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Developing of a 3M cod MSE

by

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Abstract

The aim of this document is to define the MSE structure for evaluating the proposed FC SC RBMS 3M cod Management Procedure (MP) or Harvest Control Rule (HCR) and identify the major inputs required to simulation-test and the main areas of uncertainty of the method. The document discussed the way to carry out the simulations in the 3M cod MSE and present the best data available to implement the 3M cod MSE. Six different Operating Models (OM) based in different assumptions in the Stock/Recruitment relationship and different assumptions about Natural mortality (M) are suggested as the most appropriated for this case. We recommend using the EU Flemish Cap Survey 3+ biomass index to implement the Model free HCR and to estimate the slope using the most recent 4 years. It was proposed that the final values of the λ parameter will be chosen after made deterministic projections to understand how different λ values perform. It was also suggested some changes in the FCSC RBMS MSE proposal to reduce the high number of scenarios.

Introduction

The 3M cod stock is managed by NAFO. In 2007 a Bayesian model was presented to assess this stock (Fernández *et al.*, 2007) and in 2008 this Bayesian model was further developed and approved by the NAFO SC (Fernández *et al.*, 2008). In 2014 an assessment based on the Bayesian model was approved by NAFO SC (González-Troncoso *et al.*, 2014). The cod stock in Division 3M (Flemish Cap) experienced very low biomass levels in the 1990s and was under moratorium to direct fishing between 1999 and 2009. The stock rebuilt and the direct fishery reopened in 2010. The spawning stock biomass increased substantially since mid-2000s and is now well above the limit reference point and among the highest levels observed since the 1970s. The rebuilding of this cod stock was a success for NAFO.

The NAFO Fisheries Commission formally adopted a Precautionary Approach (PA) framework in 2004 (NAFO/FC Doc. 04/17) as proposed by NAFO Scientific Council (NAFO SCR Doc. 03/23). The SC framework provides a structure that includes limits, buffers, targets and Harvest Control Rules that adjust fishing mortality to keep stocks in the Safe Zone. A B_{lim} of 14 000 tons was approved by the NAFO Scientific Council in 2000 for the 3M cod stock. In 2008 the appropriateness of this value given the results from the new method used to assess the stock was examined, concluding that it is still an appropriate reference (Fernández *et al.*, 2008). In 2012, Fisheries Commission requested to Scientific Council: to provide B_{msy} and F_{msy} for 3M cod. Gonzalez-Troncoso *et al.* in 2013 estimated the Yield per Recruit (YPR), Spawner per Recruit (SPR) and Maximum Sustainable Yield (MSY) reference points with uncertainty to provide candidates for B_{msy} and F_{msy} for 3M cod (SCR Doc. 13/50). Scientific

Council concluded that the results of the B_{msy} and F_{msy} estimated based on different stock-recruitment relationships (Ricker, Beverton-Holt and Segmented Regression) were not plausible due to the high uncertainty in the stock recruit relationship for this stock and noted that the level of B_{msy} estimated from YPR-SPR depends on assumptions about the level of recruitment and more research about the possibility of changes in productivity and the level of recruitment that should be used to estimate the MSY is needed (NAFO SCS Doc. 13/17).

NAFO identified the development of a risk-based management strategy for 3M cod as a priority in 2012, and reaffirmed that priority in 2013. The Fisheries Commission and Scientific Council Joint Working Group on Risk-Based Management Strategies (FC SC RBMS) proposed in February 2014 draft plans for 3M cod (Annex 1) and 3LN redfish based on the General Framework on Risk-based Management Strategies (NAFO FC/SC Doc. 14/02). It was noted that the draft plans represent a first step and may need further elaboration and adjustment once feedback is received from SC and FC. The development of such a management plan should be based on scientific advice.

Management Strategy Evaluation (MSE) is based on a time-proven approach of evaluating models through simulation before using them as a basis for decision-making. This approach gained increased prominence though the evaluation of management procedures by the International Whaling Commission and is described in Kirkwood and Smith (1996) and more recently in ICES by Kell *et al*. (2007) in the context of a new stock assessment environment in R-code called FLR (Fisheries Library in R). The intention is to develop for 3M cod a MSE study within the FLR environment.

The aim of this document is to define the MSE structure for evaluating the proposed FC SC RBMS 3M cod Management Procedure (MP) or Harvest Control Rule (HCR) and identify the major inputs required to simulation-test and the main areas of uncertainty of the method.

Management Strategy Evaluation

MSE is a general framework aimed at designing and testing MPs which specify previously agreed decision rules (HCR) for setting and adjusting TACs or effort levels to achieve a set of fishery management objectives. Simulation testing is used to determine the extent to which an MP is robust to uncertainty, and MPs are usually selected so that there is a reasonable likelihood that the (pre-specified and quantified) management goals can be satisfied (De Oliviera *et al.*, 2008). Butterworth, Cochrane and De Oliveira (1997) defined an MP as a simulation-tested set of rules used to determine management actions, in which the data, the methods for analyzing the data (including any method of stock assessment) as well as the harvest control rule (HCR) are pre-agreed and pre-specified.

Conceptual framework

A prototypical MSE incorporates a number of interlinked model structures: population dynamics; data collection; data analysis and stock assessment; an HCR that dictates a specific management action (e.g., the TAC); the harvest decision process; and implementation of that management action (McAllister *et al.*, 1999). An operating model or a reference set of different plausible scenarios of past and future population and fishery dynamics are typically used to generate "true" ecosystem dynamics including the natural variations in the system. Holland (2010) described the MSE process as follow: "Data are sampled from the operating model to mimic collection of fishery dependent data and research surveys (and their inherent variability). These data are passed to the assessment model. Based on this assessment and the HCR, a management action is determined (e.g., a change in the TAC). Fleet effort and catch are then modeled, ideally accounting for potential error in implementation, and resulting catches are fed into the operating model. By repeating this cycle the full management cycle is modeled. It is possible to test the effect of modifying any part of this cycle including changes to the operating model, assumptions about noise, etc". Alternative MPs can be compared by running many stochastic simulations for several years to identify the performance of a rule according to different metrics under the likely range of conditions. The objective is to identify MPs that perform "well" under the range of conditions based on the pre-determined objectives and constraints. The choice of the MP generally involves a compromise between various objectives.

In the end, the MP is only as good as the underlying models and assumptions it is based on. The success of the MSE framework depends on the extent to which the true range of uncertainty can be identified and represented in operating models (De Oliveira *et al.*, 2008).

