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UPDATED EVALUATION OF HARVEST CONTROL RULES FOR NORTH ATLANTIC ALBACORE THROUGH MANAGEMENT STRATEGY EVALUATION

Gorka Merino[1], Haritz Arrizabalaga[1], Josu Santiago[2], Rishi Sharma[3],
Victoria Ortiz de Zarate[4], Paul De Bruyn[5], Laurence T. Kell[5]

SUMMARY

ICCAT's management objective is to maintain high long-term catch with a high probability of stocks not being overfished nor overfishing occurring and a high probability of not being outside biological limits. To achieve this, Harvest Control Rules (HCRs) can be used to determine annual catch limits. HCRs need to be agreed by policymakers and understood and accepted by stakeholders, which is often difficult due to the many uncertainties inherent to fisheries. For this, Management Strategy Evaluation (MSE) is used to estimate different levels of probability of achieving management objectives by alternative HCRs. Based on the feedback from ICCAT's WGSAM, Panel 2, albacore WG and SCRS, improvements have been made to the MSE framework presented in 2016 to provide updated evaluations of Harvest Control Rules: (i) extended grid of Operating Models, (ii) a modified Observation Error Model to generate CPUE series, and (iii) bounds to the TAC changes through HCRs. The results shown here indicate that all the HCRs evaluated would allow achieving the management objective of p(Green)>60% but would perform differently for other indicators. We show results in accordance with the performance statistics requested by the Commission, in order to support the potential adoption of a HCR for this stock.

RÉSUMÉ

L'objectif de gestion de l'ICCAT consiste à maintenir un niveau élevé de capture à long terme avec une probabilité élevée que le stock ne soit pas surexploité ni victime de surpêche et une probabilité élevée de ne pas se situer en dehors des limites biologiques. Pour atteindre cet objectif, des règles de contrôle de l'exploitation (HCR) peuvent être utilisées pour déterminer les limites de capture annuelle. Les HCR doivent être convenues par des décideurs politiques et comprises et acceptées par les parties intéressées, ce qui est souvent difficile en raison des nombreuses incertitudes inhérentes aux pêcheries. Pour ce faire, une évaluation de la stratégie de gestion (MSE) est utilisée pour estimer différents niveaux de probabilité d'atteindre les objectifs de gestion au moyen de HCR alternatives. Sur la base des commentaires formulés par le WGSAM, la Sous-commission 2, le groupe d'espèces sur le germon et le SCRS, des améliorations ont été apportées au cadre de MSE présenté en 2016 en vue de fournir des évaluations mises à jour des règles de contrôle de l'exploitation : (1) gamme plus large de modèles opérationnels, (ii) modèle d'erreur d'observation modifié servant à générer des séries de CPUE et (iii) limites des changements du TAC par le biais de HCR. Les résultats présentés ici indiquent que toutes les HCR évaluées permettraient d'atteindre l'objectif de gestion de p (vert)>60%, mais qu'elles fonctionneraient différemment pour d'autres indicateurs. Les résultats sont présentés conformément aux statistiques des performances requises par la Commission, dans le but d'appuyer l'adoption potentielle d'une HCR pour ce stock.

RESUMEN

El objetivo de ordenación de ICCAT es mantener una captura elevada a largo plazo con una elevada probabilidad de que los stocks no estén sobrepescados y de que no se produzca sobrepesca y una elevada probabilidad de que no superen los límites biológicos. Para lograrlo, las normas de control de la captura (HCR) pueden utilizarse para determinar los límites de captura anuales. Las HCR deben ser acordadas por los responsables de elaborar las políticas, y deben ser comprendidas y aceptadas por las partes interesadas, lo que a menudo resulta difícil debido a las numerosas incertidumbres inherentes a las pesquerías. Para ello, se utiliza la

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[1] AZTI, Herrera Kaia Portualdea, 20110, Pasaia, Spain; E-mail: gmerino@azti.es
[2] AZTI, Txatxarramendi uhartea, 48395, Sukarrieta, Spain.
[3] NOAA-Fisheries, Southeast Fisheries Science Center, 75 Virginia Beach Dr., Miami, FL 33149, US.
[4] Instituto Español de Oceanografía, Apdo.240, 39080 Santander, Spain.
[5] ICCAT Secretariat, c/Corazón de María, 8. 28002 Madrid, Spain

evaluación de estrategias de ordenación (MSE) con el fin de estimar los diferentes niveles de probabilidad de las HCR alternativas de alcanzar los objetivos de ordenación. Basándose en el feedback del WGSAM, la Subcomisión 2, el Grupo de especies de atún blanco y el SCRS se han realizado mejoras al marco MSE presentado en 2016 para proporcionar evaluaciones actualizadas de normas de control de la captura: (i) una gama más amplia de modelos operativos, (ii) un modelo de error de observación modificado para generar series de CPUE y (iii) límites a los cambios de TAC mediante HCR. Los resultados que se muestran aquí indican que todas las HCR evaluadas permitirían alcanzar el objetivo de ordenación de p(verde)>60% pero funcionarían de manera diferente para otros indicadores. Se muestran los resultados de un modo acorde con las estadísticas de desempeño solicitadas por la Comisión, con el fin de respaldar una posible adopción de una HCR para este stock.

KEYWORDS

Tuna fisheries, Stock Assessment, Fishery Management,
Quota Regulations, Resource Conservation, Harvest Control Rules,
Management Strategy Evaluation, North Atlantic albacore, management objectives, trade-offs

1. Introduction

The foundational objective of the International Commission for the Conservation of Atlantic Tunas (ICCAT) is to maintain populations at levels that can permit the maximum sustainable yield (or above). For that, a series of recommendations have fostered the development of reference points (Rec 11-04) and guidelines of decision making including Harvest Control Rules (Rec 11-13 and Rec 15-04). In 2016, the Commission adopted a multiannual conservation and management program for North Atlantic albacore (Rec. 16-06). This Rec. states that "*in 2017, the SCRS shall refine the testing of candidate reference points (e.g., $SSB_{THRESHOLD}$, SSB_{LIM} and F_{TARGET}) and associated harvest control rules (HCRs) that would support the management objective (…). The SCRS shall also provide statistics to support decision-making in accordance with the performance indicators (…). The result of the analyses described (…) will be discussed in a dialogue between scientists and managers to be organized in 2017, either during a meeting of the SWGSM or as an inter-sessional meeting of Panel 2. Based on the SCRS inputs and advice provided (…) and the dialogue process (…), the Commission shall then endeavor in 2017 to adopt HCRs for the North Atlantic albacore, including pre-agreed management actions to be taken under various stock conditions*".

In 2016, a series of Harvest Control Rules (HCR) were evaluated using Management Strategy Evaluation (MSE) (Merino, Arrizabalaga *et al.* 2016). ICCAT's Working Group on Stock Assessment Methods (WGSAM), Panel 2, SCRS and albacore working group raised concerns about some components of the MSE used and suggested ways of improving the framework ahead of new evaluations. In brief, the WGSAM considered that the Observation Error Model (OEM) used in 2016 generated a catch per unit of effort (CPUE) index that was representative of the total stock biomass and not the fishable biomass, and suggested that consideration should be given to simulating actual CPUE series (ICCAT 2016e). In 2017, alternative options for OEMs and simulated indices have been explored (Merino, Arrizabalaga *et al.* 2017a), and a method to simulate the indices used in stock assessment is included in the MSE framework used in this study. The new method simulates abundance indices through fleet specific CPUE and selectivity.

Also in 2016, the SCRS scheduled the development of MSE and Harvest Control Rules, including further evaluations of HCRs for North Atlantic albacore. In the workplan agreed by the SCRS as part of the multiyear Albacore Research program, priority was given to some improvements over the 2016 MSE, among others to: (i) developing a OEM that considers actual CPUE series' structure, age-classes, dynamic catchability and other properties; (ii) expanding the grid of Operating Models; (iii) implementing alternatives for HCRs, including bounded TACs (ICCAT 2016b), and, (iv) improving ways of communicating the results of the evaluations, including recommendations on performance indicators from Panel 2.

In this study we present new evaluations of HCRs for North Atlantic albacore using an improved MSE framework. The MSE used here contains (i) a new Observation Error Model (Merino, Arrizabalaga *et al.* 2017a), (ii) an extended grid of Operating Models (Merino, Arrizabalaga *et al.* 2017b) and (iii) alternatives for bounded Harvest Control Rules. We evaluate the impact of HCRs for this fishery through a series of performance indicators recommended by ICCAT's Panel 2, which include measures of stock status, safety, yield and stability (ICCAT 2016a). We also explore visualization options developed for the Indian Ocean Tuna Commission MSE (Williams, Larcombe *et al.* 2016).

2. Material and Methods

MSE involves using simulation to compare the relative effectiveness of different combinations of (i) data collection schemes, (ii) methods of analysis and (iii) subsequent process leading management actions (Punt, Butterworth *et al.* 2014), i.e. different Management Procedures (MP), for achieving fisheries management objectives. In this document, MSE is used to identify which of a series of HCRs, used in combination with the biomass dynamic stock assessment method used in the latest assessment of this stock, will enable achieving conservation and production objectives. For this, we use a MSE framework following a series of guidelines and best practices (Rademayer, Plaganyi *et al.* 2007; Punt, Butterworth *et al.* 2014), including the basic steps needed to be followed when conducting an MSE (Punt, Butterworth *et al.* 2014):

Step 1. Identification of management objectives and performance statistics

The conceptual objective of ICCAT is to maintain populations at levels that can permit the maximum sustainable yield (or above). This is converted into operational objectives relative to stock status, safety, catch and stability through ICCAT's recommendations 15-04 and 16-06: The management objective is to maintain the stock in the green quadrant of the Kobe plot with at least 60% of probability and a low probability of being outside biological limits, while maximizing long-term yield and average catch, and minimizing the inter-annual fluctuations in TAC levels.

