# A multi-stock harvest control rule based on “pretty good yield” ranges to support mixed-fisheries management

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## Abstract

Advice for commercially exploited fish stocks is usually given on a stock-by-stock basis. In light of the ecosystem-based fisheries management the need to move towards a holistic approach has been largely acknowledged. In addition, the discard bans in some countries requires consistent catch advice among stocks to mitigate choke species limiting fisheries activity. In this context, in 2015, the European Commission proposed the use of fishing mortality ranges around fishing mortality targets to give flexibility to the catch advice system and improve the use of fishing opportunities in mixed-fisheries. We present a multi-stock harvest control rule (HCR) that uses single stock assessment results and fishing mortality ranges to generate a consistent catch advice among stocks. We tested the performance of the HCR in two different case studies. An artificial case study with three stocks exploited simultaneously by a single fleet and the demersal mixed-fishery operating in Bay of Biscay and Celtic Sea. The HCR produced consistent catch advice among stocks when there was only a single fleet exploiting them. Even more, the HCR removed the impact of the discard ban. However, in a multi-fleet framework the performance of the HCR varied depending on the characteristics of the fleets.

*Keywords: harvest control rule, landing obligation, mixed-fisheries, pretty good yield, EBFM.*

# 1 Introduction

There is growing focus worldwide on implementation of ecosystem based fisheries management (EBFM) (Pikitch *et al.*, 2004), recognising the need for a holistic approach. Nevertheless, most fisheries management is still undertaken on a stock-by-stock basis, using tools such as total allowable catch (Ballesteros et al., 2018) which centre around the goal of maximum sustainable yield (MSY) (Kempf *et al.*, 2016). This form of management does not reflect the reality of most mixed-fisheries where multiple species are caught together. Particularly in the case of demersal fisheries where fishers have limited flexibility to discriminate between species during fishing operations. This mismatch between the multi-species outcomes of fishing operations and the single species catch advice produces an incentive to generate over-quota discards (Ulrich et al., 2011a). In places where there is a discard ban (EU, 2013) (Gullestad *et al.*, 2015) the mismatch of catch advices results in the emergence of choke species (Schrope, 2010). Choke species arise when the catch advice of one stock for a certain fleet or vessel is so restrictive that it does not allow them to fish a great part of the catch quotas of the rest of the stocks because it would mean exceeding the quota of that stock, thereby “choking” the fishery. Considering these challenges, there is a real requirement to expand the management tools available to support the implementation of mixed-fisheries management.

Over the last decade, mixed-fisheries research has focused on quantifying and describing the complex nature of fisheries by modelling fleet dynamics in a multi-specific framework (Salas and Gaertner, 2004; Branch *et al.*, 2006; van Putten *et al.*, 2012). Within Europe, this research has been translated into the generation of mixed-fisheries management advice (ICES, 2018). This advice is produced using the Fleet and Fisheries Forecast model (FCube) (Ulrich *et al.*, 2011, Iriondo *et al.*, 2012 Maravelias *et al.*, 2012). FCube uses the output from the single species stock assessments and catch and effort data at fleet and métier level to explore the consequences of different management alternatives based on the single species stock total allowable catch (TAC).

In 2014, fishing mortality ranges (FMRs) around the MSY objective (ICES, 2015) were developed with the goal of alleviating the choke effect of some species under a landing obligation policy (Salomon et al., 2014; ICES, 2015). The International Council for the Exploration of the Sea (ICES) and the Scientific, Technical and Economic Committee for Fisheries of the European Commission (STECF) identified the FMRs and evaluated their sustainability for the stocks with quantitative impact assessments (ICES, 2015; STECF, 2015). Although these FMRs provide an upper and lower bound for fishing mortality, the use of the upper end of the FMR by decision makers is considered exceptional and not the norm, to avoid a permanent fishing pressure above the fishing mortality target at MSY (Kirkegaard, 2018). Yet in practice, there are no currently defined guidelines to operationalise the use of FMRs. Single stock catch advice is usually produced using harvest control rules (HCRs), which are mathematical formulas that produce management advice based on stock status indicators and reference points (Deroba and Bence, 2008; Froese *et al.*, 2010; Dichmont *et al.*, 2016). Therefore, extending existing HCRs using the bounds of the FMRs as reference points and considering technical interactions among the stocks seems a natural way to move forward.

Several publications have presented methods for implementing the FMRs in a mixed-fisheries context. Thorpe *et al.* (2017) analysed, with a sized-based multispecies model, the use of the

FMRs on the North Sea demersal fishery. They concluded that fishing in the lower bound of the FMR results in a much lower risk to the sustainability of the stocks while the impact on long term yield was small. Rindorf *et al.* (2017a) defined an operating framework to translate the principles of the "pretty good yield" (capture <= 95% MSY) to "pretty good multispecies yield" (very good multi-specific performance). Ulrich *et al.* (2017) developed a method to operationalise the use of FMRs minimising the difference in catches obtained in two opposite fleet dynamic scenarios. This method was then translated into mixed-fisheries advice where the FMRs were used to provide an optimal set of fishing mortality within the ranges. These fishing rates were intended to minimise the risk of total allowable catch advice mismatches and address trade-offs between the most and least productive stocks (Ulrich *et al.*, 2017; ICES, 2017).

In this work we present a new harvest control rule (HCR) to operationalise catch advice using the flexibility provided by these FMRs. The method proposed by Ulrich et al. (2017) operates at fleet level, whereas the HCR proposed in this paper operates at the stock level, based on the output of the single species stock assessment models. The objective of the harvest control rule is to produce consistent TAC advice among stocks within the FMRs while maximising the use of fishing opportunities. To illustrate the use of the proposed HCR, it is applied in two case studies.  The first case study is a hypothetical case study with three stocks and a single fleet which harvests them in a mixed-fisheries framework. The second case study is the demersal multi-fleet fishery which operates in Bay of Biscay and Celtic Sea. The first case study allows us to evaluate the performance and properties of the HCR under ideal conditions, while the second one allows us to test it in a real scenario where the multi-fleet interactions could affect its performance. The bio-economic performance of the HCR was compared with the performance of the current single stock MSY approach used by ICES to produce TAC advice. The comparison was done in terms of, (i) the ability of the HCR to bring the fishing mortality within the FMRs, (ii) the probability of the biomass being above the limit reference point and (iii) the uptake of fishing opportunities. The utility and application of this work is discussed in terms of mixed-fisheries within the region and wider implications for management.

# 2 Material and methods

## 2.1 Multi-Stock HCR

A multi-stock HCR was developed with the objective of fulfilling the following conditions:

1. To produce compatible catch advice among the stocks.
2. To maximise uptake of fishing opportunities.
3. To generate fishing mortality levels compatible with FMRs.

*1. Compatible catch advice.*

First, we assume a linear relationship between fishing mortality (F) and effort (E), with catchability, *q*, as proportionality parameter, i.e., F = q*E. Under this assumption to obtain consistent fishing mortality advice among the stocks we can multiply the current fishing mortalities, i.e., the *status-quo* fishing mortalities, $F_{sq}$, by the same parameter, µ. Mathematically:

$$\mathrm{Fadv}_{st} = \mu \cdot \mathrm{Fsq}_{st} \quad (1)$$

where *st* denotes the subscript for stock and $F_{\mathrm{adv}}$ the fishing mortality that will correspond with the TAC advice. Then, the solution consists on defining a µ that fulfils conditions 2 and 3.

*2. Maximise uptake of fishing opportunities*

If the $F_{\text{adv}}$ for all the stocks is equal or higher than the corresponding $F_{\text{target}}$ then all the fishing opportunities corresponding with MSY are being used. Then, we need to define $\mu_0$ such that:

$$\mathrm{Fadv}_{st} = \mu_0 \cdot \mathrm{Fsq}_{st} = \max_{st}\left(\frac{\mathrm{Ftarget}_{st}}{\mathrm{Fsq}_{st}}\right) \cdot \mathrm{Fsq}_{st} \quad (2)$$

However, this option could produce fishing mortality advice in the upper part of the FMR more often than desired. To avoid this, the 'max' option can be replaced by the mean or the minimum. The multiplier obtained with the maximum option corresponds with the lowest multiplier that ensures the advice of all the stocks is equal or above $F_{\text{target}}$. However, if the 'max' option results in exploitation levels for a stock that are too often above the target, replacing it by 'mean' is a more conservative alternative. The most conservative option is to use the minimum of the ratios, but this option would produce a loss of fishing opportunities for all the stocks except for the one that corresponds with the minimum.

*3. Compatible with FMRs*

With the 'max' and 'mean' options, the F advice in the previous step could be higher than the upper bound of the FMR of some stocks. Conversely, with the 'min' option, it could be lower than the lower bound. Hence, if necessary, the multiplier $\mu_0$ is corrected applying a second multiplier to ensure that $F_{\text{adv}}$ falls within the FMRs for all the stocks:

$$F\mathrm{adv}_{st} = \begin{cases} \mu_0 \cdot \mathrm{Fsq}_{st} & \text{if } F\mathrm{low}_{st} \leq \mu_0 \cdot \mathrm{Fsq}_{st} \leq F\mathrm{upp}_{st} \text{ for all } st, \\ \mu_1 \cdot \mu_0 \cdot \mathrm{Fsq}_{st} & \text{if } \exists\, st \;:\; \mu_0 \cdot \mathrm{Fsq}_{st} < F\mathrm{low}_{st} \mid \mu_0 \cdot \mathrm{Fsq}_{st} > F\mathrm{upp}_{st} \end{cases} . \quad (3)$$

where $F_{\text{upp}}$ *and* $F_{\text{low}}$ are the upper and lower bounds of the FMRs respectively and the calculation of the second multiplier $\mu_1$ depends on the options used. If 'max' or 'mean' options were used:

$$\mu_1 = \min_{st}\left(\frac{\mathrm{Fupp}_{st}}{\mathrm{Fadv}_{2,st}}\right) \quad (4)$$

Where $\mathrm{Fadv}_{2,st}$ correspond with the fishing mortality advice obtained in step 2. If ‘min’ option was used:

$$\mu_1 = \mathrm{min}_{st}\left(\mathrm{max}_{st}\left(\frac{\mathrm{Flow}_{st}}{\mathrm{Fadv}_{2,st}}\right), \frac{\mathrm{Fupp}_{st}}{\mathrm{Fadv}_{2,st}}\right) \quad (5)$$

The HCR with ‘max’ or ‘mean’ options could result in fishing mortality advice for some stocks below the lower bound of the FMR. However, as the fishing mortalities of all the stocks are moved by the same proportion, moving them to the lower bound would imply moving the fishing mortality advice of one of the other stocks above the upper bound of the FMR. Conversely, with the ‘min’ option, the multiplier is corrected to move the fishing mortality advice for all stocks above the lower bound (Equation 5) so to ensure that none of them exceed the upper bound. A graphical representation of the HCR is provided in Figure 1.

