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Specifications of the Operating Models and the projections for the 3M cod MSE

by

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Abstract

The general specifications of the Operating Models (OMs) and the projections for the NAFO 3M cod MSE are presented in this document as a starting point for the Scientific Council (SC) to decide the final set of specifications. The base case reference OM was agreed by the SC as the model assessment approved in the 2018 June SC meeting. Alternative operational models included different M priors, different CVs for the survey indices and the catch-at-age and different groups of *qs*. In this document the details of the suggested specifications are described, as well as the specifications of the 20 years projections (2018-2037) for the MSE. Seven different approaches were analyzed to obtain the future values for the maturity ogive, the mean weights-at-age (both in catch and in stock), M, Partial Recruitment (PR) and recruitment (R).

The input data used for testing all the 3M cod OMs is the same used in the last assessment in June 2018. The specifications of the Performance Targets and Performance Statistic are under development.

Introduction

A Bayesian Statistical Catch-at-Age (SCAA) methodology for the assessment of the 3M cod was approved during the June 2018 SC meeting and it is described in González-Troncoso *et al.* (2018), as well as in this document. This methodology was discussed in the SC Benchmark of the 3M cod (NAFO, 2018) within other possibilities, namely Bayesian XSA, SAM and GADGET.

The SC agreed, as base case reference OM for the MSE of the 3M cod, the model assessment approved in the 2018 June SC meeting. Other operational models should be tested, including alternate M priors, different CVs for the survey indices and the catch-at-age or different groups of *qs*. In this document the details of the suggested specifications are described.

The specifications of the projections for the MSE are described too. The specifications of the Performance Targets and Performance Statistic are under development.

Material and Methods

Specification of the Operating Models (OMs)

The input data used for testing all the 3M cod OMs is the same used in the June 2018 assessment: total catch, catch-at-age, mean weights-at-age in catch, survey indices of abundance, mean weights-at-age in stock and maturity ogive at age for the period 1988 to 2017 (González-Troncoso *et al.*, 2018).

The general characteristics of the OMs described in this document are the following. The details of each of them are in Annex I. The values of the common variables are in Table 1.

1. OM base case: the one approved during the June 2018 NAFO SC meeting. Annex IA. In this case:

-M is estimated by a prior with median equal to a vector (Table 2) and CV=15%.

-q is grouped in four age groups: 1, 2, 3, 4+, each of them with a lognormal prior with the same median and CV.

-CVs of the catch-at-age and the survey indices: fix and equal to 20% and 30%, respectively.

2. OMs changing the value of M, Annex 1B:

2.1. *OMfix*: M is not estimated by the model, constant over years and ages and equal to 0.19. The value of 0.19 was chosen because it was the posterior median of M in the last Bayesian XSA assessment carried out for this stock (González-Troncoso, 2017). Annex IB1.

2.2. *OMmatrix*: M is not estimated by the model, variable over years and ages. The matrix with the values of M is in Table 2. This matrix comes from the GADGET model assessment presented in the benchmark of the 3M cod in April 2018 (Pérez and González-Costas, 2018). Annex IB2.

2.3. *OMsteps*: The M is estimated by the model by steps of two years. First, an assessment between 1988 and 2005 is performed with an M constant over years and ages and estimated by a prior. With the posterior of this M, the second step is to perform an assessment for 1988 to 2007 in another two substeps: in the first substep the M is fix for 1988-2005 and equal to the median posterior of the first step and the M for ages 2006 and 2007 is estimated constant over years and ages by a prior of mean the median posterior of the first step. With the posterior of this run, a second substep is made performing an assessment from 2006 to 2007 with M fix for 1988 to 2005 and M for 2006 and 2007 estimated by age with a prior of mean the median of the first step multiplied by a vector. The posterior median of this prior (one by age for the period 2006-2007) is the value of the mean of the prior of M in the third step for years 2008 and 2009, and so on. Schematically:

Step 1. y= 88-05, *ln*($M_{88\text{-}95}$) ~ *N*(*ln*(0.218) , 0.3) => exp posterior median $M_{88-05}^{allages}$

Step 2. Step 2.1: y=88-07, $M_{88\text{-}05} = M_{88-05}^{allages}$

ln($M_{06\text{-}07}$) ~ *N*(*ln*($M_{88-05}^{allages}$), 0.3) => exp posterior median $M_{06-07}^{allages}$

Step 2.2: y=88-07, $M_{88\text{-}05} = M_{88-05}^{allages}$

ln($M_{06\text{-}07}$[a]) ~ *N*(*ln*($M_{06-07}^{allages} * vectM[a]$), 0.3) => exp posterior median M_{06-07}^{a} , a=1,…,8+

Step 3. Step 3.1: y=88-09, $M_{88\text{-}05} = M_{88-05}^{allages}$; $M_{06\text{-}07}$[a] = M_{06-07}^{a}, a=1,…,8+

ln($M_{08\text{-}09}$) ~ *N*(*ln*($M_{06-07}^{allages}$), 0.3) => exp posterior median $M_{08-09}^{allages}$

