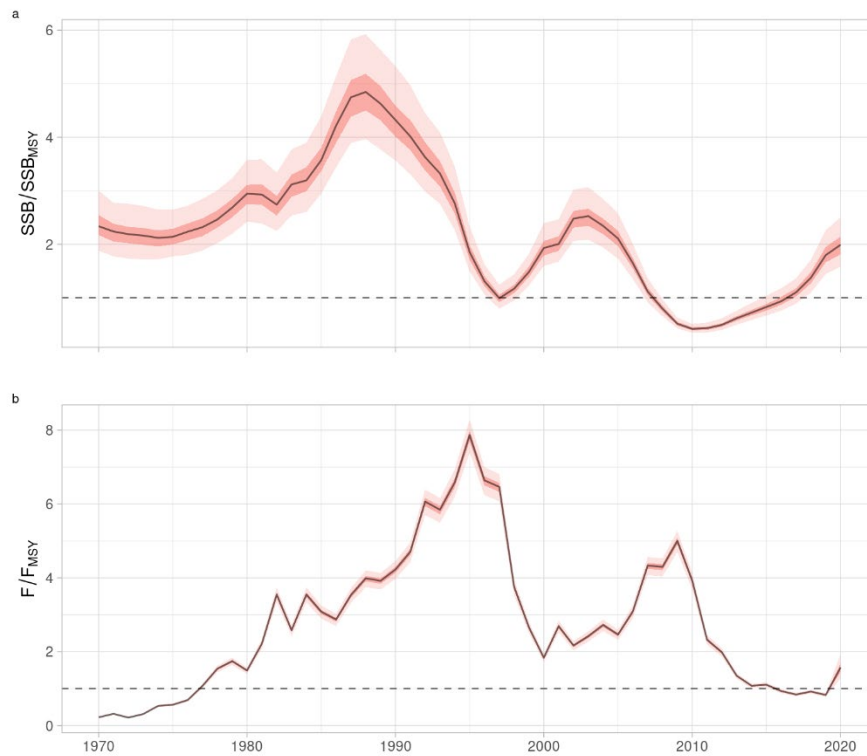


Figure 6. *SSB and mean F (ages 1-12) relative to the MSY reference points of Chilean jack mackerel (1970-2019) as determined by the output of the MCMC sampler on operating model 2 (one stock, $h=0.80$).*

The alternative values for the stock-recruit relationship steepness (h) between models 1 and 2 (single stock, $h=0.65$ and $h=0.80$ respectively) provide different estimates for the main reference points (Figure 7). A higher steepness leads to a higher value for the fishing mortality at MSY (F_{MSY}), as well as for the other MSY-based quantities, and to smaller differences in the estimates of virgin biomass and recruitment (SB_0 and R_0).