[Insert Figure 1]

## 2.2 Case studies

The HCR was tested in two case studies. The stocks and their conditioning were the same in both case studies. The stocks included were the northern stock of hake (*Merluccius merluccius*), megrim (*Lepidorhombus whiffiagonis*) and white anglerfish (*Lophius piscatorious*) in the Bay of Biscay and Celtic Sea. In the first case study the fishery comprised a single fleet with a single métier which caught the three stocks simultaneously. In contrast, in the second case study the fishery was disaggregated in fleets and métiers which differed in the country, gear, mesh size, target species and area.

## 2.3 Area

The distribution of two of the stocks considered, white anglerfish and megrim, comprises ICES Subarea 7 and Divisions 8a,b,d (Figure 2). This area includes the Bay of Biscay and Celtic Seas ecoregion and the English Channel which is part of the Greater North Sea ecoregion (http://www.ices.dk/community/advisory-process/Pages/Ecosystem-overviews.aspx). The distribution of the third stock, northern hake, is much broader, from the Bay of Biscay to Norway, ICES Subareas 4, 6, and 7, and in Divisions 3a and 8a,b,d, (Figure 2). Although the catch advice for the stocks is calculated by ICES (ICES, 2018b) for the whole area of distribution, in terms of management, catch quotas are assigned to different areas. The catch quota of megrim and white anglerfish is given separately for Bay of Biscay (ICES Divisions 8a,b,d) and Celtic Sea and English Channel (ICES Subarea 7). In turn, the catch quota of hake is assigned to four different areas, two areas with a low quota share, the Skagerrak & Kattegat and the North Sea, a third one in the Celtic Sea and a fourth one in the Bay of Biscay. These quotas were established in 1983 ((EEC) No 170/83) according to historical catch records. However, as the quotas were based on landings, the composition and technology of the fishery has evolved over time and the abundance and even the availability of the stocks have also changed, at present, there is a mismatch between the quotas and real catches. The study is focused solely in the Bay of Biscay and Celtic Seas ecoregion.

[Insert Figure 2]

## 2.4 The stocks

The three stocks considered are assessed annually by ICES in the Bay of Biscay and Iberian Waters working group (WGBIE) (ICES, 2018b). Each of them has an analytical assessment and therefore absolute estimates of stock abundance and exploitation rate. Hake is assessed with the statistical integrated assessment method SS3 (Methot Jr and Wetzel, 2013). Megrim is assessed with a Bayesian statistical catch at age model designed specifically for this stock from the model presented in Fernandez *et al.* (2010). Finally, white anglerfish is assessed with a generic statistical catch at age model (Jardim *et al.*, 2014).

The catch advice for these stocks is given using the harvest control rule defined by ICES in the framework of MSY. This HCR returns fishing mortality as a function of Spawning Stock Biomass (SSB) and afterwards the fishing mortality is translated into catch using the traditional catch production function developed by Baranov (Baranov, 1918; Branch, 2009) . The target fishing mortality in the HCR corresponds with MSY value when SSB is above the reference level $B_{trigger}$, if it is below the fishing mortality, it is decreased linearly. Case specific extraordinary measures are foreseen for the cases where SSB falls below the reference level $B_{lim}$ ($B_{lim} < B_{trigger}$ ). FMRs for the three stocks were calculated by ICES experts in several working groups (ICES, 2015; ICES, 2016; ICES, 2018a). The models used to calculate the FMRs project age structured populations forward using exponential survival equation and a stock-recruitment relationship introducing several sources of uncertainty. The FMRs were defined as the fishing mortalities levels that result in long term catches higher than 95% of MSY and which result in a probability of SSB falling below $B_{lim}$ lower than 5%.

## 2.5 The fleets

Within the study area the three species of interest are fished by a number of member states (Belgium, France, Ireland, Spain and United Kingdom), using a variety of gears; trawlers, longliners and gillnetters which respectively catch the 49%, the 28% and the 23% of the total catch of the three species, according to the data available in the ICES mixed-fisheries working group (ICES, 2018c). These percentages have been stable throughout the historic time series available for this study. Each of these gears interact with the three species of interest differently, resulting in varying mixed-fisheries interactions. For example, longliners show low level of mixed-fisheries interactions, and it is considered a highly targeted fishery, catching mostly hake. Gillnetters target hake species, however, this gear type demonstrates a mixed-fisheries interaction with white anglerfish. Finally, trawlers, depending on the season and fishing area shows a wide variety of mixed-fisheries interactions resulting in all three species becoming targets and interacting at different levels depending on the fishing operations.

Regarding selectivity, longliners catch mainly big hake individuals, from 40 cm to 80 cm, with the mean around 60 cm in a symmetric length distribution. The selectivity of gillnetters covers a greater range from 20 cm to 100 cm. In general, the length distribution has a negative skew and the mean is around 70 cm. The length distribution of trawlers depends on the area, while trawlers in ICES subarea 8 catch mainly individuals up to 40 cm, in ICES subarea 7 the individuals reach up to 80 cm. Megrim and white anglerfishes are mainly caught by demersal bottom trawlers. The length distribution in the catch of megrim comprises individuals mainly from 23 to 53 cm and in the case of white anglerfish from 10 to 100 cm.

The effort and catch data of the fishing activity are collected and classified according to the fleet segments and métiers defined in the European Data Collection Framework (DCF) (2010/93/EU Appendix IV). A fleet (or fleet segment) is a group of vessels with the same length class and predominant fishing gear during the year (EC, 2008). A métier is a group of fishing operations targeting a similar (assemblage of) species, using similar gear, during the same period of the year and/or within the same area and which are characterised by a similar exploitation pattern (EC, 2008). As such, the fleet describes the vessels while the métier(s) describes the fishing activity(ies) in which the fleet engages (EC, 2008).

## 2.6 The simulation

The performance of the HCR was evaluated using the FLBEIA simulation model (Garcia *et al.*, 2017). FLBEIA is a multi-fleet and multi-stock bio-economic model developed in R using FLR libraries (Kell *et al.*, 2007). The simulation started in 2018, ended in 2040 and it was run in parallel for 1000 iterations to take account of uncertainty in stock and fleet parameters.

### 2.6.1 The stocks

Stock data used in the conditioning of the model was taken from ICES assessment working group of the stocks (ICES, 2018b). Models used to describe the stock dynamics, the parameters used and the conditioning of the uncertainty were the same as those used in the calculation of the FMRs of these stocks (ICES, 2015; ICES, 2016; ICES, 2018a).

The historical populations were projected forward using the exponential survival equation and a stock-recruitment relationship. Uncertainty in recruitment was introduced by varying the parameters of the stock-recruitment model in each iteration and adding a random variation around the stock-recruitment curve. For hake and megrim, a segmented regression stock recruitment relationship was used. Initially Beverton and Holt, Ricker and segmented regression models were fitted, in a Bayesian framework for hake and using bootstrap in the case of white anglerfish and megrim. For hake and megrim the segmented regression stock recruitment model was the best model in more than 80% of the iterations and the working group decided to use only segmented regression model to simulate the dynamics of these stocks (ICES, 2015; ICES, 2016). Furthermore, the breakpoint in the megrim stock recruitment model was fixed at the lowest observed biomass, because there was no apparent relationship between stock and recruitment. Hence, only the second parameter varied with iterations. For white anglerfish there was not a clear predominant relationship and a mixture of Beverton and Holt, Ricker and segmented regression was used (ICES, 2018a). In each iteration one of the three was chosen, Beverton and Holt in 9% of the iterations, Ricker in 35% and segmented regression in 56%. The conditioning of biological parameters carried out by the ICES working groups in the calculation of FMRs was based on the data used in the assessment models of the stocks (ICES, 2015; ICES, 2016; ICES, 2018b; ICES, 2018a). For the three stocks, natural mortality and maturity were constant in the projection. For hake, weight at age was also constant but for white anglerfish and megrim it was sampled randomly from the last ten years.

Ten years is the default value recommended by ICES to bootstrap selection pattern and biological parameters when there are no trends in the data (ICES, 2015). In the calculation of FMRs, assessment error was also introduced. However, in the present analysis, we did not include any error in the assessment in order to isolate the performance of the HCR from the errors in the management procedure.

In the single fleet case study, no uncertainty was introduced because the objective of the case study was to demonstrate the performance of the HCR under ideal conditions. Otherwise, it would not have been possible to distinguish between the effect of the HCR and the effect of the uncertainty. Hence, the median values were used to simulate the population. In this case study, the recruitment of white anglerfish was simulated with the segmented regression model that was the most probable of the three considered (see above). The performance of the HCR in a complex case study which includes technical interactions at fleet and stock level and including uncertainty in the key input factors was analysed in the multi-fleet case study.

### 2.6.2 The fleets

Catch and effort data at métier level are annually reported by the member states to ICES. The data reported comprises a huge number of fleets and métiers which makes it difficult to consider all of them in a simulation framework. Hence, to reduce the number of fleets and métiers, the fleets with a contribution to the total catch lower than 1% were merged into a single fleet. The merging process was done by stock, and one fleet per stock was defined to merge the catches of these marginal fleets. Furthermore, catches of hake in the North Sea were aggregated in an additional fleet with a single métier. The distributions of megrim and white anglerfish do not include the North Sea, hence there was no need to consider catches of these stocks for the North Sea fleet. The final configuration resulted in 22 fleets distinguished by country: France (FR), Ireland (IR), Spain (SP) and United Kingdom (UK), and gear type (longliners, gillnetters and different type of trawlers). In turn, each fleet had several métiers that depended on target species and mesh size used. There was a total of 51 métiers that caught some or all stocks.