The performance statistics stem from ICCAT's management objectives and the specific indications from Panel 2 which include metrics of stock status, safety, yield and stability. In particular, in this study we will evaluate HCRs using the following 15 performance indicators (ICCAT 2016a; ICCAT 2016c):

Stock Status

- Minimum spawner biomass relative to $B_{MSY.}$
- Mean spawner biomass relative to B_{MSY}.
- Mean fishing mortality relative to F_{MSY}.
- Probability of being in the Kobe green quadrant.
- Probability of being in the Kobe red quadrant.

Safety

- Probability that spawner biomass is above B_{LIM} ($0.4xB_{MSY}$).
- Probability of $B_{LIM}<B<B_{THRESH}$.

Yield

- Mean catch – short term (Mean over 1-3 years)
- Mean catch – medium term (Mean over 5-10 ye
- Mean catch – long term (Mean over 15-30 years)

Stability

- Mean absolute proportional change in catch
- Variance in catch
- Probability of shutdown
- Probability of TAC change over a certain level (10%)
- Maximum amount of TAC change between management periods

Step 2. Selection of hypotheses of system dynamics

Management Strategy Evaluation (MSE) requires characterizing the main sources of uncertainty inherent to fisheries. The unknowns that challenge the interpretation of fish stock assessments include gaps on biological processes and fishery dynamics. The first are often dealt with hypotheses on input biological parameters to stock assessment models; and the second with hypotheses over the available datasets. The uncertainties explored in the North Atlantic albacore MSE used in 2016 included the range of stock assessment scenarios tested in 2013 with the statistical, size-based, age structured model Multican-CL (Merino, Arrizabalaga *et al.* 2016). These explore the impacts of hypotheses on the available data series to characterize uncertainty, together with a natural mortality scenario. In 2017, Merino *et al.* (2017b), expand the initial set of runs from 2013 using additional hypotheses for input biological parameters (natural mortality and steepness) and fishery dynamics (1% annual increase of catchability). This work aims to expand the grid of OMs so that the tested HCRs are robust to a wider range of uncertainties. The uncertainties considered in the present MSE result from the combination of the scenarios and hypotheses listed in **Table 1** (additional information can be found in Merino et al 2017b). For the present analysis, the scenarios with catchability increase have been restricted to the Base scenario, in order to downweigh the impact of this hypothesis on the results. For this stock, due to its spatial distribution during the fishing season, it is more likely that catchability has decreased due to reduced availability rather than increased due to improvements in technology. In total, 132 scenarios have been considered in this study (**Table 1**).

Step 3. Constructing OMs

Operating Models are representations of the "true" dynamics of the system and may include a set of the most plausible hypotheses or unlikely but not impossible situations (ISSF 2013). In MSE frameworks the OMs represent the system that has to be managed through MPs, i.e. the "true" system that is observed, analyzed and managed through data collection systems, stock assessment and harvest control rules.

The outputs of the Multifan-CL runs (**Table 1**) using the combinations of scenarios listed in **Table 1** were used to condition 132 OMs. The OMs were conditioned using libraries from the FLR-project (www.flr-project.org). The conditioned OMs are FLR objects composed by a single fishery and include parameters (selectivity, growth, natural mortality, stock-recruitment and maturity), time series of catch and biomass (in total and by age) and harvest time series, among other information. Finally, the OMs were projected forward to 2015 with total catch information from 2012-2014.

Step 4. Defining MPs

Management Procedures represent how the true dynamics underlying fisheries exploitation are represented through stock assessment and driven by fisheries management. A population-model-based framework within which the data obtained from the fishery are analyzed and the current status, productivity and RPs of the fishery are estimated through a stock assessment model (Rademayer, Plaganyi *et al.* 2007). The outputs of this are plugged into a HCR that, in combination with RPs, provides recommendation for management action. In this study, the observation error model (OEM) generates simulated abundance indices for fitting a biomass dynamic model, to estimate stock status and MSY-based RPs. These are used in combination with HCRs to determine TAC every three years. The MP proposed here aims at simulating the current processes of data collection and stock assessment of North Atlantic albacore, plus a range of alternatives for Harvest Control Rules. The three components are described below:

A. Observation error model

In MSE, the Operating Model is used to simulate resource dynamics in order to evaluate the performance of a Management Procedure. Where the MP is the combination of pre-defined data, together with an algorithm to which such data are input to provide a value for a management control measure. To link the OM and the MP it is necessary to develop an Observation Error Model (OEM) to generate fishery-dependent or fishery-independent resource monitoring data. The OEM reflects the uncertainties, between the actual dynamics of the resource and perceptions arising from observations and assumptions by modelling the differences between the measured value of a resource index and the actual value in the OM (Kell and Mosqueira 2016). In Merino et al (2017a) options for an OEM are explored by combining OMs biomass trends, catch per unit of effort series, fleet specific and overall selectivity patterns and analyses of the indices used in the latest stock assessment of North Atlantic albacore, including their residuals of fit (ICCAT, 2016d). A procedure to simulate CPUE from the OM and compare the properties of the simulated to those used in the assessment is proposed. One of the options explored simulates fleet specific CPUE indices using each fleet's selectivity pattern, catch and effort, and their properties are compared with the abundance indices used in the 2016 assessment of this stock (ICCAT 2016d). The method to generate four abundance indices from the OM for Spanish baitboat, China Taipei longline, Japanese longline and a combined index to simulate Venezuelan and US longline is the following:

$$Index_f = \frac{\sum_a^{max} Catch_{a,f} \; x \; Selectivity_{a,f}}{fbar} x \; \varepsilon \; ; f = fleet; a = age; fbar = fishing\ mortality \quad \text{(eq. 4)}$$

B. Stock Assessment

The indices generated are used to fit the biomass dynamic model *mpb*, which was used in the 2016 stock assessment of North Atlantic albacore (ICCAT 2016d). The fits are made using the same specifications and modelling choices as in 2016, i.e. CPUE series from the years specified in Table 2 and the same starting values used in 2016 with the Fox model (**Table 3**).

C. Harvest Control Rules

Harvest Control Rules describe how harvest is automatically controlled by management in relation to the state of some indicator of stock status (ISSF 2013). Here, when the stock level is above the precautionary threshold (B_{THRESH}), the fishing mortality applied to the stock will be (F_{TAR}). When the stock falls below B_{THRESH} but above B_{LIM}, the fishing mortality will be lower than F_{TAR}. When the stock falls below B_{LIM}, the remedial management action will be determined by F_{MIN}. As part of a HCR, threshold and limit reference points are intended to restrict harvesting to avoid highly undesirable states of the stock, such as the impairment of the recruitment, from which recovery could be irreversible or slowly reversible. LRPs can be set based on fishing mortality rates or related to biomass levels. A biomass related LRP is defined as a boundary (e.g. in terms of absolute or relative biomass levels, spawning potential ratios (SPR), etc., which, if crossed, would require the cessation (or setting it to a minimum, F_{MIN}) of harvesting until the stock has recovered to a level above the LRP). The fishing mortality applied when the stock is evaluated to be above the B_{LIM} but below B_{THRESH} will be determined by the line that connects the coordinates (B_{LIM}, F_{MIN}) and (B_{THRESH}, F_{TAR}), see **Figure 1** for a generic HCR.

Specifically, ICCAT's Recommendation 16-06 states the following in relation to HCRs:

(a) If the average spawning stock biomass (SSB) level is less than SSB_{LIM} (i.e., $SSB<SSB_{LIM}$), the Commission shall adopt severe management actions immediately to reduce the fishing mortality rate, including measures that suspend the fishery and initiate a scientific monitoring quota to be able to evaluate stock status. This scientific monitoring quota shall be set at the lowest possible level to be effective. The Commission shall not consider re-opening the fishery until the average SSB level exceeds SSB_{LIM} with a high probability. Further, before reopening the fishery, the Commission shall develop a rebuilding programme in order to ensure that the stock returns to the green zone of the Kobe plot.

(b) If the average SSB level is equal to or less than $SSB_{THRESHOLD}$ and equal to or above SSB_{LIM} (i.e., $SSB_{LIM} \leq SSB \leq SS_{BTHRESHOLD}$) and

i. F is at or below the level specified in the HCR, the Commission shall assure that that applied management measures will maintain F at or below the level specified in the HCR until the average SSB is above $SS_{BTHRESHOLD}$;

ii. F is above the level specified in the HCR, the Commission shall take steps to reduce F as specified in the HCR to ensure F is at a level that will rebuild SSB to SSB_{MSY} or above that level.

(c) If the average SSB is above $SSB_{THRESHOLD}$ but F exceeds F_{TARGET} (i.e., $SSB>SSB_{THRESHOLD}$ and $F>F_{TARGET}$), the Commission shall immediately take steps to reduce F to F_{TARGET}.

(d) Once the average SSB level reaches or exceeds $SSB_{THRESHOLD}$ and F is less or equal than F_{TARGET} (i.e., $SSB > SSB_{THRESHOLD}$ and $F \leq F_{TARGET}$), the Commission shall assure that applied management measures will maintain F at or below F_{TARGET} and in case F is increased to F_{TARGET} this is done with a gradual and moderate increase.

A range of alternative HCRs are evaluated in this study (Figure 2). Combinations of five target fishing mortalities: F_{TAR} [0.6, 0.7, 0.8, 0.9, 1] x F_{MSY}; three threshold biomass: B_{THRESH} [0.6, 0.8, 1] x B_{MSY}; one limit biomass: $B_{LIM}=0.4$ x F_{MSY} and $F_{MIN}=0.01$ x F_{MSY}. All 15 HCRs evaluated have the same $B_{LIM} = 0.4$ x B_{MSY} which is the interim LRP considered in the 2013 stock assessment (ICCAT 2013b) and the North Atlantic swordfish (Rec. 13-02), and which is consistent with robust limits recommended for a number of Pacific and Indian Ocean tuna stocks (Preece, Hillary *et al.* 2011).