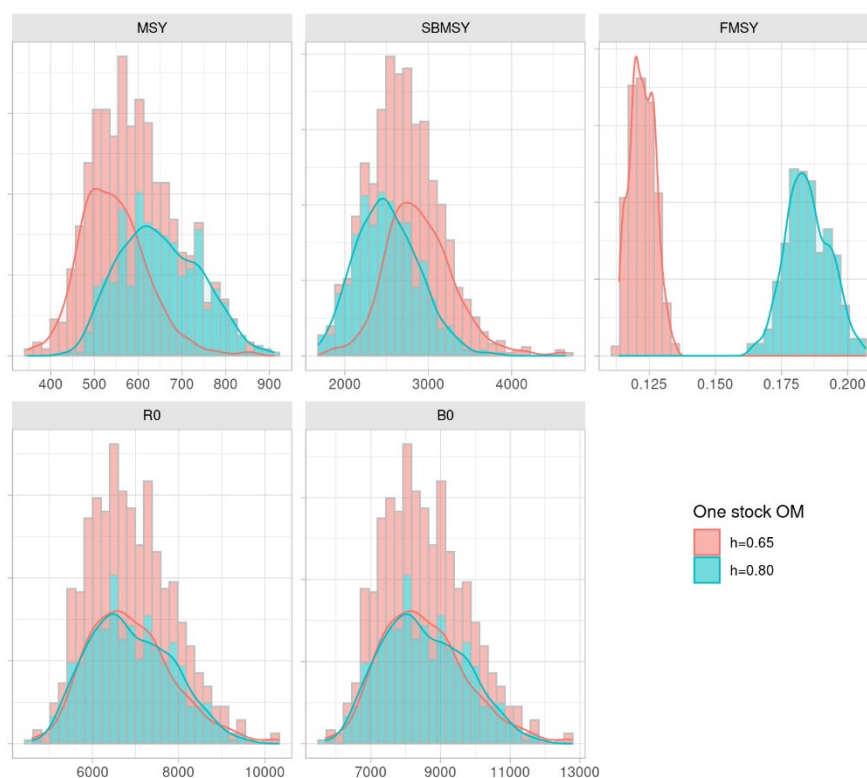


Figure 7. Distribution of 500 samples of the estimates of various reference points for Chilean jack mackerel as determined by the output of the MCMC sampler on operating models 1 and 2 (one stock, $h=0.65$ and $h=0.80$).

Similar results have been obtained for the two stocks operating model, shown here with steepness of 0.65 (Figures 8 and 9).

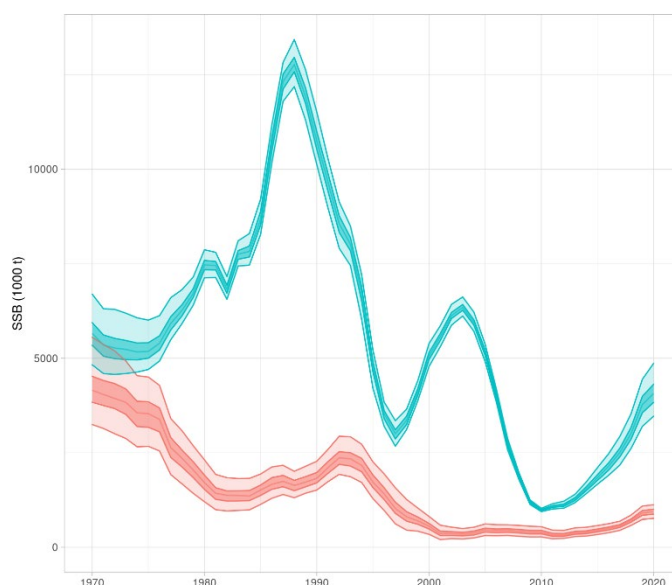


Figure 8. Spawning biomass of Chilean jack mackerel (1970-2019) as determined by the output of the MCMC sampler on operating model 3 (two stocks, $h=0.65$). Line shows the median value, while the darker and lighter bands show the 65% and 33% probabilities.