Weight at age of landings and discards for each métier were sampled from the last ten years, synchronised with the sampling of weight at age in the population as done in ICES working groups. In the working groups uncertainty in catchability was introduced by sampling the last 10 years in the historical time series. However, the data available at fleet and métier level comprised only 5 years, and for some fleets data was incomplete. Hence it was not possible to conduct a bootstrap. Alternatively, as catchability is the cornerstone in the mathematical formulation of the HCR (equation 1) a local sensitivity analysis was carried out to analyse the performance of the HCR under different scenarios of variability in catchability:

1. Catchability equal to the last three historical years' average. Catchability is constant along years and iterations and varies with fleet (fl), métier (mt) and stock (st), $q_{fl,mt,st}$ . This scenario is referred as 'NoUnc' along the manuscript
2. Catchability variable along iterations and stocks. The same variability is introduced in all years using a lognormal error with median equal to one and coefficient of variation equal to 25%:

   $$q_{it,yr,fl,mt,st} = q_{fl,mt,st} \cdot \varepsilon_{it,fl,mt,st} \qquad \varepsilon \sim lognormal(1,0.25)$$

   This scenario is referred as 'Unc_Stk' along the manuscript.
3. Catchability variable along iterations and years. The same variability is introduced in all fleets, métiers and stocks using a lognormal error with median equal to one and coefficient of variation equal to 25%:

   $$q_{it,yr,fl,mt,st} = q_{fl,mt,st} \cdot \varepsilon_{it,yr} \qquad \varepsilon \sim lognormal(1,0.25)$$

   This scenario is referred as 'Unc_Yr' along the manuscript.

4. Catchability variable along iterations, years, fleets, métiers and stocks. The variability is modelled using a lognormal error with median equal to one and coefficient of variation equal to 25%:

$$q_{it,yr,fl,mt,st} = q_{fl,mt,st} \cdot \varepsilon_{it,yr,fl,mt,st} \qquad \varepsilon \sim lognormal(1,0.25)$$

This scenario is referred as 'Unc_YrStk' along the manuscript.

The first scenario allowed to evaluate the performance of the HCR under perfect conditions in terms of the stability of the fleet, while the other three allowed us to analyse the capacity of the HCR to cope with inter-annual changes in catchability and independent changes in catchability at stock level. In the fourth scenario the cumulative effect of both variabilities was analysed. In the last two scenarios the changes in the catchability along the stocks produced a stock dependent change in the position of the status-quo fishing mortality in relation to $F_{target}$.

## 2.7 The management procedure

In the management procedure, the HCRs were applied to the real stock status and exploitation rate indicators . Hence, the HCR was applied to the real values in the fishery system. However, there was a two-year time lag between the population used to generate the advice and the year for which the advice was being generated. In all scenarios, including the multi-stock HCR scenario, first the HCR used by ICES in the MSY framework (referred here as single-stock HCR and described in section 2.4) was applied to find the fishing mortality by stock to be used in the generation of the catch advice. In the case of single-stock HCR scenarios these fishing mortalities were transformed into catch using the Baranov catch equation to generate the TAC advice. In the case of multi-stock HCR the fishing mortalities obtained using the single-stock HCR were used as input to the multi-stock HCR to calculate the $F_{\text{target}}$ . Afterwards the steps in Section 2.1 were followed to obtain the advised fishing mortality, that were transformed into catch using the Baranov catch equation.

## 2.8 The scenarios

In the single fleet case study eight scenarios were run. These included management scenarios which simulated either the landing obligation, where the fleets stopped fishing when the first quota was consumed; or a Business as Usual (BaU) situation, where the fleets stopped fishing when the last catch quota was exhausted. Under BaU the over-quota catches were discarded. For each of these management scenarios four different harvest control rules were applied, the single-stock HCR and the three variants of the multi-stock HCR described before. The three variants of the multi-stock HCR, ‘max’, ‘mean’ and ‘min’, were described and explained in detail in Section 2.1. In the multi-fleet case study, these eight scenarios were combined with the four catchability scenarios introduced in section 2.3.4, resulting in a total of 32 scenarios (see Table 1).

## 2.9 Performance indicators

The following indicators were used to assess the performance of the HCR in terms of sustainability of the stocks, ability to reach $F_{MSY}$ and the use of fishing opportunities:

- Probability of SSB being below $B_{lim}$ in each projection year: $p(SSB<B_{lim})$. Where $B_{lim}$ is the limit reference point for SSB used by ICES in the precautionary approach framework. The values used were the ones used by the assessment working group of the stocks (ICES, 2018b).
- Fishing mortality along the whole time series (F).
- The catch along the whole time series.
- Quota uptake per stock defined as the ratio between the catch and the catch advice in year 2040.
- Overall quota uptake in year 2040 defined as the sum of the squares of the ratio between the difference between the catch advice (TAC) and the real catch (C), and the TAC in 2018:

$$I = \sum_{st} \left(\frac{TAC_{st} - C_{st}}{TAC_{2018,st}}\right)^2 \quad (6)$$

The closer the value of the indicator to 0 the greater uptake of fishing opportunities. The difference between the catch and the TAC was divided by the TAC in 2018 to put the values of all the stocks in the same scale.  As in the projection the TAC for white anglerfish was 0 in some years and iterations, the TAC of 2018 was used instead of the annual TACs.

## 2.10 Illustration of the Multi-Stock HCR in practice.

To illustrate the behaviour of the HCR using the three options defined in Section 2.1 ‘min’, ‘max’ and ‘mean’ the multi-stock HCR was applied directly to three vectors of stock specific fishing mortalities:

1. The *status-quo* fishing mortalities obtained in the latest assessments of the stocks (ICES, 2018).
2. Alternative 1: The *status-quo* fishing mortalities in (1) were reduced to bring the fishing mortality of hake within the FMR and fishing mortality of megrim and white anglerfish to the upper bounds of the FMRs.
3. Alternative 2: The fishing mortalities of megrim and white anglerfish were set close to the fishing mortality target and the fishing mortality of hake in the middle of the target and the upper bound.

The final and intermediate fishing mortalities obtained with the three vectors are shown in Figure 3. In the intermediate step, the application of formula (2), the ‘max’ option brought the fishing mortality of hake to $F_{MSY}$ and the fishing mortality of the other two stocks (white anglerfish and megrim) well above the upper bound of the FMR. In contrast the HCR with the ‘min’ option, moved the fishing mortality of the most restrictive stocks, white anglerfish and megrim, around the target and that of hake well below the lower bound. The fishing mortalities obtained with the 'mean' option were between the 'min' and 'max' options. In the final step, the fishing mortalities were the same for the three options, fishing mortality of white anglerfish equal to the upper bound of the FMR; megrim between $F_{MSY}$ and the upper bound; and hake well below the lower bound. In the first alternative scenario, the distance between fishing mortalities was reduced. In the first step of the HCR, all the fishing mortalities obtained with the 'mean' option were within the FMR, while with the other two options the fishing mortality of some stocks were outside the FMRs. Hence, in the second step, the fishing mortalities under the 'mean' option were not changed. With the 'max' option the fishing mortalities were reduced until all the fishing mortalities were within the FMRs, and were increased in the 'min' option. In the second artificial scenario, the *status-quo* fishing mortalities were already within the FMRs. With the 'max' option, the fishing mortalities were increased until all the fishing mortalities were at or above $F_{MSY}$ and with the 'min' option they were decreased. The fishing mortalities obtained with the 'mean' option were somewhere in between. In the second step, the fishing mortalities were not changed with any of the options.

[Insert Figure 3]

# 3 Results

## 3.1 Single fleet case study

The fishing mortality time series obtained in the single fleet case study using the two are shown Figure 4. In the single fleet case study and under current management system the HCR used by ICES produced fishing mortality for hake close to the target and for the other two stocks (white anglerfish and megrim) produced fishing mortalities well above the upper bound of the FMR. Under landing obligation, fishing mortality for megrim was around the target, for hake below the lower bound and for white anglerfish in the lower part of the FMR. The multi-stock HCR produced similar results under current management system and landing obligation. The multi-stock HCR with the 'max' setting produced fishing mortality of hake slightly above the lower bound of the FMR and fishing mortality for the other two stocks around the upper bound of the FMR. In turn, the 'mean' option moved the fishing mortality of hake to the lower bound, and that of the other two stocks slightly below the upper bound. Finally, the 'min' option reduced the fishing mortalities slightly below the 'min' option.

[Insert Figure 4]

Figure 5 shows the quota-uptake obtained in 2040 for the scenarios tested in the single fleet case study. The single-stock HCR produced an overshoot of the TAC greater than 60% in the case of megrim and white anglerfish under the actual management system. In contrast, the landing obligation produced a loss, of around 40%, in the fishing opportunities of hake. Using the multi-stock HCR, the overshoot of the TAC decreased for megrim and white anglerfish under actual management system which in the worst case was 15%. In turn, under landing obligation, the loss of fishing opportunities for hake decreased significantly, from 43% to 15%, but the loss increased for megrim, from 2% to 10% in the worst scenario.

[Insert Figure 5]

## 3.2 Multi fleet case study

### 3.2.1 p(SSB<$B_{lim}$)

Probability of SSB falling below $B_{lim}$ was always zero for hake and it was always lower than 1% for megrim. For white anglerfish the probability varied by year and scenario from 0% to almost 100%. The probabilities obtained for each year and scenario for white anglerfish are shown in Table 1. The probabilities obtained in 'NoUnc' and 'Unc_Yr' scenarios were similar. Without the landing obligation, the highest probabilities were obtained in the SSHCR scenario. From

2023 onwards, the probability was higher or equal to 90% in all scenarios except the 'Unc_Stk' scenario where the probability decreased to 70% in most of the years. The probabilities decreased with the multi-stock HCR, in the long term with the 'max' option the probabilities were around 24%, 55% and 81% in the 'NoUnc', 'Unc_Stk' and 'Unc_YrStk' scenarios respectively. With the 'mean' and 'min' options these probabilities decreased considerably. In the case of the 'mean' scenarios the probabilities were almost 0 in the 'NoUnc' and 'Unc_Yr' scenarios and around 34% and 53% in the 'Unc_Stk' and 'Unc_YrStk' scenarios respectively. In the case of 'min' scenarios, the probabilities were slightly above 5% since 2032 in the 'NoUnc' and 'Unc_Yr' scenarios and was equal to zero in the other two. With landing obligation, except in the MSHCR-max scenarios, the probability of SSB being below $B_{lim}$ was almost zero. In the MSHCR-max scenario, the probability increased up to 52% when variability was introduced at stock and year level, and up to 33% when it was only introduced at stock level. In the other two scenarios the probability was zero in all the years. The time series of SSB are available in the supplementary material.