Step 3.2: y=88-09, $M_{88\text{-}05} = M_{88-05}^{allages}$; $M_{06\text{-}07}$[a] = M_{06-07}^{a}, a=1,…,8+

ln($M_{08\text{-}09}$[a]) ~ *N*(*ln*($M_{08-09}^{allages} * vectM[a]$), 0.3) => exp posterior median M_{08-09}^{a} , a=1,…,8+

Step 4 to 7: As 2 and 3, to finalize in y=88-17

Final M:

M_{88-17} =

	1	2	…	7	8
1988	M_{88-05}	M_{88-05}	…	M_{88-05}	M_{88-05}
1989	M_{88-05}	M_{88-05}	…	M_{88-05}	M_{88-05}
…	…	…	…	…	…
2004	M_{88-05}	M_{88-05}	…	M_{88-05}	M_{88-05}
2005	M_{88-05}	M_{88-05}	…	M_{88-05}	M_{88-05}
2006	M_{06-07}^1	M_{06-07}^2	…	M_{06-07}^7	M_{06-07}^8
2007	M_{06-07}^1	M_{06-07}^2	…	M_{06-07}^7	M_{06-07}^8
2008	M_{08-09}^1	M_{08-09}^2	…	M_{08-09}^7	M_{08-09}^8
2009	M_{08-09}^1	M_{08-09}^2	…	M_{08-09}^7	M_{08-09}^8
…	…	…	…	…	…
2016	M_{16-17}^1	M_{16-17}^2	…	M_{16-17}^7	M_{16-17}^8
2017	M_{16-17}^1	M_{16-17}^2	…	M_{16-17}^7	M_{16-17}^8

vectM is set as the vector of M used in the base case normalized to the mean of ages 6 to 8.

Another difference of this configuration with regard the base case is that the CV of the catch-ate-age is estimated via a prior. Annex IB3.

Other two different approaches of this OM were made, but finally this OM was the one chosen. The specifications and the results of those OMs are in another document (González-Troncoso and Ávila de Melo, 2019).

2.4. A new vector based M (*OMvec*): The M is calculated as in the base case, but the prior medians by age and their CV are different and equal to medM[a]= c(0.82, 0.57, 0.43, 0.37, 0.33, 0.31, 0.28, 0.28), cvM = 0.30 (NAFO, 2019). Annex IB4.

3. OMs changing the estimation of the CVs in the catch-at-age and in the survey indices:

3.1. *OMCV*: In this OM the CV is estimated via a prior. This was explored during the benchmark but a deep exploration is needed. As during the benchmark it was seen that the CVs are different by age (NAFO, 2018), three different age classes of CVs were set for the survey numbers-at-age (1, 2, 3+) and another three for the catch-at-age (2, 3-6, 7+; take into account that age 1 is assumed to be 0 and are not modeled). Annex IC.

4. OMs changing the grouping of q, Annex 1D:

4.1. *OMgruq1*: survey catchabilities (q) estimated for three group ages, 1, 2 and 3+. The reason to consider this OM is because the Base Case results show that the *q* at age 3 and *q* at age 4+ are very similar and probably it would be better to estimate *q*3+. Annex 1D1.

4.2. *OMgruq2*: in this case, we have four different age groups: 1, 2, 3-6 and 7+. This OM was set based on the results of the survey, in which the youngest and the oldest ages seem to be different from the rest of the ages. Annex 1D2.

A summary of the settings that vary between the OMs is in Table 3.

Specification of the projections (MSE)

A projection of 20 years was performed, from 2018 to 2037.

Seven different approaches were analyzed to obtain the future values for the maturity ogive, the mean weights-at-age (both in catch and in stock), M, PR and the residuals of the R. For the recruitment, four different Stock-Recruitment relationships, based on Ricker and Segmented Regression, were considered (NAFO, 2019) and fitted by iteration, adding the residuals as explained in González-Costas *et al.* (2019).

1. A boostrap over 2012-2017 (6 years) for the projected years (*projboot1*).

2. A boostrap over 1989-2017 (29 years) for the projected years (*projboot2*).

3. A Random Walk, taking a random year as the starting point and then taken a sample in the five-year window around this first year (*projRW*).

4. A Random Walk, taking 2017 as the starting point and then taken a sample in the five-year window around this first year (*projRW17*).

5. Mean of the last 3 years, i.e. 2015-2017 (*projmean*).

6. A density dependent model, in which the mean weights are modeled as a function of the stock biomass (explained in Brunel, 2019) (*projden*).

7. Residuals of the recruitment selected by bins (*resRbin*): Residuals of the recruitment will be re-sampled from historic recruitment, however, given the magnitude of some residuals there was concern that re-sampling over the entire series would result in predicted values that were unrealistic when compared to historic values, and that potentially very high recruitment values could be drawn even at very low SSB. As an alternative, it was suggested to slice the distribution into several SSB bins, and to re-sample residuals from within those bins (selecting in each future year the bin in which SSB lies in that year). The advantage of this approach is that it would confine the largest SSB residuals within the SSB range that they were observed. The selected cut-off SSB levels for the SSB bins in the Ricker scenario were the SSB estimated in 1997, 2007 and 2010. In the segmented regression scenario, the cut-off SSB level suggested was only SSB_{2007}, so two bins were chosen: residuals from the period in which SSB was below B_{lim} and from the period in which SSB was above B_{lim}, depending on the future value of the SSB.