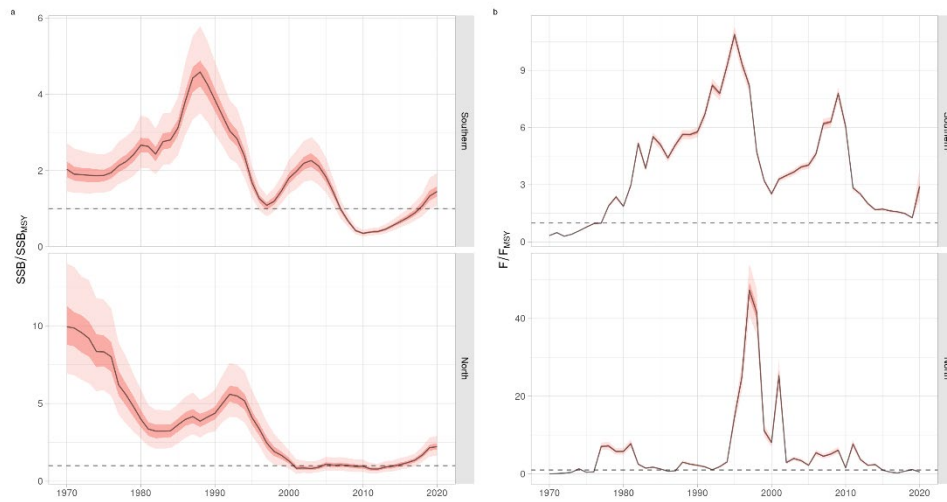


Figure 9. SSB and mean F (ages 1-12) relative to the MSY reference points of Chilean jack mackerel (1970-2019) as determined by the output of the MCMC sampler on operating model 2 (two stocks, $h=0.65$).

Operating Model projections

The projections of various operating models under the scenarios outlined above show the expected dynamics of the stock or stocks as captured by the conditioning procedure. The examples shown here all correspond to the one stock, low steepness operating models. Figures 10 and 11 present the projection under a fishing mortality equal to the 2019 level, 12 and 13 to a no fishing scenario, and 14 and 15 for the F at MSY projection. On each of those pairs, the first plot shows the biomass trajectory, with the shaded area indicating the projection years, 2020 to 2039. The second figure show the trajectories of biomass and fishing mortality, relative to the corresponding MSY reference points.

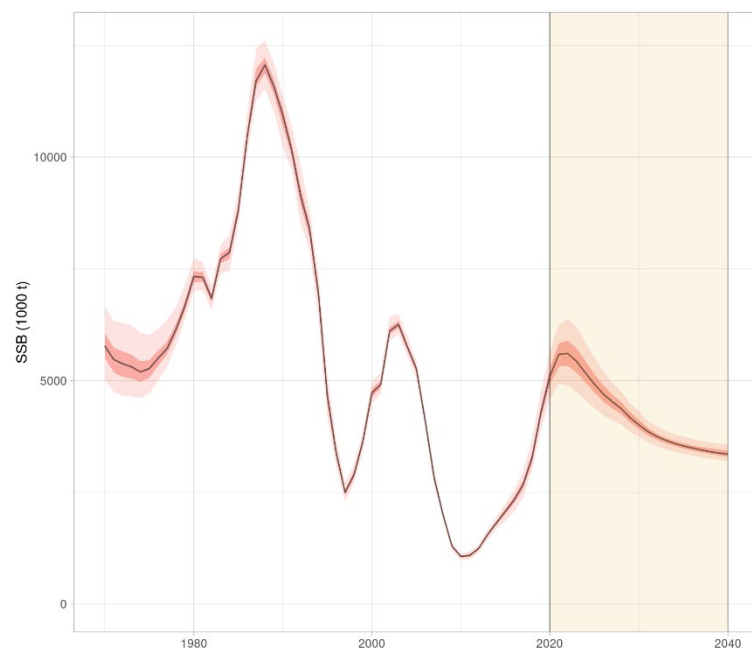


Figure 10. Spawning stock biomass (SSB) of Chilean jack mackerel for the one stock, low steepness model, projected between 2020 and 2040 for $F=F_{2019}$.