[Insert Table 1]

### 3.2.2 Fishing mortality

The fishing mortality times series at stock level obtained in the scenarios tested in the multi-fleet case study are shown in Figure 6. In this case study, under current management system and with no uncertainty, the SSHCR scenario produced fishing mortality around the target for hake, and around the upper bound for the other two stocks. Under the landing obligation, the fishing mortality of hake was close to the lower bound, that of megrim close to the target, although slightly below, and that of white anglerfish in the middle of the target and the lower bound. Under current management system, the multi-stock HCR with the 'max' option produced fishing mortality levels similar to those obtained with the single-stock HCR. However, the 'mean' option, under the current management system, drove all the fishing mortalities within the corresponding FMR, hake’s fishing mortality to the lower part of the FMR and the fishing mortality of the other two stocks to the upper part. The ‘min´ option moved the fishing mortality of hake to around the lower bound and the other two around the target. In the case of landing obligation the single-stock HCR  produced fishing mortalities below the lower bound of the FMR for all stocks. With the multi-stock HCR and the ‘max’ option, the fishing mortalities of megrim and white anglerfish were situated in the upper part of the FMR and that of hake in the lower. The trends obtained with the ‘min’ and ‘mean’ options were similar to those obtained in the ‘max’ option but at lower levels. The lowest fishing mortality level was obtained with the ‘min’ option, in that case, hake’s fishing mortality was below the lower bound and the fishing mortality of the other two stocks in the lower part of the FMR. The introduction of uncertainty at year and stock level in the BaU scenario did not only result in a large increase in the width of the intervals but also an increase in the median fishing mortality of megrim and white anglerfish, above the upper bound of the FMR when multi-stock HCR was applied and a slight movement upwards in the case of single-stock HCR. The fishing mortality of hake also increased slightly with the multi-stock HCR and ‘min’ option. Under the landing obligation, the impact of the uncertainty was the opposite, with a decrease in the fishing mortalities of megrim and white anglerfish and an increase in that of hake. The results for the other uncertainty scenarios are provided as supplementary material; the scenario with uncertainty at year level produced practically the same catches as the scenario with no uncertainty. The other scenario generated similar results to the scenario with uncertainty at stock and year level, but the uncertainty was slightly larger.

[Insert Figure 6]

### 3.2.3 Catch

Figure 7 shows the catch time series obtained in the scenarios tested in the multi-fleet case study for each of the stocks. Median hake catches in the long term were similar in all scenarios.

Some slight differences arose in the confidence intervals that were larger in the scenarios with uncertainty in catchability. In the short term there were big differences driven principally by the HCR used and the implementation or not of the landing obligation. In the short term, the catches under landing obligation were lower and the HCR that produced the lowest catches was the multi-stock HCR with the 'min' option. In turn, the maximum catches were produced by the single-stock HCR in BaU scenarios and the multi-stock HCR with 'max' option in the landing obligation scenarios. For megrim something similar happened. However, for this stock the impact of uncertainty was larger and in the 'Unc_YrStk' with the landing obligation scenario the catches obtained were higher than those obtained in the rest of the scenarios. In the short term when the landing obligation was implemented, some differences appeared also in the case of hake. In the case of megrim catches produced by the single-stock HCR were similar to those obtained in the multi-stock HCR with 'min' option instead of with 'max' option as in the case of hake. For white anglerfish under the landing obligation, the catches in the long term were similar for all scenarios and in the short term trends were similar to those observed in the case of megrim but the difference between scenarios was lower. Under BaU management, in the long term, in the MSHCR scenarios with 'mean' and 'min' options and no uncertainty, catches stabilised around the same value as in the landing obligation scenario. However, in the rest of the scenarios catches had a decreasing trend, especially in the case of single-stock HCR and the multi-stock HCR with 'max' option in 'Unc_YrStk' scenario. In the short term the general trends were similar to those observed for megrim. The results for the other uncertainty scenarios are provided as supplementary material, the scenario with uncertainty at year level produced practically the same catches as the scenario with no uncertainty. The other scenario generated similar results to the scenario with uncertainty at stock and year level, but the uncertainty was slightly larger.

[Insert Figure 7]

### 3.2.4 Overall quota uptake

The radar plot in Figure 8 shows the overall quota uptake indicator defined in section 2.9 for each of the scenarios run in the multi-fleet case study. The value of the indicator in the scenario with no uncertainty (‘NoUnc’) and the scenario with uncertainty at year level (‘Unc_Yr’) were practically the same. In these two scenarios, when the multi-stock HCR was used, the indicator was close to 0, i.e the TACs were fully consumed for all stocks and there were no over-quota catches. In the BaU scenario with single-stock HCR the value of the over-quota indicator was close to 0.3, when landing obligation was applied the value of the indicator decreased below 0.025 (Figure 8). In the scenarios with uncertainty at stock level (‘Unc_Stk’ and ‘Unc_YrStk’) the uptake of fishing opportunities decreased (Figure 8). Both scenarios produced similar results but the quota uptake in ‘Unc_YrStk’ scenarios was the worst. In the BaU scenarios the indicator was close to 0.3 and between 0.05 and 0.025 in the rest of scenarios. In the landing obligation scenarios, there were no big differences in the value of the indicator but the lowest value was obtained with the multi-stock HCR and ‘max’ option, and the highest with the ‘min’ option.

[Insert Figure 8]

### 3.2.5 Quota uptake by stock

The median quota uptake by stock is shown in Figure 9. The scenarios with no uncertainty and with uncertainty only at year level (‘NoUnc’ and ‘Unc_Yr’) and the two scenarios that included uncertainty at stock level (‘Unc_Stk’ and ‘Unc_YrStk’) produced similar results. When there was no uncertainty, except in the scenarios ‘BaU_SSHCR’ and ‘LO_SSHCR’, the quota consumption was close to full consumption for all stocks. In ‘BaU_SSHCR’ there was a big over-quota catch of megrim and white anglerfish, especially the latter. Conversely, in the ‘LO_SSHCR’ scenario, there was a large amount of quota left for hake. In the scenarios that included uncertainty at stock level the differences with the other two scenarios were observed especially for hake. In the 'BaU' scenarios with multi-stock HCR , when uncertainty at stock level was introduced, the implementation of the quota changed from almost perfect to an over-quota of around 13% and in the scenarios with the landing obligation the impact of the uncertainty was just the opposite; it caused a surplus of quota of around a 13%.

[Insert Figure 9]

### 3.2.6 Quota uptake by fleet

Figure 10 shows the median quota uptake by fleet and stock in year 2040 forthe scenarios without variability in catchability ('NoUnc') and with uncertainty at stock and year level are shown ('Unc_YrStk'). Although, the results were similar to those obtained overall at stock level, some differences appeared at fleet level. The fleet that differentiated more from the rest was the 'OT8_SP' (the Spanish trawlers operating in ICES subarea 8). In the BaU scenario without uncertainty, while the other fleets almost fully consumed their quota of hake, the 'OT8_SP' fleet had an over-quota catch larger than 10%. In the case of megrim and white anglerfish, in the BaU scenario, there was a large overshoot of the quota for all fleets and the two uncertainty scenarios. The quota overshoot was mitigated using the multi-stock HCR, especially for white anglerfish. For megrim, for some fleets ('OT8_SP', 'OTB_UK' and 'TBB_IR'), the overshoot persisted but at lower level (<15%) in the case of no uncertainty. When uncertainty was introduced the consistency of catch with the quota of both stocks deteriorated, especially for 'OT8_SP' in the case of megrim and 'TBB_IR' in the case of white anglerfish. Under the landing obligation, megrim was the stock that limited the fishing activity for most of the fleets. This limitation produced a loss in the catch of hake and white anglerfish but the level was fleet dependent. The biggest losses were observed for hake and for all the fleets when uncertainty was introduced in catchability and for white anglerfish in 'OT8_SP' fleet. When uncertainty was added to catchability, the general trends were similar, but the differences between the catch-quotas and the real catches increased. For example, in the case of hake and BaU it resulted in going from barely no over-quota catches under BaU scenarios to having more than 30% for almost all fleets.

[Insert Figure 10]

# 4 Discussion and Conclusions

This proposed multi-stock HCR generates compatible catch advice for stocks exploited in a mixed-fishery, resulting in no choke species when the stocks are exploited by a single fleet. When the HCR is applied in a complex fishery, with several fleets and métiers, the problem with the mismatch between the different catch advice is not fully solved. However, the consistency in quota uptake is better than with the application of single-stock HCR. The minimal data requirements of this method, requiring just the reference points and the output of stock assessment models make it easily applicable to the periodic generation of catch advice.

When uncertainty was not included in catchability, the HCR in the ‘min’ and ‘mean’ scenarios was able to bring the fishing mortality within the FMRs, when implemented without the landing obligation. However, in the ‘max’ scenario the probability of the fishing mortality of the most restrictive stocks being above the upper bound was estimated to be around 50%. With the landing obligation, both HCRs brought the fishing mortalities within the FMRs. In the single fleet case study, the fishing mortalities under the landing obligation were similar to those obtained under current management system. Hence, in a real situation, if the fleet-based selection patterns were similar to the overall one, the multi-stock HCR would generate consistent catch advice for all fleets and the implementation of landing obligation to overcome discards derived from quota mismatches would not be necessary. Nevertheless, in multi-fleet fisheries it is weird that the overall and fleet level selection patterns are similar. Moreover, the problem with discards related with minimum landings sizes or high grading would remain unresolved. In general the long term catches produced by both HCRs were similar. Some differences arose for monkfish with the single-stock HCR and the multi-stock HCR with ‘max’ option. The use of fishing opportunities was better with the multi-stock HCR.

