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EU SC05 project: "Multispecies Fisheries Assessment for NAFO". Estimation of multispecies based HCRs and use of a multispecies MSE framework to assess the risk of collapse and the fishery-ecological trade-offs.

by

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ABSTRACT

The multispecies tier is an essential part of the NAFO roadmap for an Ecosystem Approach to Fisheries management, connecting the "Ecosystem" tier with the "Single species" tier. The EU DG-MARE launched in 2017 the project SC05 "Multispecies Fisheries Assessment for NAFO" with the intention of identifying the potential alternatives to implement a multispecies approach in NAFO, with the Flemish Cap as a case study. In this paper, an MSE framework is developed, with GadCap (cod, redfish and shrimp Gadget multispecies model in the Flemish Cap) as operating model. Reference points and Harvest Control Rules (HCR) are designed taking into account the multispecies interactions. Finally, traditional single species and new multispecies HCRs are assessed from the precautionary and MSY perspectives. The results suggest that HCRs designed under a single species approach are not precautionary for all the stocks and that it is not possible maintaining the 3 stocks above B_{lim} at the same time due to strong trophic interactions. Disregarding one stock may allow finding precautionary multispecies reference points for the other stocks. Precautionary HCRs for two stocks at once were only found when shrimp SSB in relation to B_{lim} was disregarded. The results showed that the two stages HCRs for cod reduces predation and increases probability of cod and redfish being above B_{lim}. This result supports that alternative two stage HCRs, or some other HCRs with other shapes, may increase the possible combinations of fishing pressure for these three stocks.

INTRODUCTION

It is a common practice in the single species approach that natural mortality is assumed equal for all ages and constant over time. Under this assumption reference points and Harvest Control Rules HCRs are set and evaluated performing long term simulations within a Management Strategy Evaluation framework with a single species operating model. These HCR are guidelines which, in conjunction with the output of short term projections of population dynamic, allow the provision of scientific advice and facilitate agreements in the decision-making process. However, it has been widely demonstrated that natural mortality varies with age within a cohort and over time between cohorts as a result of different environmental pressures, very importantly species interactions like predation or competition.

Since natural mortality is one of the main elements determining productivity and hence the surplus production available for human exploitation, underestimates of natural mortality and especially its variability over time may lead to overestimation of productivity and overfishing. Due to the interdependent dynamic and productivity of interacting commercial stocks, a regime shift in the productivity of one stock induced by human or natural factors will affect the dynamic of the other stocks, but also the reference points that define their HCRs. All these issues cannot be assessed with a single species framework. A multispecies assessment approach considering exploited species as part of a complex system of interacting species would contribute to solve this problem by estimating predation mortality that can be used in the stock assessment, but also in short term single species models to provide catch advice, but also estimating multispecies based reference points and HCRs evaluated in MSE frameworks with a multispecies operating model.

The multispecies assessment and advice approach is implicit in the recently approved new NAFO convention as the "commitment to apply an ecosystem approach to fisheries management" and it is already addressed as part of the discussion on the Precautionary Approach Framework (PAF) and the development of the Ecosystem Approach (EAF) roadmap. With the aim of contributing to the development of an EAF in the NAFO area, the EU DG-MARE launched, in year 2017, the project SC05 "A Multispecies Fisheries Assessment for NAFO". The main purpose of this study is providing a comprehensive overview (from the economic and ecological perspective) on how multispecies assessments would fit into the scientific and decision-making processes within NAFO and develop specific analyses and techniques on a case study, the Flemish Cap. As a first step (task 2 of SC05 project) the multispecies model GadCap (Flemish Cap cod, redfish and shrimp multispecies Gadget model; Pérez-Rodríguez et al. (2016)) was updated until 2016, and several biological, ecological and fisheries components were improved (Pérez-Rodríguez and González Troncoso 2018). This model was used to provide alternative values of natural mortality during the 3M cod benchmark (see Pérez-Rodríguez and González-Costas (2018)).

However, within the NAFO roadmap for an EAF (NAFO 2010), the interaction between the tier 2 (multispecies level) and tier 3 (single species level) is envisioned not only by providing estimates of ecological parameters like the natural mortality, but specially supporting decisions about management strategies. With the intention of contributing in this task, the SC05 project aims at developing an MSE framework, with GadCap as operating model (i.e. a multispecies MSE), that allows estimating reference points and designing Harvest Control Rules (HCR) that take into account the multispecies interactions, and where traditional single species and potential new multispecies HCRs could be assessed from the precautionary and MSY perspectives (task 3 of SC05 project). This MSE framework could then be used to provide a first analysis of the implications of moving from single to multispecies assessment and management, the trade-offs from an ecological perspective. In the present working document, the methods, main achievements and future work is presented, HCRs are defined using single and multispecies criteria, and their performance is assessed using the multispecies MSE framework.

MATERIAL AND METHODS

Criteria for the definition of Precautionary and MSY reference points in NAFO

NAFO Scientific Council (SC) PA framework commenced to be developed in 1997. This initial framework incorporated limit, buffer and target reference points, specified in terms of both fishing mortality and SSB. In 2003 a new PA framework was developed (NAFO 2004), that described zones of gradual increase in collapse risk and defined proposed management strategies and courses of action within each zone. These zones (Figure 1) were delimited by limit and buffer reference points (B_{lim}, B_{buf}, F_{lim} and F_{buf}). The reference points associated with the 2003 Framework were defined as follows:

Fishing Mortality Reference Points

- F_{lim} = F limit, is a fishing mortality rate that should only have a low probability of being exceeded (usually around 10% risk). F_{lim} cannot be greater than fishing mortality providing MSY (F_{MSY}).
- F_{buf} = F_{target}: F target, is a fishing mortality rate lower than F_{lim} that is required in the absence of analyses of the probability that current or projected F exceeds F_{lim}. It is an common approach in NAFO estimating F_{target} as 2/3*F_{lim}. This is the approach that will be followed in this project, since gadget is a deterministic type model that does not produce estimates of uncertainty.

Spawning stock biomass reference points

• B_{lim}: B limit, is a spawning stock biomass level, below which stock productivity is likely to be seriously impaired, that should have a very low probability of being violated (usually around 10% risk).

• B_{buf} = $B_{trigger}$: B trigger, is a stock biomass level above B_{lim} that is required in the absence of analyses of the probability that current or projected biomass is below B_{lim}.

In this study the NAFO PA framework has been followed in the determination of the precautionary (B_{lim} and $B_{trigger}$) and MSY based reference points (F_{MSY} and F_{target}) to define single and multispecies HCRs. B_{lim} and $B_{trigger}$ were estimated for cod, redfish and shrimp using their respective SSB-Recruitment relationship, as it is explained in the next section. F_{MSY} and F_{target} were estimated for each stock using the multispecies model GadCap to run long term simulations. The settings that allowed GadCap being used as a simulation model are explained in the next section. HCRs were designed in a way that F=0 when SSB≤B_{lim} (**Error! Reference source not found.**), i.e. a traditional one stage hokey stick HCR. However, as it is presented later, two stage HCRs were also tested.

Modelling the SSB-Recruitment relationship and the estimation of B_{lim} and $B_{trigger}$

The SSB estimated annually in GadCap over the period 1988-2015 (Pérez-Rodríguez and González Troncoso 2018) was used to model the recruitment estimated in the period 1989-2016, i.e. a one year delay between the SSB and the recruitment values that accounts for the fact that the recruitment in GadCap is modeled at age 1 for all the three stocks. There is little evidence in the available data to select the form of the SSB-recruitment function for the Flemish Cap stocks. However, the Ricker SSB-Recruitment model has been used due to its capacity to avoid unrealistic high estimates of recruitment produced by extremely high levels of SSB in some of the scenarios, as well as contributing to account for the cannibalistic behaviour observed in cod and redfish in the Flemish Cap (Pérez-Rodríguez et al, 2016).

$$R = \mu\, SSB\, e^{-\lambda\, \mathrm{SSB}} \qquad (1)$$

Where R is the recruitment in number of individuals at age 1, the SSB is the Spawning Stock Biomass, and μ and λ are parameters estimated when fitting the model.

The fitted Ricker SSB-Recruitment models was used in the estimation of both precautionary and MSY reference points. For the estimation of precautionary reference points it is used directly, and B_{lim} (B_{lim_50} and B_{lim_75}) and $B_{trigger}$ were defined as the SSB at which the recruitment was, respectively, 50%, 75% and 90% of maximum predicted recruitment. For the calculation of MSY related reference points, these SSB-recruitment models were used as part of the simulation model (GadCap), allowing the long term projection of the modelled system by determining the number of recruits that will enter in the population every year as a function of the SSB.

Adapting GadCap for long term projections

GadCap is a gadget stock assessment model which structure has been created to assess the state and dynamic of the cod, redfish and shrimp Flemish Cap stocks and their respective fisheries as a function of the recruitment process, the fishing activity itself and the ecological interactions that occur between them (Pérez-Rodríguez and González Troncoso 2018). In order to estimate the MSY reference points (F_{target}) for cod, redfish and shrimp, GadCap has been used to run long term forecast simulations. Several different fishing pressure values have been used in these simulations with the intention of finding the F value that produce the highest productivity with the lowest ecological risk. In preparing the GadCap model to run forward simulations, several elements have to be modified in the structure of the model.

The first element changed in the structure of GadCap was the time frame, which was modified to cover the period from 2017 to 2050. This time period was considered enough for the three stocks to reach the equilibrium in their dynamics, necessary to define the F_{target}. Next, the Ricker SSB-Recruitment model described in the previous section, was incorporated to the structure of GadCap. When running the long term simulations, this model determined the new individuals that entered in the population at age 1 every year based in the level of the SSB in the previous year.

After setting the time period and the SSB-Recruitment, all the parameters needed to simulate the different processes affecting the dynamic of the three stocks were defined using the parameter values that were optimized when fitting the historic period databases. These processes were: annual growth, length-weight relationship, maturation, sex change (from male to female primiparous shrimp), suitability of each prey for each of the predators, gear selectivity for the trawl fleets, residual natural mortality at age. These parameters were defined as the average value of the values optimized/fixed in GadCap during the period 2014-2016.

Deterministic long term forecast and selection criteria to define single and multispecies F_{target} reference points

Once the multispecies model GadCap was set up as described in the previous section, fishing activity was the only process to be defined, the level of fishing mortality F that each of the three trawl fleets (one per stock) was going to produce on each targeted stock in those long term simulations over the period 2017-2050. Running multiple independent simulation over this period with different fishing pressure allows assessing how the stock dynamic and the fishing catches (SSB and yield) changes over time as a function of F. This is the traditional method used to find the optimal F (usually F_{MSY}) when using numerical models. In a single species approach, for each stock several levels of F need to be tested. In this work, 20 different values of fishing mortality F were simulated for cod, redfish and shrimp (Table 1). However, in a multispecies approach it is necessary assessing the effect of combined levels of F for all the stocks that show strong interactions, since the level of F in one stock will affect the productivity in the other stocks. In our study, this resulted in 20^3=8000 combinations of Fs, i.e. 8000 different long term forecast simulations.

Gadget is a deterministic model, and hence, for each combination of F the forecast simulation produced, by stock, a single estimate of catch, SSB, abundance at age, etc. Accordingly, the probability of a given combination of Fs to drive the SSB of each of the stocks bellow B_{lim} cannot be assessed with GadCap at this first stage. The risk assessment associated to each F level combination will be conducted in a second stage using the multispecies MSE framework developed as part of the subtask 3.3 (see the next section). Despite of this limitation the deterministic approach developed in this task 3.2 can be used as a first step to reject those combinations of F that, already in a deterministic simulation, would bring the stocks below their respective B_{lim}.

In order to assess if a given combination of F would, in the equilibrium, bring the stocks bellow B_{lim} in a deterministic way, the mean SSB in the last 15 years of the simulated period (2035-2050) was estimated. The long term yield or catch associated to that combination of Fs was also assessed by estimating for each stock the mean catch during the that same period. This information about mean SSB and yield in the period 2035-2050 for each stock was used to select combinations of reference points for all the three stocks that will be used to define candidate HCRs. As indicated, in a second stage the risk assessment considering uncertainty in some of the biological processes (at this stage mostly uncertainty in the recruitment process) will be used to finally select the reference points by stock. As it is described next, the approaches to define the candidate reference points are different from a single and multispecies approach.

Criteria to determine MSY reference points from a single-species perspective:

As the name indicates, in a single species approach, interactions between species are disregarded. Accordingly, there is no interest in considering the result of combining different values of F for the three stocks. For this reason, when assessing the performance of each of the 20 different F levels for one of the three stocks, the different fishing levels for the other two stocks are disregarded. In this process, the steps followed were:

1. Calculate, for each stock and each F level, the mean SSB and yield over the period 2035-2050 (average SSB and yield obtained in the 400 simulations of the 20x20 Fs of the other two stocks).
2. For each stock, select the F that produces the highest yield while SSB is above B_{lim} in a deterministic way. This is a candidate F_{lim}=F_{MSY}.

3. Estimate F_{target} as $2/3*F_{lim}$: as explained above this is a standard procedure in NAFO when using a deterministic model like gadget.

Criteria to determine MSY reference points from a multi-species perspective:

As indicated above, whether a single or a multi-species approach is being developed, the precautionary reference points (B_{lim} and $B_{trigger}$) used when designing a HCR will be the same. However, the criteria for the determination of F_{target} are very different. The basic and essencial difference between a multispecies and a single species approach is that in the multispecies approach there is not a single solution to define F_{target} as it is the case in the single species approach, but multiple potential valid combinations of F_{target} for the stocks under consideration. Which combination/s of F_{target} are the most convenient will be determined by management priorities and the level of accepted ecological risk. Experience in previous projects indicated that the selection of management objectives, performance measures, constraints and the final HCRs should be agreed with all the stakeholders (Kempf et al. 2016, Rindorf et al. 2017).

In this study, the selection of potential candidate F combinations for F_{target} was guided exclusively by ecological criteria. Those combinations of F that resulted in mean SSB above B_{lim} in the long term (period 2035-2050) in a deterministic simulation were selected for a further step in the selection of candidate HCRs combinations. That step is presented next and consisted on a risk analysis using the multispecies MSE framework to estimate the probability that each of those combinations of F_{target} drives one or more stocks below B_{lim} in the long term. In this study, a variety of posibilites is explored, and presented in the results section.