There are five key elements in the MSE approach (Smith *et al.*, 1999):

1. Management objectives
2. Performance measures
3. Management strategies
4. Simulation evaluation of alternative management strategy performance
5. Presenting the results to decision makers

1. Management objectives

Clear management objectives are necessary before any evaluation of potential management strategies can be undertaken. Normally the objective will be set by the managers taking into account the Precautionary Approach (PA) principles and the opinion of the stakeholders. The Fisheries Commission and Scientific Council Joint Working Group on Risk-Based Management Strategies (FC SC RBMS) proposed as general objective for 3M cod management plan the following (Annex 1): "maintain the 3M cod Spawning Stock Biomass (SSB) in the safe zone as defined by the NAFO precautionary approach framework and to assure the optimum utilization, rational management and conservation of the 3M cod stock". This general objective should be reach attending the following performance objectives established by the FC SC RBMS (ranked from higher to lower priority): 1) low risk of breaching B_{lim}, 2) low risk of overfishing, 3) low risk of steep biomass decline, 4) to maximize average catch and 5) limited annual catch variation.

1. **Very low risk of breaching B_{lim}**. The probability of a spawning stock biomass under B_{lim} at 10% or lower.
2. **Low risk of overfishing**. For the model free HCR only: The probability of F exceeding F_{msy} during the evaluation period should be kept at 30% or lower.
3. **Low risk of steep decline**. The probability of the decline of 25% or more of spawning stock biomass from year 0 to year 5 is kept at 10% or lower.
4. **Maximum averages catch over the period**. The average TAC over the period should be maximized.
5. **Limited annual catch variation**.

2. Performance measures

The results of the stochastic MSE simulations can be divided into two broad categories: descriptive statistics and performance measures. The former includes results that are produced to develop an understanding of the dynamics of the simulated stock and the fishery. The latter are measures that can be used to assess the relative merits of candidate MSs, either how they perform with regards to critical performance criteria or what trade-offs in performance they represent. Performance measures need to be quantifiable statistics that can be used to directly compare the performance of each candidate management strategy in terms of the management objectives. These are needed in addition to descriptive statistics of the stock dynamics under a given management strategy.

In the current MSE, descriptive statistics that shall be presented are annual biomass, SSB, recruitment (age 1), mean F (ages 3-5) and annual catch. These statistics will be presented by OM as time series plots for each MS. We also propose a new descriptive statistics to measure the risk of overfishing in the Model based HCR described below. This new descriptive statistics measures the probability that the F_{target} used in the HCR is higher than the F_{msy} or its proxy estimated each year in the assessment process model with the last three years means inputs.

The FC SC RBMS proposed in February 2014 the following Performance Statistics (PS) (Table 1) to measure the different performance objectives for 3M cod:

Noting that this MP proposal shall be in force initially until 2019 and that the last TAC with this proposal should be made for 2020; taking into account that we are going to suggest performing the projections a minimum of 20 years; and noting that the NAFO SC approved a 3M cod analytical assessment in 2014 with the data till 2013, we propose two different time periods to measure the performance targets 3, 4 and 5: medium term 2015-2020 (projection years 1-7) and long term 2015-2034 (projection years 1-20).

We have written mathematically the FC SC RBMS proposed Performance targets. Table 2 presents the FC SC RBMS proposed Management Objectives and the new PS and PT proposed by us:

3. Management Strategies

The FC SC RBMS proposed two HCRs to be tested under the MSE approach (Annex 1). The first one is based on fishing mortality assessment model results (model based HCR) and the second one is based on survey indices (model free HCR). Both HCRs establish how the TAC is calculated each year when the 3M cod SSB is above B_{lim} and the fishery is open. When SSB is below B_{lim}, no directed fishing can be carried out and by-catch should be restricted to unavoidable by-catch in fisheries directed to other species. For this purpose, fisheries managers will consider the probability and establish risk tolerance, noting that the probability of biomass to be above B_{lim} is an integral part of the HCR proposed in option 1.

Option 1 (Model based HCR): TAC(y) = Total Biomass(y) x F_{target} x P(SSB(y)>B_{lim})

$$TAC_y = \text{Total Biomass}_y \; F_{target} \; P\left(SSB_y > B_{lim}\right)$$

Four different levels of F will be considered as F_{target}, corresponding to probabilities of 20%, 30%, 40% and 50% of exceeding F_{msy}. If F_{msy} is not available, an appropriate proxy (e.g. F_{max}, current proxy) should be used.

Option 2 (Model free HCR): TAC(y)=TAC(y-1) x (1 + λ x slope)

$$TAC_y = TAC_{y-1}\left(1+\lambda \, slope\right)$$

Where: slope = is the slope of the log-linear regression lines fit to a recent period of the survey biomass indices for an age range.

λ = an adjustment variable to ensure that the relative change in TAC is greater than the perceived relative decline in stock size (i.e. λ > 1, therefore allowing the strategy to halt the decline of the stock size through positive feedback).

For both options and noting the desire for relative TAC stability, TAC should be constraint to a fixed percentage of annual change. Level of constraint is to be defined by Managers. Different scenarios will be tested in the MSE: 10%, 15% and 20%

The model based HCR (Option 1) is based on the F_{msy} reference point or its proxies A B_{lim} of 14 000 tons was approved by the NAFO Scientific Council in 2000 for the 3M cod stock. Due to the impossibility of estimating F_{msy} in the 3M cod stock, the MSE should be carried out based on a proxy. In June 2014, NAFO SC decided that F30% (The fishing mortality which reduces Spawner Per Recruit (SPR) to 30% of its value at F=0) is the best F_{msy} proxy at this moment for 3M cod (NAFO, 2014).

The model free HCR (option 2) is a simple TAC adjustment strategy that uses the change in perceived status of the stock from research surveys to adjust the TAC accordingly. This HCR is similar to the approved HCR for Greenland halibut Subarea 2+3KLMNO (Shelton and Miller, 2009 and NAFO, 2010).

In the 3M cod case we need to decide the survey indices, the age and the period to estimate the slope of the survey indices as well as the value for λ. The EU Flemish Cap Survey is the only research survey available to implement this HCR in the 3M cod case. Figure 1 presents the EU Flemish Cap survey total and 3+ biomass indices for 3M cod. We can observe that in the most recent period both biomass indices have very different slopes due to the recruitment variability. Figure 2 presents the accumulative % catch biomass by age for the last three years (2010-2012) since the fishery has been opened. We can see that the percentage of the 3+ biomass in catches is very high in the mentioned period and most of the weight in catches is for ages 5+. We propose to use the EU Flemish Cap Survey 3+ biomass index to implement the Model free HCR. The reason to choose the 3+ biomass is to take only into account the exploitable biomass for the estimation of the TAC in the HCR and to avoid the recruitment variability. The internal consistency for the survey indices of age 2 and 3 is not quite good and this is the main reason to propose 3+ biomass index instead of 2+ index. To estimate the slope we propose to use the most recent 4 years as the age composition of this stock is not very wide, most of the biomass is distributed in the age range 5+

and it is very difficult to find individuals with more than 9 years old. Ranges bigger than 4 years may be not representative of the stock status at the time when the TAC will be taken.