Under current management system, in the long term, only the multi-stock HCR was precautionary in the sense defined by ICES (probability of being below $B_{lim}$ lower than 5%). In evaluations carried out previously by ICES using the same population dynamics and the same conditioning the single-stock HCR proved to be precautionary (ICES, 2015; ICES, 2016; ICES, 2018a). Therefore, this study highlights the importance of considering fleet dynamics, or at least implementation error, when management plans are evaluated as already noted by other authors  (Punt et al., 2016).

When uncertainty was introduced the performance of both HCRs deteriorated. The probability of the SSB of white anglerfish being below $B_{lim}$ increased, under current management  system the HCR was not able to bring the fishing mortality within the FMRs, and the uptake of catch quota was worse. Furthermore, there arose differences in the long-term catches produced for white anglerfish using different HCR settings.

When there is only a single fleet the method in Ulrich *et al.* (2017) is similar to the HCR presented here, because the catch advices are fully compatible. However, the methods differ when several fleets are considered. For example, if there were two fleets, one which catch only one stock and a second one that catches all the stocks in the system the algorithm in Ulrich *et al.* (2017) would generate the advice that correspond with the catch profile of the second fleet. However, in the HCR presented here the catch profile used to produce the catch advice is a weighted mean of the individual catch profiles, where the weight is equal to the catches of the stocks at fleet level. One of the advantages of the multi-stock HCR compared to the method in Ulrich *et al.* (2017) is that the HCR can be applied directly to the output of the stocks assessment models without the need of using any fleet/métier catch and effort data. Although the necessary condition for the HCR to work satisfactorily is that there is a linear relationship between fleets' effort and fishing mortality, for the calculation of the TAC advice only the overall fishing mortalities at stock level are used.

García *et al.* (2017) proposed the use of multi-stock reference points based on a bio-economic dynamic optimisation model (Da Rocha *et al.*, 2012). In this approach, the catch profiles among the stocks are considered only when the reference points are calculated. Hence, the management advice is not adapted to changes in catch profiles. As the multi-stock HCR uses the latest available information on fishing mortality, it adapts to changes in the catch profile of the fleets. The adaptability of HCR is especially important to account for changes in catchability. This is particularly relevant in mixed-fisheries systems because catchability is the link between the stock (fishing mortality) and the fleet (effort) (Rijnsdorp et al., 2007; Baudron et al., 2010; Ulrich et al., 2011a) and it models the productivity of the fleets. Furthermore, fleet dynamic models are usually sensitive to small variations in catchability (Dichmont *et al.*, 2003; Iriondo *et al.*, 2012). The multi-stock HCR has demonstrated to be robust to inter-annual changes in catchability. However, the introduction of uncertainty at stock level worsened the performance of the HCR. The uncertainty introduced in catchability is potentially over-estimated because the coefficient of variation used is high (25%) and the correlation between the catchability of the stocks was not considered. However, the data available did not allow to estimate the variance-covariance matrices of the catchability.

The performance of the HCR was found to be fleet dependent. If the catch profile of a fleet is similar to the overall catch profile, the fleet would consume the catch quotas of all stocks simultaneously. However, the consistency of the generated catch quotas degrades with the difference in the catch profiles. Furthermore, it penalises or rewards single stock fleets, depending if the advice fishing mortality of the stock is below or above the target. However, this is not a problem of the HCR itself but of the management system as already acknowledged by other authors (Ulrich *et al.*, 2012; Voss *et al.*, 2017).

The multi-stock HCR provides an objective mechanistic way to generate yearly catch advice within the FMRs without inertia at one or other end of the bounds (Table 2). If adopted, it would avoid discussions about which point, within the FMR, should be used to provide advice, always the lower bound as proposed by Thorpe *et al.* (2017) or the upper bound as fishermen are expected to demand (Rindorf *et al.*, 2017b).

[Insert Table 2]

The performance of the HCR would improve if it were applied at fleet level.. In which case catch and effort data at fleet and métier level would be needed, the same data used in the mixed-fisheries management advice generation (Ulrich et al., 2011b; Ulrich et al., 2017). Then, the HCR could be applied multiplying ‘µ’ to the reference effort levels.

In the simulation of the landing obligation, we used the average historical effort share and catchability to forecast fleets’ dynamics. However, when fully implemented (i.e., year 2019), the landing obligation is expected to produce a change in the fishing practices (Batsleer et al., 2013; Simons et al., 2015)(Catchpole and Gray, 2010; Simons et al., 2015; Alzorriz et al., 2018). Thereby, producing a change in the effort-share, the catchabilities and/or the catch profiles. However, the objective of the work was not to forecast the fleet dynamics but to test if the use of a more holistic approach to fisheries management could result in a higher consumption of catch quotas given current fishing patterns.

A cornerstone of the HCR is the relationship between fishing mortality patterns, using a linear relationship is a common practice but also widely criticised (Arreguín-Sánchez, 1996; van Oostenbrugge et al., 2008). Nevertheless, it could be replaced by any other relationship.

The FMRs were introduced to provide flexibility to the advice system when defining the catch advice in a mixed-fisheries framework. The HCR presented here provides a simple procedure to operationalise the use of FMRs in the generation of mixed-fisheries advice.  However, as the performance of the HCR depends on the composition of the fishery, before applying it in reality it would be necessary to evaluate it in a management strategy evaluation framework (Punt et al., 2016).

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## Tables and Figures

Table 1. Probability of SSB being below Blim from 2018 to 2040 for **white anglerfish**. The first column refers to the management system (Mng system), the second one to the harvest control rule used (HCR), the third to the variability in catchability scenarios (Scenario) and the rest to the simulation years.

| Mng System | Scenario | Uncertainty | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2031 | 2032 | 2033 | 2034 | 2035 | 2036 | 2037 | 2038 | 2039 | 2040 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Bussines as Usual (BaU) | SSHCR | NoUnc | 0 | 0 | 0 | 0 | 0 | 0.04 | 0.51 | 0.74 | 0.80 | 0.80 | 0.81 | 0.81 | 0.85 | 0.86 | 0.88 | 0.89 | 0.89 | 0.90 | 0.89 | 0.88 | 0.88 | 0.90 | 0.88 |
| | | Unc_Stk | 0 | 0 | 0 | 0.01 | 0.15 | 0.41 | 0.54 | 0.62 | 0.65 | 0.67 | 0.64 | 0.65 | 0.66 | 0.66 | 0.67 | 0.67 | 0.69 | 0.69 | 0.69 | 0.70 | 0.69 | 0.69 | 0.70 |
| | | Unc_Yr | 0 | 0 | 0 | 0 | 0.00 | 0.05 | 0.52 | 0.76 | 0.82 | 0.83 | 0.83 | 0.81 | 0.85 | 0.86 | 0.87 | 0.88 | 0.87 | 0.90 | 0.89 | 0.91 | 0.91 | 0.89 | 0.90 |
| | | Unc_YrStk | 0 | 0 | 0 | 0 | 0.04 | 0.53 | 0.78 | 0.87 | 0.92 | 0.91 | 0.91 | 0.92 | 0.91 | 0.94 | 0.94 | 0.96 | 0.95 | 0.95 | 0.96 | 0.96 | 0.96 | 0.95 | 0.96 |
| | MSHCR max | NoUnc | 0 | 0 | 0 | 0 | 0 | 0 | 0.01 | 0.09 | 0.12 | 0.14 | 0.14 | 0.14 | 0.13 | 0.15 | 0.17 | 0.18 | 0.20 | 0.20 | 0.23 | 0.22 | 0.24 | 0.24 | 0.25 |
| | | Unc_Stk | 0 | 0 | 0 | 0.01 | 0.08 | 0.29 | 0.39 | 0.45 | 0.49 | 0.51 | 0.49 | 0.51 | 0.50 | 0.52 | 0.53 | 0.52 | 0.54 | 0.55 | 0.53 | 0.56 | 0.56 | 0.54 | 0.56 |
| | | Unc_Yr | 0 | 0 | 0 | 0.00 | 0.00 | 0.00 | 0.01 | 0.08 | 0.13 | 0.17 | 0.15 | 0.15 | 0.16 | 0.17 | 0.19 | 0.21 | 0.22 | 0.21 | 0.23 | 0.23 | 0.23 | 0.25 | 0.24 |
| | | Unc_YrStk | 0 | 0 | 0 | 0.006 | 0.032 | 0.37 | 0.57 | 0.66 | 0.69 | 0.70 | 0.71 | 0.71 | 0.75 | 0.76 | 0.78 | 0.81 | 0.81 | 0.81 | 0.80 | 0.81 | 0.80 | 0.81 | 0.82 |
| | MSHCR mean | NoUnc | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 | 0.00 | 0.00 | 0 | 0 | 0.00 | 0.00 | 0.00 | 0.01 | 0 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 |
| | | Unc_Stk | 0 | 0 | 0 | 0.01 | 0.01 | 0.06 | 0.13 | 0.24 | 0.29 | 0.29 | 0.27 | 0.29 | 0.28 | 0.30 | 0.31 | 0.31 | 0.30 | 0.32 | 0.32 | 0.33 | 0.35 | 0.34 | 0.35 |
| | | Unc_Yr | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 | 0.00 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.01 | 0.01 |
| | | Unc_YrStk | 0 | 0 | 0 | 0 | 0 | 0.01 | 0.104 | 0.24 | 0.32 | 0.32 | 0.35 | 0.36 | 0.37 | 0.40 | 0.43 | 0.45 | 0.49 | 0.50 | 0.50 | 0.54 | 0.54 | 0.55 | 0.54 |
| | MSHCR min | NoUnc | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.006 | 0.044 | 0.056 | 0.04 | 0.036 | 0.042 | 0.048 | 0.06 | 0.06 | 0.066 | 0.066 | 0.082 | 0.082 | 0.09 | 0.09 | 0.08 |
| | | Unc_Stk | 0 | 0 | 0 | 0 | 0 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.00 | 0.00 | 0.01 | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 | 0.01 |
| | | Unc_Yr | 0 | 0 | 0 | 0 | 0 | 0.00 | 0.00 | 0.01 | 0.03 | 0.05 | 0.04 | 0.05 | 0.05 | 0.05 | 0.06 | 0.07 | 0.09 | 0.08 | 0.08 | 0.07 | 0.09 | 0.10 | 0.11 |
| | | Unc_YrStk | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 |
| Landing Obligation (LO) | SSHCR | NoUnc | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | Unc_Stk | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | Unc_Yr | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.002 | 0.004 |
| | | Unc_YrStk | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | MSHCR max | NoUnc | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | | Unc_Stk | 0 | 0 | 0 | 0 | 0 | 0.01 | 0.052 | 0.154 | 0.21 | 0.24 | 0.26 | 0.27 | 0.25 | 0.28 | 0.27 | 0.29 | 0.29 | 0.28 | 0.29 | 0.31 | 0.33 | 0.33 | 0.33 |
| | | Unc_Yr | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | | Unc_YrStk | 0 | 0 | 0 | 0 | 0 | 0.002 | 0.012 | 0.09 | 0.16 | 0.23 | 0.28 | 0.31 | 0.31 | 0.36 | 0.39 | 0.41 | 0.45 | 0.47 | 0.48 | 0.51 | 0.52 | 0.52 | 0.51 |
| | MSHCR mean | NoUnc | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 | 0 | 0 | 0 | 0.00 | 0.00 | 0 | 0 | 0 | 0 | 0.00 | 0.00 | 0.01 |
| | | Unc_Stk | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 | 0.00 | 0.00 | 0 | 0 |
| | | Unc_Yr | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.006 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 | 0 | 0.002 | 0.004 | 0.006 |
| | | Unc_YrStk | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0 | 0.002 | 0 | 0 | 0 | 0.00 |
| | MSHCR min | NoUnc | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 |
| | | Unc_Stk | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 | 0.00 | 0.00 |
| | | Unc_Yr | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.002 |
| | | Unc_YrStk | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