One and two stage hockey stick HCRs

The most common HCR is, as presented in figure 2, a rule with a minimum level of SSB (B_{lim}) bellow which the adviced F becomes zero; and an SSB level ($B_{trigger}$) above which the adviced F is set constant at the level of F_{target}. Between $B_{trigger}$ and B_{lim} the adviced F decreases linearly. This is the so-called one stage hockey stick HCR, and is the one currently used in NAFO.

A more innovative type of HCR is the so-called two stage hockey stick HCR, which includes a second set of B_{lim}, $B_{trigger}$ and F_{target} defining a second slope and flat areas for F advice as a function of SSB (Figure 2). This HCR produces higher F values at high stock sizes and is implicitly multispecies, as it aims to avoid excessive stock sizes that may cause reduced productivity due to increased natural mortality, but also density-dependent processes. Two stage HCRs are currently used for Barents Sea cod.

Although the main effort in this study is focused on the standard single stage HCRs, with the intention of exploring new HCRs that take into account the species interactions, the two stage HCRs have also been tested. In first place several single stage HCRs have been tested for all the three stocks. Second, from those combinations of HCRs that succeeded in the risk analysis, a reduced number was used to set up two stage HCRs by adding a second set of B_{lim}, $B_{trigger}$ and F_{target}. The first set of reference points was taken from the one stage HCR, while the second was defined based the historic information. These two-stage HCRs were also tested in a probabilistic multispecies MSE framework.

Multispecies Management Strategy Evaluation framework and risk assessment

In this work a multispecies MSE framework is developed, where the multispecies model GadCap is used as an operating model (OM). This framework allows for an ecosystem approach when selecting the best management practices, by assessing the performance of single and multispecies based HCRs when the species interactions are taken into account. A full MSE has not been conducted in this study due to resources and time limitations, however, as a first step, uncertainty has been considered in the recruitment and the stock assessment.

The MSE framework developed within the SC05 project is based in the a4a approach to MSE[1]. This a4a-MSE framework was developed as a set of common methods and procedures to build a minimal standard MSE algorithm, including the most common elements of both uncertainty and management options. The FLR platform has been used with a modular design framework. The advantages of a modular design for MSE algorithms are the ability to easily reuse code across case studies. Each element of the MSE framework (Figure 3) maps to a single module, allowing the practitioner to focus on each part of the model without having to build new interactions with other relevant parts. One of this modular components is the operating model (OM), that represents the natural and human system and allow simulating the dynamic of the population or populations of interest as well as their fisheries. It is commonly generated by formally conditioning on the available sources of data, through statistical fitting of a fishery and population model. The complexity of an OM can vary widely, from biomass dynamics models to ecosystem model with spatial components and seasonal time steps. The complexity of the OM will have a direct influence on the complexity of the management options that can be explored with it, and on the range of future robustness scenarios they can be tested against. The type of OM for which this a4a-MSE framework has been initially designed is a single stock, age-based, yearly population model, exploited by an aggregated fleet. However, both the FLR tools and the a4a MSE framework allow extensions of this structure in various ways.

In this project SC05, the modular structure of the a4a-MSE framework was modified to develop a multispecies MSE framework for the Flemish Cap cod, redfish and shrimp, that can be used to conduct risk assessments for different combinations of HCRs selected in the previous step. The a4a-MSE framework was deeply modified to 1) introduce in the OM module a gadget multispecies model (and specifically GadCap as a case study) 2) running several MPs in parallel, as many as stocks considered in the multispecies model 3) Include different sources of structural, process and observation uncertainty and error. At this stage, the structural uncertainty was only considered through the uncertainty in the recruitment process.

Introduction of uncertainty in the recruitment process in forward simulations

In order to assess the importance of recruitment uncertainty in the risk associated with a given combination of HCRs for the three stocks, it is necessary introducing variability in the number of recruits that a given level of SSB will produce every year during the long term simulations (period 2017-2050). Although there are different ways to do that, in our study we chose the option of estimating the year factor as the residuals from the optimized Ricker model for each of the three stocks, calculated as the ratio between the observed recruitment (output from GadCap) and the predicted recruitment (Ricker model). The year factor can be thought of as representative of the deviations from the recruitment expected due to the SSB level, produced by the effect of particular annual environmental conditions in the recruitment success of each stock. These environmental conditions may be water temperature or other oceanographic factors, but also predation, diseases or any other factor affecting survivorship of early recruits before age 1. Accordingly, by estimating the residuals of the observed-estimated recruitment for the historic time period, we obtain a time series of year effect on recruitment for each of the three species from 1989 to 2016. These year effects on recruitment can then be used to simulated long time series of year effects over the period 2017-2050. Each of these time series of year factors will produce variability in the SSB-Recruitment relationships between years, by multiplying the parameter α of the fitted Ricker model for each stock times the year factor (equation 1).

$$Recruitment = year\_factor \; x \; \alpha SSB e^{-\mu SSB} \qquad (2)$$

The uncertainty in the SSB-Recruitment relationship is traditionally the most important source of uncertainty when running forward simulations, and hence, the risk assessment of different management strategies is highly sensitive to the assumptions made to produce stochasticity in the recruitment process when running long term simulations. In this study, for each of the three stocks, 100 time series of year factors over the period 2017-2050 were produced by randomly selecting with replacement from the year factors estimated

[1] (http://www.flr-project.org/)

in the historic period. These 100 time series of year factors for each of the three stocks were then be provided to the GadCap operating model (OM) in the multispecies MSE framework to run 100 forward simulations over the period 2017-2050. Each of these 100 time series of year factors will produce variability in the SSB-Recruitment relationships and hence will produce 100 of different dynamics in the three exploited stocks, in their fisheries, trophic interactions and population structures.

Considering error in the assessment:

At this initial stage, the assessment option that has been selected is the so-called *'shortcut option'* (ICES 2008). This assessment option consist on taking the information of the SSB directly from the OM for each of the three stocks and apply an assessment error to that SSB. This will result in an approximation to the SSB that the actual assessment conducted by the NAFO SC would have estimated. Accordingly, the error in the assessment of the SSB by the currently approved stock assessment methods in NAFO has to be estimated. The approach followed in this study has been analyzing the retrospective patterns obtained in the last year that the stock assessment has been conducted for each of the stocks. The mean error at age has been calculated as the ratio between the estimated abundance at age in the last year of each retrospective pattern and the abundance at age estimated for that year in the most updated assessment. In addition to the mean ratio by age, the variance-covariance matrix of the ratios between the different ages was also estimated. The mean ratio at age and the variance-covariance matrix defines a multivariate distribution of the error between ages, which allow producing new error ratios sampled randomly every year but with certain covariance between ages. During the long term simulations, every year the information about the 'real' abundance at age for each stock coming from the OM in the MSE framework will be transformed by multiplying it times the sampled ratio. In the case of shrimp currently there is not an assessment model. In this case it was assumed that the assessment error for cod was applicable.

Risk assessment of the HCRs considering the recruitment uncertainty, observation and assessment errors. First selection of candidate HCRs for economic calculation.

As indicated above, the MSE framework was used for the risk assessment running simulations using the estimated 100 different recruitment time series. On each of these 100 different simulations, the average SSB and yield was estimated in the last 15 years of the simulation period (2035-2050). Therefore, 100 SSB and yield values were obtained for each combination of HCRs. The NAFO precautionary approach considers that a management strategy is not precautionary when more than 10% of the simulations the SSB is driven below B_{lim}. This is the criterion that has been followed in this study to consider a precautionary strategy or not. It should be noted that this 10% criterion is considered approximate, and that, especially in a context with a multispecies approach some flexibility is allowed.

The risk assessment was conducted separately for single and multispecies HCRs. In the case of the single species approach three HCRs were selected from the work conducted on subtask 3.2, one HCR per species and were implemented simultaneously in the multispecies MSE framework. In the multispecies approach, unlike the single species approach, there is not a single solution when defining the HCRs. The management of a stock as result of the application of a given HCR will affect the dynamic of the other stocks, and may even involve higher risks of being below B_{lim}. In this project different options have been tested, and risk assessment was conducted on combinations of HCRs for which, in a deterministic way (subtask 3.2), priority was given to 1) keeping all stocks above B_{lim} or 2) subgroups of stocks or 3) individual stocks.

To avoid excessive and unrealistic population growth during the long term simulations, limitations were introduced to the shrimp and redfish population growth. This was done by introducing a carrying capacity in the OM, based on the maximum population sizes observed in the historical period. It was assumed that the collapse of cod allowed its prey stocks shrimp and redfish, reaching values that may be close to the maximum carrying capacity. To simulate this limitation to population growth, a source of extra mortality has been introduced in the shrimp submodel when it approached 150000 tons of total biomass, and a source of extra mortality for the redfish submodel when it was approaching a SSB of 70000 tons. For cod, it has not been necessary, since cannibalism has worked as a source of mortality limiting the productivity of the stock.

RESULTS and DISCUSSION

Precautionary reference points: B_{lim} and $B_{trigger}$

The relation of the recruitment with the SSB showed the typical dome shaped Ricker model shape, with recruitment decreasing at higher values of SSB (Figure 4). The fit Ricker SSB-Recruitment curve was then used to estimate the precautionary reference points, B_{lim_50}, B_{lim_75} and $B_{trigger}$, as the SSB at which the recruitment is, respectively, 50%, 75% and 90% of maximum predicted recruitment (Figure 4). The criteria followed to define the precautionary reference points were different for each of the three stocks, and this is something that may be subjected to discussion. As a first approach, in this study it was decided that B_{lim} for shrimp would be taken as the SSB at B_{lim_50} (10206 tons), while for cod B_{lim} would be taken as the SSB at B_{lim_75} (17906 tons). The reason is that it was deemed that for cod B_{lim_50} (9892 tons) was an excessively low SSB value based in what have been previously defined as reference points for cod (González-Troncoso et al. 2013). For shrimp, B_{lim_50} was approximately four times higher than the B_{lim} value (2564 tons) defined for the survey index stock assessment (Casas-Sánchez 2012), and this value was consider appropriate based in the relationship between the biomass survey index and the estimated total stock biomass (approx. 5 times higher stock biomass than survey index). In relation to redfish, both the B_{lim_50} and B_{lim_75} seemed very low in relation to the observed values over the historic period. For this reason, the criteria used for redfish was changed, and B_{lim} was considered for this stock the level of SSB for which the first above average recruitment was observed (see **Error! Reference source not found.**Figure 4, right bottom panel), while $B_{trigger}$ was defined the SSB at maximum recruitment. Following this criteria, B_{lim} was defined at 22027 tons and $B_{trigger}$ at 35361 tons. The table 2 shows the B_{lim} and $B_{trigger}$ to be used in the HCRs for each of the three stocks in this study.

Deterministic long term forecast and definition of single and multispecies F_{target} reference points

Once the precautionary reference points were defined for each of the three stocks, the next parameter required to define the one stage HCRs was the F_{target}, for which long term simulations over the period 2017-2050 were run using the GadCap model. As described in the methodology section, 20 different values of F were defined for each species, resulting in 8000 different combinations for the three stocks (see **Error! Reference source not found.** in the methodology section). In this simulations the fitted Ricker SSB-Recruitment models were used to generate every year in the long term simulation the new recruits at age one in a deterministic way, i.e. each SSB would produce an only value of recruitment for each stock. Once the 8000 long term simulations were run, the mean SSB and mean Yield over the period 2035-2050 was estimated for each stock. From **Error! Reference source not found.** to **Error! Reference source not found.** the mean long term SSB and yield are shown for each of the three species as a function of the fishing pressure applied to the three stocks.

For the cod stock, the impact of changes in fishing pressure on redfish didn´t seem to have an important effect when the fishing pressure on shrimp is low. However, when fishing pressure on shrimp is increased there is a decline in cod mean SSB as the F on redfish is increased. It is when the fishing pressure on shrimp is increased when the most important differences in the estimated mean long term cod SSB is observed. This is especially evident when the fishing pressure on cod is low. This negative effects on cod SSB in the long term simulation as result of a higher fishing pressure on redfish and shrimp were due to the increased cannibalism occurring on cod when the availability of these prey stocks is reduced due to the high fishing pressure. In the case of fishing pressure on cod, as expected, the SSB decreased as the F on cod was increased. It is interesting to note that the fishing pressure that cod is able to stand before the SSB (in a deterministic way, without uncertainty ranges around it) goes bellow the B_{lim} (17906 tons) is very high. Specifically in the three F shrimp values presented in the figure 5, cod SSB was below B_{lim} only when F was above 0.8. Variations in the mean long term cod yield showed a similar pattern to that explained in relation to the SSB, i.e. increased fishing pressure on redfish and shrimp produced reduced productivity on cod, being especially evident when both F on shrimp and redfish was high. However, unlike the SSB, the increase of fishing pressure on cod showed a dome shaped curve, irrespective of the F value applied for redfish and shrimp. The maximum yield for cod was always observed when the F for cod was between 0.45 and 0.65.

In the case of the redfish stock, the mean long term SSB was very independent of the fishing pressure applied on shrimp. However, it was extremely dependent on the F applied on cod (figure 6). For a given F value on redfish, the lower the F on cod the lower the redfish long term SSB. In different words, higher fishing pressure on cod allows higher F on redfish before the redfish SSB declined below the B_{lim}. The results indicate that the absence of fishing on cod could bring redfish below B_{lim} even at very low fishing pressure. However, it is important highlighting that those SSB and Yield values obtained in situations that have not been observed before should be taken with caution, as it is the case for a scenario of very low fishing on cod when cod is at very high biomass level. In relation to the fishing pressure on redfish, increasing the F lead to lower values of SSB, but this relation was highly dependent on the fishing activity on cod. Regarding the long term yield for redfish, it also showed the typical dome shape as a function of fishing effort. This shape was independent of the fishing pressure on shrimp, but it was very dependent on the fishing pressure on cod. The higher the F on cod the higher the peak of yield for redfish. Unlike for cod, in redfish the peak of yield was always observed at low F values, being usually between 0.1 and 0.2.