The specification of the different approaches to get those indices is in Annex IIA.

The projection is made forwards as explained in Annex IIB.

The HCRs applied in this MSE are model-free, based on the biomass index of the Flemish Cap survey. For that, we need estimations of the future biomass index of the survey. Several methods were explored in order to get the errors in the indices in the future, explained in another document (Fernández *et al.*, 2019).

Conclusions

After discussion by the SC of the different proposed OMs during the SC Flemish Cap Cod Stock MSE meeting, it was agreed that the initial set of OMs to be conducted in the MSE will be:

1. Base Case
2. *OMmatrix*
3. *OMsteps*
4. *OMGroup2*.

The rest of the OMs were discarded for different reasons (NAFO, 2019).

With regard to the biological parameters for future years, i.e. 2018 onwards (mean weights at age in stock and catch, natural mortality and maturity), three OMs were agreed:

1. *projRW17* (Base Case)
2. *projmean*
3. *projden*.

With regard to the recruitment, two stock-recruitment relationships for future years, i.e. 2018 onwards, were agreed:

1. $SegRegB_{lim}$
2. *RickerB*.

The residuals of the recruitment in the future will be resampled following the *resRbin* procedure.

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Table 1. Unchanged parameters in the priors of the Bayesian SCAA. These parameters are common to all the OMs for which the parameter is applicable.

Parameter	Value	Parameter	Value
medrec	45000	*shpsi*	2
cvrec	10	*rtpsi*	0.07
medF	c(0.0001,0.1,0.5,0.7,0.7,0.7,0.7,0.7)	*alpha.EU*	0.07
cvyear1	10	*beta.EU*	0.5
aref	5	*S1.C*	4
medf	0.2	*S2.C*	0.345
cvf	4	*medlogphi*	0
medrC	c(0.001,0.3,0.6,0.9,1,1,1)	*taulogphi*	1/5
cvrC	4	*adep*	1
cvrCcond	0.2	*medgama*	1
cvCW	0.077	*taugama*	1/0.25

Table 2. Values used for M: input and prior medians.

M value	0.19

M vector

Age	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
M	1.26	0.65	0.44	0.35	0.3	0.27	0.24	0.24

M matrix (from the GADGET model)

Age/Year	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
1988	0.766	0.397	0.358	0.352	0.350	0.350	0.350	0.350
1989	1.125	0.842	0.388	0.356	0.351	0.350	0.350	0.350
1990	0.910	0.656	0.581	0.368	0.353	0.351	0.350	0.350
1991	0.455	0.410	0.367	0.361	0.351	0.350	0.350	0.350
1992	0.479	0.374	0.355	0.352	0.351	0.350	0.350	0.350
1993	0.406	0.389	0.355	0.351	0.350	0.350	0.350	0.350
1994	0.410	0.395	0.360	0.351	0.350	0.350	0.350	0.350
1995	0.471	0.419	0.357	0.351	0.350	0.350	0.350	0.350
1996	0.392	0.385	0.362	0.351	0.350	0.350	0.350	0.350
1997	0.373	0.362	0.358	0.353	0.350	0.350	0.350	0.350
1998	0.362	0.359	0.351	0.351	0.350	0.350	0.350	0.350
1999	0.367	0.363	0.353	0.350	0.350	0.350	0.350	0.350
2000	0.350	0.350	0.350	0.350	0.350	0.350	0.350	0.350
2001	0.350	0.350	0.350	0.350	0.350	0.350	0.350	0.350
2002	0.350	0.350	0.350	0.350	0.350	0.350	0.350	0.350
2003	0.350	0.350	0.350	0.350	0.350	0.350	0.350	0.350
2004	0.350	0.350	0.350	0.350	0.350	0.350	0.350	0.350
2005	0.350	0.350	0.350	0.350	0.350	0.350	0.350	0.350
2006	0.350	0.350	0.350	0.350	0.350	0.350	0.350	0.350
2007	0.350	0.350	0.350	0.350	0.350	0.350	0.350	0.350
2008	0.350	0.350	0.350	0.350	0.350	0.350	0.350	0.350
2009	0.350	0.350	0.350	0.350	0.350	0.350	0.350	0.350
2010	0.876	0.692	0.412	0.365	0.352	0.350	0.350	0.350
2011	0.822	0.683	0.457	0.370	0.354	0.351	0.350	0.350
2012	0.581	0.622	0.506	0.392	0.356	0.352	0.350	0.350
2013	0.592	0.656	0.497	0.403	0.363	0.353	0.351	0.350
2014	1.441	0.693	0.517	0.384	0.361	0.353	0.351	0.350
2015	1.425	0.894	0.480	0.415	0.364	0.356	0.352	0.350
2016	0.809	0.789	0.527	0.392	0.373	0.356	0.352	0.350
2017	0.809	0.789	0.527	0.392	0.373	0.356	0.352	0.350

Table 3. Settings of Bayesian SCAA runs.