Based on the analyses made for the Greenland halibut Subarea 2+3KLMNO HCR (NAFO, 2010) different values are required for the λ parameter. It is required a $\lambda > 1$ in the case of a perceived decline in stock size (slope < 0), but this value of λ could hamper stock recovery in the case of a perceived increase in stock size (slope > 0). A variable λ approach with different values for slope > 0 and slope < 0 could be a good solution. We will start the MSE process with a value of 1.25 in the case of a declining stock (allows for adequate adjustment of the TAC without having excessively large fluctuations from year to year) and a value of 1 in the case of an increasing stock. The final values of the λ parameter will be chosen after made deterministic projections to understand how different λ values perform.

Based on these, our proposal for option 2 Model free HCR is the following:

$$\mathrm{TAC}_y = \mathrm{TAC}_{y\text{-}1}\left(1+\lambda\,\mathrm{slope}_{3+}\right)$$

Where slope_{3+} is the slope of the log-linear regression lines fit of the EU Flemish Cap survey B_{3+} index from y-5 to y-2.
$\lambda = 1.25$ when $\mathrm{slope}_{3+} < 0$ and $\lambda = 1$ when $\mathrm{slope}_{3+} > 0$

The combination of these HCRs with the OMs proposed below generates 90 scenarios to test. This number of scenarios makes very difficult to present in a clear way the results and probably will difficult the choice of the best HCR. We propose some changes in the proposed HCRs in the point 5 (Presenting the results to decision makers) to reduce this number of scenarios.

4. The simulation algorithm

The simulation algorithm that we are going to use in the 3M cod MSE is a R package to conduct Bio-Economic Impact assessments using FLR (FLBEIA) developed by Garcia *et al.* (2013). FLBEIA is an R package build on top of FLR libraries. The purpose of the package is to provide a flexible and generic simulation model to conduct Bio-Economic Impact Assessments of harvest control rule based management strategies under a Management Strategy Evaluation (MSE) framework. As such, the model is divided into two main blocks, the operating model (OM) that it is the part of the model that simulates the real dynamics of the fishery system and the management procedure model (MPM) that simulates the whole management process. In turn, these two blocks are divided in 3 components. The OM is formed by the biological, the fleet and the covariables components and the MPM by the observation, the assessment and the management advice components (Figure 3).

This simulation algorithm explicitly or implicitly acknowledges different sources of uncertainty in both the “real” system and the management strategies (Francis and Shotton, 1997; Kell *et al.*, 2007; Rosenberg and Restrepo, 1994). The simulation algorithm in the 3M cod case takes an initial population, presently from 1972 to 2013, and projects it into the future. The real biological population and fishery are projected, in yearly time steps, using the OM and the MP is applied annually to produce the management advice for the next year. The advice obtained within the MP for a certain year constrains the behavior of the fleets in the next year.

4.1. The operating models

The MP is only as good as the underlying models and assumptions it is based on. The success of the MSE framework depends on the extent to which the true range of uncertainty can be identified and represented in operating models (De Oliveira *et al.*, 2008). A lot of uncertainty usually exists around the dynamics of fish stocks, so instead of a single representation of ‘reality” it is advisable to consider many options encompassing most of the possibilities to deal with this uncertainty. A group of operating models, each conditioned on different data or based on an alternative realistic hypothesis of the stock dynamics or future trends in the fishery, is referred to as a reference set of operating models (Miller *et al.*, 2008).

The OM consists of an age-structured biological population and a single fishery inducing fishing mortality during the harvesting process. The operating model requires consideration of the past system and initial starting point of the population, biological parameters of the stock, behavior of the fishery/fleet(s) and the level of uncertainty/error in the observation of the system. In the 3M case we propose a reference set of 5 operating models. These operating models are distinguished by: stock-recruit function and M values (Table 3).

4.1.1 The initial population

To assess the ability of a management strategy to achieve the objectives it is necessary to construct the past system and the projections starting point to be as close as possible to the real stock at the present time.

Important elements that are needed to construct the past system/starting point includes: age structure of the stock, stock abundance (numbers at age), fishery catch data (age disaggregated), weights at age, maturities at age and natural mortality. The age structure of the simulated stock should agree with the best hypotheses and data available for the stock.

The Bayesian XSA model approved by the NAFO SC in 2014 for 3M cod works as a XSA, calculating the population numbers and F from the last year and the last age, assuming a lognormal prior over the survivors. The goal of this assessment model is that it works with years with no catch at age information, as in the case of the 3M cod for which there are no catch at age data for years 2002-2005. In these years the model assumes a prior over F in all true ages (1-7) and over the total catch in order to continue with the calculation of the numbers. In the years with catch at age it works exactly as an XSA just assuming a lognormal prior over the survivors as starting point. Moreover, in 2011 and 2012 there was a lack of total catches in the data, due to a change in the way of estimating the catch data that makes the time series inconsistent. In this case the assessment uses a lognormal prior in order to make an estimation of the total catch. As tuning, the Canadian survey in 3M (1978-1985) and the EU Flemish Cap survey (1988-2013) were used. 5000 iterations were made via MCMC in order to get uncertainty over the assessment results. Detailed descriptions of the Bayesian model approved in 2014 are in Fernandez *et al.* (2008) and Gonzalez-Troncoso *et al.* (2014). 5000 iterations probably is a very large number for carrying out the MSE process and may create technical computational problems when performing the simulations. The final iterations numbers to perform the 3M cod MSE will be decided taking into account the technical computational problems and they will be enough to measure the uncertainty correctly.

The catch discrepancy is a general problem for all NAFO stocks. NAFO has created this year a Fisheries Commission Ad hoc Working Group on Catch Reporting to try to solve the catch discrepancies (NAFO, 2014).
NAFO Scientific Council decided to use for 3M cod the total catches from the Daily Catch Reports (DCR) in 2013 (13 985 t), maintaining the model catch estimation for 2011 and 2012 (NAFO, 2014). The MSE starting point will be based on the data and results (age structure of the stock, stock abundance numbers at age, fishery catch data age disaggregated, weights at age, maturities at age and natural mortality) of the 3M cod approved assessment in 2014 (Gonzalez-Troncoso *et al.*, 2014).

We propose to use the same Bayesian XSA model and input data approved in 2014 to estimate the abundance at age starting point of the OM.

In the approved 2014 assessment, M was estimated by the XSA Bayesian model. M was considered constant for all ages and years. M is one of the most uncertain parameters to estimate a starting point and has a very big influence to estimate proxies of F_{msy}. We propose to create two sets of operating models with different starting points based on the same XSA Bayesian model structure but with different assumptions of M. One options is as in the last approved assessment, with M constant estimated by the model for all ages and for all years, and other is based on the results of Gonzalez-Troncoso and Gonzalez-Costas (2014), where it has proposed to estimate M by the model for three different ages ranges (1-2, 3-5, 6-8+) and for three different time periods (1972-1995, 1996-2008, 2009-last assessment year).

The catch by year, mean weights at age in catches and stock and maturity ogives (1972-2013) will be the same used in the 2014 assessment. The mean weights in catch and stock are both inputs of the model and have no uncertainty. The maturity ogive is calculated from the microscopic reading of the ogives from the survey applying a Bayesian logistic regression model to proportion mature at age. They have been fitted independently for each year, fitting 5000 iterations in order to get uncertainty in the maturity ogives.