Shrimp, due to its trophic role being a very important prey of two dominant species in the Flemish Cap, showed (in the SSB and Yield) a high sensitivity and dependency on the fishing strategies selected for these two predators. Only when fishing pressure on cod was very low or, interestingly, very high, the mean shrimp SSB in the long term could achieve values above the B_{lim}. At intermediate levels of fishing pressure on cod, the shrimp SSB was bellow B_{lim} independently of what fishing pressure was set on redfish (figure 7). The reason for this pattern is that cod is a main predator of shrimp, and hence very intense fishing on cod would benefit the development of the shrimp sotck, and would bring the SSB above B_{lim}. However, cod is also a main predator for redfish, which in turn is also a main predator for shrimp. For this reason a low fishing pressure on cod would involve high predation on redfish and hence a decrease in redfish stock (as it was already indicated in the previous paragraph). That decrease in redfish biomass would allow also an increase in the shrimp SSB above B_{lim}. However, as indicated above, this is a scenario that has never being observed before and hence the model is getting into the extrapolation territory, which should be taken with caution. In both cases (high or low fishing pressure on cod) the long term shrimp SSB was very dependent on redfish fishing pressure: low fishing pressure did not allowed shrimp SSB above B_{lim}. The long term mean yield on shrimp showed also a dome shape as a function of F on shrimp, but only when, as indicated for the SSB, the fishing pressure on cod was either very high or very low. The peak on the shrimp stock was hence very dependent on the fishing pressure on cod and redfish, but, in any case was always very low (bellow 0.15).

Once the long term SSB and yield have been calculated for each combination of fishing pressures (F_{cod}, $F_{redfish}$ and F_{shrimp}), the next step is selecting those HCRs that produce the highest and sustainable yields. However, as explained in the methodology section, the way the single and multispecies approaches will use all the information showed in figures 5 to 7 is very different. In the next sections the procedures used in both approaches are explained in depth and the F reference points and hence the HCRs are estimated from a single and multispecies perspectives.

- *Single species based reference points*

In a single species approach all that variability in the long term mean SSB and yield as a function of the fishing pressure on the three stocks is disregarded. In this study, in order to simulate that approach, for each of the 20 different F levels tested for each species the mean SSB and Yield was estimated, and the yield and SSB curves were plotted disregarding the variability due to different management strategies in other species (Figure 8). Based in this approach, the F_{MSY} is selected as the F value that produces the highest yield while the SSB is above B_{lim}. The resulting F_{MSY} is, as explained in the methodology section, a limit to the fishing pressure, and usually a lower value is used as F_{target}. It is a standard in NAFO that the F_{target} is calculated as 2/3 of F_{MSY}. Both F_{MSY} and F_{target} are presented in table 3.

- *Multispecies based reference points*

In the multispecies approach the value of F_{target} for a stock is decided considering the F_{target} for the rest of species, following a list of management objectives that must be defined a priori by all the stakeholders. In this study the criteria have been based exclusively on biological aspects, following as much as possible the NAFO precatory approach defined for a single species approach. Five different criteria have been defined to select combinations of F_{target}:

1. Combinations of F_{target} (and hence HCRs) that allowed the SSB being above B_{lim} at the end of the simulation period (2035-2050) for all the 3 stocks.
2. Combinations of F_{target} for which at the end of the simulation period cod and redfish SSB is above their B_{lim}, but disregarding the estate of the SSB for shrimp.
3. Combinations of F_{target} for which at the end of the simulation period shrimp and redfish SSB is above their B_{lim}, but disregarding the estate of the SSB for cod.
4. Combinations of F_{target} for which at the end of the simulation period shrimp and cod SSB is above their B_{lim}, but disregarding the estate of the SSB for redfish.
5. Combinations of F_{target} for which at the end of the simulation period shrimp SSB is above their B_{lim}, but disregarding the estate of the SSB for redfish and cod.

Out of 8000 F combinations, only 96 maintained all the three stocks above their respective B_{lim} values (criteria 1) at the end of the simulation period. A subset of 13 cases representative of the range of Fs applied for each of the three stocks that fulfilled this criteria 1 was selected (see table 4), maintaining all stocks above B_{lim} at the same time. It is important to note that the F values for cod and redfish were very high, and very close to the B_{lim} (see figure 9).

However, when the restrictions were released by allowing the shrimp stock going below its B_{lim} (criteria 2), the number of combinations of Fs for which the SSB in cod and redfish was maintained above B_{lim} was increased substantially, with 2595 possible combinations. It is not possible conducting a risk analysis to all those combinations, and hence, a reduced number of 19 combinations were selected (table 5). It was decided that in the selected F combinations, for simplicity the F values for shrimp would be set to zero. The reason is that in all the 2595 combinations, catches for shrimp were very low, and hence, in practice the shrimp fishery wouldnt have occurred. As it can be observed in the figure 10, even when the F was set to zero for shrimp the SSB was clearly bellow the Blim.

When the state of the cod SSB was disregarded, a total of 365 F combinations maintaind redfish and shrimp SSB above their respective B_{lim} values in a deterministic way. A subset of 17 F combinations were selected for risk analysis (table 6). The selected combinations showed that for cod, in a deterministic way, the fishing pressure brought the SSB bellow or very close to B_{lim} (figure 11).

When the state of the SSB for redfish is disregarded (criteria 4), again the number of possible F combinations is higher, with 1068 combinations that allow maintaining the SSB for cod and shrimp above their respective B_{lim}. A subset of 40 F combinations was selected for a risk assessment (table 7). In a deterministic way it is already evident that these combinations resulted in the redfish SSB being much lower than B_{lim} (figure 12), and producing a very low yield, while for cod and shrimp the SSB was above B_{lim}, in line with the criteria. In cod, with the exception of a few F combinations, most of the cases the SSB was much larger than B_{lim}.

When the state of both cod and redfish was disregarded (criteria 5), 1604 F combinations resulted in shrimp SSB above its established B_{lim}. A subset of 21 F combinations was selected for risk analysis (table 8). In these combinations, the deterministic long term simulations showed that in the equilibrium the SSB for redfish was bellow B_{lim} most of the cases, while for cod, it was close to B_{lim} in several combinations, but never below it (figure 13).

Multispecies Management Strategy Evaluation framework and risk analysis.

Running long term simulations with 8000 combinations of F for the 3 stocks (20 F levels per stock determining the fishing pressure on each scenario) has allowed identifying candidate HCRs combinations from a single species perspective and from a multispecies approach considering 5 different criteria. In total 110 combinations of F have been selected for risk analysis. The risk analysis will show if, when the uncertainty in the recruitment and the error in the assessment processes are considered, these combinations of F will still maintain the stocks above B_{lim} with high probability.

- *Adaptation of the a4a-MSE framework:*

The MSE framework developed is based in the a4a-MSE R package, on which four main modifications have been introduced:

- Introduction of the multispecies model GadCap as OM
- Parallel Management Procedures (MPs)
- Implementation of a "shortcut" assessment option with assessment error
- Integration of the MSE framework in a loop to account for uncertainty in the recruitment process and the assessment error.

The first challenge was replacing the single species a4a model with the gadget multispecies model GadCap as an operational model. The a4a-MSE belongs to the FLR project and is an R package. For this reason it was necessary creating another R package that was able to interact and execute gadget as well as serving as bridge between gadget and a4a-MSE. This package has been called gadgetR[2] and provides the user with a two-way interface to Hafro's Globally applicable Area Disaggregated General Ecosystem Toolbox (Gadget)[3]. The next step was modifying the code and the structure of the a4a-MSE framework to create multiple MPs, as many as stock in the multispecies model, which can be run in parallel during the long term simulations. In the case of GadCap, the gadget-a4a-MSE framework was modified to run three MPs in parallel: cod, redfish and shrimp MPs (Figure 14). Within each of the three MPs, each stock will have a different stock assessment (so far designed to be an a4a catch at age assessment model or a shortcut option), a different HCR (with different values for B_{lim}, $B_{trigger}$ and F_{target}), and separate management decisions, that, after passing through their respective implementation error model, will indicate the fleets in the GadCap OM the catch that has to be targeted for each of the three stocks.

As indicated, at in this project the so-called 'shortcut assessment' option was applied to simulate the assessment in the MSE framework. In this study, two options were possible for the shortcut assessment. The first option was 'no error shortcut', and, as the name indicates, no any error was applied to the SSB provided by the OM. Hence, this may be considered a perfect assessment option. The second option was a 'truth plus error shortcut' option, and consisted of multiplying the abundance at age in the assessment year provided by the OM times an error value. As described in the methodology section, the mean ratio of the difference between the estimated abundance at age in the last approved assessment for each of the three stocks, and the abundance at age estimated in the retrospective pattern. This ratio is usually close to 1, but can be lower or higher. A ratio higher than one means that usually the estimated abundance in the assessment is higher than in reality, and the opposite when the ratio is smaller than one. With the exception of ages 2 to 3 in cod, and 11 to 15 in redfish, in both stocks the estimated ratio was lower than 1 for most ages (see **Error! Reference source not found.** and **Error! Reference source not found.**). In addition to the mean ratio at age, the analysis of relationship in the ratio between ages over time in the retrospective pattern allows estimating a variance-covariance matrix. Assuming a multivariate normal distribution, the mean ratio at age and the variance-covariance matrix were used during the long term simulations to produce new values of assessment error at age every year, considering the covariance of this ratio bewteen ages.

Finally the gadget-a4a-FLR tool was integrated in a framework that would run simulations one after another, using, at each time a different time series of 'recruitment success' level. The estimated year factors in the recruitment process (Figure 15) were selected randomly with replacement for each of the three species to produce 100 time series of year factors covering the long term simulation period, i.e. from 2017 to 2050. As

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[2] https://github.com/REDUS-IMR/gadget

[3] http://www.hafro.is/gadget/

indicated in the material and methods section, the gadget-a4a-MSE framework will use these time series, one at a time, to produce variability in the relationship between the SSB and the recruitment every year.

- *Risk assessment of single species and multispecies one stage HCRs combinations considering recruitment uncertainty*

The MSE framework was used to perform the risk analysis. The 'no error shortcut' option was used as a first option in the risk assessment for all the selected combinations of HCRs. The 'truth plus error shortcut' option was used for a reduced number of HCRs combinations, with the intention of assessing if the selected best combinations of HCRs are still precautionary when the assessment error is considered.

- *Single species based HCRs combinations*

When the HCRs selected based in single species criteria were used in long term simulations and the uncertainty in the SSB-recruitment relationship was considered, the SSB went bellow the B_{lim} in the three stocks all over the simulated period 2017-2050 (Figure 16), but especially on shrimp and cod. In the equilibrium (over the period 2035-2050), the probability of being below B_{lim} at least one year was clearly above the 10% limit considered in NAFO to be precautionary in cod and shrimp, while in redfish the combinations of HCRs maintained the stock in the safe zone, with less than 10% of the simulations being below Blim at least one year (Table 11).

- *Multispecies based HCRs combinations: 3 species above B_{lim}*

The results indicate that none of the HCR combinations selected as potentially being able to maintain the three stocks above their respective B_{lim} were precautionary for cod and shrimp, while for redfish the probability of being below B_{lim} was lower than 10%. Despite the high risk of collapse, the median yield over the period 2035-2050 was high for cod. However, the percentage of interannual variability (percentage of the median yield) was very high, being usually above 100% due to the frequent collapses and closures of the fishery. The low risk of collapse, high median yield and low interannual variability for redfish was probably due to the released predation from cod.

- *Multispecies based HCRs combinations: disregarding shrimp*

The candidate combinations of HCRs selected when the level of SSB on shrimp in relation to its B_{lim} reference point is disregarded showed better performance than those combinations of HCRs intended to maintain the three stocks above B_{lim}. Although none of the options were precautionary for shrimp, some combinations maintained cod below or around the 10% probability, while a larger number allowed redfish to be at precautionary levels (table 13). But the most interesting output is that there was a number of combinations for which the probability of being below B_{lim} was lower or only slightly higher than 10% both for cod and redfish at the same time (e.g. combinations 5 and 6). Hence, when the shrimp is disregarded it is possible finding combinations of HCRs that allow exploiting cod and redfish within the precautionary constraints. With these HCRs combinations yield values are comparable to the TACs for Flemish Cap cod and redfish in the last years (see (Ávila de Melo et al. 2017, González-Troncoso 2017), and the interannual variability is lower than 20% of the median yield.

- *Multispecies based HCRs combinations: disregarding redfish*

The HCRs combinations where the redfish state in relation to B_{lim} was disregarded while prioritizing cod and shrimp resulted in very low probability of cod SSB being bellow B_{lim} (less than 10%) with the exception of those combinations where the F_{target} for cod was above 0.35. However, shrimp did not get risk lower than 45% in any of these combinations, and redfish risk of being below Blim was very high (above 80%), with the exception of those combinations for which the risk was higher for cod (see HCRs combinations 38-40 in **Error!**

Reference source not found.). Yield in redfish was relatively low (table 14), and interannual variability high (above 100% in most cases) in those years for which the risk was high, while the opposite pattern was observed in HCR combinations 38-40. For shrimp yield was always low in comparison to historical catches (Casas-Sánchez 2017), and interannual variability was above 50%, although it was higher when yield was high, due to the higher risk of collapse result of higher fishing pressure. Interannual variability was low in cod in all HCRs combination, excepting 39-40 when F_{target} was high. Cod yield increased when F_{target} on cod was higher, however, it was clear that, for each level of F_{target} on cod, yield decreased when the F_{target} on redfish and shrimp was increased. This was the result of an increased cannibalism on cod in reaction to a lower availability and higher collapse risk of prey (redfish and shrimp) due to higher fishing removals.

- *Multispecies based HCRs combinations: disregarding cod*

In those HCRs combinations selected when the state of cod SSB in relation to B_{lim} was disregarded, the risk of being bellow B_{lim} for cod was, as expected, very high (table 15). Still the yield was high for cod, but this was at the cost of an extremely high interannual variability, usually above 200% of the median yield (often closed fishery). On the contrary, for redfish the risk was very low due to the release from cod predation, resulting in an increased productivity and hence higher yield for the fishery. However, shrimp did not benefitted from these scenarios, probably due to the high predation from redfish.

- *Multispecies based HCRs combinations: disregarding cod and redfish*

The HCRs combinations where cod and redfish were ignored, regarding to their SSB in relation to B_{lim}, were expected to result in a lower collapse risk for shrimp. However, the simulations showed that the risk of shrimp SSB being below B_{lim}, despite being lower than in previous scenarios for some HCRs combinations, it was still very high, far from the precautionary limits (table 16). This may be related with the fact that, when the F_{target} and hence the risk of collapse was low for cod, the predation on shrimp was high. And, when F_{target} was high on cod, the redfish benefited of that, and even when the fishing pressure was high the risk of collapse was relatively low, involving high predation on shrimp.