**Table 2.** Proportion of iterations in which the upper bound of the stock was used to generate the management advice. Overall, in each scenario, the proportion of iterations in which any of the upper bounds was used correspond with the sum of the stock

specific proportions. HKE is the FAO code for HKE, MEG for megrim and MON for white anglerfish.

| Scenario | Management | HCR | Uncertainty | HKE | MEG | MON | Overall |
|---|---|---|---|---|---|---|---|
| SC1a_max_01 | Business as Usual (BaU) | MSHCR max | NoUnc | 0 | 0 | 0.83 | 0.28 |
| SC1a_max_02 | | | Unc_Yr | 0 | 0 | 0.83 | 0.28 |
| SC1a_max_03 | | | Unc_Stk | 0 | 0.28 | 0.44 | 0.24 |
| SC1a_max_04 | | | Unc_YrStk | 0 | 0.35 | 0.55 | 0.3 |
| SC1a_mean_01 | | MSHCR mean | NoUnc | 0 | 0 | 0.94 | 0.31 |
| SC1a_mean_02 | | | Unc_Yr | 0 | 0 | 0.94 | 0.31 |
| SC1a_mean_03 | | | Unc_Stk | 0 | 0.31 | 0.43 | 0.25 |
| SC1a_mean_04 | | | Unc_YrStk | 0 | 0.37 | 0.52 | 0.3 |
| SC1a_min_01 | | MSHCR min | NoUnc | 0 | 0 | 0.3 | 0.1 |
| SC1a_min_02 | | | Unc_Yr | 0 | 0 | 0.3 | 0.1 |
| SC1a_min_03 | | | Unc_Stk | 0 | 0.31 | 0.42 | 0.24 |
| SC1a_min_04 | | | Unc_YrStk | 0 | 0.38 | 0.52 | 0.3 |
| SC1b_max_01 | Landing Obligation | MSHCR max | NoUnc | 0 | 0 | 0.92 | 0.31 |
| SC1b_max_02 | | | Unc_Yr | 0 | 0 | 0.92 | 0.31 |
| SC1b_max_03 | | | Unc_Stk | 0 | 0.25 | 0.41 | 0.22 |
| SC1b_max_04 | | | Unc_YrStk | 0 | 0.32 | 0.51 | 0.28 |
| SC1b_mean_01 | | MSHCR mean | NoUnc | 0 | 0 | 0.66 | 0.22 |
| SC1b_mean_02 | | | Unc_Yr | 0 | 0 | 0.65 | 0.22 |
| SC1b_mean_03 | | | Unc_Stk | 0 | 0.06 | 0.07 | 0.04 |
| SC1b_mean_04 | | | Unc_YrStk | 0 | 0.04 | 0.05 | 0.03 |
| SC1b_min_01 | | MSHCR min | NoUnc | 0 | 0 | 0.05 | 0.02 |
| SC1b_min_02 | | | Unc_Yr | 0 | 0 | 0.05 | 0.02 |
| SC1b_min_03 | | | Unc_Stk | 0 | 0.02 | 0.03 | 0.02 |
| SC1b_min_04 | | | Unc_YrStk | 0 | 0.02 | 0.03 | 0.02 |

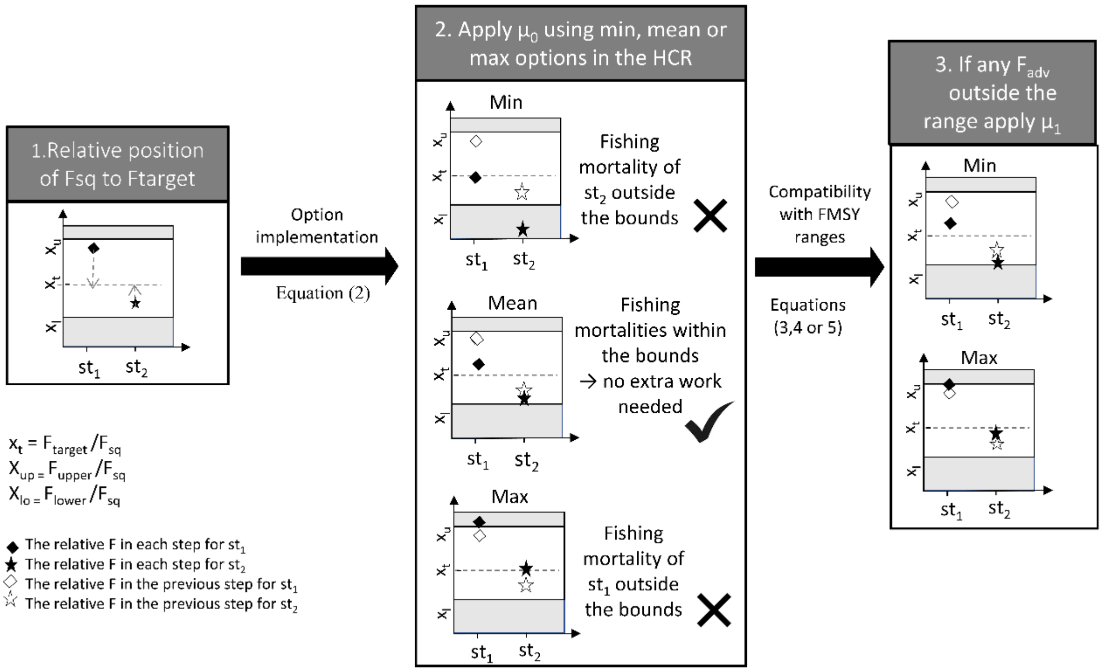

**Figure 1.** Graphical representation of the steps for applying the multi-stock HCR to two stocks, st$_1$ and st$_2$ . The y-axis of the plots represent the ratio between status-quo fishing mortality (Fsq) and the fishing mortality target (F$_{target}$). The white area comprises the area of the fishing mortality delimited by the ratio between Fupper and Flower, and Ftarget. For simplicity, in this example, the ratio between Fupper and Flower, and Ftarget is the same for both stocks but in general they are different. Step 1 illustrates the initial incompatibility in the F ratio between st$_1$ (diamond) and st$_2$ (star). In step 2 the three options of the multi-stock HCR  (max, mean and max) are implemented using equation (2), the dashed arrows denote the direction of change in the F ratio under these scenarios. Finally in step 3, cases which still remain outside the F$_{MSY}$ ranges are projected forward using equations 3, 4 or 5, contracting the F ratio to ensure that the resulting level of is compatible with the F$_{MSY}$ ranges of both species.

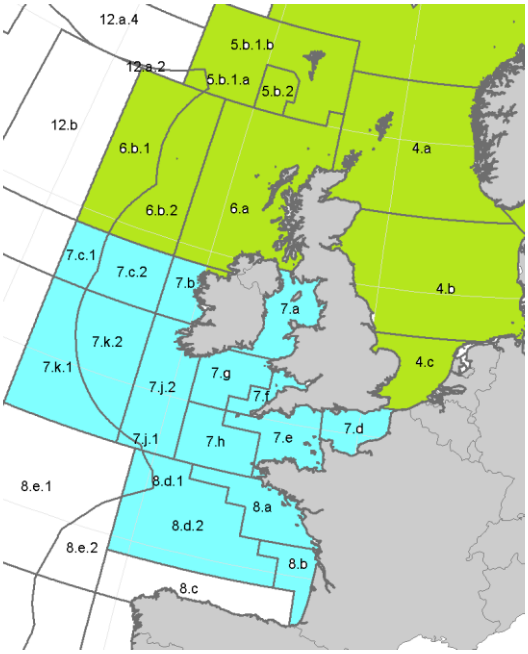

**Figure 2**. Case study area. The blue area corresponds with the distribution of megrim and white anglerfish and the distributions of hake comprises also the green area.