4.1.2 The projection

Beginning at the initial starting point of the projections, numbers at age for ages 2 and up are projected using the basic equation for updating population size. Natural mortality (M), mean weights and partial recruitment (PR) are specified by the operating model, while fishing mortality (F) depends on the harvest control rule (HCR) based on the management strategy being evaluated. Recruitment (numbers at age 1) is determined by the stock-recruit model applied in the operating model. In subsequent years, given the matrix of numbers-at-age of the previous years, the population numbers are carried forward using the exponential survival equation and a predefined SR relationship with a lognormal multiplicative random error to generate the recruits. As the real TAC for 2014 is known, it is assumed that the fleets will comply exactly with this TAC. The catchability of the fishery is an input parameter and it varies through iterations. The catch is estimated each year by iteration using the Baranov catch equation (Baranov, 1918), constraining it to produce exactly the TAC, given the catchability-, numbers-, weights- and natural mortality-at-age of the real population. In each scenario the biological population and fishery were projected until 2034 for each of the starting point iterations. Thus, the last management process is run in 2033 and the last 'perceived' population is obtained for 2032.

In the projection of the "true" biological population, maturity, weights, Partial Recruitment and M for each year will be obtained from the 1972-1995 and 2009-2013 periods based on the analysis of the biological parameters variation made by Gonzalez-Costas and Gonzalez-Troncoso in 2014. For each iteration we select a year randomly from these periods and the maturity, partial recruitment, stock and catch weights are taken together from the selected year and a period of the next years. The main reason to obtain the biological parameters for the projections in blocks of years is to take in account the possible autocorrelation of the parameters. The variability of weights, maturity and partial recruitment should be related with the abundance and the particular environmental conditions of each period. In the projections we do not take into account the 1996-2008 period due to in this period the abundance were very low, the fishery was mainly close and the mean weights and maturity values were very different than in the periods were the abundance was higher and the fishery was open.

4.1.3. Stock-recruit relationship

There is a considerable uncertainty regarding the appropriate stock-recruit function for this stock. Three different S/R models (Ricker, Beverton-Holt and segmented regression) were fit to 3M cod data in 2013 (Gonzalez-Troncoso *et al.*, 2013). Results showed that none of these stock recruitment relationship fits appropriately the 3M cod data. Given this large degree of uncertainty, and the importance of the stock-recruit relationship in MSE simulations, it is necessary to consider a number of possible ways to estimate the recruitment to ensure potential management strategies are robust to this uncertainty.

For 3M cod MSE we propose to test several Operating Models (OMs) based on three different Stock/Recruitment (S/R) relationships: Recruitment independent of SSB, Segmented Regression with Beta=Approved B_{lim} and Segmented Regression fit with the assessment results. These three operating models will be applied to the two different starting points based on different assumptions of M (Table 1).

4.1.3.1 Recruitment independent of SSB: Bootstrapping recruitment values from 1972-2011. We propose to eliminate the last 3 recruitments of the time series to do the bootstrap due to these recruitments have a high uncertainty and they are not well calculated by the model.

4.1.3.2 Segmented Regression with Beta=Approved B_{lim}: Segmented regression provides a simple description of the stock-recruit data with constant recruitment above the breakpoint (Beta) and recruitment declining linearly to zero below the breakpoint. We fit a constrained segmented regression model to have a beta parameter equal to the approved 3M cod B_{lim} (14 000 tons).

4.1.3.3 Segmented Regression fit with the assessment results: Although the Segmented Regression fit with the assessment results has a no well defined beta parameter in the observed SSB range (Gonzalez-Troncoso *et al.*, 2013), we consider this scenario that is consistent with a stock that has been severely recruitment-overfished.

The stock–recruitment relationship for each scenario will be fitted using the numbers at age 1 and the SSB in the initial population. One SR relationship will be fitted in each of the iterations.

4.1.4. Biological points (RPs)

A B_{lim} of 14 000 tons was proposed by the NAFO Scientific Council in 2000 for the 3M cod stock. In 2008 the appropriateness of this value given the results from the new method used to assess the stock was examined, concluding that it is still an appropriate reference (Fernández *et al.*, 2008). In 2012, Fisheries Commission requested to Scientific Council: to provide B_{msy} and F_{msy} for cod in Div. 3M. Scientific Council in 2013 estimated the Yield per Recruit (YPR), Spawner per Recruit (SPR) and Maximum Sustainable Yield (MSY) reference points with uncertainty to provide candidates for B_{msy} and F_{msy} for cod Div. 3M. The results of the B_{msy} and F_{msy} estimated based on different stock-recruitment relationship (Ricker, Beverton-Holt and Segmented Regression) were not plausible due to the high uncertainty in the stock recruit relationship for this stock.

The model based HCR (Option 1) is based on the F_{msy} reference point or its proxies. Due to the impossibility of estimating F_{msy}, in this case the MSE should be carried out based on a proxy. In 2014, NAFO SC decided that $F_{30\%SPR}$ (The fishing mortality which reduces Spawner Per Recruit (SPR) to 30% of its value at F=0) is the best F_{msy} proxy at this moment for 3M cod. It was also analyzed the YPR and SPR inputs (mean weights, partial recruitment and maturity ogive) to study the possibility of changes in productivity in the past and its impact in the reference points estimated values. The SC proposed to use data from 1972 to 2013 to estimate the $F_{30\%SPR}$ to avoid the big trends in biological parameters observed in the most recent years (2009-2013).

4.2. The management procedure

The MP model is divided into three sub-models: (i) the observation model which simulates the data collection and thereby links the MP with the OM, (ii) the assessment process model that generates a ‘perceived’ population based on the data, including the assessment model and the short term forecast; (iii) the management decision model which uses an HCR based on the perceived population and the estimated reference points to derive management advice (Figure 4).

For 3M cod the MP is applied on 2014 and produces the TAC advice for 2015 based on the different Harvest Control Rules (HCRs) proposed by FC SC RBMS. Each HCR is applied every year up to the end of the projections period. FC SC RBMS proposed that the Risk-based Management for cod stock in Subarea 3M shall be in force initially until 2019. We suggest performing the projections a minimum of 20 years. This time period would allow observing the stabilized biomass results of applying the different management strategies. The reasons for proposing this period are based on the age composition of this stock (1-8+) and the need for the projections period covering at least several generations to have an idea of the long term results.

4.2.1. The observation model.

Catch-at-age is considered to be known without error in the observation model and the abundance indices are generated with a multiplicative random error assuming a linear relationship between catchability and abundance-at-age. Mean weights at age, maturity ogive and natural mortality assessment data in the Management Procedure assessment model are known without error and equal to the real world.

4.2.2. The assessment process model and the management decision model

For the Model based HCR ($TAC_y = \text{Total Biomass}_y \, F_{target} \, P\left(SSB_y > B_{lim}\right)$) we propose to use as assessment process model the Bayesian XSA. The TAC for year “y” is set based on the assessment carried out in previous year (“y−1”) with assessment data available up to year “y−2”. The stock assessment therefore produces fishing mortality estimates for year “y−2” and population estimates for the beginning of year “y−1” (except for the recruitment).