OM		M	Age groups		
			CV of catch-at-age	**CV of survey**	**Survey catchability**
1	*Base Case*	8 priors, *cvM* =0.15	Fix (20%)	Fix (30%)	1, 2, 3, 4+
2	*OMfix*	*Mcte* = 0.19	Fix (20%)	Fix (30%)	1, 2, 3, 4+
3	*OMmatrix*	*Mmatrix*	Fix (20%)	Fix (30%)	1, 2, 3, 4+
4	*OMsteps*	M steps, *cvM* =0.3	2, 3-6, 7+	Fix (30%)	1, 2, 3, 4+
5	*OMvec*	8 priors, *cvM* =0.3	Fix (20%)	Fix (30%)	1, 2, 3, 4+
6	*OMCV*	8 priors, *cvM* =0.15	2, 3-6, 7+	1, 2, 3+	1, 2, 3, 4+
7	*OMgruq1*	8 priors, *cvM* =0.15	Fix (20%)	Fix (30%)	1, 2, 3+
8	*OMgruq2*	8 priors, *cvM* =0.15	Fix (20%)	Fix (30%)	1, 2, 3-6, 7+

Annex I

Annex IA: Settings of the Base Case

Ages: a = 1,…,A+

Years: y = 1,…,Y

1. Recruits (age 1) each year, N[y,1], for y = 1,…,Y. The following prior is taken:

$$N[y,1] \sim logN(median = medrec, CV = cvrec)$$

   - *medrec* = 45000 and *cvrec* = 10

2. Numbers at age in the first year, N[1,a], for a = 2,…A+. The following priors are taken:

$$N[1,a] \sim logN(median = medrec * e^{\sum_{i=1}^{a-1}(M[1,i]+medF[i])}, CV = cvyear1) \ , a = 2,\ldots,A\text{-}1$$

$$N[1,A+] \sim logN\left(median = medrec * \frac{e^{\sum_{i=1}^{A-1}(M[1,i]+medF[i])}}{1-e^{-(M[1,A+]+medF[A+])}}, CV = cvrec\right)$$

   - *medF* = c(0.0001,0.1,0.5,0.7,0.7,0.7,0.7,0.7) and *cvyear1* = 10

3. Forward population each year and age, N[y,a], for y=2,…,Y and a=2,…,A+. Standard exponential decay equations:

$$N[y,a] = N[y-1,a-1]e^{-Z[y-1, \ a-1]}, a = 2,\ldots,A\text{-}1$$

$$N[y,A+] = N[y-1,A-1]e^{-Z[y-1, \ A-1]} + N[y-1,A+]e^{-Z[y-1,A+]}$$

$$Z[y,a] = M[y,a] + F[y,a]$$

4. Fishing mortality is modeled as $F[y,a] = f[y]*rC[y,a]$, for y=1,…,Y and a=1,…,A+

   It is assumed that $rC[y,A+] = rC[y,A-1]$ and that $rC[y, aref] = 1$, for a chosen reference age $aref$ = 5.

   The factors $f[y]$ and $rC[y,a]$ are modeled as follows:

   a. *log*(*f[y]*) is modeled as an AR(1) process over the years, with autocorrelation parameter *rhof*. The median and CV of the marginal prior distribution of $f[y]$ in each year are *medf* and *cvf*, respectively.

      - *rhof* is assigned an *Uniform(0,1)* prior distribution,
      - *medf* = 0.2 and *cvf* = 4

   b. For each age different from *aref* = 5 and A+, *log*(*rC*[y,a]) is modeled as random walk over the years, independently from age to age.

      The distribution in the first assessment year (y=1) is:

$$rC[1,a] \sim logN(median = medrec[a], CV = cvrC[a])$$

      - *medrC* = c(0.001,0.3,0.6,0.9,1,1,1) and *cvrC* = c(4,4,4,4,4,4,4).

The distribution in subsequent years (y>1) is given by a random walk in log scale:

$$log(rC[y,a] \sim N(median = log(rC[y-1,a]), CV = cvrCond)$$

- *cvrCcond* = 0.2

5. Observation equation for annual commercial total catch in weight, Cton[*y*], for *y*=1,…,Y

$$Cton[y] \sim logN(median = \sum_{a=1}^{A+} mu.C[y,a] * wcatch[y,a], CV = cvCW) \; ,$$

being $mu.C[y,a] = N[y,a]\left(1-e^{-Z[y,a]}\right)\frac{F[y,a]}{Z[y,a]}$ the standard Baranov catch equation

- *cvCW* = 0.077 (95% probability of no more than 15% deviation)

6. Observation equations for commercial catch numbers-at-age, C[*y*,*a*], for each year *y* excluding 2002-2005, and age *a* = 1,…,A+

$$log\ (C[y,a]) \sim N(median = \log\ (mu.C[y,a], CV = psi.C)$$

- *psi.C* = 25.5 corresponds to CV = 0.2 on catch numbers-at-age (in original, not log-scale)