In addition, in the spirit of avoiding the adverse effects of potentially inaccurate stock assessments, two control parameters are added to the HCRs in the form of constraints: First, HCRs shall not recommend a catch limit greater than a maximum or lower than a minimum value. The maximum value is based on the 90th percentile of the smoothed catch series of North Atlantic albacore, which approximately corresponds to 50 k tons. The minimum value is 15 k tons, which corresponds to the minimum catch of this stock in modern times. Second, three alternatives for a maximum percentage of change in the catch limit will be explored in order to increase the stability of the management measures. With this, the HCR shall not recommend a catch limit that is 20%, 25% or 30% higher or lower than the catch limit recommended three years before. These control measures stem from Resolution 16/02 from the Indian Ocean Tuna Commission (IOTC) on Harvest Control Rules for skipjack tuna, which determines a maximum inter-annual variability of 30%.

Step 5. Simulation with feedback

The Operating Models and the Management Procedures have been linked through specifically tailored R functions and libraries from the FLR project (www.flr-project.org). In SCRS/2016/015, deterministic projections of the Operating Models were used to generate scenarios of scenarios of perfect knowledge and control and simulations with HCRs and feedback between MP and OM. Here we only explore simulations with feedback and the differences with SCRS/2016/015 refer to the wider grid of OMs, the new OEM and a smaller range of bounded HCRs.

The MSE framework used is shown in Figure 3. The OMs produce series of biomass, catch, fishing mortality, recruitment and other fishery trends, which are measured every three years to generate series of catch and abundance indices through an Observation Error Model. These are then used to fit the surplus production stock assessment model *mpb*. The outputs of this model include estimates of relative biomass and fishing mortality, of RPs (B_{MSY}, F_{MSY}, MSY) and model parameters. These are used in combination with HCRs to set catch limits, which are then used to project forward the OMs for another three years. This process is simulated every three years for the duration of simulation, in this case 30 years, which corresponds to two generations of North Atlantic albacore. The interest is on the outcome of the OMs and therefore, biomass, catch and harvest series of the OMs are used to produce performance statistics for interpretation by managers and scientists.

Step 6. Summary and interpretation of performance statistics

The evaluation of HCRs is completed with the summary and interpretation of the performance of the OMs. Four group of indicators relative to stock status, safety, yield and stability are used (see *Step 1*). A succinct summary of the performance of HCRs is also provided. Should further results be required, these will be made available.

3. Results

The results for the HCRs are shown in Table 4. Overall, the HCRs tested would enable achieving ICCAT's management objective of maintaining stocks at or above SSB_{MSY} with a probability of 60% or more. However, notable differences are found between HCRs (**Figures 4 to 7**). The performance of the HCRs is evaluated following the indicators agreed by ICCAT's Panel 2:

The HCRs performance for stock status is illustrated with three indicators (**Figure 4**). All figures show three panels for indicator (three values for B_{THRESH}) and F_{TARGET} in the x-axis. Also, results are shown for alternative applications of HCRs with TAC change constraints of 20%, 25% and 30% from the TAC during the preceding management period. The minimum biomass observed decreases for increasing values of F_{TAR} and very minor differences are found across B_{THRESH} levels. The average SSB is above SSB_{MSY} for all HCRs but also decreases for increasing F_{TAR}. The average fishing mortality is estimated to be below F_{MSY} for all HCRs and increases with F_{TAR}. With regards to the probability of being in the green quadrant of the Kobe plot, this probability decreases with F_{TAR} and also, is lower for lower values of B_{THRESH}. For the HCRs with B_{THRESH}=0.6 and F_{TAR} =1, the probability of being in the green quadrant is the lowest from the tested HCRs. For the probability of being in the red quadrant of the Kobe plot, this increases for higher values of F_{TAR} and decreases with increasing B_{THRESH}. Overall, for the stock status indicators, there are not significant differences for the alternative TAC change constraints, and with all HCRs and all change constraints the management objective of p(Green)>60% would be achieved.

With the HCRs tested, the stock would be above its biological limit reference point of 0.4xSSB_{MSY} with more than 95% probability (**Figure 5**). However, this probability would be lowest with B B_{THRESH} =0.6 and F_{TAR} =1. The probability of the SSB being between the LRP and SSB_{MSY} would be highest for F_{TAR} =1 and very similar for all B B_{THRESH} values. In general, for the safety indicators, there are not significant differences for the alternative TAC change constraints.

In general, the HCRs with higher F_{TAR} would produce larger catch in the short, mid and long terms, with some differences across levels of B_{THRESH} (**Figure 6**). In general, the MP used in this MSE underestimates recent years' stock recovery and fixes short and medium term TAC at values below or similar to the current values (2014-2017, 28 k tons). This is because regardless the OMs stock being above B_{MSY}, the MP estimates biomass below B_{MSY} for the majority of iterations and therefore, the TAC corresponds to levels of fishing mortality below F_{TAR} in all cases. This will be explained further in the following sections of this manuscript. In the long term, all HCRs with $F_{TAR}>0.6$ are expected to yield catches above 30 k tons and for $F_{TAR}=1$, catch would fluctuate around 35 k tons. For the mid and long term yield, there are not significant differences for the alternative TAC change constraints and only for the short term some differences can be appreciated.

The alternative TAC change constraints produce more notable differences in the stability indicators (**Figure 7**). The mean absolute proportional change in catch between years ranges from 1.2 to 2.25 k tons. The standard deviation of catch (and variance) increases for larger values of B_{THRESH} and F_{TAR}. With regards to the probability of shutdown, with all the HCRs this remains null. This is partly because of the TAC constraints of minimum TAC and TAC change but also because the abundance of fish is always enough to support the catch levels plotted in Figure 6. With the minimum TAC and TAC change constraint, the only possibility for a shutdown would be that the HCRs have performed so badly that the stock has collapsed and therefore, despite the TAC being above the minimum limit, there would not be fishable biomass. This is not a possibility with the HCRs tested. With regards to the probability of TAC change of more than 10%, this ranges between 19-24% for all the HCRs tested and the TAC change constraints. With regards to the maximum amount of TAC change between management periods, this ranges between 8 and 16 k tons across HCRs and almost 4 k tons across TAC change constraints.

In general, the relative biomass (B/B_{MSY}) changes more quickly in the OM (**Figure 8**, upper left panel) than in the MP (bottom left panel). The CPUEs generated to fit in the MP are also shown in **Figure 8** (right). For example, the stock in the OM declined very rapidly (from 2.1 to 1) between 1940 to 1955 and this decline is smoother in the MP. Also, in 1981, year of the first CPUE available for stock assessment, the stock in the OM starts to decline very rapidly from 1.2 to 0.5 x B_{MSY} in 15 years. In the MP, this decline is estimated to be very smooth, from 0.8 to 0.7. The minimum biomass in the OM and the MP occur in the same year and since then, the stock recovers rapidly until 2015 in the OM, the year where the simulation is started in the MSE. This recovery is estimated to be smoother in the MP and reaches lower levels than in the OM, where the stock peaks at values above 1.5, which are never reached in the MP.

At the beginning of the MSE simulation, the majority of OMs are following a recovery trend with many of them showing a completely recovered stock level, i.e. biomass above B_{MSY} (Merino *et al*., 2017b). For example, using the OM built upon the Base Case of the 2013 stock assessment (ICCAT, 2013), stock biomass is at 1.1 x B_{MSY} (**Figure 9**). However, the biomass dynamic model of the MP, using the generated CPUE series, systematically underestimates the stock recovery that commenced in 2000, and estimates current biomass below B_{MSY} for most iterations. This explains that the TAC imposed in the short term (Figure 6) is lower than the TAC for 2014-2016 (28 k tons). **Figure 10** shows the histogram of the estimated stock status in 2015, the first year of the MSE simulation. This figure again shows that the estimated stock biomass is generally lower than the "true" represented by the OM. The relative stock biomass trend and status estimated in the 2016 stock assessment are also shown in Figures 9 and 10 (green). This is done to put in context the results of this study with regards to the latest stock assessment. The 2016 stock assessment was carried out using a series of CPUE indices that were simulated in the MSE. However, the simulated CPUEs do not contain data from the CPUE used in the assessment except for the estimated selectivity used to generate them. The trajectory estimated in 2016 falls within the range of trajectories estimated in the MSE, but relatively far from the average trend.

TACs are set using HCRs, which reduce the fishing mortality if the stock is assessed to be below a threshold level. For example, using a HCR with $B_{THRESH}=1$, the TAC imposed are very low, so low that they hit the lower bound of the TAC change constraint (**Figure 11**). However, there are a number of fits that estimate stock status above B_{MSY} and therefore, use F_{TAR} to estimate the TAC. In many cases, the stock is assessed to be such high that the TAC hits the upper bound of the TAC change constraint. In brief, either the upper or the lower bounds are hit in most iterations, being the resulting average what is plotted in **Figure 6** (upper), and also shown in **Figure 11**.

4. Discussion

The aim of this study is to test a series of Harvest Control Rules that would support the management objective of maintaining fish stocks in the green quadrant of the Kobe plot with at least 60% of probability (Rec. 16-06). We also provide statistics that would support the adoption of a HCR in 2017 in accordance with the performance statistics requested by the Commission. Our results have been produced using MSE, in particular, an MSE framework specifically tailored for North Atlantic albacore and the purposes of this study.