To carry out the short term projections we propose to use the usual method. The recruitment and maturity ogive in years “y−1” and “y” are estimated as the mean of the “y−4” and “y−2” period from the Management Procedure assessment model. To estimate the fishing mortality in “y−1” it is assumed that the fleet catches exactly the TAC set for year “y−1” with the selection pattern and mean weights equal to the average of Management Procedure assessment model between years “y−4” and “y−2”. With the abundance and F of year “y−1” we can estimate the “y” abundance and assuming that the “y” mean weights are equal to the “y−1” mean weights, we can estimate the Total and the Spawning biomass to apply the HCR and know the “y” TAC.

For the Model free HCR ($TAC_y = TAC_{y-1}(1+\lambda slope_{3+})$) the TAC for year "y" is set based on the EU Flemish Cap survey slope of the log-linear regression line fit to "y−2" till "y-5" period of the survey indices for 3+ biomass. λ is an adjustment variable for the relative change in TAC to the perceived change in stock size: λ = 1.25 when $slope_{3+}$ <0 and λ =1 when $slope_{3+}$ >0.

Management implementation error, including TAC-overruns, is a serious problem with respect to many NAFO stocks. It may be considered necessary to incorporate some form of implementation error in the MSE simulation process. This could be done by adding a proportional TAC overrun. However, TAC overrun is likely to vary by year depending on the availability of fish to the fishery and the level of TAC. In addition to this, there is very little information to apply the management implementation error in the 3M cod case because the fishery was close between 1999-2009 and the fishery behavior information is very scarce. Incorporating implementation error makes it difficult to determine the true success of a management strategy – is the failure of a strategy due to inherent shortcomings or to the non-compliance in the fishery? Implementation error could be considered to be more a problem for managers to deal with. Based on these we propose not to apply the implementation error in the 3M cod MSE.

5. Presenting the results to decision makers.

Results of MSE simulations need to be presented in a clear and concise manner to permit that the decision makers can easily interpret the outcome. When there is a large amount of uncertainty and HCRs to be tested, the different scenarios can easily become excessive. It is important that an MSE is well planned so that only the most likely and influential sources of uncertainty and the most appropriated HCR are fully explored to keep the number of scenarios manageable.

In the 3M cod we have 6 OMs that cover part of the M and S/R uncertainty but due to the different requirements in the proposed two HCRs we have 90 scenarios to analyze (Table 3). This number of scenarios makes very difficult to present in a clear way the results and probably will difficult the choice of the best HCR. We propose, in priority order, the following changes to reduce this high number of scenarios:

The three different TAC constraints (10%, 15% and 20%) probably difficult to know the true behavior of the different HCRs tested and its productivity in catch. We propose to test only the 20% TAC constraints in a first stage and measure the importance of the 10% and 15% constraints creating a new PS under the Limited annual catch variation performance objective. This new PS will measure in the medium and long term the number of times that TAC(y) > TAC(y-1) + %TAC(y-1) and TAC(y) < TAC(y-1) - %TAC(y-1). The percentage levels that should be measured are 10% and 15%. This PS would allow us to know the importance to impose a TAC constraint of 10% or 15%.. After analyze the results of this new PS we can decide the better constraint level to be tested. If this proposal is accepted the number scenarios to analyze will be reduced to 30.

In the Model based HCR, F_{target} is defined as four different levels of F_{msy}, corresponding to probabilities of 20%, 30%, 40% and 50% of exceeding F_{msy}. Based on the analysis made by Gonzalez-Costas and Gonzalez-Troncoso in 2014 where $F_{30\%SPR}$ (the best approved F_{max} proxie) was estimated with uncertainty (Table 4), the difference between the 20% and 50% probabilities of $F_{30\%SPR}$ is only 0.017 and this difference, translated to the equilibrium catches (Table 5), is only 1 760 tons. Taking into account these small differences and to make more manageable the number of final scenarios, we propose three different probability levels to be tested: 20%, 35% and 50%. With this proposal we reduce 6 scenarios and the final scenarios to be tested will be 24.

We think that these proposals do not change so much the HCR ideas to be tested and greatly facilitate the presentation of results and the choice of one of the HCRs. Table 6 shows the final scenarios of our proposal. And Table 7 shows the Management Objectives defined by FC SC RBMS and our proposal for the Performance Statistics (PS) Performance Targets (PT) to measure these objectives.

Acknowledgements

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Table 1.- FC SC RBMS proposed Management Objectives, Performance Statistics and Performance Targets for the 3M cod MSE (Annex 1).

Management Objectives	Performance Statistics (PS)	Performance Targets (PT)
Very low risk of breaching Blim	SSB / Blim	The probability of a spawning stock biomass under Blim at 10% or lower
Low risk of overfishing	F/Fmsy Fmax is used as a proxy for Fmsy.	*For the model free HCR only:* The probability of F exceeding F_{msy} during the evaluation period should be kept at 30% or lower.
Low risk of steep decline	SSB10/SSB0, where SSB10 = spawning stock biomass in year 10 and SSB0 = spawning stock biomass in year 0, where year 0 is the current year SSB_5/ SSB_0 SSBlowest / SSB0, where SSBlowest = lowest spawning stock biomass level during projected evaluation period	The probability of the decline of 25% or more of spawning stock biomass from year 0 to year 5 is kept at 10% or lower.
Maximum average catch over the period	Yearly TAC for the period Average TAC over the period	The average TAC over the period should be maximized
Limited annual catch variation	Number of times the constraint (at the lower and at the higher boundaries) has been applied on average during the period.	This will be achieved through the constraint on the TAC variation.

Table 2.- Management Objectives and the new Performance Statistics and Performance Targets proposed by the SAFEwaters2 for the 3M cod MSE.

Management Objectives	Performance Statistics (PS)	Performance Targets (PT)
Very low risk of breaching Blim	$SSB_y / B_{\lim}$ SSB_y is the Spawning Stock Biomass in the year y of the projection period.	$P\left(SSB_y / B_{\lim} < 1\right) \le 0.1$ y=1,…,20
Low risk of overfishing	**For the model-free HCR:** F_y / F_{msy} F_y is the Fishing Mortality in the year y of the projection period.	$P\left(F_y / F_{msy} > 1\right) \le 0.3$ y=1,…,20
Low risk of steep decline	SSB_7 / SSB_0 SSB_{20} / SSB_0 SSB_{lowest_7} / SSB_0 SSB_{lowest_20} / SSB_0 SSB_y is the Spawning Stock Biomass in the year y of the projection period. SSB_{lowest_y} is the lowest Spawning Stock Biomass level in the period 1-y of the projection	$P\left(SSB_7 / SSB_0 \ge 0.25\right) \le 0.1$ $P\left(SSB_{20} / SSB_0 \ge 0.25\right) \le 0.1$ $P\left(SSB_{lowest\_7} / SSB_0 \ge 0.25\right) \le 0.1$ $P\left(SSB_{lowest\_20} / SSB_0 \ge 0.25\right) \le 0.1$
Maximum average catch over the period	$\sum_{i=1}^{7} TAC_i / 7$ $\sum_{i=1}^{20} TAC_i / 20$	$\max\left(\sum_{i=1}^{7} TAC_i / 7\right)$ $\max\left(\sum_{i=1}^{20} TAC_i / 20\right)$
Limited annual catch variation	$TAC_{assess\_y+1} / TAC_{assess\_y}$ TAC_{assess_y} is the TAC given by the assessment in year y before constraints	$count\left(TAC_{assess\_y+1} / TAC_{assess\_y} \ge 1+x\right)$ $count\left(TAC_{assess\_y+1} / TAC_{assess\_y} \le 1-x\right)$ x=0.1, 0.15, 0.2 y=1,…,7 y=1,…,20