7. Observation equations for survey indices, CPUE.EU[*y*,*a*], *y*=1,…,Y and *a*=1,…,A+

$$log\ (CPUE.EU[y,a] \sim N(median = log\ (mu.CPUE.EU[y,a], CV = psi.EU)$$

where

$$mu.CPUE.EU[y,a] = phi.EU[a]\left\{N[y,a]\frac{e^{-alpha.EU*Z[y,a]} - e^{-beta.EU*Z[y,a]}}{(beta.EU - alpha.EU)*Z[y,a]}\right\}^{gama.EU[a]}$$

- *alpha.EU* = 0.50 and *beta.EU* = 0.58 correspond to the timing of the survey (July)
- *psi.EU* = 11.6 corresponds to CV = 0.3 on abundance index at age (in original, not log-scale)

7.1. Prior on phi.EU[*a*], equal by groups: 1, 2, 3, 4+:

$$ln(phi.EU[a]) \sim N\left(mean = medlogphi, \frac{1}{variance} = taulogphi\right)$$

- *medlogphi* = 0 and *taulogphi* = $\frac{1}{5}$

7.2. Prior on gama.EU[*a*]:

For ages *a* in the set *adep*, *gama.EU*[*a*]= 1, whereas for other ages *a*:

$$gama.EU[a] \sim N\left(mean = medgama, \frac{1}{variance} = taugama\right) \; ,$$

- *medgama* = 1 and *taugama* = $\frac{1}{0.25}$

8. Observation equations for Natural Mortality, M[*a*], *a*=1,…,A+:

$$log\ (M[a]) \sim N(median = log\ (medM[a]), CV = cvM)$$

- *medM* = c(1.26,0.65,0.44,0.35,0.30,0.27,0.24,0.24) and *cvM* = 0.15

Annex IB: Settings of the OMs changing the estimation of M

Annex IB1: Settings of the *OMfix*

All the settings equal to Base Case except:

Natural Mortality, M=*cstM*, constant for all ages and all years, and for all iterations.

- *cstM* = 0.19

Annex IB2: Settings of the *OMmatrix*

All the settings equal to Base Case except:

Natural Mortality, M=*matrixM*, constant matrix for all the iterations, variable by age and year.

- *matrixM* is the following matrix (from GADGET model):

matrixM=

	1	2	3	4	5	6	7	8
1988	0.766	0.397	0.358	0.352	0.350	0.350	0.350	0.350
1989	1.125	0.842	0.388	0.356	0.351	0.350	0.350	0.350
1990	0.910	0.656	0.581	0.368	0.353	0.351	0.350	0.350
1991	0.455	0.410	0.367	0.361	0.351	0.350	0.350	0.350
1992	0.479	0.374	0.355	0.352	0.351	0.350	0.350	0.350
1993	0.406	0.389	0.355	0.351	0.350	0.350	0.350	0.350
1994	0.410	0.395	0.360	0.351	0.350	0.350	0.350	0.350
1995	0.471	0.419	0.357	0.351	0.350	0.350	0.350	0.350
1996	0.392	0.385	0.362	0.351	0.350	0.350	0.350	0.350
1997	0.373	0.362	0.358	0.353	0.350	0.350	0.350	0.350
1998	0.362	0.359	0.351	0.351	0.350	0.350	0.350	0.350
1999	0.367	0.363	0.353	0.350	0.350	0.350	0.350	0.350
2000	0.350	0.350	0.350	0.350	0.350	0.350	0.350	0.350
2001	0.350	0.350	0.350	0.350	0.350	0.350	0.350	0.350
2002	0.350	0.350	0.350	0.350	0.350	0.350	0.350	0.350
2003	0.350	0.350	0.350	0.350	0.350	0.350	0.350	0.350
2004	0.350	0.350	0.350	0.350	0.350	0.350	0.350	0.350
2005	0.350	0.350	0.350	0.350	0.350	0.350	0.350	0.350
2006	0.350	0.350	0.350	0.350	0.350	0.350	0.350	0.350
2007	0.350	0.350	0.350	0.350	0.350	0.350	0.350	0.350
2008	0.350	0.350	0.350	0.350	0.350	0.350	0.350	0.350
2009	0.350	0.350	0.350	0.350	0.350	0.350	0.350	0.350
2010	0.876	0.692	0.412	0.365	0.352	0.350	0.350	0.350
2011	0.822	0.683	0.457	0.370	0.354	0.351	0.350	0.350
2012	0.581	0.622	0.506	0.392	0.356	0.352	0.350	0.350
2013	0.592	0.656	0.497	0.403	0.363	0.353	0.351	0.350
2014	1.441	0.693	0.517	0.384	0.361	0.353	0.351	0.350
2015	1.425	0.894	0.480	0.415	0.364	0.356	0.352	0.350
2016	0.809	0.789	0.527	0.392	0.373	0.356	0.352	0.350
2017	0.809	0.789	0.527	0.392	0.373	0.356	0.352	0.350

Annex IB3: Settings of the *OMstep*

In this case, the assessment is run in several steps performing an assessment every two years. Besides the changes in the way to estimate M, there is a change with regards the Base Case in:

Observation equations for commercial catch numbers-at-age, C[*y*,*a*], for each year *y* excluding 2002-2005, and age *a* = 1,…,A+

$$log\ (C[y,a]) \sim N(median = \log\ (mu.C[y,a], CV = psi.C)$$

where *psi.C* is equal by groups of ages: 2, 3-6, 7+ as:

$$psi.C[a] \sim Gamma(\,shape = s1.C, rate = s2.C)$$

- *S1.C* = 4 and *S2.C* = 0.345

The specification as the Base Case but changing point 6 is called above as "Base Case *Msteps*".