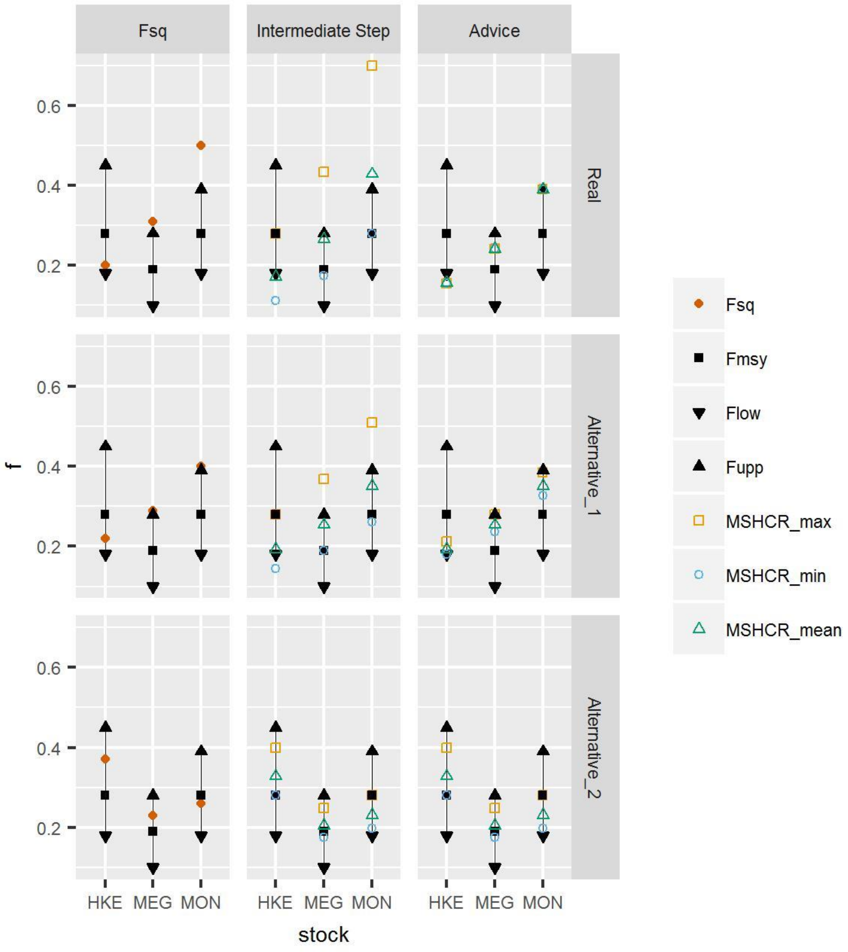

**Figure 3.** Fishing mortalities obtained in the three steps (in columns) of the application of the multi-stock HCR using different options, MSHCRmax (red square), MSHCRmean _st (dark blue circle) and MSHCRmin (light blue triangle). F statu quo (Fsq, red solid circle) is the same for all the HCRs. The obtained fishing mortalities are shown along with the fishing mortality ranges (black triangles) and Fmsy (green square). The rows represent different starting points for the application of the HCR (different Fsq), in the first row the Fsq of these stocks in 2018 is used. The values used in the second and third row are invented. HKE is the FAO code for HKE, MEG for megrim and MON for white anglerfish.

**Figure 4.** Fishing mortality time series obtained using different harvest control rules under current management scenarios (BaU, top panels) and under landing obligation scenario (LO, bottom panels) in the single fleet case study. The horizonal lines correspond with fishing mortality ranges and with MSY fishing mortality. The lines represent different HCR, the HCR used by ICES in the MSY framework (SSHCR, black) and the multi-stock HCR using different options, max (MSHCRmax, yellow), mean (MSHCRmean, blue) and min (MSHCRmin, green). HKE is the FAO code for HKE, MEG for megrim and MON for white anglerfish. Although the simulation was run until 2040, as the system was already stable in 2030, to gain detail in the short term the years with highest variability, only the time series up to 2030 are shown

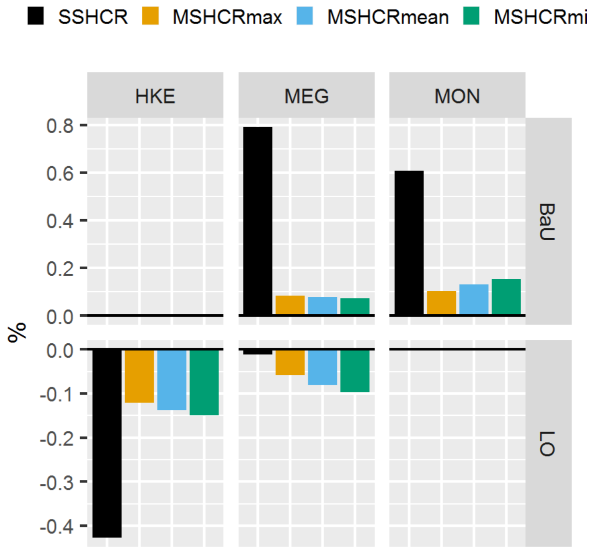

**Figure 5.** Quota uptake in 2040 in single fleet case study using different harvest control rules under current management scenarios (BaU, top panels) and under landing obligation scenario (LO, bottom panels). The horizonal lines in 0 means that the catch is equal to the catch advice. The bars correspond with different HCR, the HCR used by ICES in the MSY framework (SSHCR, black) and the multi-stock HCR using different options, max (MSHCRmax, yellow), mean (MSHCRmean, blue) and min (MSHCRmin, green). Positive bars indicate that the catch advice has been overshot and negative

ones that it has not been reached. HKE is the FAO code for HKE, MEG for megrim and MON for white anglerfish.

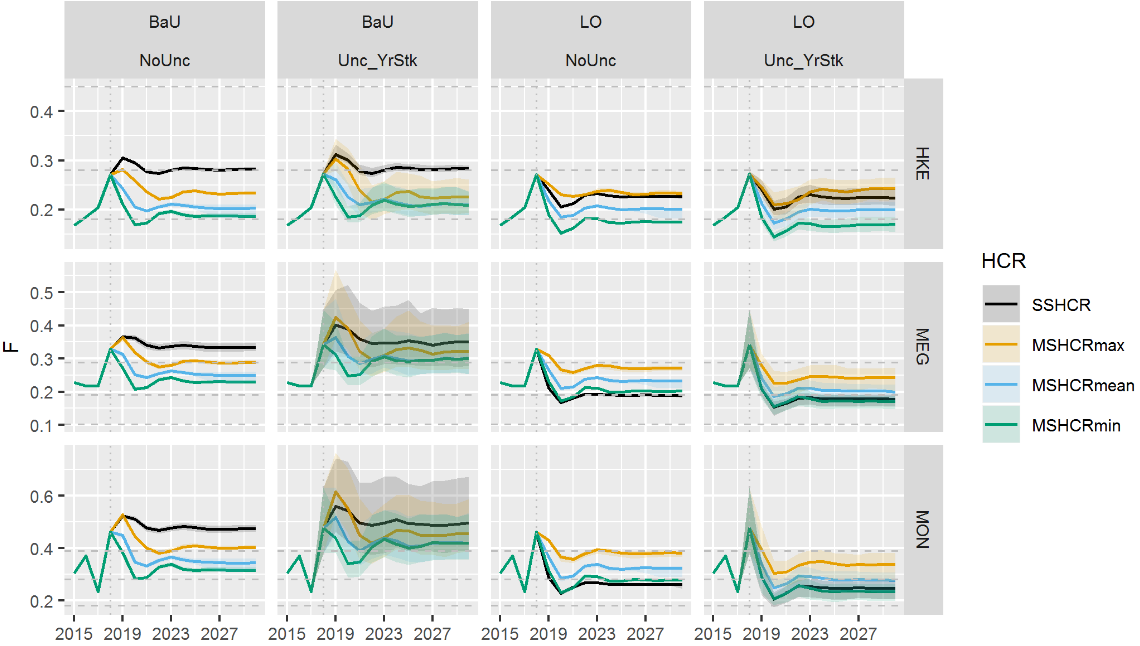

**Figure 6.** Fishing mortality time series obtained using different harvest control rules under current management scenarios (BaU, the plots in the first two columns in the left) and under landing obligation scenario (LO, the plots in the last two colums), without variability in catchability (NoUnc) and with variability in catchability at year and stock level (Unc_YrStk), in the multi-fleet case study. The horizonal lines correspond with fishing mortality ranges and with MSY fishing mortality. The lines represent different HCR, the HCR used by ICES in the MSY framework (SSHCR, black) and the multi-stock HCR using different options, max (MSHCRmax,yellow), mean (MSHCRmean, blue) and min (MSHCRmin, green). Although the simulation was run until 2040, as the fishing mortality was already stable in 2030, to gain detail in the short term the years with highest variability, only the time series up to 2030 are shown. HKE is the FAO code for HKE, MEG for megrim and MON for white anglerfish.

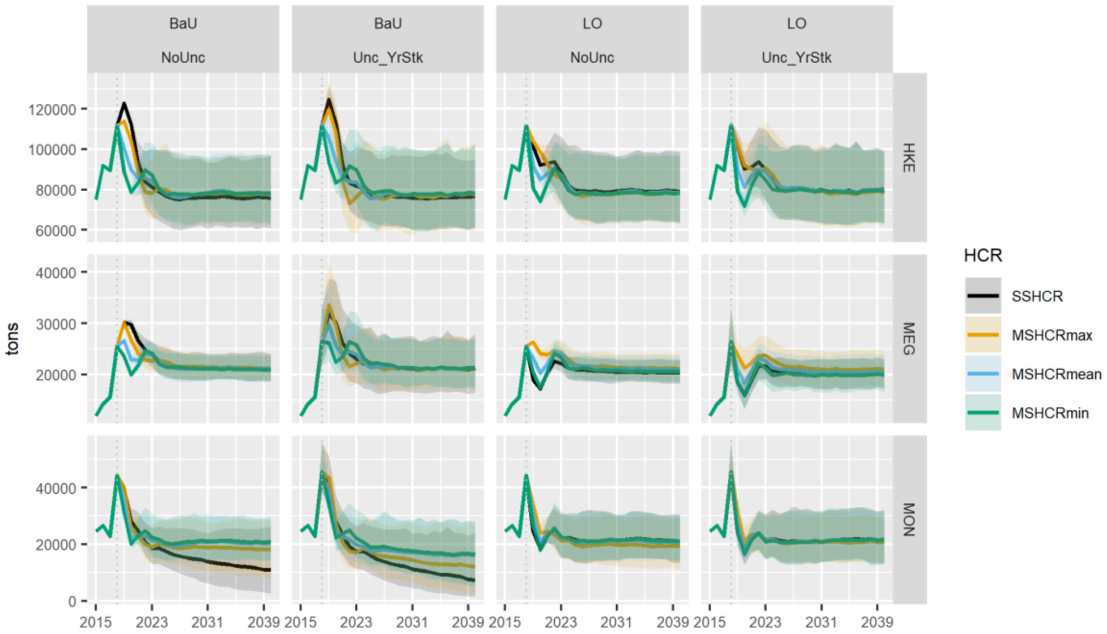

**Figure 7.** Catch time series obtained using different harvest control rules under current management scenarios (BaU, the first two columns in the left) and under landing obligation scenario (LO, the last two column of plots), without variability in catchability (NoUnc) and with variability in catchability at year and stock level (Unc_YrStk), in the multi-fleet case study. Note that the scale is different for each of the stocks. The lines represent different HCR, the HCR used by ICES in the MSY framework (SSHCR, black) and the multi-stock HCR using different options, max (MSHCRmax,yellow), mean (MSHCRmean, blue) and min (MSHCRmin, green). . HKE is the FAO code for HKE, MEG for megrim and MON for white anglerfish.