Table 3.- Operating Models proposed in this document and Management procedures propose by FC SC RBMS with their different scenarios.

OM		MP			Scenario
M value	**S/R Function**	**HCR**	**F_{target}**	**TAC constraint**	
Constant	1	Model Based	20% F_{max}	10%	1
				15%	2
				20%	3
			30% F^{max}	10%	4
				15%	5
				20%	6
			40% F_{max}	10%	7
				15%	8
				20%	9
			50% F_{max}	10%	10
				15%	11
				20%	12
	2	Model Based	20% F_{max}	10%	13
				15%	14
				20%	15
			30% F_{max}	10%	16
				15%	17
				20%	18
			40% F_{max}	10%	19
				15%	20
				20%	21
			50% F_{max}	10%	22
				15%	23
				20%	24
	3	Model Based	20% F_{max}	10%	25
				15%	26
				20%	27
			30% F_{max}	10%	28
				15%	29
				20%	30
			40% F_{max}	10%	31
				15%	32
				20%	33
			50% F_{max}	10%	34
				15%	35
				20%	36
Variable	1	Model Based	20% F_{max}	10%	37
				15%	38
				20%	39
			30% F_{max}	10%	40
				15%	41
				20%	42
			40% F_{max}	10%	43
				15%	44
				20%	45
			50% F_{max}	10%	46

				15%	47
				20%	48
	2	Model Based	20% F_{max}	10%	49
				15%	50
				20%	51
			30% F_{max}	10%	52
				15%	53
				20%	54
			40% F_{max}	10%	55
				15%	56
				20%	57
			50% F_{max}	10%	58
				15%	59
				20%	60
	3	Model Based	20% F_{max}	10%	61
				15%	62
				20%	63
			30% F_{max}	10%	64
				15%	65
				20%	66
			40% F_{max}	10%	67
				15%	68
				20%	69
			50% F_{max}	10%	70
				15%	71
				20%	72
Constant	1	Model Free		10%	73
				15%	74
				20%	75
	2	Model Free		10%	76
				15%	77
				20%	78
	3	Model Free		10%	79
				15%	80
				20%	81
Variable	1	Model Free		10%	82
				15%	83
				20%	84
	2	Model Free		10%	85
				15%	86
				20%	87
	3	Model Free		10%	88
				15%	89
				20%	90

Table 4.- YPR reference point (F_{max}) and SPR reference point ($F_{30\%}$,) estimated distribution.

	Fmax	**F30%**
10%	0.138	0.109
20%	0.145	0.116
30%	0.151	0.121
40%	0.156	0.128
50%	0.163	0.133
60%	0.168	0.137
70%	0.174	0.143
80%	0.181	0.149
90%	0.194	0.159

Table 5.- SPR $F_{30\%}$ reference points and their YPR, SPR and equilibrium yield and SSB in tons estimated distributions.

	F30% SPR	**YPR**	**SSBPR**	**Yield (t)**	**SSB (t)**
10%	0.109	0.810	3.711	19995	176509
20%	0.116	0.902	4.421	20810	157646
30%	0.121	0.971	5.014	21478	144446
40%	0.128	1.031	5.539	22033	134758
50%	0.133	1.090	6.105	22570	126545
60%	0.137	1.152	6.704	23167	118453
70%	0.143	1.220	7.427	23832	110942
80%	0.149	1.301	8.350	24610	101929
90%	0.159	1.419	9.761	25726	91931

Table 6.- Operating Models and Management procedures proposed in this study with their different scenarios.

OM		MP		Scenario
M value	**S/R Function**	**HCR**	**F_{target}**	
Constant	1	Model Based	20% F_{max}	1
			35% F_{max}	2
			50% F_{max}	3
	2	Model Based	20% F_{max}	4
			35% F_{max}	5
			50% F_{max}	6
	3	Model Based	20% F_{max}	7
			35% F_{max}	8
			50% F_{max}	9
Variable	1	Model Based	20% F_{max}	10
			35% F_{max}	11
			50% F_{max}	12
	2	Model Based	20% F_{max}	13
			35% F_{max}	14
			50% F_{max}	15
	3	Model Based	20% F_{max}	16
			35% F_{max}	17
			50% F_{max}	18
Constant	1	Model Free		19
	2	Model Free		20
	3	Model Free		21
Variable	1	Model Free		22
	2	Model Free		23
	3	Model Free		24

Table 7.- Management Objectives defined by FC SC RBMS and our proposal for the Performance Statistics (PS) and Performance Targets (PT) to measure these objectives.

Management Objectives	Performance Statistics (PS)	Performance Targets (PT)
Very low risk of breaching Blim	$SSB_y / B_{\lim}$ SSB_y is the Spawning Stock Biomass in the year y of the projection period.	$P\left(SSB_y / B_{\lim} < 1\right) \leq 0.1$ y=1,…,20
Low risk of overfishing	**For the model-free HCR:** F_y / F_{msy} F_y is the Fishing Mortality in the year y of the projection period. Fmsy or its proxy.	$P\left(F_y / F_{msy} > 1\right) \leq 0.3$ y=1,…,20
Low risk of steep decline	SSB_7 / SSB_0 SSB_{20} / SSB_0 SSB_{lowest_7} / SSB_0 SSB_{lowest_20} / SSB_0 SSB_y is the Spawning Stock Biomass in the year y of the projection period. SSB_{lowest_y} is the lowest Spawning Stock Biomass level in the year y of the projection	$P\left(SSB_7 / SSB_0 \geq 0.25\right) \leq 0.1$ $P\left(SSB_{20} / SSB_0 \geq 0.25\right) \leq 0.1$ $P\left(SSB_{lowest\_7} / SSB_0 \geq 0.25\right) \leq 0.1$ $P\left(SSB_{lowest\_20} / SSB_0 \geq 0.25\right) \leq 0.1$
Maximum average catch over the period	$\sum_{i=1}^{7} TAC_i / 7$ $\sum_{i=1}^{20} TAC_i / 20$	$\max\left(\sum_{i=1}^{7} TAC_i / 7\right)$ $\max\left(\sum_{i=1}^{20} TAC_i / 20\right)$
Limited annual catch variation	$TAC_{assess\_y+1} / TAC_{assess\_y}$	$count\left(TAC_{assess\_y+1} / TAC_{assess\_y} \geq 1+x\right)$ $count\left(TAC_{assess\_y+1} / TAC_{assess\_y} \leq 1-x\right)$ x=0.1, 0.15, 0.2 y=1,…,7 y=1,…,20