<u>Step 1</u>: Assessment from 1988 to 2005: as Base Case *Msteps* except for:

Observation equations for Natural Mortality, M for all ages and years:

$$log\ (M) \sim N(median = log\ (medM), CV = cvM)$$

- *medM*= 0.218 and *cvM* = 0.3 are the values used in the 3M cod assessment until 2017

From this assessment and with this prior, we get a value of posterior M for each iteration (constant by year and age), being the exponential of the posterior median $M_{88\text{-}05}^{allages}$.

<u>Step 2:</u>

<u>Step 2.1:</u> Assessment from 1988 to 2007: as Base Case *Msteps* except for:

Matrix of M between 1988 and 2005: $M_{88\text{-}05} = M_{88\text{-}05}^{allages}$ (fix values, no iterations):

M_{88-05} =

	1	2	…	7	8
1988	$M_{88-05}^{allages}$	$M_{88-05}^{allages}$	…	$M_{88-05}^{allages}$	$M_{88-05}^{allages}$
1989	$M_{88-05}^{allages}$	$M_{88-05}^{allages}$	…	$M_{88-05}^{allages}$	$M_{88-05}^{allages}$
…	…	…	…	…	…
2004	$M_{88-05}^{allages}$	$M_{88-05}^{allages}$	…	$M_{88-05}^{allages}$	$M_{88-05}^{allages}$
2005	$M_{88-05}^{allages}$	$M_{88-05}^{allages}$	…	$M_{88-05}^{allages}$	$M_{88-05}^{allages}$

Observation equations for Natural Mortality, M for all ages and years 2006 and 2007:

$$log(M) \sim N\left(median = log(M_{88-05}^{allages}), CV = cvM\right)$$

From this assessment and with this prior, we get a value of the posterior M for each iteration (constant for age and years 2006 and 2007), being the exponential of the posterior median $M_{06\text{-}07}^{allages}$.

<u>Step 2.2:</u> Assessment from 1988 to 2007: as Base Case *Msteps* except for:

Matrix of M between 1988 and 2005: $M_{88\text{-}05}^{allages}$ (fix values, no iterations):

M_{88-05} =

	1	2	…	7	8
1988	$M_{88-05}^{allages}$	$M_{88-05}^{allages}$	…	$M_{88-05}^{allages}$	$M_{88-05}^{allages}$
1989	$M_{88-05}^{allages}$	$M_{88-05}^{allages}$	…	$M_{88-05}^{allages}$	$M_{88-05}^{allages}$
…	…	…	…	…	…
2004	$M_{88-05}^{allages}$	$M_{88-05}^{allages}$	…	$M_{88-05}^{allages}$	$M_{88-05}^{allages}$
2005	$M_{88-05}^{allages}$	$M_{88-05}^{allages}$	…	$M_{88-05}^{allages}$	$M_{88-05}^{allages}$

Observation equations for Natural Mortality, M for and years 2006 and 2007:

$$log(M[a]) \sim N\left(median = log(M_{06-07}^{allages} * vectM[a]), CV = cvM\right)$$

Being *vectM* = c(5.04, 2.6, 1.76, 1.4, 1.2, 1.08, 0.96, 0.96) the vector used in the base case as *medM* but normalized to the mean of ages 6 to 8.

From this assessment and with this prior, we get values of the posterior M for each iteration (constant for 2006 and 2007), being the exponential of the posterior median $M^{a}_{06\text{-}07}$, a=1,…,8+.

<u>Step 3:</u>

<u>Step 3.1:</u> Assessment from 1988 to 2009: as Base Case *Msteps* except for:

Matrix of M between 1988 and 2007: $M^{allages}_{88\text{-}05}$ and $M^{a}_{06\text{-}07}$ (fix values, no iterations):

$M_{88-07} =$

	1	2	…	7	8
1988	$M^{allages}_{88-05}$	$M^{allages}_{88-05}$	…	$M^{allages}_{88-05}$	$M^{allages}_{88-05}$
1989	$M^{allages}_{88-05}$	$M^{allages}_{88-05}$	…	$M^{allages}_{88-05}$	$M^{allages}_{88-05}$
…	…	…	…	…	…
2004	$M^{allages}_{88-05}$	$M^{allages}_{88-05}$	…	$M^{allages}_{88-05}$	$M^{allages}_{88-05}$
2005	$M^{allages}_{88-05}$	$M^{allages}_{88-05}$	…	$M^{allages}_{88-05}$	$M^{allages}_{88-05}$
2006	M^{1}_{06-07}	M^{2}_{06-07}	…	M^{7}_{06-07}	M^{8}_{06-07}
2007	M^{1}_{06-07}	M^{2}_{06-07}	…	M^{7}_{06-07}	M^{8}_{06-07}

Observation equations for Natural Mortality, M for all ages and years 2008 and 2009:

$$log(M) \sim N\left(median = log(M^{allages}_{06-07}), CV = cvM\right)$$

From this assessment and with this prior, we get a value of the posterior M for each iteration (constant for age and years 2008 and 2009), being the exponential of the posterior median $M^{allages}_{08\text{-}09}$.