The adoption of a HCR consists on the acceptable balance between risks for the sustainability and the best use of the available marine resources. In order to explore the trade-offs between conservation and utilization four groups of performance indicators were recommended by ICCAT's Panel 2, including scores for stock status, safety, catch and stability. Overall, we estimate that all the HCRs evaluated in this study (B_{LIM}=0.4 x B_{MSY}, F_{TAR} [0.6, 0.7, 0.8, 0.9, 1] x F_{MSY} and B_{THRESH} [0.6, 0.8, 1] x B_{MSY} would allow achieving ICCAT's management objective of p(Green)>60% (Rec 16-06). Also, we estimate that all the HCRs are robust to the uncertainties considered for this stock, including sources of information, biological parameters (natural mortality and steepness) and fishery dynamics. Also, the HCRs are robust to a range of estimates of the initial state of exploitation of this stock (Merino *et al.*, 2017b). The accepted probability for being in the red quadrant of the Kobe plot is not defined by ICCAT yet, but our results indicate that this is halved by increasing the level of threshold from 0.6 to 1. B_{THRESH} is the point where the fishing mortality will start to be reduced from F_{TAR}. With regards to safety, the acceptable probability for the stock to be above B_{LIM} is not defined either but our results show that all HCRs would maintain stock biomass above B_{LIM} with more than 95% probability. With regards to catch, our results show that in the short term, the majority of iterations estimate TAC below the current value of 28 k tons while others are above the upper limit of TAC change. The main reason for this is the underestimation of the recent years' stock recovery. In the long term, for F_{TAR} levels above 0.7 catch would be above 30 k tons, being as high as 35 k tons for F_{TAR} of 0.9 and 1. In the long term, no differences are found across HCRs with TAC change constraints of 20, 25 or 30% relative to stock status, safety and catch indicators. With regards to stability, it is obvious that the lowest the TAC change allowed, the higher the stability for the industry. However, it is important to note that the probability of shutdown has been estimated as zero for all HCRs.

This study uses a new version of the MSE developed for North Atlantic albacore in 2016 (Merino *et al.* 2016). The main differences with the previous study are the Observation Error Model, the grid of Operating Models and the range of HCRs evaluated (see Introduction and Material and Methods). In this study, all HCRs allow achieving the management objective of p(Green)>60%. However, one of the reasons for this is that systematically the new MP underestimates stock biomass and therefore imposes TAC below what would be sustainable in the OMs, especially in the short term. The OEM used in 2016 was probably less realistic with regards to the information available in ICCAT but produced simulated indices that more accurately reflected the biomass trends of the OMs. With the framework used in 2016, HCRs with F_{TAR}>0.9 x F_{MSY} only achieved the management objective of p(Green)>60% for B_{THRESH} = B_{MSY}. In 2016, the HCRs that would maximize stock status, safety, short-mid-long term yield and stability objectives were named after as "*more precaution and less action*", which meant that B_{THRESH} could be below B_{MSY} but only for F_{TAR} below 0.9 x F_{MSY}. The same HCRs (for example F_{TAR}=0.8 and B_{THRESH} =0.8, using the 30% TAC change constraint) would enable achieving a p(Green) of 80% while maintaining long term catch at levels around 33 k tons in the current version of the MSE.

The method used to generate CPUE series together with the biomass dynamic model produce fits that systematically underestimate the recent recovery of the stock. This has important implications when comparing the results with the two latest assessments of this stock, in 2013 and 2016. As seen in the catch performance of the HCRs, the TAC in the short term is estimated to be lower than recent TAC and notably lower than the catch levels predicted to allow the stock to remain in the green quadrant of the Kobe plot in the 2016 stock assessment (ICCAT, 2016). This is because the catch shown in **Figure 6** is averaged across iterations and OMs. When looking at the estimated stock trajectory in the first simulated management period of the MSE (t=0), we can see that iterations assuming CV=0.2 in the abundance indices produce a series of estimated biomass trends (gray lines in **Figure 9**). Most trajectories underestimate recent years' stock recovery in the Base Case OM but some overestimate stock status during the period of the analysis. The trend estimated in the 2016 stock assessment falls within the range of MP estimates of this MSE. This means that the 2016 stock assessment result is comparable with the results produced in this study and would only represent one of the realizations of the biomass dynamic model, in this case, one of the iterations that estimate higher stock status. TAC will be set upon the latest stock assessment and therefore, it is expected that the HCRs, when applied to the 2016 stock assessment, will hit the upper bound of the TAC change constraint considered by the Commission (see **Table 4**).

In this study, we have used MSE to evaluate a series of HCRs. This means that the simulation is tailored to the objectives of this study. The framework used here is not a full or finalized MSE for North Atlantic albacore but required the development of some of its components. For example, alternatives for conditioning Operating Models from Multifan-CL have been explored in a few recent papers (Kell, Merino *et al.* 2013c; Kell, Merino *et al.* 2013b; Kell and Mosqueira 2016; Merino, Arrizabalaga *et al.* 2017b) resulting in a grid of 240 OM from which 132 are used in the present study. However, according to the multiannual work plan for North Atlantic albacore it is expected that the development of Operating Models for this stock will continue with emphasis on exploring regime shifts, changes in selectivity, autocorrelated recruitment and broader scenarios using MFCL but also other models such as SS3 (ICCAT 2016b).

With regards to the Observation Error Model component, for this study we have explored a series of options (Merino, Arrizabalaga *et al.* 2017a) and decided to use a model that generates abundance indices from OMs catch, effort and fishery specific selectivity. As said earlier, previous MSE frameworks included indices directly generated from OMs stock biomass and an error term (Kell, Merino *et al.* 2013b; Merino, Arrizabalaga *et al.* 2016), which raised concerns in the 2016 WGSAM and Panel 2 (ICCAT 2016a; ICCAT 2016e). In this study we haven't considered potential future changes in catchability, autocorrelation or other CPUE error structures, that can be covered in future studies (ICCAT 2016b).

The Management Procedure used here uses a biomass dynamic model only (Kell 2016), which has been previously validated for use in MP (Kell, Merino *et al.* 2013a; Kell, Arrizabalaga *et al.* 2016a). This model has been used in the 2016 stock assessment of North Atlantic albacore (Kell, Merino *et al.* 2013b; ICCAT 2016d; Kell, Arrizabalaga *et al.* 2016b; Kell, Arrizabalaga *et al.* 2016c). We have used this model only so that the evaluation of HCRs reflects their performance under the current assessment-management framework. This means that the preferred HCRs will perform as estimated when applied over the stock assessment procedure used in 2016. Therefore, our results do not in any manner preclude that the HCRs will perform in the same way if alternative models are used for stock assessment and neither that future stock assessments will need to be made using the biomass dynamic model or the datasets used in this study. Both biomass dynamic models and more complex statistic models like MFCL or SS3 can be applied to assess this stock in the future, the latter especially during benchmark assessments. Therefore, collecting detailed length composition and other information will continue being of major importance, especially since the abundance indices currently available remain questioned (ICCAT 2016d). The periodical updates of biomass dynamic and age-specific models will be necessary for the further development and revision of North Atlantic albacore MSE.

Following ICCAT's guidelines for management (ICCAT 2013a) and SCRS plan, under the MP, we have evaluated a series of bounded linear model-based HCRs, where F_{TAR} and B_{THRESH} are F_{MSY} and B_{MSY} or less and B_{LIM} is fixed at 0.4 x B_{MSY}. The options for HCR are many and include model based HCR with different shapes but also model free decision making options. All these are prone to be implemented in future developments of the North Atlantic albacore MSE. For example, in an MSE, reference points are tuned, i.e. CCSBT provides a model-free example of a MP that is based on year-to-year changes and trends in empirical indicators; reference levels are then tuned to meet management objectives using MSE, where tuning refers to adjusting the parameters of the MP to try and achieve the stated objectives represented by the OM. Model-based MPs, for example those based on a stock assessment model, may include the estimation of MSY-based reference points, but the values of F, F_{MSY}, B and B_{MSY} from the OM do not need to be equivalent to their proxies in the MP (e.g. if a stock assessment model used in the MP is structurally different from that used to condition the OM (Kell, Levontin *et al.* 2016).

In summary, the results produced in this study aim at supporting the adoption of a HCR in 2017 for its application to the latest stock assessment, but its robustness will continue to be reviewed under alternative OMs, stock assessment models and management options contemplated in the North Atlantic Albacore Tuna Research Programme (ICCAT 2016b).

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Table 1. Hypotheses and scenarios considered in the North Atlantic albacore MSE. The 10 scenarios in the upper left panel are the scenarios considered in the 2013 stock assessment.

Scenarios	*Natural Mortality*	*Steepness prior*
Base: Model specifications provided in SCRS/2013/058 (Merino, De Bruyn *et al.* 2013) **Alt1:** Includes China Taipei longline size frequency data and allows dome-shaped selectivity for this fleet. **Alt2:** Model starts in 1950 **Alt3:** All size frequency data down-weighted **Alt4:** Japanese longline CPUE data no longer down-weighted **Alt5:** Includes the Chen and Watanabe age-specific natural mortality vector (Santiago and Arrizabalaga 2005) **Alt6:** Excludes final 4 years of data (2008-2011) **Alt7:** Includes equal weights for Japan and Chinese Taipei longline size frequency data and catch per unit of effort data **Alt8:** Includes total catch in weight but effort calculated from CPUE in numbers **Tag:** Includes tagging data for release events that occurred between 1988 and 1991	• 0.2 • 0.3 • 0.4	• 0.75 (sd=0.15) • 0.7 (sd=0.05) • 0.8 (sd=0.05) • 0.9 (sd=0.05)
Base: Model specifications provided in SCRS/2013/058 (Merino, De Bruyn *et al.* 2013) with dynamic catchability (+1%)		

Table 2. CPUE series used in the 2016 stock assessment and their starting years.

Index	*First year of series*
Chinese Taipei late Longline	1999-
Japan bycatch Longline	1988-
Spanish Baitboat	1981-
US continuity Longline	1987-
Venezuela Longline	1991-

Table 3. Specifications of the biomass dynamic used for the 2016 stock assessment and also used in this MSE.

Software	Model	Catch series	Starting values
mpb	Fox (biomass dynamic)	1930-2014	Intrinsic growth rate: r=0.1 Carrying capacity: K= 3.6 x 10^6 tonnes Biomass at t=0 (fixed): 1 x K

Table 4. Performance of Harvest Control Rules. Bmin, Bmean and Fmean are relative to MSY levels. Catch (Y1=short term, Y2=mid term and Y3=long term) in k tons. Probabilities in %. MAP, sd and maxTACc in k tons.