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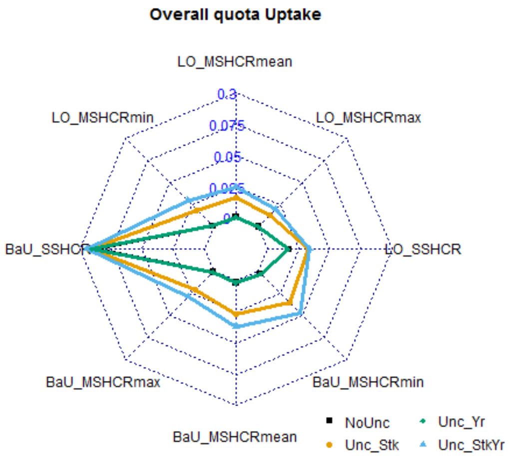

**Figure 8.** Quota use indicator for each scenario in the multi-fleet case study using different harvest control rules under current management scenarios (BaU) or under landing obligation scenario (LO) and different variability in catchability (no variability

(NoUnc, black), variability at stock level (Unc_Stk, yellow), variability at year level (Unc_Yr, green ) and uncertainty at stock and year level (Unc_StkYr, blue) . Values close to 0 indicate that the quota of all the stocks have been consumed completely. Note that the outer part of the graph has been truncated and the distance between the last two polygons is greater than between the others, this allows to show with more detail the values close to zero.

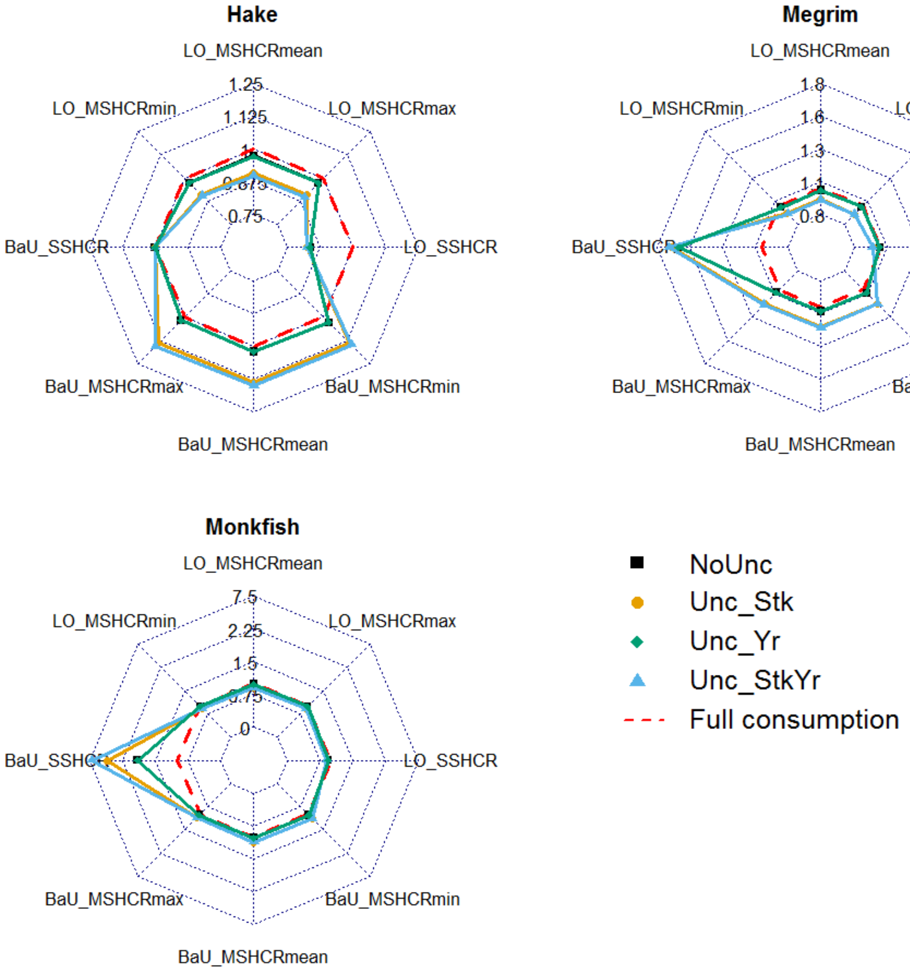

**Figure 9**. Quota uptake by stock in 2040 in multi-fleet case study using different harvest control rules under current management scenarios (BaU) or under landing obligation scenario (LO) and different variability in catchability (no variability (NoUnc, black), variability at stock level (Unc_Stk, yellow), variability at year level (Unc_Yr, green ) and uncertainty at stock and year level (Unc_StkYr, blue) . Values equal to 1 (dashed red line) indicate that the quota of the corresponding stock has been consumed completely. Note that the outer part of the White anglerfish's graph has been truncated and the distance between the last two polygons is greater than between the others, this allows to show with more detail the values close to zero.

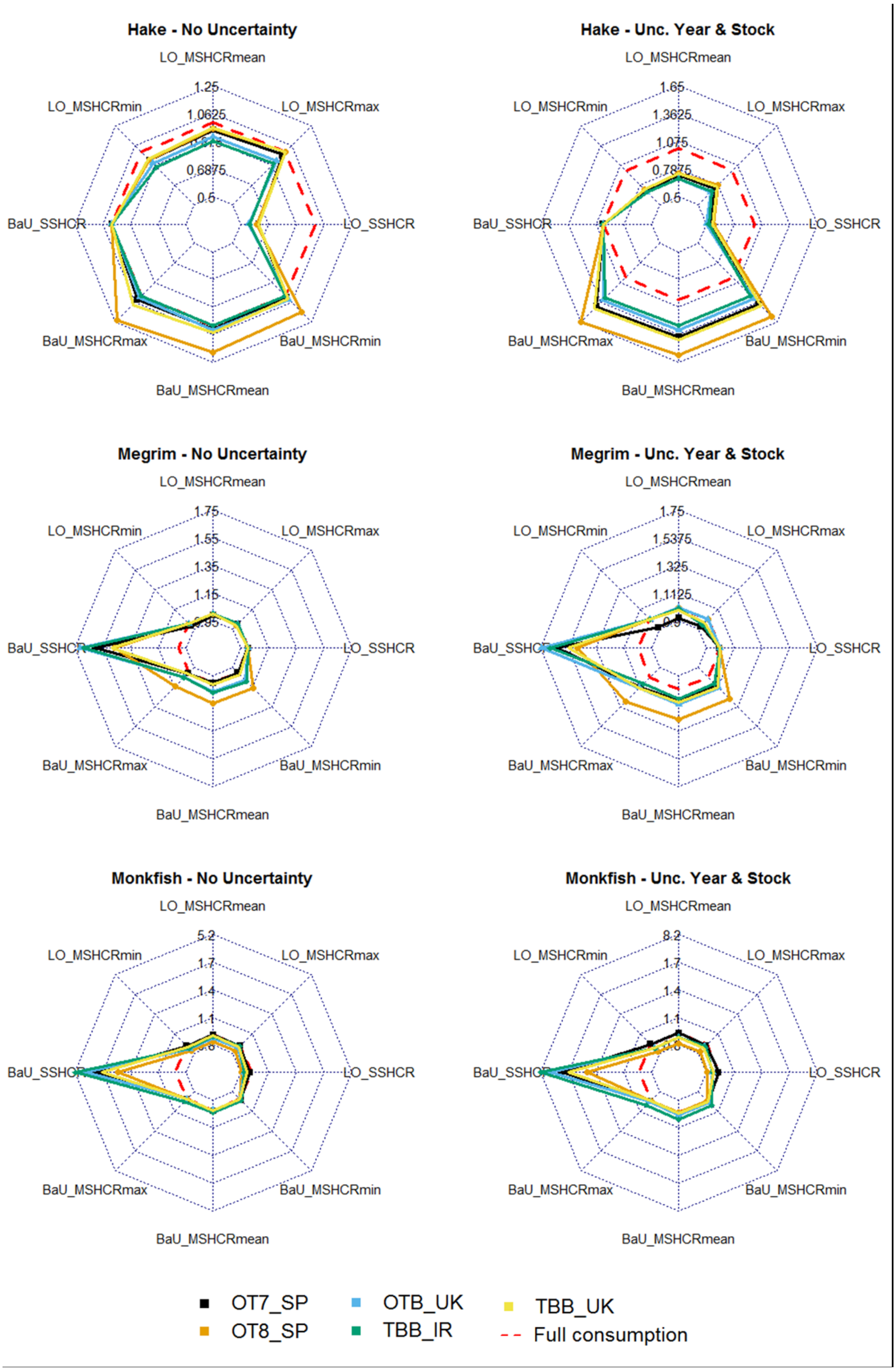

**Figure 10**. Quota by fleet and stock in 2040 in the multi-fleet case study using different harvest control rules under current management scenarios (BaU) or under landing obligation scenario (LO) and different variability in catchability (no variability in the left and uncertainty at stock and year level in the right) . The color lines correspond with different fleets (OT7_SP (black), OT8_SP (yellow), OTB_UK (blue), TBB_IR (green) and TBB_UK (yellow) ). Values equal to 1 (dashed red line) indicate that the quota of

the corresponding stock has been consumed completely. Note that the outer part of the White anglerfish's graph has been truncated and the distance between the last two polygons is greater than between the others, this allows to show with more detail the values close to zero.