- *Risk assessment of one stage HCRs combinations considering the error in the stock assessment (in addition to the recruitment uncertainty).*

The result indicate that the selected HCR are more precautionary for cod when the error in the assessment is included in the simulations (table 17). The retrospective pattern indicated that the assessment tend to underestimate the real biomass of the stock (see **Error! Reference source not found.**). Accordingly, the advised quota is lower than what it could be based in the real stock biomass. This lead to a higher survivorship of the cod stock, and then lower risk of being below B_{lim}. However, although the retrospective pattern in redfish also indicated a tendency to underestimate the real population biomass (see **Error! Reference source not found.**), the fact that cod biomass is increased when considering the assessment error, predation on redfish is higher. This produces a decrease in productivity of redfish and hence higher probability of being below B_{lim}. In any case, the differences are relatively minor in comparison with the risk assessment without considering the error in the assessment.

- *Risk assessment of two stage multispecies HCRs*

The results indicate that a two stage HCR advising a higher catch when cod SSB is above 45000 tons would result in a clear reduction of the risk of being below B_{lim} for redfish, due to the lower predation from cod (**Error! Reference source not found.**). There is also a lower risk of being below B_{lim} for cod, although the difference is not as important as for redfish. For shrimp, there is also a slight benefit in some HCRs combinations, although it is minor in comparison with the high risk of collapse.

CONCLUSIONS

The results of this work allow concluding that:

- Combinations of HCRs designed under a single species approach were not precautionary for cod and shrimp in a framework where species interactions are directly modelled and simulated.

- The risk analysis of HCRs combinations defined with multispecies criteria indicated that it is not possible maintaining the 3 stocks above B_{lim} at the same time. The reasons are the strong trophic interactions between the assessed stocks. Trying to maintain shrimp above Blim requires excessive fishing pressure on cod and redfish in order to reduce predation mortality, and this involves high risk of collapse on cod. On the contrary, maintaining cod above Blim involves high predation and high risk of collapse on shrimp and redfish.

- Disregarding one stock may allow finding precautionary multispecies reference points for the other stocks. Disregarding cod would result on fishing redfish within precautionary levels. Disregarding redfish would allow fishing cod without collapsing the stock. However, this was not possible for shrimp. It is probable that the uncertainty in the recruitment process, taken randomly in this study have been determinant on this.

- Precautionary HCRs for two stocks at once were only found when shrimp SSB in relation to B_{lim} was disregarded. Although there were not a high number of possibilities, there were a few combinations of HCRs that allowed fishing cod and redfish without collapsing the stocks. The estimated yield in the long term indicates that this strategies are in the line of the yields obtained for both stocks since the reopening of the cod fishery in 2010.

- The results showed that the two stages HCRs for cod reduces predation and increases probability of cod and redfish being above B_{lim}. This result supports that alternative two stage HCRs, or some other HCRs with other shapes, may increase the possible combinations of fishing pressure for these three stocks.

- The risk assessment indicated that the selected combinations of HCRs were still precautionary when the assessment error was included in the MSE. The assessment usually underestimates the real abundance at age, and, accordingly, the catch advice will always be below the real catch that the stock could support.

ACKNOWLEDGMENTS

This work wouldn´t have been possible without the outstanding contribution of the stock assessors and stock coordinators, as well as data managers from different institutions. I want to thanks very specially to Fernando González and Mikel Casas from the Centre of Oceanography IEO in Vigo, Antonio Avila from IPMA in Lisbon, Luis Ridao from the Faroe Marine Research Institute and Kjell Nedreas from the Institute of Marine Research in Bergen. The MSE framework was developed in tight collaboration with scientists of the department of demersal fish of the Institute of Marine Research IMR in Bergen (Norway) and the Joint Research Centre (JRC) of the European Commission in Ispra (Italy). The work developed as part of the project REDUS[4] (Reduced Uncertainty in Stock Assessments) by the IMR scientists in Norway was taken as the base to work on during a stay at the JRC as part of the FLR/a4a internships programme.

[4] http://redus.no/en/projects/redus/

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FIGURES

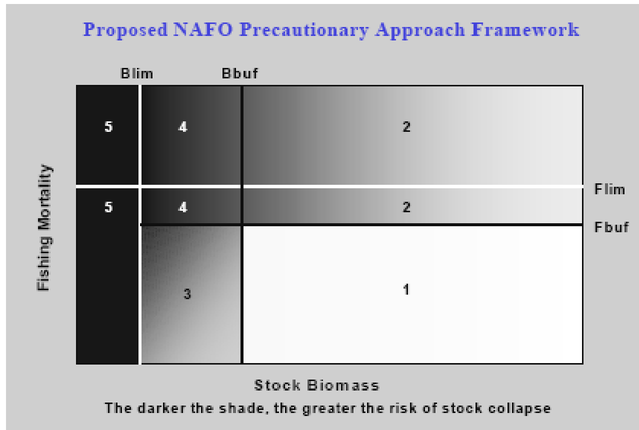

Figure 1. Schematic depicting a revision to the proposed NAFO PA framework adopted by the Scientific Council in September 2003 (Taken from NAFO (2004)).

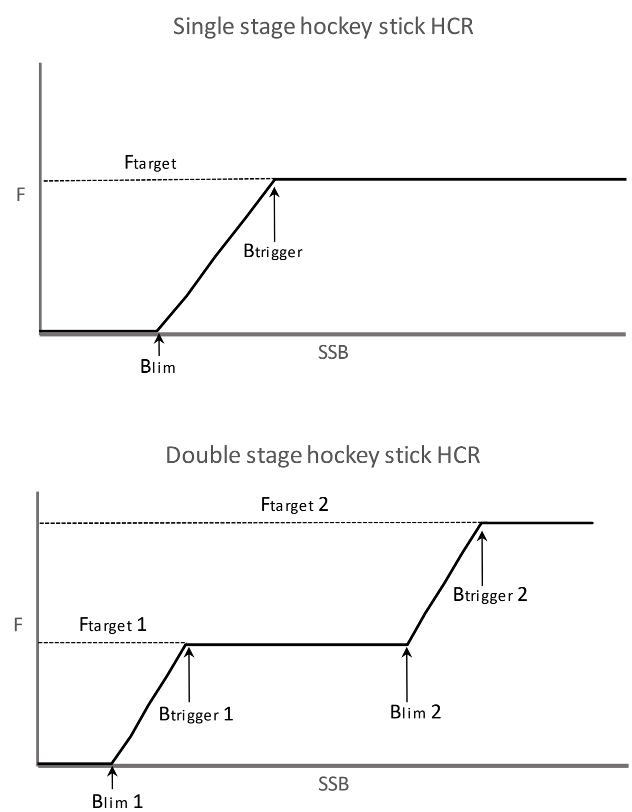

Figure 2. One stage (upper pannel) and two stage hockey stick HCR (lower pannel), showing the reference points and the set up considered in this project.

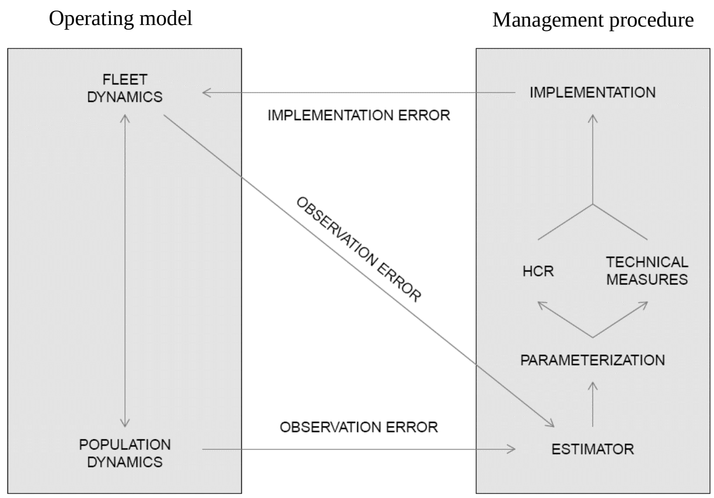

Figure 3. The a4a-MSE algorithm showing all the different modules that simulates the management cycle.

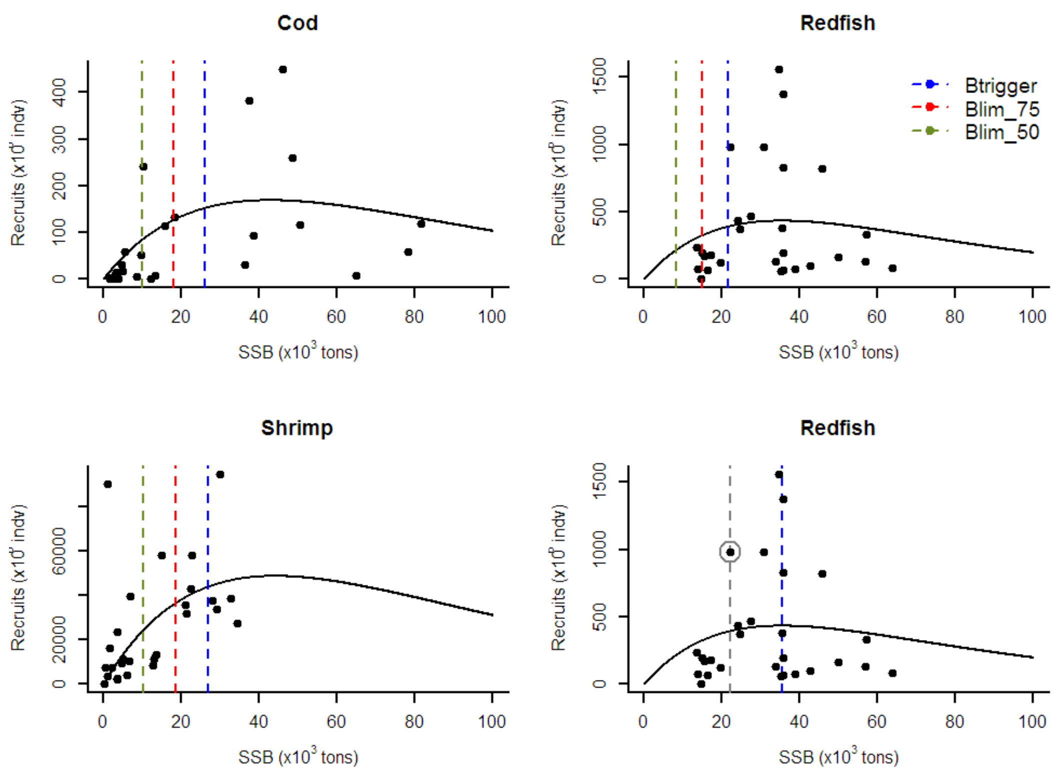

Figure 4. SSB and recruitment values result of GadCap over the historic period (black points) and fitted Ricker SSB-Recruitment model (black line). The Vertical lines represent the B_{lim_50} (green dashed line), B_{lim_75} (red dashed line) and $B_{trigger}$ (blue dashed line), defined as the SSB at which the recruitment is, respectively, 50%, 75% and 90% of maximum predicted recruitment. The right-bottom panel shows the special criteria followed to define the precautionary reference points in redifhs. The grey line an the grey circle indicates the B_{lim}, as the SSB at which it was observed the first recruitment value above the average in the historic period. The Blue dotted line in this case is $B_{trigger}$, defined as the SSB at maximum recruitment.

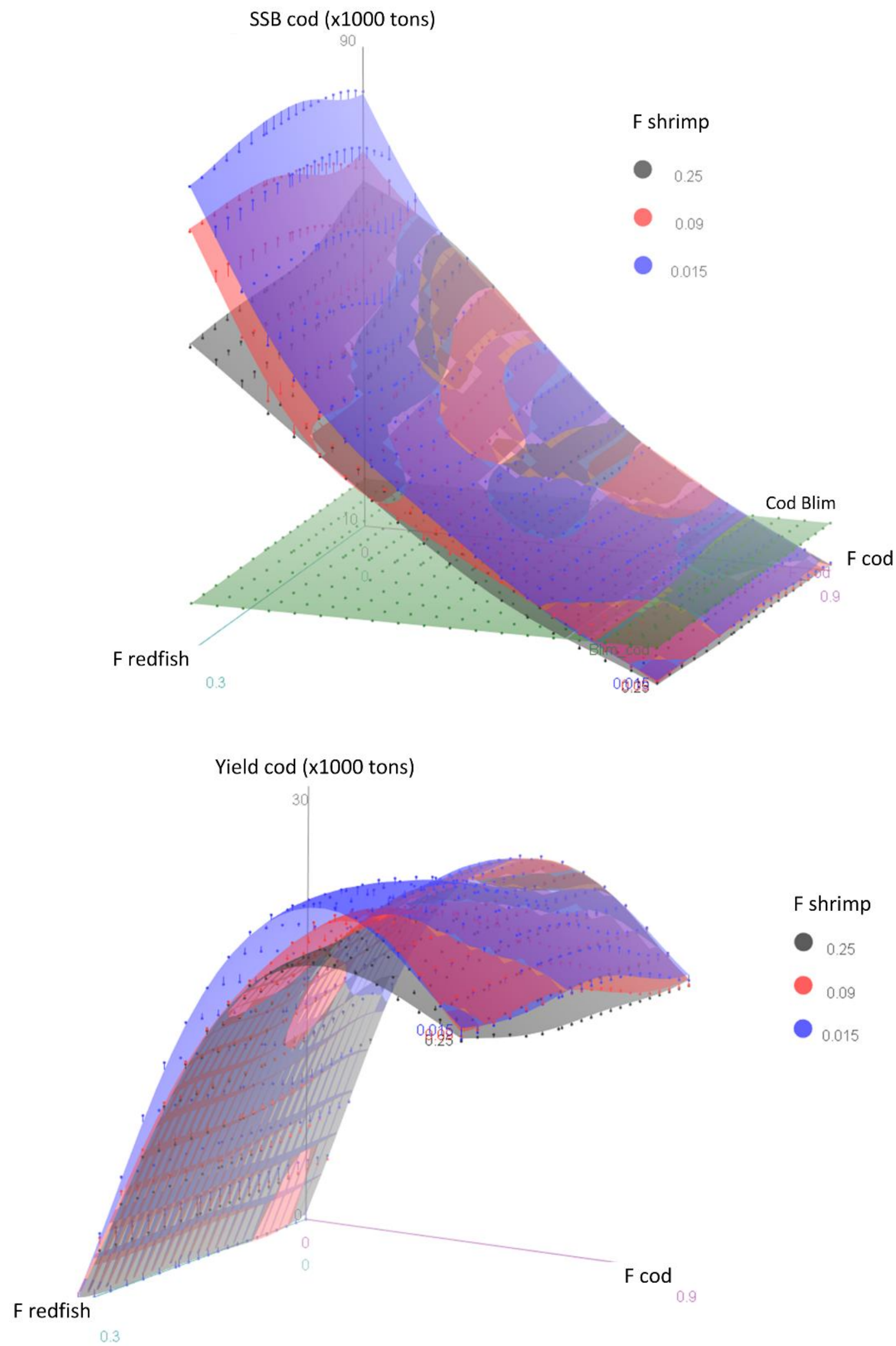

Figure 5. Mean SSB (upper panel) and Yield (lower panel) for the cod stock at the end of the forecast simulation period (2035-2050). The figures show the SSB and Yield values for the combination of 20 different F values of cod, 20 F values of redfish and 3 values of F for Shrimp. In this figures, the remaining 17 fishing mortality values for shrimp have been ommited for clarity and simplicity of the figures.