HCR			Stock Status					Safety		Catch			Stability					
Ftar	Bthresh	δTAC	Bmin	Bmean	Fmean	pGr%	pRed%	pBlim%	pBint%	Y1	Y2	Y3	MAP	sd	var	pshut	p10%	maxTACc
0.60	0.60	20%	0.65	2.02	0.51	93	0	100	5	23.17	21.14	28.24	1.20	4.82	2E+07	0	19.84	8.69
0.70	0.60		0.45	1.91	0.58	90	2	100	7	23.63	23.05	30.80	1.31	5.41	3E+07	0	19.31	9.35
0.80	0.60		0.28	1.76	0.65	83	3	100	10	24.25	24.80	32.49	1.42	5.78	3E+07	0	19.55	10.28
0.90	0.60		0.23	1.66	0.71	81	6	100	12	25.46	26.75	33.73	1.53	5.83	3E+07	0	20.21	10.76
1.00	0.60		0.12	1.44	0.87	66	13	98	19	25.45	28.68	34.54	1.67	6.26	4E+07	0	21.00	11.74
0.60	0.80		0.63	2.04	0.51	93	0	100	5	23.16	21.06	28.34	1.21	4.88	2E+07	0	19.90	8.71
0.70	0.80		0.41	1.88	0.59	88	2	100	7	23.54	22.97	30.79	1.31	5.41	3E+07	0	19.62	9.59
0.80	0.80		0.34	1.76	0.62	86	3	100	9	24.30	24.49	32.32	1.42	5.74	3E+07	0	19.95	10.25
0.90	0.80		0.23	1.65	0.70	78	6	99	14	24.81	26.22	33.42	1.51	6.13	4E+07	0	20.88	10.75
1.00	0.80		0.19	1.58	0.76	72	9	99	16	25.33	27.15	34.77	1.66	6.40	4E+07	0	21.21	11.60
0.60	1.00		0.62	2.02	0.51	92	1	100	6	23.17	20.61	28.31	1.22	5.01	3E+07	0	20.00	8.74
0.70	1.00		0.47	1.95	0.56	92	1	100	6	23.36	21.95	31.10	1.37	5.74	3E+07	0	20.48	9.78
0.80	1.00		0.37	1.81	0.61	83	2	100	11	23.93	22.62	32.56	1.49	6.34	4E+07	0	20.76	10.67
0.90	1.00		0.25	1.70	0.68	79	5	100	13	24.44	23.62	34.34	1.61	7.05	5E+07	0	21.14	11.51
1.00	1.00		0.19	1.62	0.73	76	7	99	13	24.46	24.46	35.26	1.69	7.10	5E+07	0	21.41	11.92
0.60	0.60	25%	0.58	2.03	0.51	92	0	100	6	21.46	21.14	29.06	1.40	5.61	3E+07	0	20.74	10.09
0.70	0.60		0.40	1.86	0.59	89	2	100	7	22.27	23.25	30.99	1.51	5.95	4E+07	0	20.38	10.84
0.80	0.60		0.25	1.74	0.67	80	4	100	11	23.10	25.03	32.71	1.65	6.34	4E+07	0	20.93	11.88
0.90	0.60		0.17	1.52	0.76	73	8	99	14	24.14	27.08	33.90	1.78	6.38	4E+07	0	21.34	12.73
1.00	0.60		0.14	1.47	0.82	69	12	98	18	24.99	28.79	33.99	1.92	6.73	5E+07	0	22.22	13.20
0.60	0.80		0.60	2.04	0.50	93	1	100	6	21.67	20.87	29.12	1.38	5.55	3E+07	0	20.67	10.00
0.70	0.80		0.40	1.87	0.59	88	2	100	8	22.07	22.99	31.09	1.52	6.10	4E+07	0	20.93	11.00
0.80	0.80		0.19	1.72	0.68	82	4	100	10	23.10	24.60	33.11	1.70	6.72	5E+07	0	21.53	12.18
0.90	0.80		0.18	1.60	0.74	77	7	99	14	23.42	26.09	34.25	1.79	7.00	5E+07	0	21.34	12.61
1.00	0.80		0.17	1.61	0.78	70	11	98	16	24.56	27.34	34.59	1.96	7.13	5E+07	0	22.59	13.75
0.60	1.00		0.57	2.01	0.50	93	0	100	6	21.63	20.30	29.24	1.44	5.89	3E+07	0	21.19	10.24
0.70	1.00		0.39	1.90	0.58	88	2	100	8	21.94	21.61	31.27	1.57	6.48	4E+07	0	21.45	11.36
0.80	1.00		0.30	1.81	0.62	84	3	100	9	22.62	22.78	33.37	1.75	7.26	5E+07	0	21.81	12.59
0.90	1.00		0.23	1.72	0.68	80	5	99	11	23.58	23.52	34.87	1.88	7.61	6E+07	0	22.10	13.26
1.00	1.00		0.17	1.63	0.74	74	8	99	15	23.33	24.56	35.48	1.99	7.91	6E+07	0	22.69	13.98
0.60	0.60	30%	0.51	2.01	0.52	91	1	100	7	21.00	21.09	29.33	1.51	6.09	4E+07	0	21.24	11.29
0.70	0.60		0.39	1.94	0.57	88	2	100	8	22.25	23.37	30.92	1.67	6.44	4E+07	0	21.22	12.41
0.80	0.60		0.22	1.73	0.67	81	4	100	13	23.11	25.28	32.62	1.82	6.85	5E+07	0	21.84	13.17
0.90	0.60		0.17	1.59	0.73	73	8	99	14	24.25	27.17	33.56	2.04	7.18	5E+07	0	22.48	14.51
1.00	0.60		0.16	1.52	0.82	68	13	97	18	24.90	28.53	33.68	2.08	7.08	5E+07	0	22.86	14.70
0.60	0.80		0.53	2.01	0.51	91	0	100	5	20.70	21.00	29.12	1.51	6.16	4E+07	0	21.48	11.45
0.70	0.80		0.37	1.89	0.57	85	2	100	11	21.71	22.51	31.15	1.70	6.74	5E+07	0	21.48	12.43
0.80	0.80		0.23	1.75	0.66	83	4	100	9	22.67	24.40	32.78	1.89	7.01	5E+07	0	22.19	13.57
0.90	0.80		0.19	1.63	0.73	77	7	99	14	23.75	25.65	33.96	2.02	7.85	6E+07	0	22.21	14.50
1.00	0.80		0.13	1.51	0.81	69	11	98	18	23.39	27.10	34.56	2.20	8.01	6E+07	0	23.45	15.50
0.60	1.00		0.56	2.07	0.51	94	1	100	5	21.08	19.94	29.15	1.52	6.16	4E+07	0	21.40	11.14
0.70	1.00		0.39	1.93	0.56	88	1	100	7	21.47	21.50	31.41	1.75	7.15	5E+07	0	21.91	12.62
0.80	1.00		0.28	1.81	0.62	81	3	100	10	22.09	22.68	33.41	1.93	7.92	6E+07	0	22.41	13.99
0.90	1.00		0.19	1.70	0.70	78	6	99	12	22.47	23.69	34.35	2.09	8.41	7E+07	0	23.14	15.07
1.00	1.00		0.19	1.67	0.73	74	8	99	14	22.35	24.28	34.74	2.24	8.56	7E+07	0	23.43	15.65

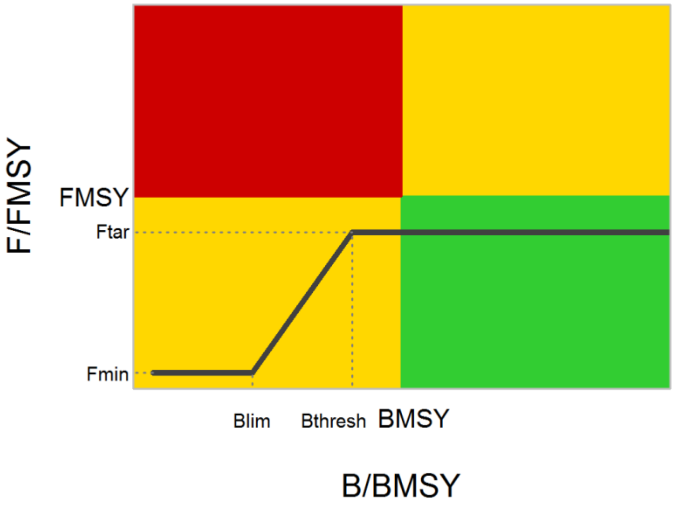

Figure 1. Generic form of the HCR recommended by SCRS and ICCAT's Rec. 16-06.

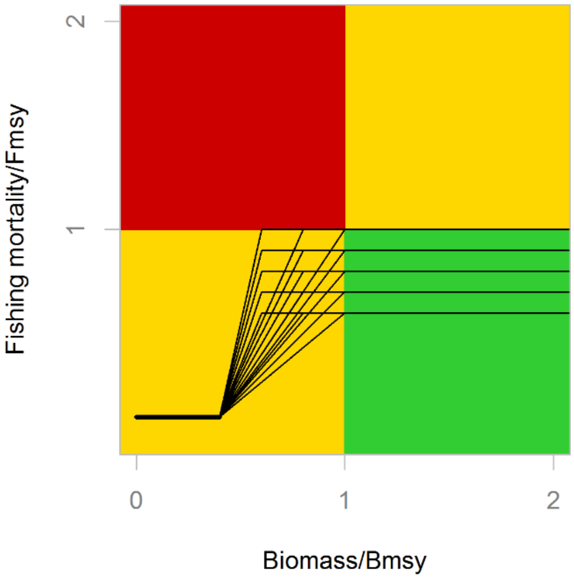

Figure 2. HCRs evaluated in this study.