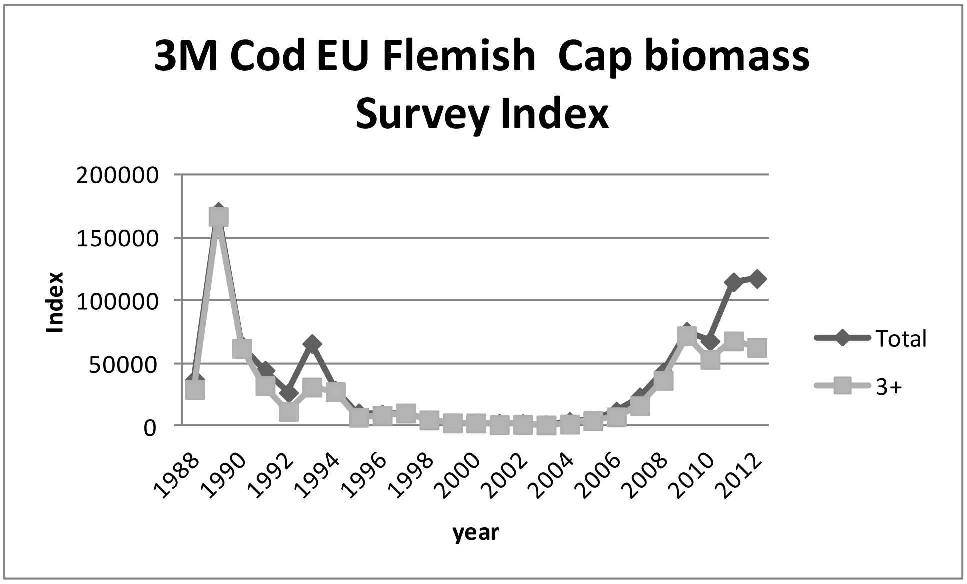

Figure 1.- EU Flemish Cap Survey 3M cod biomass indices (1988-2012).

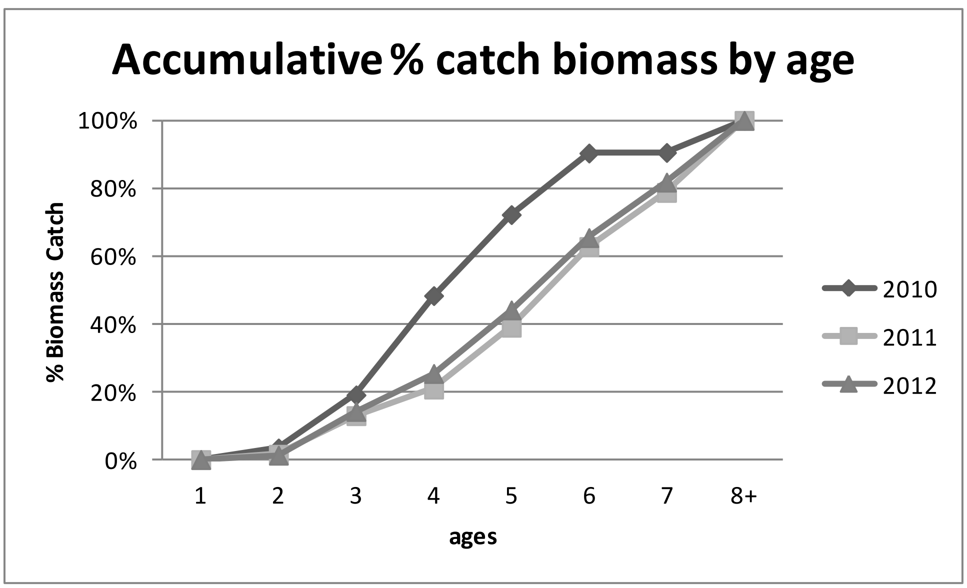

Figure 2.- Catch biomass percentage by age in the 3M cod fishery in the 2010-2012 period.

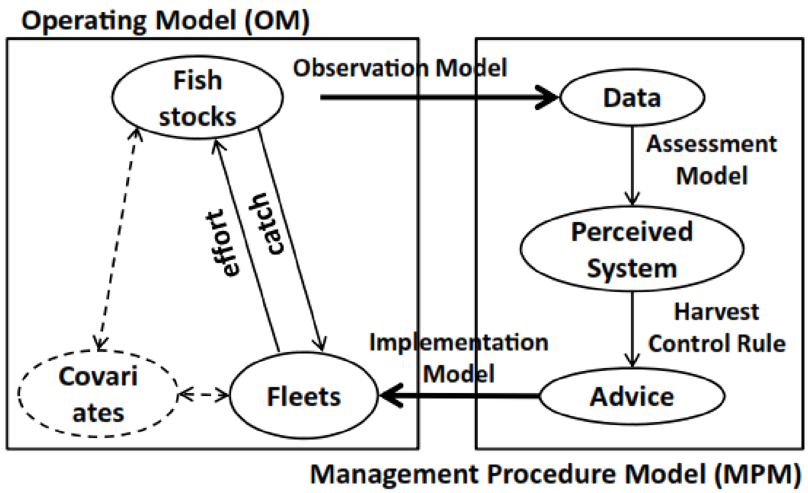

Figure 3.- Conceptual diagram of BEIA from Garcia *et al.* (2013).