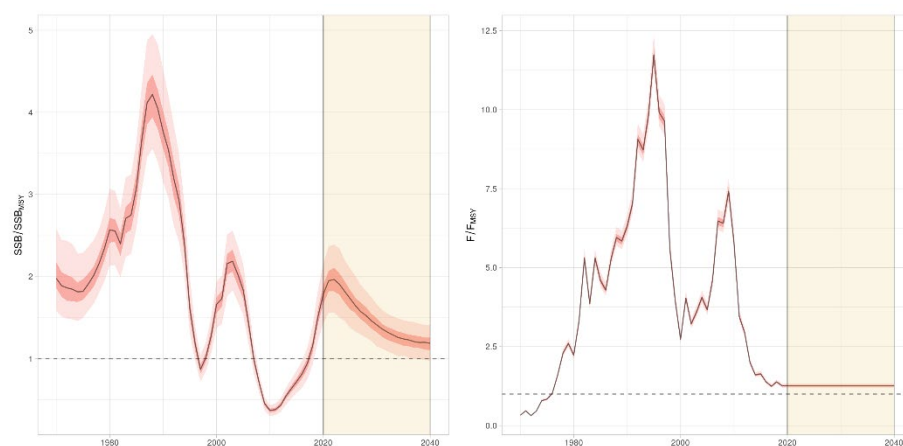


Figure 11. Spawning stock biomass and fishing mortality over the corresponding MSY reference points for the one stock, low steepness model, projected between 2020 and 2040 for $F=F_{2019}$.

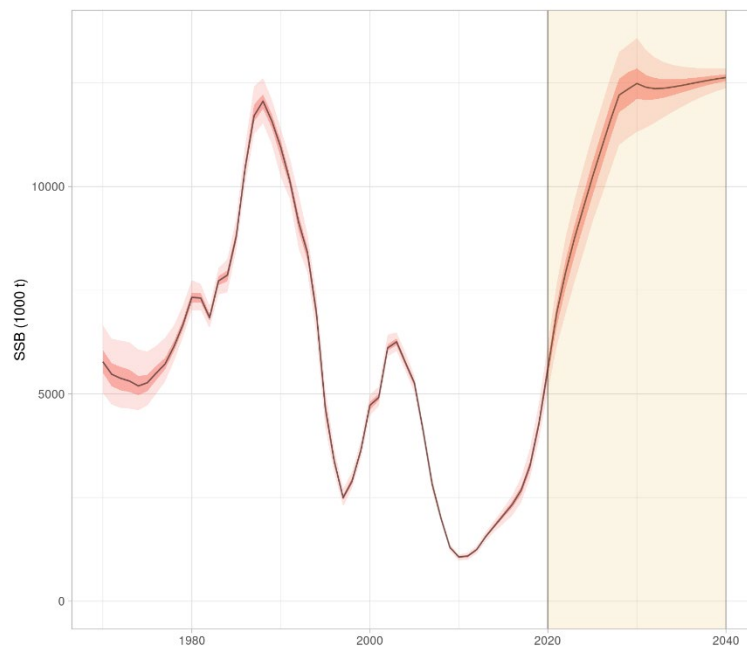


Figure 12. Spawning stock biomass (SSB) of Chilean jack mackerel for the one stock, low steepness model, projected between 2020 and 2040 for $F=0$.

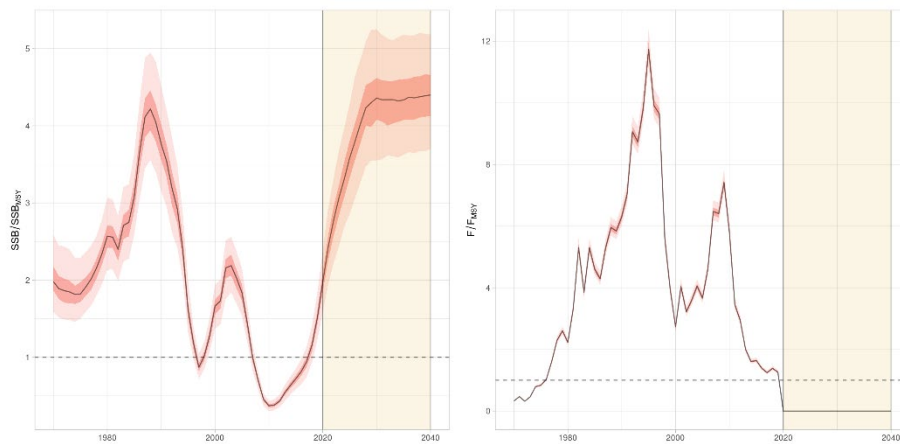


Figure 13. Spawning stock biomass and fishing mortality over the corresponding MSY reference points for the one stock, low steepness model, projected between 2020 and 2040 for $F=0$.