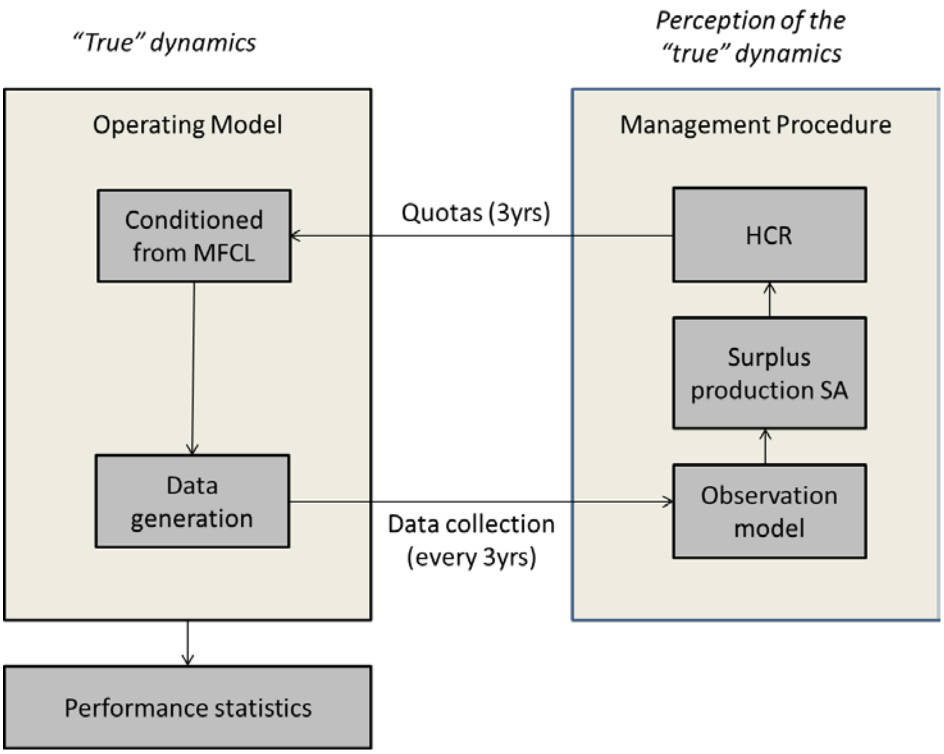

Figure 3. MSE framework and scheme of the simulation used in this study.

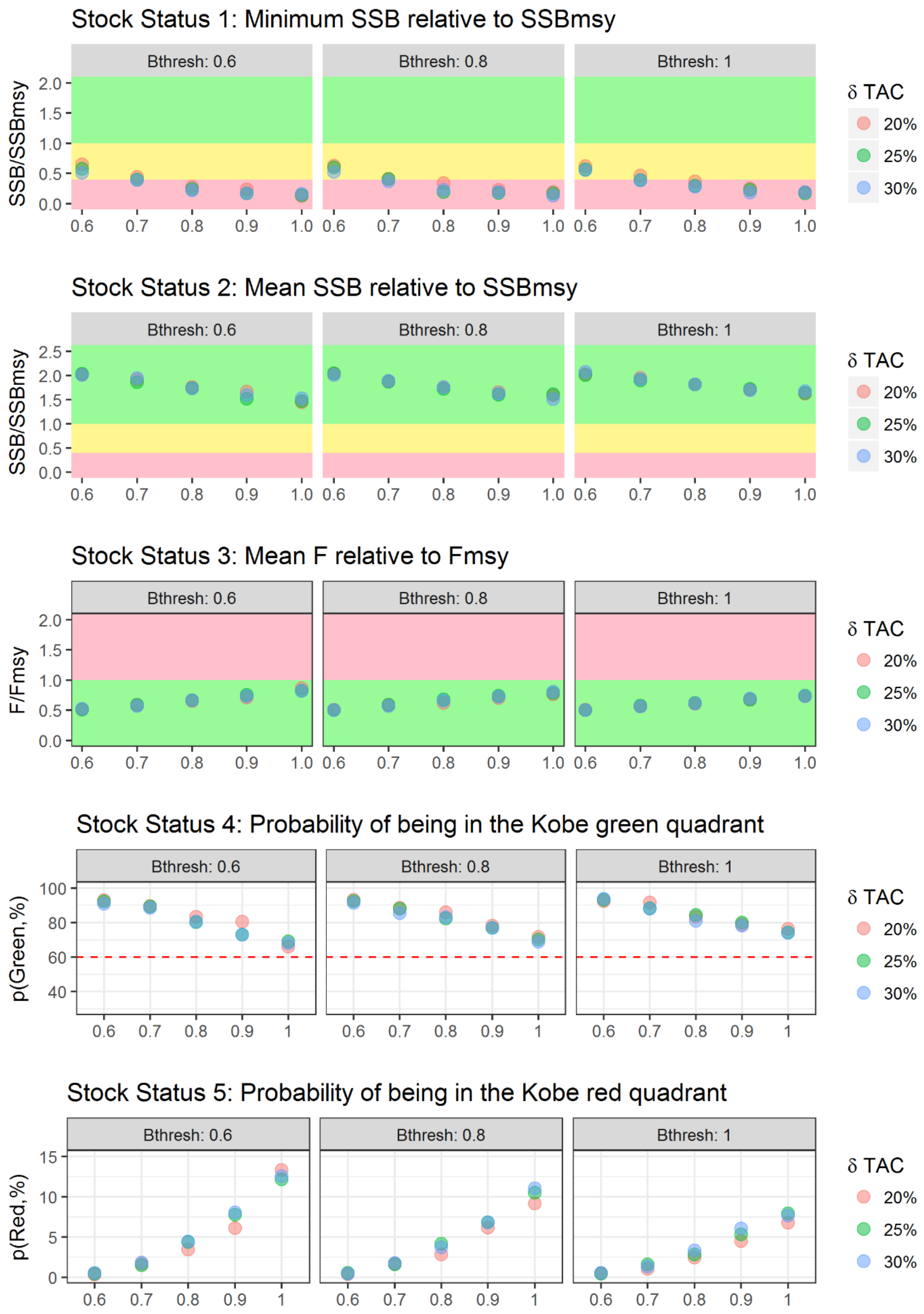

Figure 4. Stock status indicators.

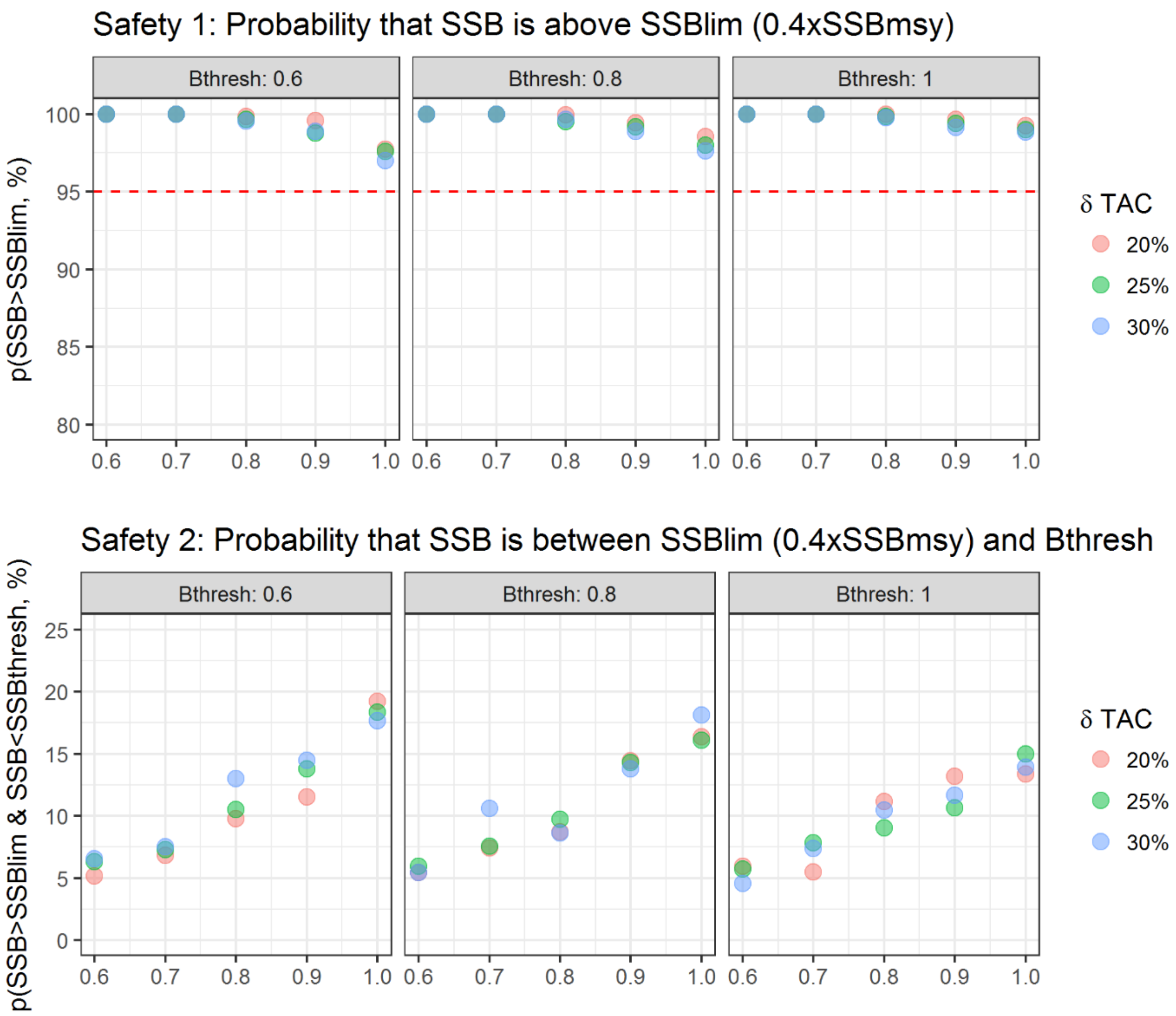

Figure 5. Safety indicators.