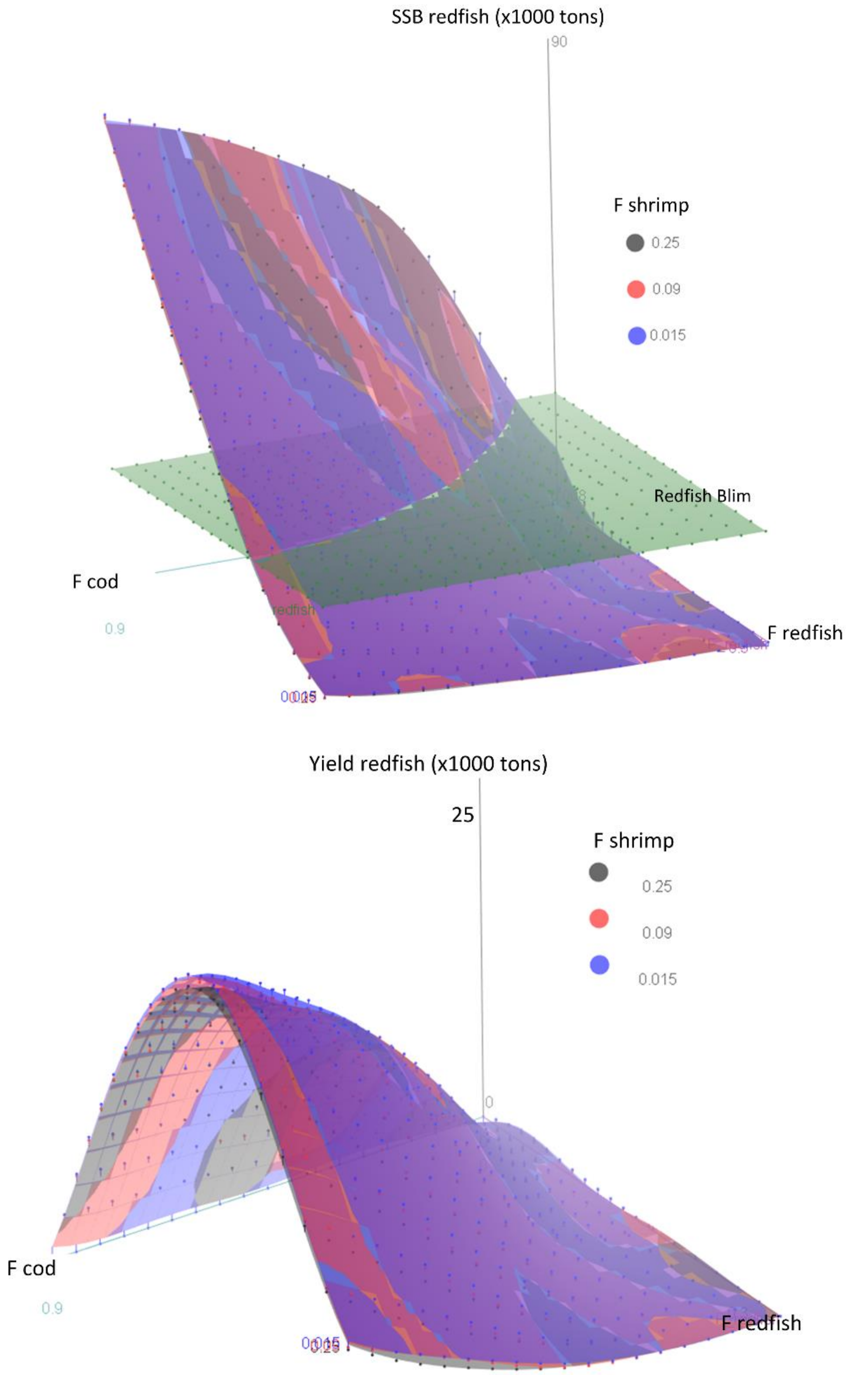

Figure 6. Mean SSB (upper panel) and Yield (lower panel) for the redfish stock at the end of the forecast simulation period (2035-2050). The figures show the SSB and Yield values for the combination of 20 different F values of cod, 20 F values of redfish and 3 values of F for Shrimp. In this figures, the remaining 17 fishing mortality values for shrimp have been ommited for clarity and simplicity of the figures.

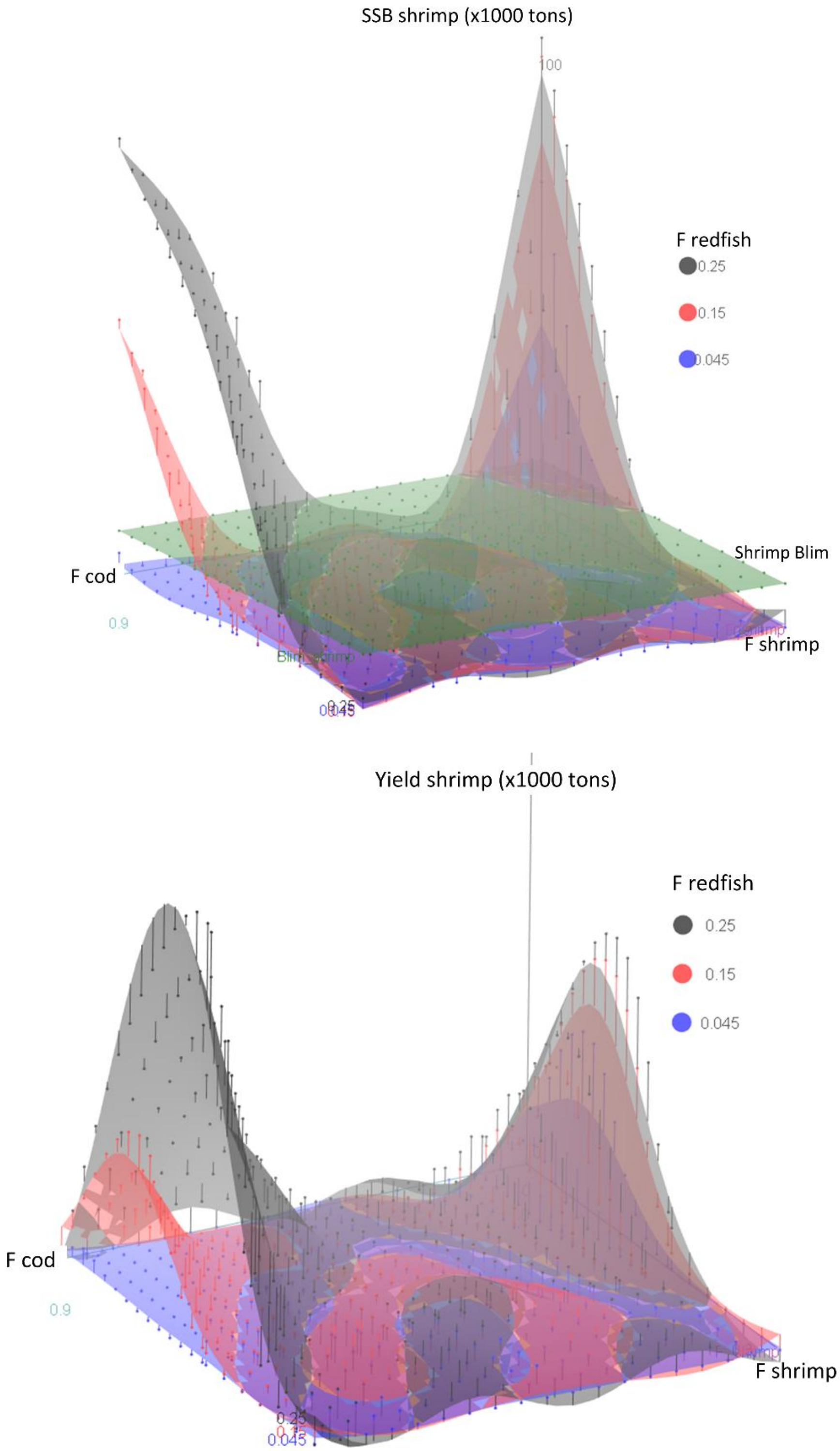

Figure 7. Mean SSB (upper panel) and Yield (lower panel) for the shrimp stock at the end of the forecast simulation period (2035-2050). The figures show the SSB and Yield values for the combination of 20 different F values of cod, 20 F values of shrimp and 3 values of F for redfish. In this figures, the remaining 17 fishing mortality values for redfish have been ommited for clarity and simplicity of the figures.

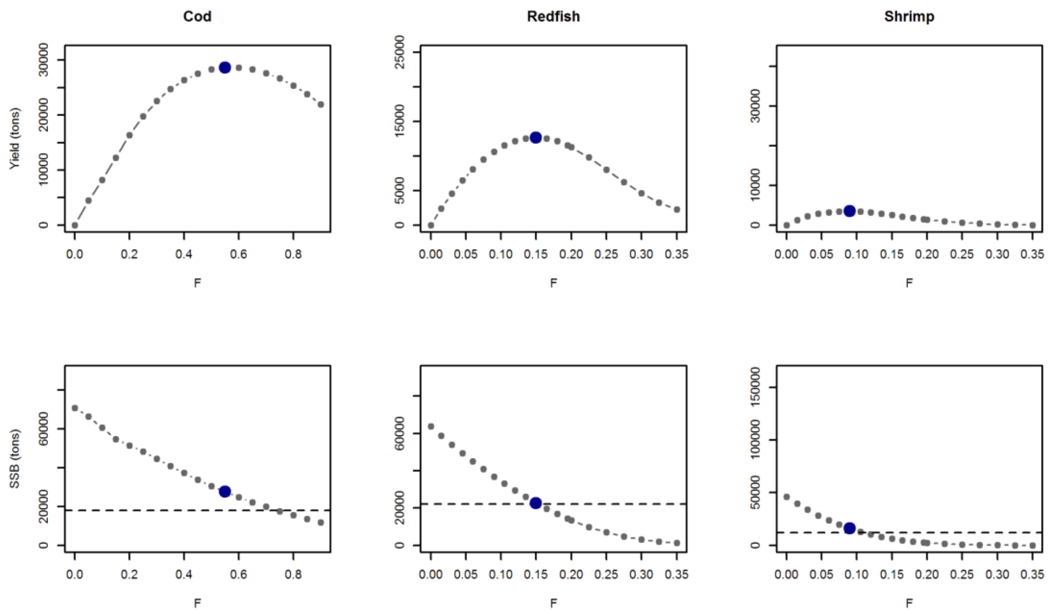

Figure 8. Average SSB and Yield in the equilibrium (years 2035-2050) by F level tested during the long forecast simulations.

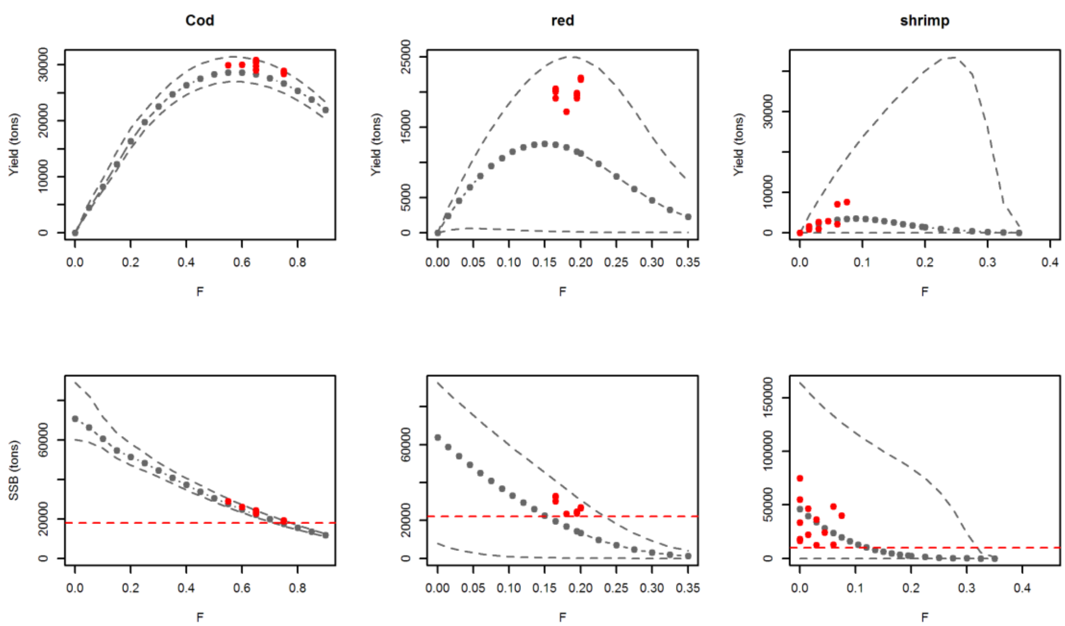

Figure 9. Mean SSB (bottom panels) and Yield (upper panels) at the end of the long term simulation period for cod, redfish and shrimp. For each of the three stocks, the dotted line represents the mean SSB and mean Yield, while the dashed lines represent the maximum and minimum SSB and Yield by F level for all the combinations of F for the other two stocks. The red points are the selected combinations of F values selected following the criteria 1 and presented in table 4.