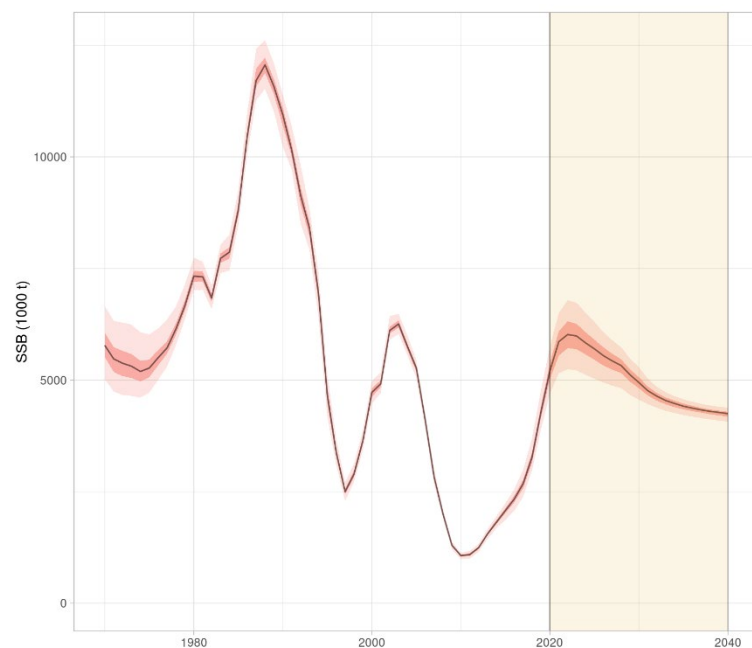


Figure 14. Spawning stock biomass (SSB) of Chilean jack mackerel for the one stock, low steepness model, projected between 2020 and 2040 for $F=F_{MSY}$.

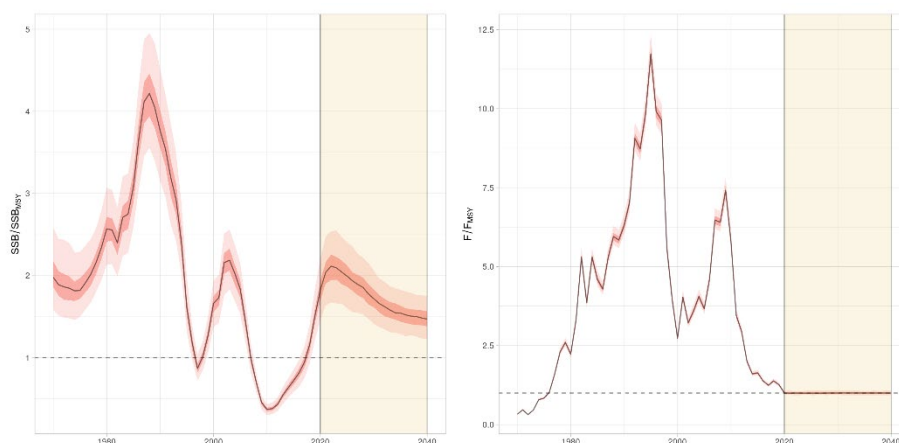


Figure 15. Spawning stock biomass and fishing mortality over the corresponding MSY reference points for the one stock, low steepness model, projected between 2020 and 2040 for $F=F_{MSY}$.