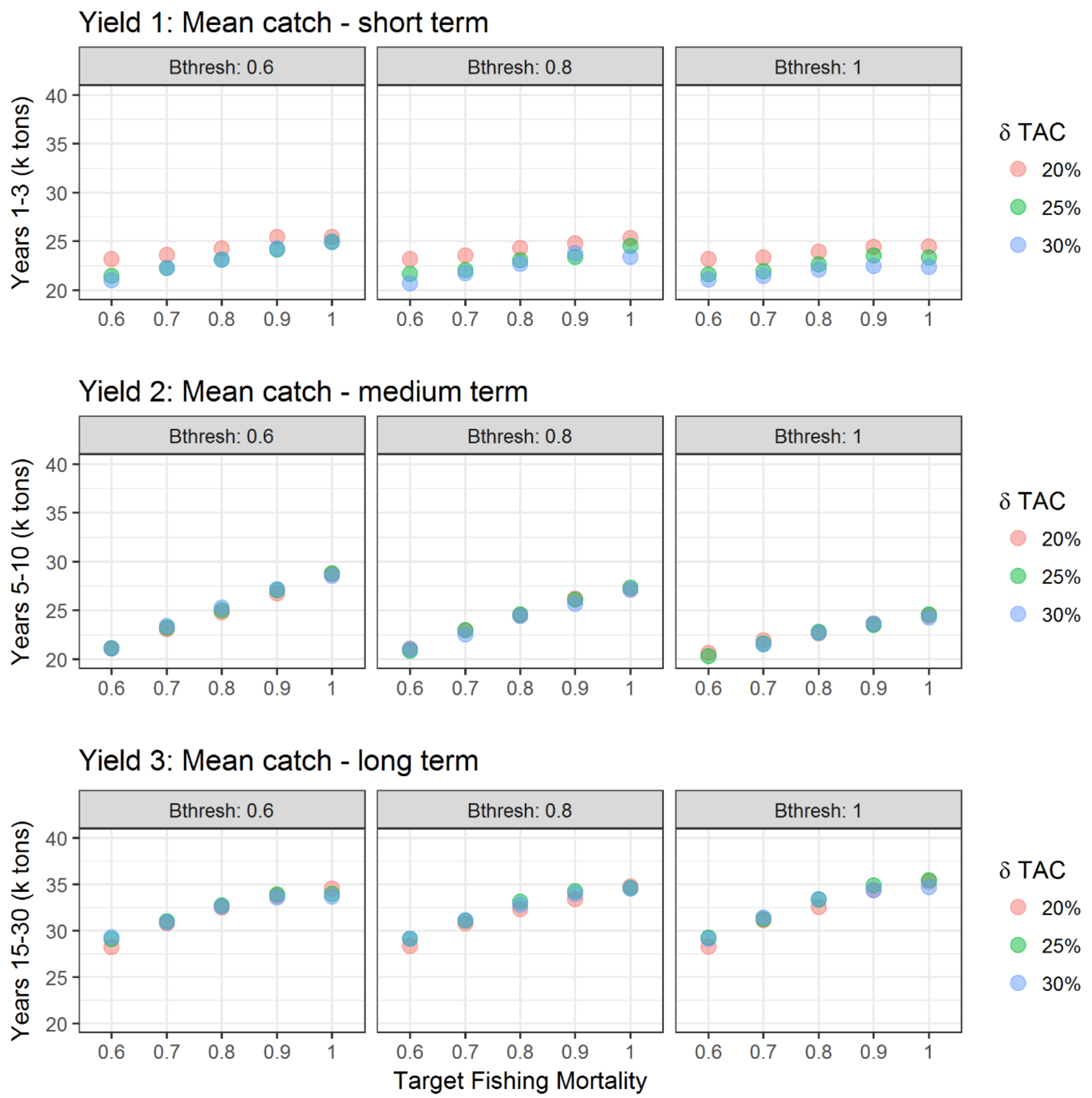

Figure 6. Catch indicators.

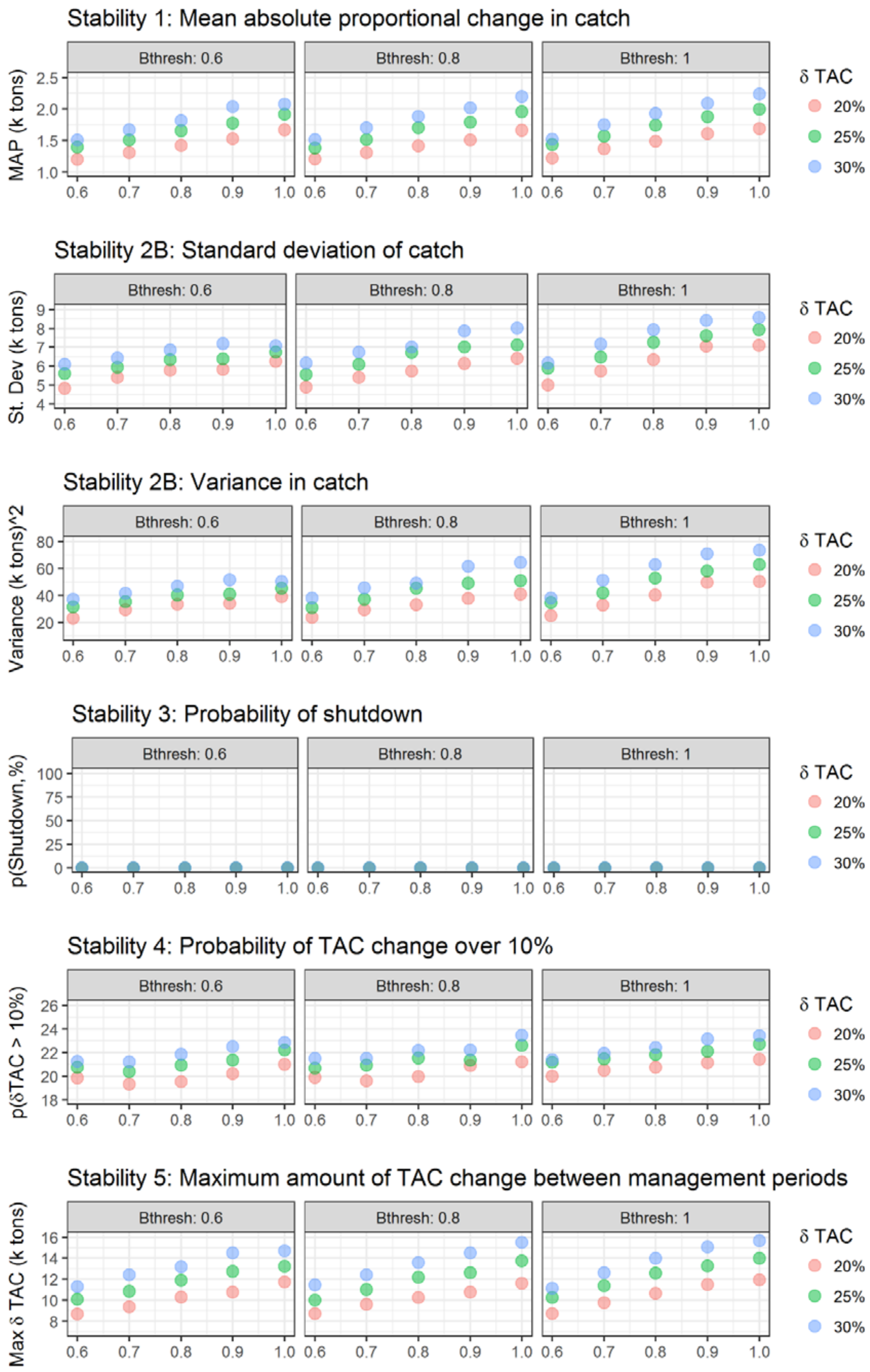

Figure 7. Stability indicators.