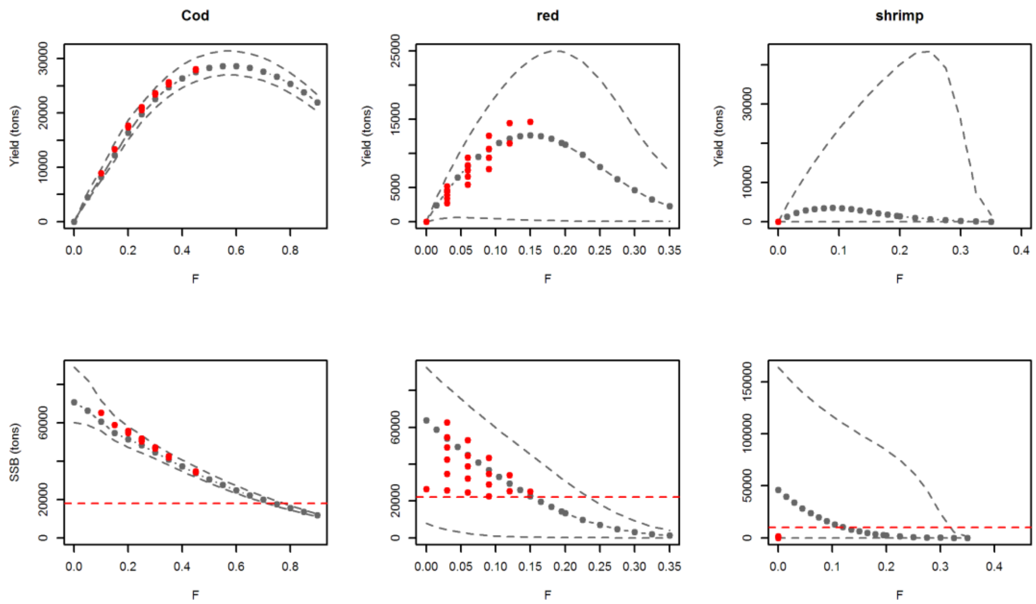

Figure 10. Mean SSB (bottom panels) and Yield (upper panels) at the end of the long term simulation period for cod, redfish and shrimp. For each of the three stocks, the dotted line represents the mean SSB and mean Yield, while the dashed lines represent the maximum and minimum SSB and Yield by F level for all the combinations of F for the other two stocks. The red points are the selected combinations of F values selected following the criteria 2 and presented in table 5.

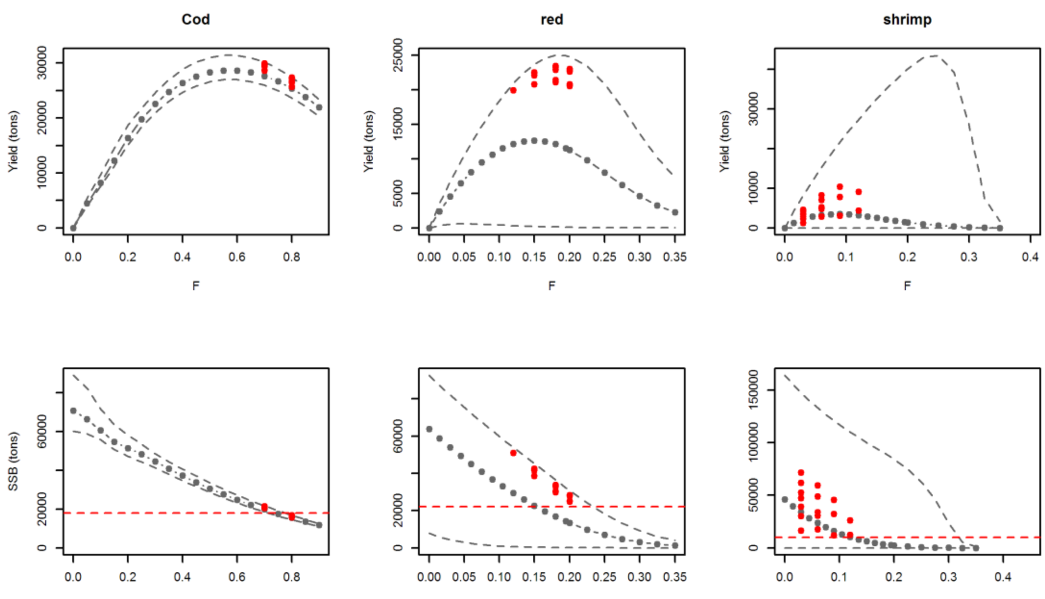

Figure 11. Mean SSB (bottom panels) and Yield (upper panels) at the end of the long term simulation period for cod, redfish and shrimp. For each of the three stocks, the dotted line represents the mean SSB and mean Yield, while the dashed lines represent the maximum and minimum SSB and Yield by F level for all the combinations of F for the other two stocks. The red points are the selected combinations of F selected following the criteria 3 and presented in table 6**Error! Reference source not found.**.

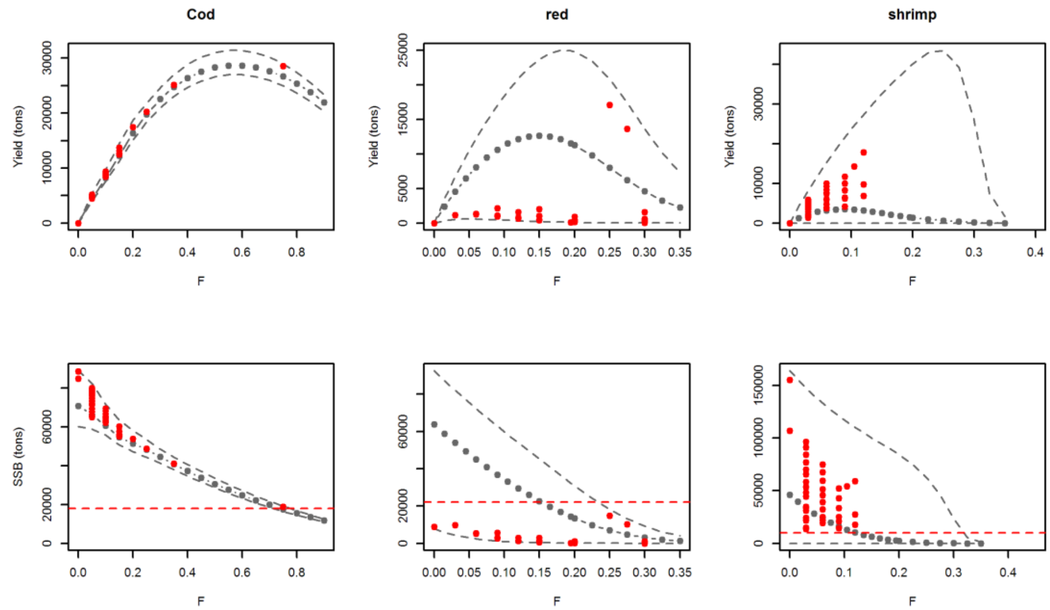

Figure 12. Mean SSB (bottom panels) and Yield (upper panels) at the end of the long term simulation period for cod, redfish and shrimp. For each of the three stocks, the dotted line represents the mean SSB and mean Yield, while the dashed lines represent the maximum and minimum SSB and Yield by F level for all the combinations of F for the other two stocks. The red points are the selected combinations of F selected following the criteria 4 and presented in table 7.

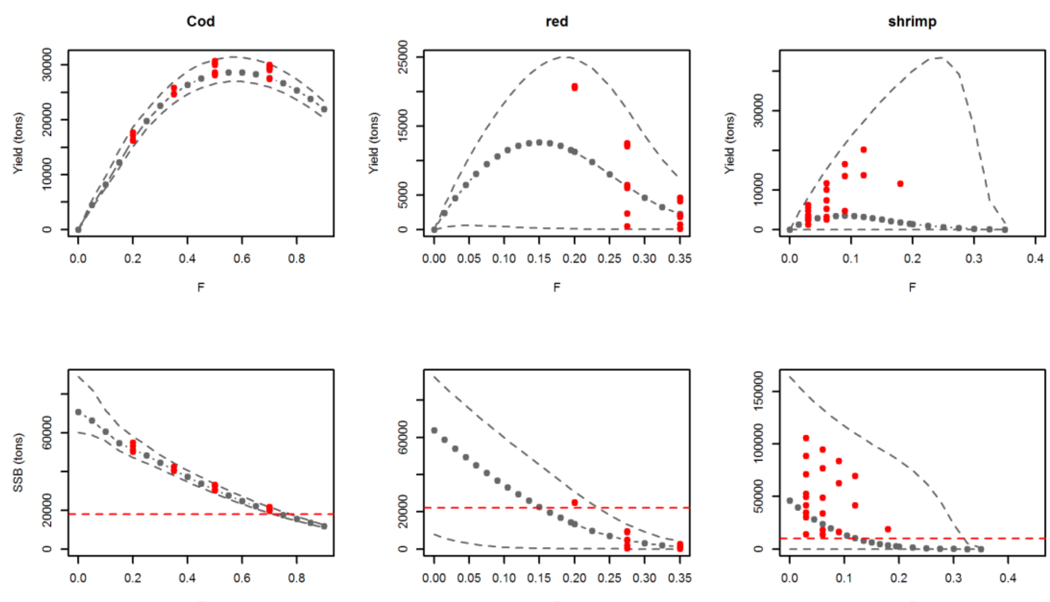

Figure 13. Mean SSB (bottom panels) and Yield (upper panels) at the end of the long term simulation period for cod, redfish and shrimp. For each of the three stocks, the dotted line represents the mean SSB and mean Yield, while the dashed lines represent the maximum and minimum SSB and Yield by F level for all the combinations of F for the other two stocks. The red points are the selected combinations of F selected following the criteria 5 and presented in table 8.

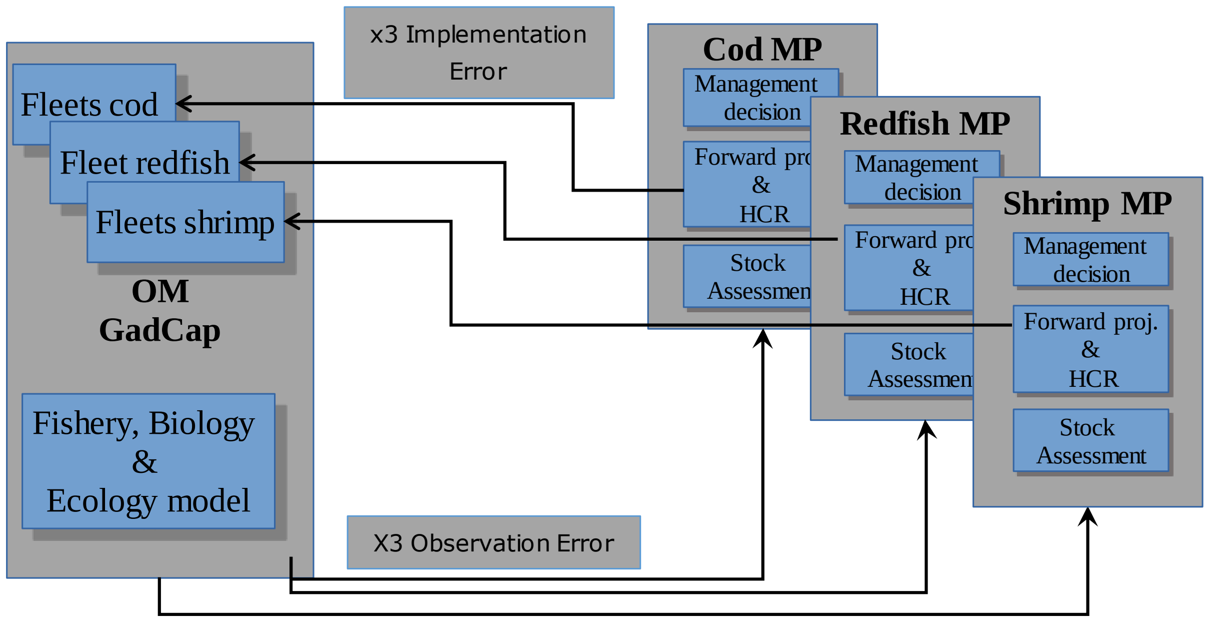

Figure 14. Multispecies gadget-a4a-MSE framework. The multispecies model GadCap developed as part of task 2 was used as OM. Uncertainty on the knowledge of the system was expressed as SSB-Recruitment uncertainty in the OM. Uncertainty in the MP

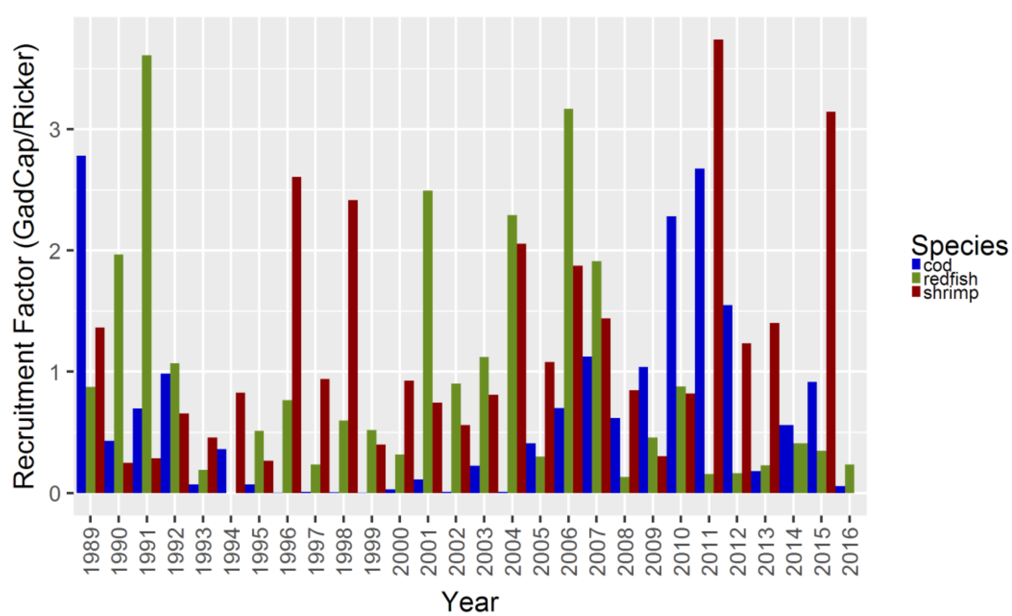

Figure 15. Estimated annual factor for SSB-Recruitment relationship. These values result of dividing the recruitment estimated with GadCap in section 3.2 by the predicted recruitment with the fitted Ricker model. These annual factors are assumed to reflect the environmental conditions affecting recruitment and were used to change annually the Richer SSB-Recruitment curve.