Test runs of candidate MPs: CatchHockeyStick on one stock, low steepness OM

Some test runs are presented here of the *jjms*-based procedure with a catch hockey-stock harvest control rule. No full tuning has been carried out to select the HCR parameters that would achieve a given management objective and probability. Instead, an initial search was carried out on a grid of possible values for the biomass below which catch is reduced ($B_{trigger}$) and the level of catch to aim for (C_{target}). Search on this 2D grid was carried out applying a shortcut to the assessment method, so a direct observation of the operating model is available. A management objective of a 50% probability of spawning biomass being at the MSY level (SB/SB_{MSY}), computed over the 2030-2039 period, was chosen for this test. Two alternative cells in the grid, named as A and B, with similar performance for the primary objective, were chosen for a complete run of the procedures, this time including the *jjms* stock assessment:

- $B_{trigger} = 1000$ and 800 kt
- $C_{target} = 260$ and 350 kt
- $B_{lim} = 250$ and 200 kt
- $C_{min} = 1$ kt

Application of these procedures over the 2020-2039 period leads to a significant decline in stock biomass (Figure 16) after an initial period of increase. Computation of performance indicators over a range of years can sometimes cause overcompensation of the stock metric (SSB in this case) if the stock is above the intended target at the start of the series, as it is the case here.

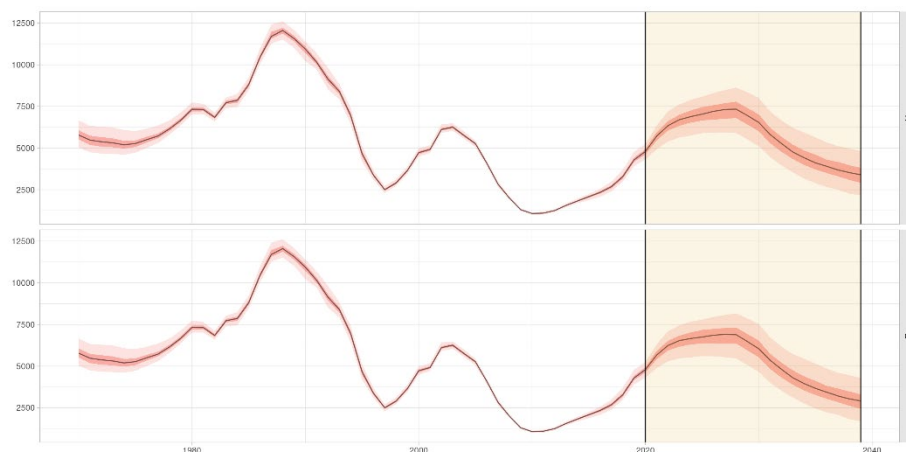


Figure 16. Spawning stock biomass (SSB) for the one-stock, low steepness operating model of Chilean jack mackerel. Projections for the 2020-2039 period under the tested management procedures (A and B).

Once a series of candidate procedures have been run, comparisons can be made across all performance indicators. Figure 17, for example, presents the median and range over the initial performance indicators for the two example procedures.