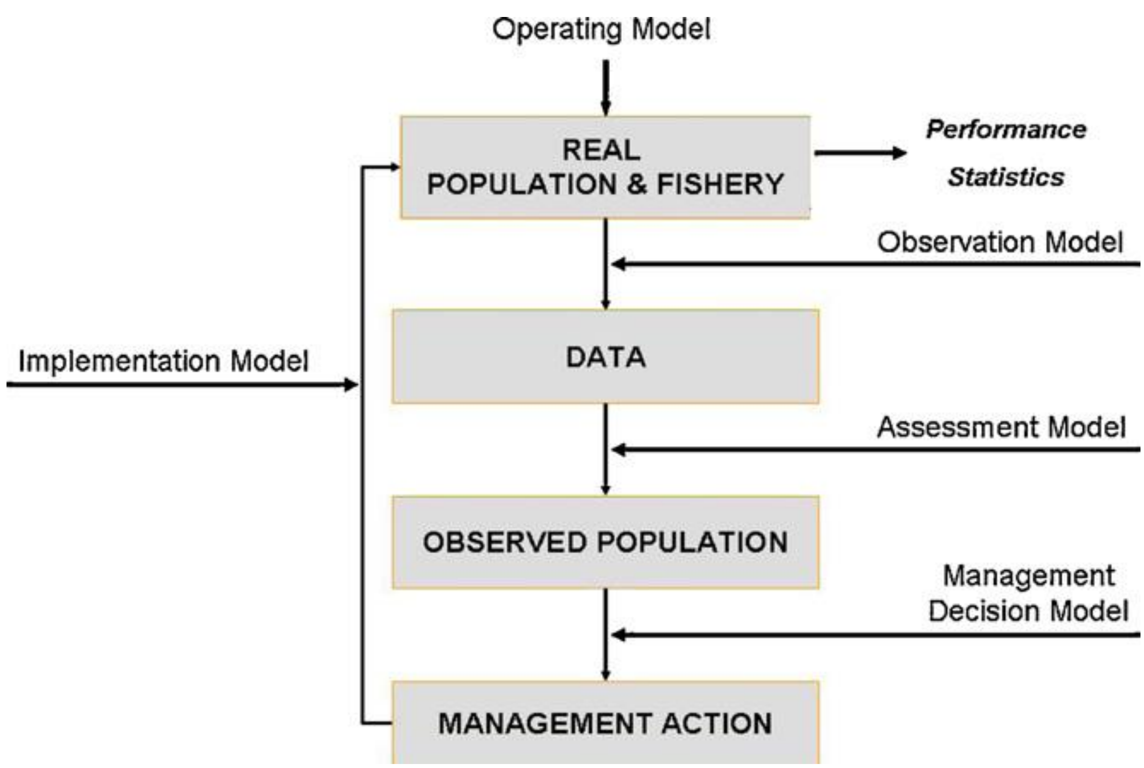

Figure 4.- Conceptual diagram of the Management Procedure.

Annex 1

Development of a Risk-Based Management Strategy for 3M Cod
(FC-SC RBMS WP 14/2 Rev2)

Background

The cod stock in Division 3M (Flemish cap) experienced very low biomass levels in the 1990s and was under moratorium to direct fishing between 1999 and 2009. The stock rebuilt and the direct fishery reopened in 2010. The spawning stock biomass increased substantially since mid-2000s and is now well above the limit reference point and among the highest levels observed since the 1970s. The rebuilding of this cod stock was a success for NAFO. NAFO identified the development of a risk-based management strategy for 3M cod as a priority in 2012, and reaffirmed that priority in 2013. The development of such a management plan should be based on scientific advice.

This paper presents the outline of a future 3M Cod Risk-based Management Strategy, indicating reference points with associated risks, options of candidate Harvest Control Rules (HCR) and performance statistics and targets to evaluate these HCR. Two candidate HCRs are proposed: 1) a model based HCR, with different options of target fishing mortality (Ftarget) and 2) a model free HCR based on survey trends. The model based HCR would require a stock assessment each year, to estimate the necessary stock parameters, while the model free HCR would only be based on surveys and assessments would not be necessary.

These different HCR will give managers a wide range of options to choose from, based on the different risk and performances. The Scientific Council should review this plan, propose alternative HCRs and performance statistics and perform a Management Strategy Evaluation (MSE).

1. Objective

The objective of this Conservation Plan is to maintain the 3M cod Spawning Stock Biomass in the safe zone as defined by the NAFO precautionary approach framework and to assure the optimum utilization, rational management and conservation of the 3M cod stock.

2. Reference Points:

(a) A limit reference point for spawning stock biomass (Blim) – 14 000 tons
(b) A target reference point for fishing mortality (Ftarget)

Ftarget is to be defined by Managers. Several options regarding risks of being above FMSY are indicated in one of the HCRs.

Reference points should be calculated and updated by the Scientific Council (SC).

3. Harvest Control Rule:

(a) When SSB is above B_{lim}, the future total allowable catch (TAC) shall be adjusted each year according to the following harvest control rule (HCR):

- OPTION 1 (Model based HCR): TAC = Biomass X F_{target} X Probability of SSB above B_{lim}

F_{target}: Four different levels of F will be considered as F_{target}, corresponding to probabilities of 20%, 30%, 40% and 50% of exceeding F_{msy}.

If F_{msy} is not available, an appropriate proxy (e.g. F_{max}, current proxy) should be used.

- OPTION 2 (Model free HCR): TACy+1=TACy X (1 + λ x slope)

Biomass projections should apply a risk neutral approach (*i.e.* mean probabilities).

(b) When SSB is below B_{lim}, no directed fishing and by-catch should be restricted to unavoidable by-catch in fisheries directing for other species

For this purpose, fisheries managers will consider the probability and establish risk tolerance, noting that the probability of biomass to be above Blim is an integral part of the HCR proposed in option 1.

(c) Noting the desire for relative TAC stability, TAC should be constraint to a fixed percentage of annual change (+- [XX]%).

Level of constraint is to be defined by Managers. Different scenarii will be tested: 10%, 15% and 20%.

The management objectives, performance statistics (PS) and performance target (PT) are indicated in Annex 1.

4. By-catch Provisions

The by-catch provisions in the CEM for 3M cod are defined in Article 6.3.

5. Reviews

Reviews should be completed on a regular basis at intervals such that failures of the plan (e.g. prolonged declining stock) can be detected, and changes made as required.

6. Final provisions

The current Risk-based Management Strategy (RBMS) for Cod stock in Subarea 3M shall be applied in consistency with the Precautionary Approach Framework and the General Framework on Risk-based Management Strategies.

It shall be in force initially until 2019.

Parameters for the evaluation of the management strategy

The priority regarding management objectives is (ranked from higher to lower priority): 1) low risk of breaching B_{lim}, 2) low risk of overfishing and 3) low risk of steep biomass decline, 4) maximise average catch and 5) limited annual catch variation.

The HCRs, PS and PT are not fully mathematically specified and are left open for the Scientific Council to propose adequate formulation. The length of the evaluation period is to be defined by the Scientific Council.

Management Objectives	Performance Statistics (PS)	Performance Targets (PT)
Low risk of steep decline	SSB_{10}/SSB_0, where SSB_{10} = spawning stock biomass in year 10 and SSB_0 = spawning stock biomass in year 0, where year 0 is the current year SSB_5/ SSB_0 SSB_{lowest} / SSB_0, where SSB_{lowest} = lowest spawning stock biomass level during projected evaluation period	The probability of the decline of 25% or more of spawning stock biomass from year 0 to year 5 is kept at 10% or lower.
Very low risk of breaching B_{lim}	SSB / B_{lim}	The probability of a spawning stock biomass under B_{lim} at 10% or lower
Limited annual catch variation	Number of times the constraint (at the lower and at the higher boundaries) has been applied on average during the period.	This will be achieved through the constraint on the TAC variation.
Maximum average catch over the period	Yearly TAC for the period Average TAC over the period	The average TAC over the period should be maximized
Low risk of overfishing	F/F_{msy} F_{max} is used as a proxy for F_{msy}.	For the model free HCR only: The probability of F exceeding F_{msy} during the evaluation period should be kept at 30% or lower.