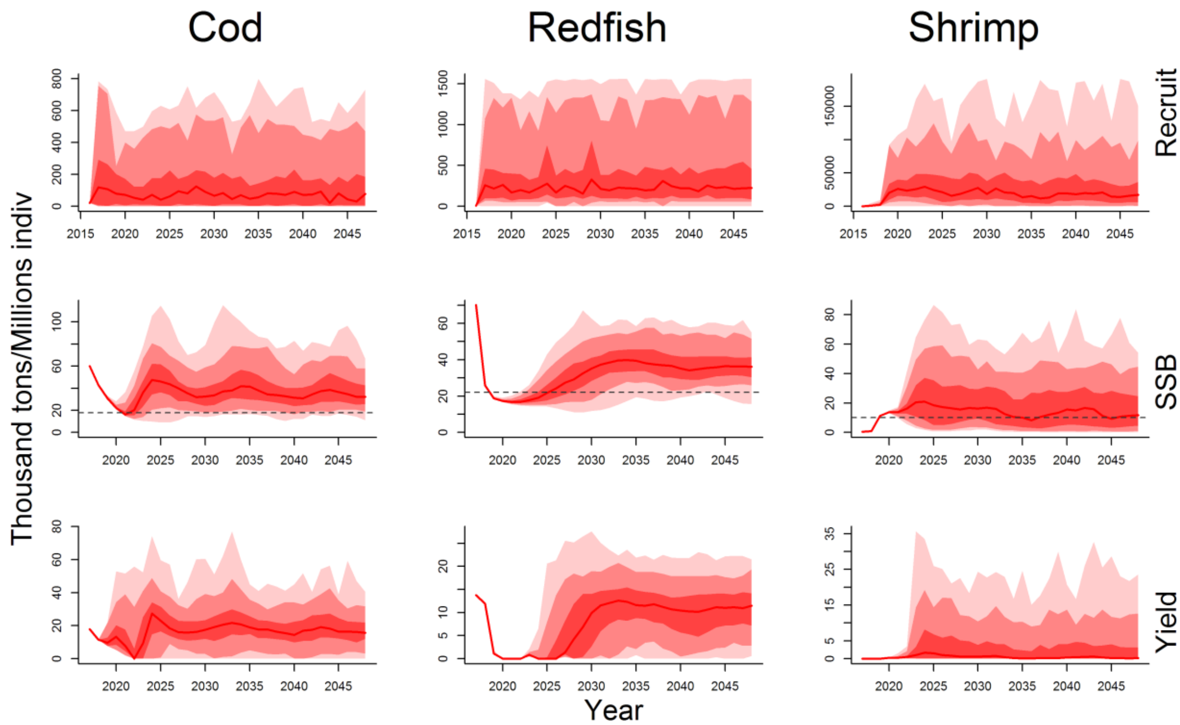

Figure 16. Long term simulations using the multispecies MSE framework with GadCap as an OM, while in the MP, the HCRs defined with single species considerations are used to define the fishing quota annualy. The red line defines the median Recruit, SSB and yield. From darker to clearer, the coloured areas define the 25-75, the 5-95 and the 0-100 percentiles. These ranges of uncertainty were produced by running 100 simulations, each of them with a different time series of year effects in the SSB-Recruitment relationship.

TABLES

Table 1. List of F values (20 values) tested for each of the three stocks considered in this study. All the possible combinations (8000 in total) were implemented in GadCap when running long term simulations over the period 2017-2050. The resulting estimates of yield and SSB were used to produce yield and SSB curves as a function of F, and serve to find MSY related F reference points.

F_{cod}	F_{red}	F_{shrimp}
0	0	0
0.05	0.015	0.015
0.1	0.03	0.03
0.15	0.045	0.045
0.2	0.06	0.06
0.25	0.075	0.075
0.3	0.09	0.09
0.35	0.105	0.105
0.4	0.12	0.12
0.45	0.135	0.135
0.5	0.15	0.15
0.55	0.165	0.165
0.6	0.18	0.18
0.65	0.195	0.195
0.7	0.2	0.2
0.75	0.225	0.225
0.8	0.25	0.25
0.85	0.275	0.275
0.9	0.3	0.3
0.95	0.325	0.325

Table 2. B_{lim} and $B_{trigger}$ finally selected for each of the three stocks following the criteria described in the text.

Stock	B_{lim}	$B_{trigger}$
cod	17906	25943
redfish	22027	35361
shrimp	11864	31114

Table 3. F_{MSY}, F_{target}, mean long term yield and mean long term SSB (both in tons) for the Flemish Cap cod, redfish and shrimp and estimated with a single species approach.

Stock	F_{MSY}	F_{target}	Yield	SSB
cod	0.55	0.367	28652	27605
redfish	0.15	0.1	12669	22689
shrimp	0.09	0.06	3463	16050

Table 4. Reduced selection of F combinations from all those that resulted in SSB higher than Blim in the equilibrium for all the three stocks, cod, redfish and shrimp (criteria 1).

Criteria_code	Criteria	F_cod	F_redfish	F_shrimp
1	3 stocks above B_{lim}	0.55	0.18	0
1	3 stocks above B_{lim}	0.6	0.165	0
1	3 stocks above B_{lim}	0.65	0.165	0
1	3 stocks above B_{lim}	0.65	0.165	0.015
1	3 stocks above B_{lim}	0.65	0.165	0.03
1	3 stocks above B_{lim}	0.65	0.195	0
1	3 stocks above B_{lim}	0.65	0.195	0.015
1	3 stocks above B_{lim}	0.65	0.195	0.03
1	3 stocks above B_{lim}	0.65	0.195	0.045
1	3 stocks above B_{lim}	0.65	0.195	0.06
1	3 stocks above B_{lim}	0.75	0.2	0
1	3 stocks above B_{lim}	0.75	0.2	0.06
1	3 stocks above B_{lim}	0.75	0.2	0.075

Table 5. Reduced selection of F combinations from all those that resulted in SSB higher than B_{lim} in the equilibrium for cod and redfish, but disregarded the state of the SSB for shrimp (criteria 2).

Criteria_code	Criteria	F_cod	F_redfish	F_shrimp
2	Disregard shrimp SSB	0.1	0	0
2	Disregard shrimp SSB	0.15	0.03	0
2	Disregard shrimp SSB	0.2	0.03	0
2	Disregard shrimp SSB	0.2	0.06	0
2	Disregard shrimp SSB	0.25	0.03	0
2	Disregard shrimp SSB	0.25	0.06	0
2	Disregard shrimp SSB	0.25	0.09	0
2	Disregard shrimp SSB	0.3	0.03	0
2	Disregard shrimp SSB	0.3	0.06	0
2	Disregard shrimp SSB	0.3	0.09	0
2	Disregard shrimp SSB	0.35	0.03	0
2	Disregard shrimp SSB	0.35	0.06	0
2	Disregard shrimp SSB	0.35	0.09	0
2	Disregard shrimp SSB	0.35	0.12	0
2	Disregard shrimp SSB	0.45	0.03	0
2	Disregard shrimp SSB	0.45	0.06	0
2	Disregard shrimp SSB	0.45	0.09	0
2	Disregard shrimp SSB	0.45	0.12	0
2	Disregard shrimp SSB	0.45	0.15	0

Table 6. Reduced selection of F combinations from all those that resulted in SSB higher than Blim in the equilibrium for shrimp and redfish, but disregarded the state of the SSB for cod (criteria 3).

Criteria_code	Criteria	F_cod	F_redfish	F_shrimp
3	Disregard cod SSB	0.7	0.15	0.03
3	Disregard cod SSB	0.7	0.18	0.03
3	Disregard cod SSB	0.7	0.18	0.06
3	Disregard cod SSB	0.7	0.2	0.03
3	Disregard cod SSB	0.7	0.2	0.06
3	Disregard cod SSB	0.8	0.12	0.03
3	Disregard cod SSB	0.8	0.15	0.03
3	Disregard cod SSB	0.8	0.15	0.06
3	Disregard cod SSB	0.8	0.15	0.09
3	Disregard cod SSB	0.8	0.18	0.03
3	Disregard cod SSB	0.8	0.18	0.06
3	Disregard cod SSB	0.8	0.18	0.09
3	Disregard cod SSB	0.8	0.18	0.12
3	Disregard cod SSB	0.8	0.2	0.03
3	Disregard cod SSB	0.8	0.2	0.06
3	Disregard cod SSB	0.8	0.2	0.09
3	Disregard cod SSB	0.8	0.2	0.12

Table 7. Reduced selection of F combinations from all those that resulted in SSB higher than Blim in the equilibrium for shrimp and cod, but disregarded the state of the SSB for redfish (criteria 4).

Criteria_code	Criteria	F_cod	F_redfish	F_shrimp
4	Disregard redfish SSB	0	0	0
4	Disregard redfish SSB	0	0.195	0
4	Disregard redfish SSB	0.05	0.03	0.03
4	Disregard redfish SSB	0.05	0.06	0.03
4	Disregard redfish SSB	0.05	0.06	0.06
4	Disregard redfish SSB	0.05	0.09	0.03
4	Disregard redfish SSB	0.05	0.09	0.06
4	Disregard redfish SSB	0.05	0.09	0.09
4	Disregard redfish SSB	0.05	0.12	0.03
4	Disregard redfish SSB	0.05	0.12	0.06
4	Disregard redfish SSB	0.05	0.12	0.09
4	Disregard redfish SSB	0.05	0.15	0.03
4	Disregard redfish SSB	0.05	0.15	0.06
4	Disregard redfish SSB	0.05	0.15	0.09
4	Disregard redfish SSB	0.05	0.2	0.03
4	Disregard redfish SSB	0.05	0.2	0.06
4	Disregard redfish SSB	0.05	0.2	0.09
4	Disregard redfish SSB	0.05	0.2	0.12
4	Disregard redfish SSB	0.05	0.3	0.03
4	Disregard redfish SSB	0.05	0.3	0.06
4	Disregard redfish SSB	0.05	0.3	0.09
4	Disregard redfish SSB	0.05	0.3	0.12
4	Disregard redfish SSB	0.1	0.09	0.03
4	Disregard redfish SSB	0.1	0.12	0.03
4	Disregard redfish SSB	0.1	0.15	0.03
4	Disregard redfish SSB	0.1	0.15	0.06
4	Disregard redfish SSB	0.1	0.2	0.03
4	Disregard redfish SSB	0.1	0.2	0.06
4	Disregard redfish SSB	0.1	0.3	0.03
4	Disregard redfish SSB	0.1	0.3	0.06
4	Disregard redfish SSB	0.1	0.3	0.09
4	Disregard redfish SSB	0.15	0.15	0.03
4	Disregard redfish SSB	0.15	0.2	0.03
4	Disregard redfish SSB	0.15	0.3	0.03
4	Disregard redfish SSB	0.15	0.3	0.06
4	Disregard redfish SSB	0.2	0.3	0.03
4	Disregard redfish SSB	0.25	0.3	0.03
4	Disregard redfish SSB	0.35	0.3	0.03
4	Disregard redfish SSB	0.75	0.25	0.105
4	Disregard redfish SSB	0.75	0.275	0.12

Table 8. Reduced selection of F combinations from all those that resulted in SSB higher than Blim in the equilibrium for shrimp, but disregarded the state of the SSB for cod and redfish (criteria 5).

Criteria_code	Criteria	F_cod	F_redfish	F_shrimp
5	Disregard cod and redfish SSB	0.2	0.275	0.03
5	Disregard cod and redfish SSB	0.2	0.35	0.03
5	Disregard cod and redfish SSB	0.2	0.35	0.06
5	Disregard cod and redfish SSB	0.35	0.275	0.03
5	Disregard cod and redfish SSB	0.35	0.35	0.03
5	Disregard cod and redfish SSB	0.5	0.275	0.03
5	Disregard cod and redfish SSB	0.5	0.275	0.06
5	Disregard cod and redfish SSB	0.5	0.35	0.03
5	Disregard cod and redfish SSB	0.5	0.35	0.06
5	Disregard cod and redfish SSB	0.5	0.35	0.09
5	Disregard cod and redfish SSB	0.7	0.2	0.03
5	Disregard cod and redfish SSB	0.7	0.2	0.06
5	Disregard cod and redfish SSB	0.7	0.275	0.03
5	Disregard cod and redfish SSB	0.7	0.275	0.06
5	Disregard cod and redfish SSB	0.7	0.275	0.09
5	Disregard cod and redfish SSB	0.7	0.275	0.12
5	Disregard cod and redfish SSB	0.7	0.35	0.03
5	Disregard cod and redfish SSB	0.7	0.35	0.06
5	Disregard cod and redfish SSB	0.7	0.35	0.09
5	Disregard cod and redfish SSB	0.7	0.35	0.12
5	Disregard cod and redfish SSB	0.7	0.35	0.18

Table 9. Mean ratio of the difference between the estimated abundance at age for cod in the last approved assessment for each of the three stocks, and the abundance at age estimated in the retrospective pattern.

age	meanratio
1	0.920441
2	1.160129
3	1.133066
4	1.02969
5	0.955309
6	0.951849
7	0.940828
8	0.944203
9	0.944203
10	0.944203
11	0.944203
12	0.944203

Table 10. Mean ratio of the difference between the estimated abundance at age for redfish in the last approved assessment for each of the three stocks, and the abundance at age estimated in the retrospective pattern.

age	meanratio
1	0.972452
2	0.972452
3	0.972452
4	0.788327
5	0.823222
6	0.842748
7	0.972452
8	0.942793
9	0.921678
10	0.910833
11	1.017579
12	1.050842
13	1.003778
14	1.007053
15	1.019722
16	0.893988
17	0.821866
18	0.932904
19	0.932904
20	0.932904
21	0.932904
22	0.932904
23	0.932904
24	0.932904
25	0.932904

Table 11. Results of the risk analysis on the HCRs defined with single species criteria candidate to maintain the three stocks above Blim when the recruitment uncertainty is included in the long term simulations. The second column shows the F_{target} for each of the stocks in the selected combinations. The third column shows the probability (proportion of the 100 simulation runs) of being below Blim in the long term (period 2035-2050). The forth column shows the median yield and the last column the interannual variability in the catch, as percentage of difference in relation to the median yield.