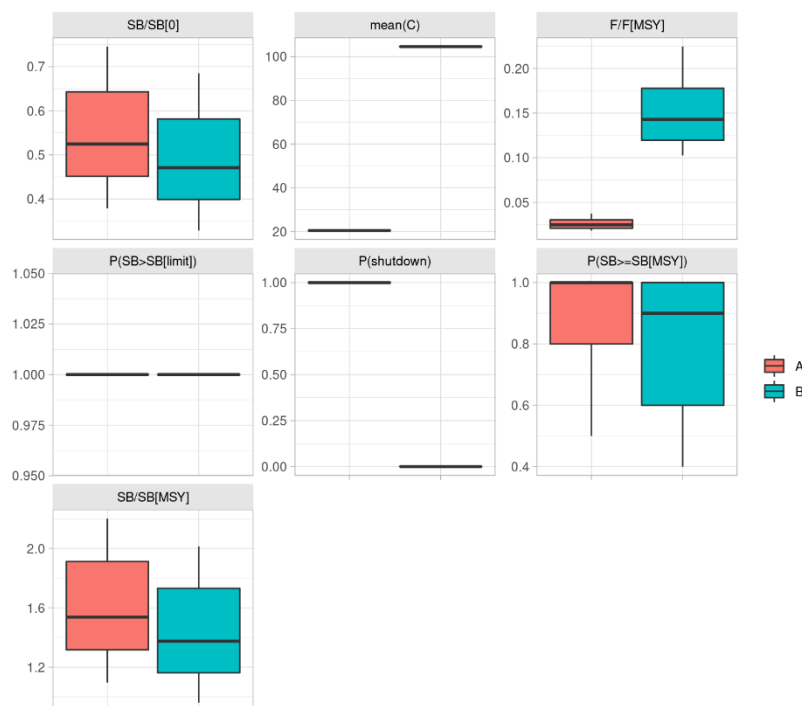


Figure 17. Values (shown as median and 90% probabilities) for a number of performance indicators for the two test management procedures (A and B).

The trade-offs of the application of either procedure are presented in Figure 18, where the x axis shows the values of the mean catch over the 2030-2039 period, plotted against all other indicators.

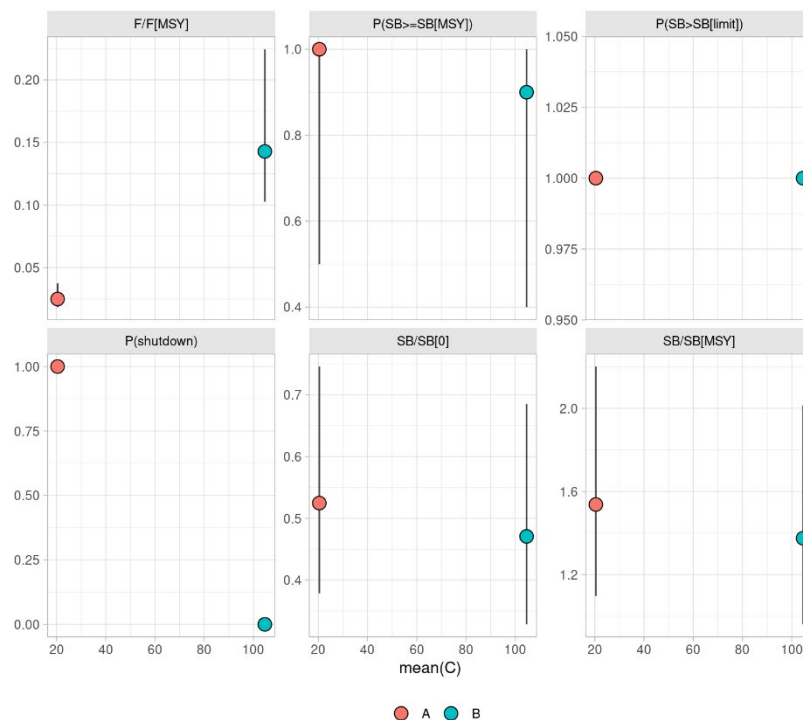


Figure 18. Values for a number of performance indicators for the two test management procedures (A and B) plotted against the mean catch (C), as median and 90% probabilities.

The *mse* platform keeps track of the estimates and decisions taken at each step of the evaluation, the runs by the estimation model and the harvest control rule. For example the estimates of spawning biomass and fishing mortality in the final year of estimation, then used for the HCR decision. The actual values of these metrics for the operating model are also stored, so a comparison between the two can be easily made. The differences in the estimated and actual SSB for this evaluation is shown in Figure 19. The assessment model appears to overestimate biomass, which leads the harvest control rule to propose catches that are higher than necessary. The reasons for this discrepancy need to be fully explored, and at this point could still be due to errors in the generation by the OEM function of the inputs required by *jjms*.