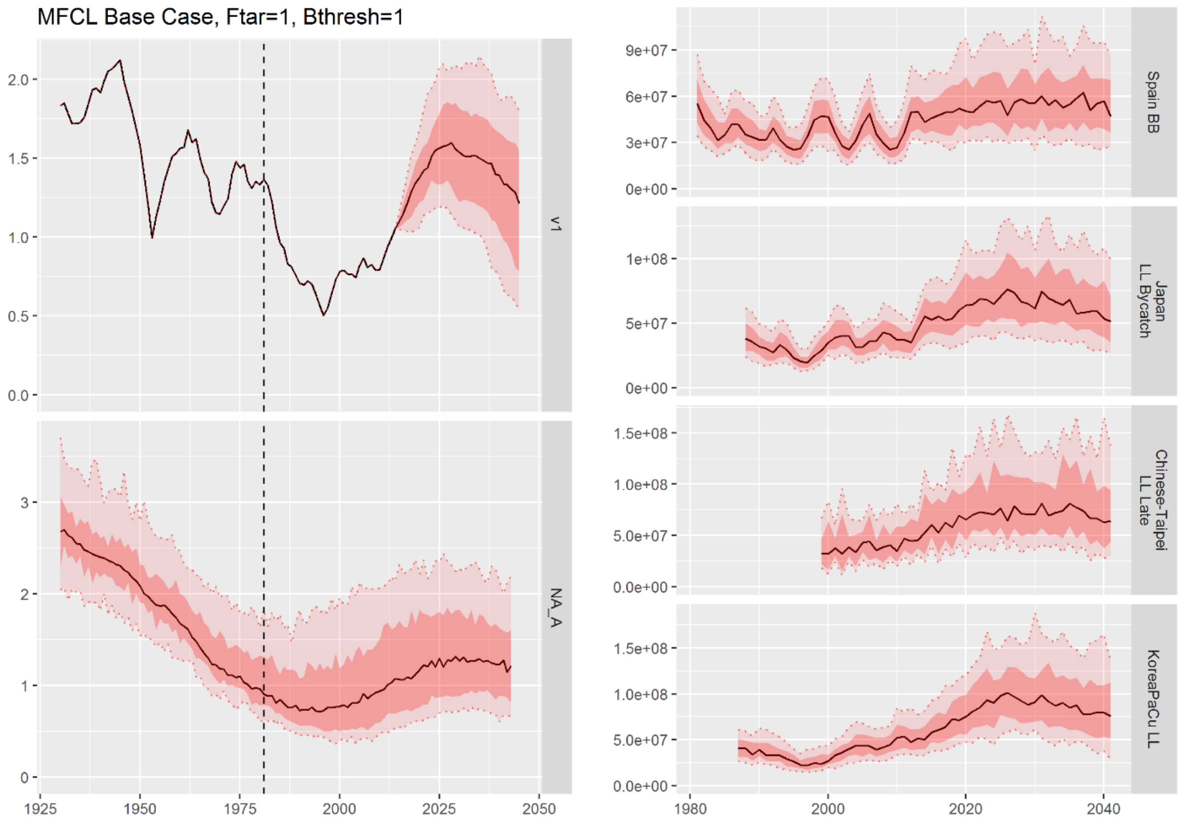

Figure 8. Upper left: Base Case operating model's relative biomass from the 2013 stock assessment projected with F_{TAR}=1 and B_{THRESH}=1. Bottom-left: MP estimate of the Base Case OM relative stock biomass. The vertical dashed line represents the first year with CPUE observations. Also note that the simulation with MSE starts in 2015. Right: Generated CPUE indices from the Base Case OM.

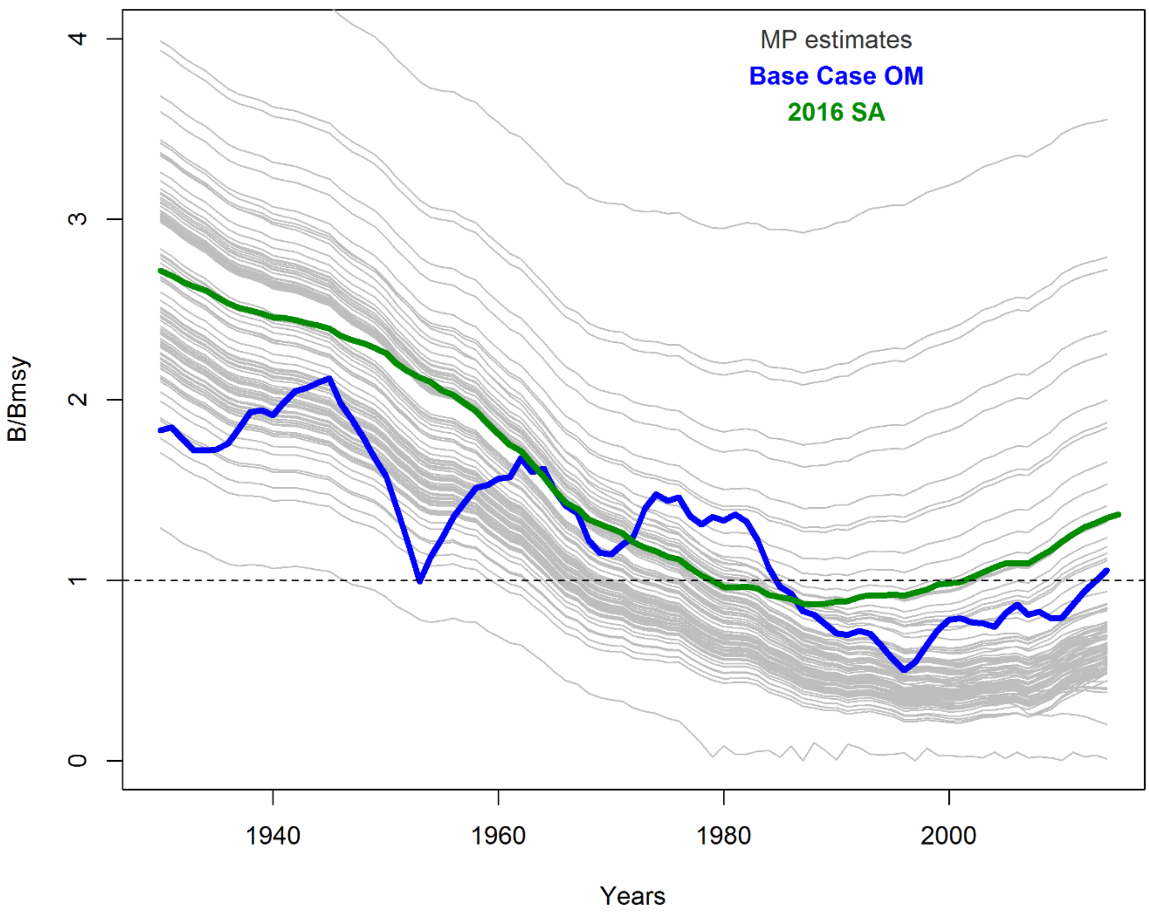

Figure 9. MP-Estimated relative stock trajectory (gray), Base Case OM (blue) and trajectory estimated in the 2016 stock assessment (green). Note that iterations are fits to the generated CPUE series with 0.2 CV.

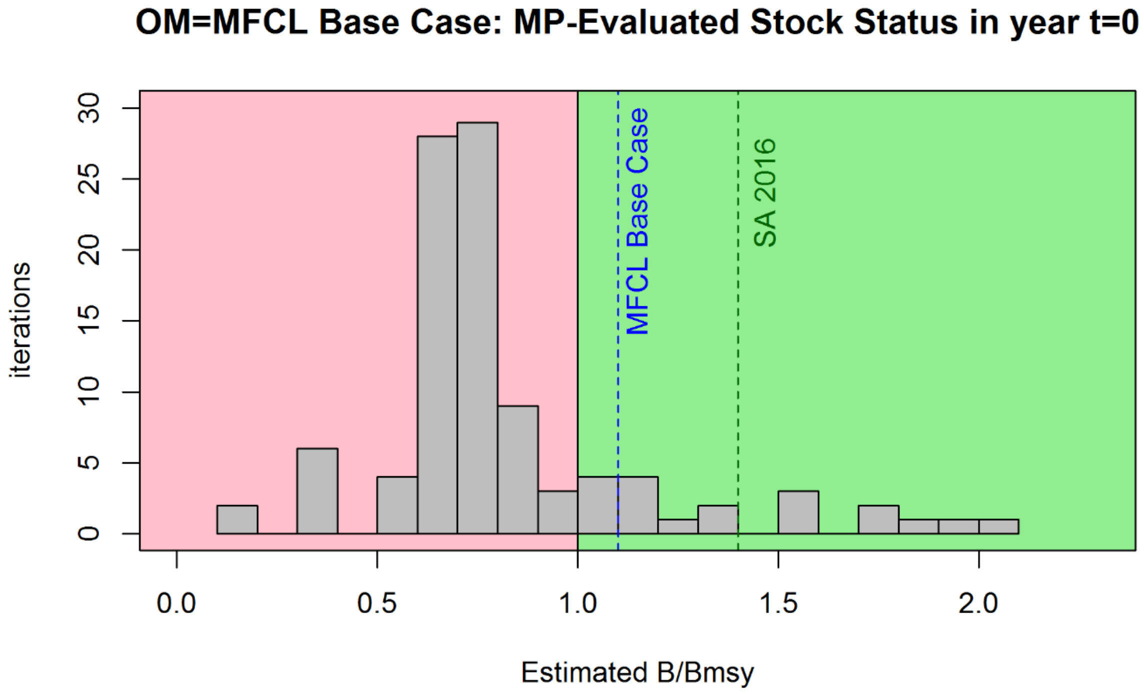

Figure 10. Histogram of MP-estimated stock status in 2015 (gray bars) from the Base Case OM (blue). In green, the estimated stock status in 2015 from the 2016 stock assessment.

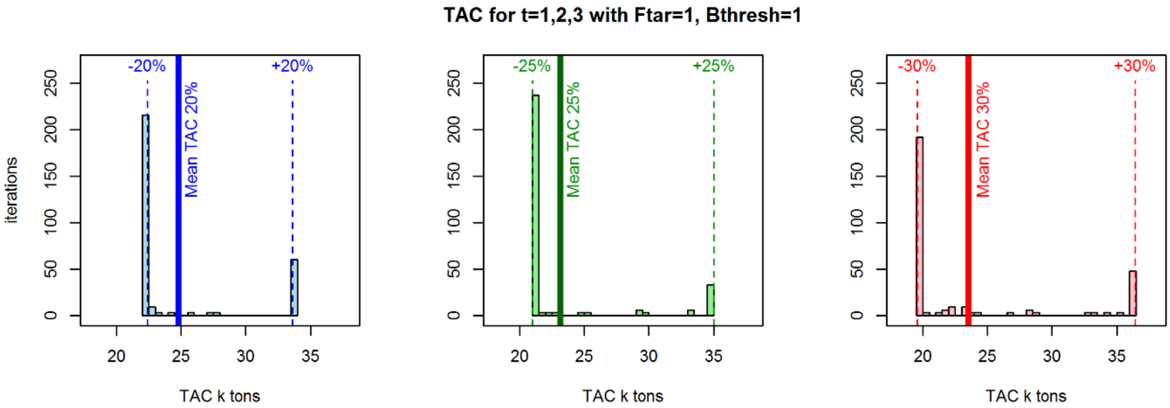

Figure 11. Histograms of short term TAC determined by the MP applied to the Base Case OM using a HCR with F_{TAR}=1 and B_{THRESH}=1. Blue represents TAC with the 20% constraint, green with 25% and red with 30%.