Species	F_{target}	Perc_below_B_{lim}	Median_Yield	Interannual_variance
cod	0.353	26	16719	23
redfish	0.1	4	11021	12
shrimp	0.067	77	2730	81

Table 12. Results of the risk analysis on the HCRs combinations defined with multispecies criteria and selected as candidate management strategies to maintain the three stocks above Blim when the recruitment uncertainty is considered in the simulations. The first group of columns shows the F_{target} for each of the stocks in the selected combinations. The second group of columns shows the probability (proportion of the 100 different simulations) of being below Blim in the long term (period 2035-2050). The third group of columns show the median yield and the forth column the interannual variability in the catch, as percentage of difference in relation to the median yield.

	F_{target}			Risk_below_B_{lim}			Median_yield			Interannual_variance		
HCR_combi	cod	redfish	shrimp	cod	redfish	shrimp	cod	redfish	shrimp	cod	redfish	shrimp
1	0.55	0.18	0	81	3	40	17118	15547	0	62	11	0
2	0.6	0.165	0	92	2	38	16798	15762	0	100	11	0
3	0.65	0.165	0	92	1	39	17649	14870	0	48	12	0
4	0.65	0.165	0.015	93	1	40	16835	15687	0	99	13	0
5	0.65	0.165	0.03	93	1	43	14398	15894	0	134	13	0
6	0.65	0.195	0	92	1	36	16755	15705	1526	101	11	55
7	0.65	0.195	0.015	92	1	37	16764	15641	1673	100	13	58
8	0.65	0.195	0.03	92	1	41	16687	15642	2812	101	11	54
9	0.65	0.195	0.045	93	1	44	16658	15595	3067	100	13	47
10	0.65	0.195	0.06	92	1	49	16552	15536	4189	100	13	52
11	0.75	0.2	0	99	1	35	16520	15469	5146	99	13	63
12	0.75	0.2	0.06	100	1	51	13888	15648	5616	162	13	69
13	0.75	0.2	0.075	100	1	53	13826	15577	6411	170	13	257

Table 13. Results of the risk analysis on the HCRs combinations defined with multispecies criteria and selected as candidate management strategies to maintain cod and redfish above Blim while disregarding shrimp when the recruitment uncertainty is considered in the simulations. The first group of columns shows the F_{target} for each of the stocks in the selected combinations. The second group of columns shows the probability (proportion of the 100 different simulations) of being below Blim in the long term (period 2035-2050). The third group of columns show the median yield and the forth column the interannual variability in the catch, as percentage of difference in relation to the median yield.

	F_{target}			Risk_below_B_{lim}			Median_yield			Interannual_variance		
HCR_combi	cod	redfish	shrimp	cod	redfish	shrimp	cod	redfish	shrimp	cod	redfish	shrimp
1	0.1	0	0	9	66	75	7528	0	0	16	0	0
2	0.15	0.03	0	9	53	76	10410	2459	0	17	38	0
3	0.2	0.03	0	11	22	78	12729	3322	0	17	22	0
4	0.2	0.06	0	9	30	73	12788	5246	0	17	27	0
5	0.25	0.03	0	13	6	82	14712	4022	0	18	10	0
6	0.25	0.06	0	14	15	73	14768	6527	0	18	13	0
7	0.25	0.09	0	14	23	67	14783	7750	0	19	22	0
8	0.3	0.03	0	18	3	79	16039	4586	0	20	8	0
9	0.3	0.06	0	18	5	72	16135	7685	0	20	11	0
10	0.3	0.09	0	17	10	66	16197	9418	0	20	13	0
11	0.35	0.03	0	25	1	78	16876	5062	0	23	5	0
12	0.35	0.06	0	25	1	72	17003	8602	0	23	6	0
13	0.35	0.09	0	27	4	65	17069	10667	0	23	9	0
14	0.35	0.12	0	27	6	58	17112	11570	0	23	12	0
15	0.45	0.03	0	51	0	77	17429	5610	0	32	4	0
16	0.45	0.06	0	51	0	69	17594	9629	0	32	5	0
17	0.45	0.09	0	51	0	58	17693	12244	0	32	6	0
18	0.45	0.12	0	51	2	54	17807	13525	0	32	9	0
19	0.45	0.15	0	50	2	48	17910	13733	0	32	12	0

Table 14. Results of the risk analysis on the HCRs combinations defined with multispecies criteria and selected as candidate management strategies to maintain cod and shrimp above Blim while disregarding redfish when the recruitment uncertainty is considered in the simulations. The first group of columns shows the F_{target} for each of the stocks in the selected combinations. The second group of columns shows the probability (proportion of the 100 different simulations) of being below Blim in the long term (period 2035-2050). The third group of columns show the median yield and the forth column the interannual variability in the catch, as percentage of difference in relation to the median yield.

	F_{target}			Risk_below_B_{lim}			Median_yield			Interannual_variance		
HCR_combi	cod	redfish	shrimp	cod	redfish	shrimp	cod	redfish	shrimp	cod	redfish	shrimp
1	0	0	0	5	96	54	0	0	0	0	0	0
2	0	0.195	0	4	99	39	0	287	0	0	153	0
3	0.05	0.03	0.03	9	90	63	4101	798	3062	16	768	113
4	0.05	0.06	0.03	7	92	58	4117	1131	3359	16	88	69
5	0.05	0.06	0.06	8	93	64	4046	1102	5613	16	209	80
6	0.05	0.09	0.03	7	95	55	4126	1259	3516	16	220	82
7	0.05	0.09	0.06	8	95	62	4053	1224	6000	16	183	76
8	0.05	0.09	0.09	8	94	66	3994	1196	7715	16	170	90
9	0.05	0.12	0.03	7	98	52	4136	1294	3658	16	112	69
10	0.05	0.12	0.06	8	97	61	4058	1256	6269	16	116	81
11	0.05	0.12	0.09	8	97	65	3997	1223	8082	16	103	94
12	0.05	0.15	0.03	7	99	49	4143	1220	3821	16	148	71
13	0.05	0.15	0.06	7	99	61	4061	1179	6466	16	167	70
14	0.05	0.15	0.09	8	99	62	3998	1163	8360	16	130	88
15	0.05	0.2	0.03	8	99	48	4155	977	3981	16	131	58
16	0.05	0.2	0.06	9	100	55	4079	974	6723	16	129	71
17	0.05	0.2	0.09	10	100	63	4007	950	8616	16	133	92
18	0.05	0.2	0.12	10	100	68	3948	948	10009	16	125	92
19	0.05	0.3	0.03	9	100	46	4173	676	4270	16	329	56
20	0.05	0.3	0.06	9	100	52	4096	647	7095	16	255	72
21	0.05	0.3	0.09	10	100	57	4019	657	9079	16	127	75
22	0.05	0.3	0.12	10	100	63	3953	663	10612	16	126	89
23	0.1	0.09	0.03	9	85	64	7540	2799	2363	16	86	89
24	0.1	0.12	0.03	9	90	61	7545	2819	2521	17	102	78
25	0.1	0.15	0.03	10	91	61	7554	2796	2664	17	193	79
26	0.1	0.15	0.06	10	91	66	7455	2744	4467	17	189	94
27	0.1	0.2	0.03	11	91	58	7576	2479	2830	17	197	163
28	0.1	0.2	0.06	11	91	63	7469	2447	4711	17	125	87
29	0.1	0.3	0.03	11	96	54	7598	1759	3055	17	261	69
30	0.1	0.3	0.06	11	96	62	7485	1717	5185	17	148	98
31	0.1	0.3	0.09	11	96	66	7371	1666	6526	17	170	109
32	0.15	0.15	0.03	8	78	63	10429	4792	2016	17	118	86
33	0.15	0.2	0.03	8	82	62	10447	4460	2205	17	82	81
34	0.15	0.3	0.03	8	87	57	10496	3802	2425	17	237	66
35	0.15	0.3	0.06	9	88	60	10378	3787	4029	17	93	77
36	0.2	0.3	0.03	10	67	58	12859	6163	2190	17	74	78
37	0.25	0.3	0.03	14	50	59	14819	8009	2129	19	64	73
38	0.35	0.3	0.03	27	18	53	17165	11186	2477	23	32	98
39	0.75	0.25	0.105	100	1	55	13953	15454	7994	172	16	170
40	0.75	0.275	0.12	100	1	57	13831	15409	8489	173	19	83

Table 15. Results of the risk analysis on the HCRs combinations defined with multispecies criteria and selected as candidate management strategies to maintain redfish and shrimp above Blim while disregarding cod when the recruitment uncertainty is considered in the simulations. The first group of columns shows the F_{target} for each of the stocks in the selected combinations. The second group of columns shows the probability (proportion of the 100 different simulations) of being below Blim in the long term (period 2035-2050). The third group of columns show the median yield and the forth column the interannual variability in the catch, as percentage of difference in relation to the median yield.

	F_{target}			Risk_below_B_{lim}			Median_yield			Interannual_variance		
HCR_combi	cod	redfish	shrimp	cod	redfish	shrimp	cod	redfish	shrimp	cod	redfish	shrimp
1	0.7	0.15	0.03	97	1	49	12656	15500	2436	241	7	47
2	0.7	0.18	0.03	97	1	44	16121	15703	2790	125	10	52
3	0.7	0.18	0.06	97	1	51	12489	16121	2973	275	9	65
4	0.7	0.2	0.03	97	1	44	16163	15697	3091	188	12	53
5	0.7	0.2	0.06	97	1	50	12530	16186	3299	262	12	53
6	0.8	0.12	0.03	100	0	55	16136	15685	3264	104	14	50
7	0.8	0.15	0.03	100	0	46	12671	16111	3439	259	13	52
8	0.8	0.15	0.06	100	0	55	12463	16015	4953	255	9	48
9	0.8	0.15	0.09	100	0	63	15811	15572	5200	99	12	67
10	0.8	0.18	0.03	100	0	40	12596	16039	5530	246	12	50
11	0.8	0.18	0.06	100	0	48	15808	15567	5482	98	14	56
12	0.8	0.18	0.09	100	0	58	12755	15988	5764	243	13	54
13	0.8	0.18	0.12	100	0	64	12210	15914	6054	246	10	79
14	0.8	0.2	0.03	100	0	41	12316	15916	6833	240	12	56
15	0.8	0.2	0.06	100	0	47	12544	15862	7187	238	13	79
16	0.8	0.2	0.09	100	0	54	12130	15746	7441	244	12	97
17	0.8	0.2	0.12	100	0	63	12308	15673	7830	241	13	128

Table 16. Results of the risk analysis on the HCRs combinations defined with multispecies criteria and selected as candidate management strategies to maintain shrimp above Blim while disregarding cod and redfish. The first group of columns shows the F_{target} for each of the stocks in the selected combinations. The second group of columns shows the probability (proportion of the 100 different simulations) of being below Blim in the long term (period 2035-2050). The third group of columns show the median yield and the forth column the interannual variability in the catch, as percentage of difference in relation to the median yield.

	F_{target}			Risk_below_B_{lim}			Median_yield			Interannual_variance		
HCR_combi	cod	redfish	shrimp	cod	redfish	shrimp	cod	redfish	shrimp	cod	redfish	shrimp
1	0.2	0.275	0.03	10	65	58	12843	6267	2152	17	63	70
2	0.2	0.35	0.03	10	75	57	12877	5808	2284	17	85	77
3	0.2	0.35	0.06	11	75	62	12715	5791	3843	18	81	140
4	0.35	0.275	0.03	27	17	53	17140	11257	2417	23	30	106
5	0.35	0.35	0.03	27	22	52	17205	11064	2562	23	42	85
6	0.5	0.275	0.03	71	4	42	17796	14236	2899	39	19	63
7	0.5	0.275	0.06	72	4	49	17717	14112	4835	40	19	79
8	0.5	0.35	0.03	71	8	38	17899	14200	3120	38	27	47
9	0.5	0.35	0.06	72	10	44	17726	14088	5203	40	27	61
10	0.5	0.35	0.09	72	10	55	17622	13965	6551	40	28	110
11	0.7	0.2	0.03	97	1	44	16136	15685	3264	104	14	50
12	0.7	0.2	0.06	97	1	50	15808	15567	5482	98	14	56
13	0.7	0.275	0.03	97	2	38	16128	15636	3600	98	20	38
14	0.7	0.275	0.06	97	2	45	15854	15489	5922	99	20	43
15	0.7	0.275	0.09	97	2	52	15606	15355	7371	99	20	54
16	0.7	0.275	0.12	97	2	56	15479	15257	8095	100	20	79
17	0.7	0.35	0.03	97	12	34	16255	15474	3791	98	32	39
18	0.7	0.35	0.06	97	13	44	15991	15348	6346	99	32	45
19	0.7	0.35	0.09	97	14	52	15665	15227	7810	99	33	53
20	0.7	0.35	0.12	97	14	55	15485	15116	8587	99	33	111
21	0.7	0.35	0.18	98	16	64	15243	14928	9339	119	33	106
22	0.4	0.5	0.03	36	90	39	18000	10343	3023	25	129	57
23	0.4	0.5	0.06	35	91	47	17825	10249	5022	25	120	76
24	0.4	0.5	0.09	38	91	56	17658	10257	6327	25	116	145

Table 17. Selection of HCRs for comparison of risk analysis results when the assessment error is considered in the shortcut assesment ('truth plus noise shortcut') in relation to when the error is disregarded ('no error shortcut').

		F_{target}			Risk_below_B_{lim}		
HCR combi	Type	cod	red	shrimp	cod	red	shrimp
1	disregard redfish	0.2	0.3	0.03	7	60	63
2	disregard redfish	0.35	0.3	0.03	22	14	51
3	disregard shrimp	0.25	0.03	0	12	8	83
4	disregard shrimp	0.3	0.03	0	17	2	82
5	disregard shrimp	0.3	0.09	0	18	7	67
6	B_{lim} 3 sp	0.65	0.195	0	99	1	33
7	disregard cod	0.8	0.2	0.03	100	3	38
8	disregard cod and redfish	0.7	0.35	0.03	97	6	28

Table 18. Comparison of probability, for the three stocks, of SSB being below their respectives Blim when a single versus a two stage HCRs is used for cod.

		F_{target}		Perc_B_{lim}_cod		Perc_B_{lim}_redfish		Perc_B_{lim}_shrimp	
comb.N	cod	redfish	shrimp	one-stage	two-stage	one-stage	two-stage	one-stage	two-stage
1	0.25	0.03	0	13	10	6	0	82	82
2	0.25	0.06	0	14	11	15	0	73	75
3	0.25	0.09	0	14	12	23	2	67	65
4	0.35	0.12	0	27	28	6	2	58	54