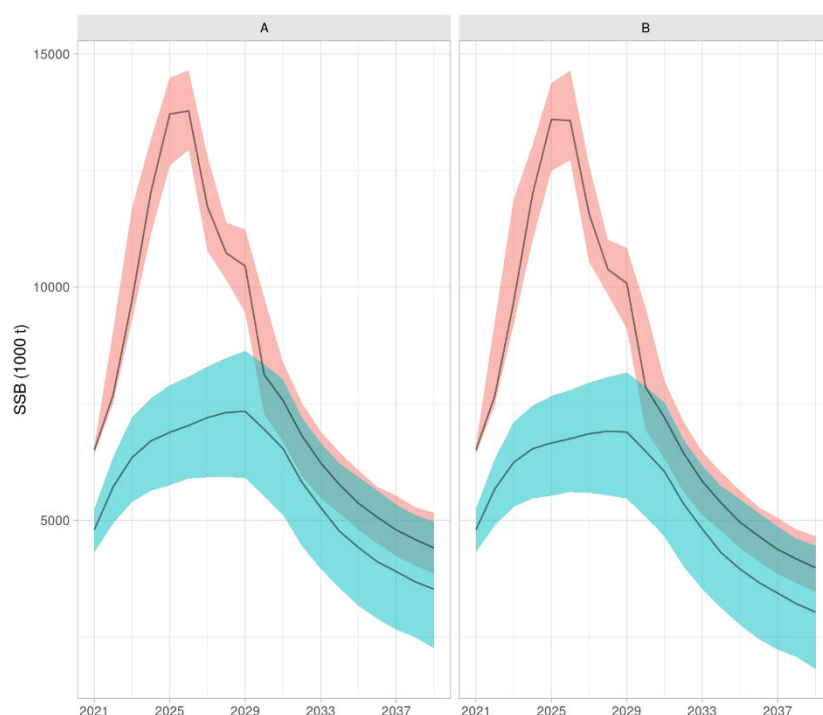


Figure 19. Spawning stock biomass (SSB) during the projection years (2020-2040) under the tested procedures (A and B), for the operating model (OM, in green) and as estimated by the stock assessment (SA, in red).

Discussion

This document presents the progress and status of work for the development of a platform for the evaluation of management procedures for Chilean jack mackerel. The code is based on the FLR toolset, which is widely used in a number of other scientific and advice bodies. However, a significant number of extensions and additions have been made, specific to this fishery. They have been subject to careful testing and have been successfully applied to the models shown, but they would benefit from a final review and quality control, ideally with the involvement of the *jjms* developers.

The platform can already be used to carry out the various analysis required by an analysis of the comparative performance of management procedures for the stock. The current default procedure is based on the *jjms* stock assessment model and a simple hockey-stick harvest control rule. Output of the rule is a total allowable catch, which is then split across fisheries with the same proportions as in the 2019 total catch data. From this starting point, extending of the platform to include other harvest control rules is relatively easy. The *mse* package of the FLR suite follows a well defined modular approach that simplifies this task greatly. An alternative harvest control rule is already available but its use requires some decisions on the methodology to use for a short-term forecast, which it requires.

The evaluation of model-based procedures implies a substantial increase in the computational load of each evaluation, when compared with model-free alternatives. A single run of a candidate procedure over a 20 year period, working on a sample of 500 replicates of the operating model, requires between 175 and 200 CPU hours. Access to High Performance Computing facilities of a medium size (100 to 300 processors) is thus essential for runs to be conducted in a reasonable time frame.

Model-free management procedures can also be easily explored, with the advantage of being far less computationally intensive. The estimation module developed to fit *jjms* at every time step in the simulation, only needs to be substituted by one that

computes an indicator of changes in stock status, for example, from the current indices of abundance. Work would still be required on how best to combine the various indices.

The characterization of uncertainty that the operating models presented here must be discussed and improved. The MCMC samplers applied to *jjms* appear to be unable to work as expected. Some elements in the model structure might need to be revisited to make them amenable to this methodology, and this could require a significant amount of work. Ideally, any change in model parametrization should take place before the next benchmark for the stock in 2021.

Acknowledgements

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