<u>Step 3.2:</u> Assessment from 1988 to 2009: as Base Case *Msteps* except for:

Matrix of M between 1988 and 2007: $medM_{88\text{-}05}$ and $medM^{a}_{06\text{-}07}$ (fix values):

$M_{88-07} =$

	1	2	…	7	8
1988	$M^{allages}_{88-05}$	$M^{allages}_{88-05}$	…	$M^{allages}_{88-05}$	$M^{allages}_{88-05}$
1989	$M^{allages}_{88-05}$	$M^{allages}_{88-05}$	…	$M^{allages}_{88-05}$	$M^{allages}_{88-05}$
…	…	…	…	…	…
2004	$M^{allages}_{88-05}$	$M^{allages}_{88-05}$	…	$M^{allages}_{88-05}$	$M^{allages}_{88-05}$
2005	$M^{allages}_{88-05}$	$M^{allages}_{88-05}$	…	$M^{allages}_{88-05}$	$M^{allages}_{88-05}$
2006	M^{1}_{06-07}	M^{2}_{06-07}	…	M^{7}_{06-07}	M^{8}_{06-07}
2007	M^{1}_{06-07}	M^{2}_{06-07}	…	M^{7}_{06-07}	M^{8}_{06-07}

Observation equations for Natural Mortality, M for and years 2008 and 2009:

$$log(M[a]) \sim N\left(median = log(M^{allages}_{08-09} * vectM[a]), CV = cvM\right)$$

From this assessment and with this prior, we get values of the posterior M for each iteration (constant for 2008 and 2009), being the exponential of the posterior median $M^{a}_{08\text{-}09}$, a=1,…,8+.

<u>Step 4-7</u>: As steps 2 and 3

At the end, we get the following matrix as a result of the OM (fix values, without uncertainty):

M_{88-17} =

	1	2	…	7	8
1988	$M_{88-05}^{allages}$	$M_{88-05}^{allages}$	…	$M_{88-05}^{allages}$	$M_{88-05}^{allages}$
1989	$M_{88-05}^{allages}$	$M_{88-05}^{allages}$	…	$M_{88-05}^{allages}$	$M_{88-05}^{allages}$
…	…	…	…	…	…
2004	$M_{88-05}^{allages}$	$M_{88-05}^{allages}$	…	$M_{88-05}^{allages}$	$M_{88-05}^{allages}$
2005	$M_{88-05}^{allages}$	$M_{88-05}^{allages}$	…	$M_{88-05}^{allages}$	$M_{88-05}^{allages}$
2006	M_{06-07}^{1}	M_{06-07}^{2}	…	M_{06-07}^{7}	M_{06-07}^{8}
2007	M_{06-07}^{1}	M_{06-07}^{2}	…	M_{06-07}^{7}	M_{06-07}^{8}
2008	M_{08-09}^{1}	M_{08-09}^{2}	…	M_{08-09}^{7}	M_{08-09}^{8}
2009	M_{08-09}^{1}	M_{08-09}^{2}	…	M_{08-09}^{7}	M_{08-09}^{8}
	…	…	…	…	…
2016	M_{16-17}^{1}	M_{16-17}^{2}	…	M_{16-17}^{7}	M_{16-17}^{8}
2017	M_{16-17}^{1}	M_{16-17}^{2}	…	M_{16-17}^{7}	M_{16-17}^{8}

Annex IB4: Settings of the *OMvec*

All the settings equal to Base Case except:

Observation equations for Natural Mortality, M[*a*], *a*=1,…,A+:

$$log\ (M[a]\ ) \sim N(median = log\ (medM[a]), CV = cvM)$$

- *medM* = c(0.82, 0.57, 0.43, 0.37, 0.33, 0.31, 0.28, 0.28) and *cvM* = 0.3.

Annex IC: Settings of the *OMCV*:

All the settings equal to Base Case except:

Observation equations for commercial catch numbers-at-age, C[*y*,*a*], for each year *y* excluding 2002-2005, and age *a* = 1,…,A+

$$log\ (C[y,a]) \sim N(median = \log\ (mu.C[y,a], CV = psi.C)$$

where *psi.C* is equal by groups of ages: 2, 3-6, 7+ as:

$$psi.C[a] \sim Gamma(\ shape = s1.C, rate = s2.C)$$

- *S1.C* = 4 and *S2.C* = 0.345

Observation equations for survey indices, CPUE.EU[*y*,*a*], *y*=1,…,Y and *a*=1,…,A+

$$log\ (CPUE.EU[y,a] \sim N(median = log\ (mu.CPUE.EU[y,a], CV = psi.EU)$$

where *psi.EU* is equal by groups of ages: 1, 2, 3+ as:

$$psi.C[a] \sim Gamma(\ shape = shpsi, rate = rtpsi)$$

- *shpsi* = 2 and *rtpsi* = 0.07

Annex ID: Settings of the changing the estimation of the *q* of the survey:

Annex ID1: Settings of the *OMGruq1*:

All the settings equal to Base Case except:

Prior on phi.EU[*a*], equal by groups: 1, 2, 3+:

$$ln(phi.EU[a]) \sim N\left(mean \ = \frac{1}{5} medlogphi, \frac{1}{variance} = taulogphi\right)$$

- *medlogphi* = 0 and *taulogphi* = $\frac{1}{5}$

Annex ID2: Settings of the *OMGruq2*:

All the settings equal to Base Case except:

Prior on phi.EU[*a*], equal by groups: 1, 2, 3-6, 7+:

$$ln(phi.EU[a]) \sim N\left(mean \ = \frac{1}{5} medlogphi, \frac{1}{variance} = taulogphi\right)$$

- *medlogphi* = 0 and *taulogphi* = $\frac{1}{5}$

Annex II: Projection methodology

Annex IIA: Inputs in the projections

The variables estimated as inputs in the projections are: *mat* (maturity-at-age), *wstock* (mean weight-at-age in stock), *wcatch* (mean weight-at-age in catch), *M*, *PR* and *resR* (residuals of R).

The residuals of the recruitment are calculated as the residuals of the fit of a stock-recruitment relationship for each iteration of the OM. The potential stock-recruitment relationships are explained in Annex IIB(5).

Six different estimations were made in order to extract the inputs in the future, and one more only for the residuals of the recruitment. For each of the estimations, we have in the future:

$$matproj_{y_{proj}}^{a,i} = \left(mat_{y_1}^{a,i}, mat_{y_2}^{a,i}, \dots, mat_{y_{20}}^{a,i}\right)$$

$$wstockproj_{y_{proj}}^{a} = \left(wstock_{y_1}^{a}, wstock_{y_2}^{a}, \dots, wstock_{y_{20}}^{a}\right)$$

$$wcatchproj_{y_{proj}}^{a} = \left(wcatch_{y_1}^{a}, wcatch_{y_2}^{a}, \dots, wcatch_{y_{20}}^{a}\right)$$

$$Mproj_{y_{proj}}^{a,i} = \left(M_{y_1}^{a,i}, M_{y_2}^{a,i}, \dots, M_{y_{20}}^{a,i}\right)$$

$$PRproj_{y_{proj}}^{a} = \left(PR_{y_1}^{a,i}, PR_{y_2}^{a,i}, \dots, PR_{y_{20}}^{a,i}\right)$$

$$resRproj_{y_{proj}}^{a} = \left(resR_{y_1}^{a,i}, resR_{y_2}^{a,i}, \dots, resR_{y_{20}}^{a,i}\right)$$

So, we take the parameters from the same years in order to get the correlation between them.

Projection Boot 1 (*projboot1*)

Historical years: y_{hist}=1988-2017 (30 years). Used years: $y_{histused}$=2012-2017 (6 years)

Projection years: y_{proj}=2018-2037 (20 years)

<u>For each iteration, i:</u>

$y_1,\dots,y_{20}$: Sample with replacement of 20 years over the historical years used ($y_{histused}$).

This is repeated for each iteration, so at the end we have 1000 values of each projected parameter. In the case of the parameters that have iterations *per se* (mat, M, PR and resR), the iterations match.

Projection Boot 2 (*projboot2*)

Historical years: y_{hist}=1988-2017 (30 years). Used years: $y_{histused}$=1989-2017 (29 years)

Year 1988 is not used as we do not have value of the residual of the R.

Projection years: y_{proj}=2018-2037 (20 years)

<u>For each iteration, i:</u>

$y_1,\dots,y_{20}$: Sample with replacement of 20 years over the historical years used ($y_{histused}$).

This is repeated for each iteration, so at the end we have 1000 values of each projected parameter. In the case of the parameters that have iterations *per se* (mat, M, PR and resR), the iterations match.

Projection Random Walk (*projRW*)

Historical years: y_{hist}=1988-2017 (30 years). Used years: $y_{histused}$=1989-2017 (29 years)

Year 1988 is not used as we do not have value of the residual of the R.

Projection years: y_{proj}=2018-2037 (20 years)

<u>For each iteration, i:</u>

y_1: Sample of 1 year over the historical years used.

y_2: Sample of one year in a window of 5 years around y_1, $[y_1-2:y_1+2]$

y_3: Sample of one year in a window of 5 years around y_2, $[y_2-2:y_2+2]$

$y_4,\ldots,y_{20}$: as y_2-y_3.

This is repeated for each iteration, so at the end we have 1000 values of each projected parameter. In the case of the parameters that have iterations *per se* (mat, M, PR and resR), the iterations match.

Projection Random Walk (*projRW17*)

Historical years: y_{hist}=1988-2017 (30 years). Used years: $y_{histused}$=1989-2017 (29 years)

Year 1988 is not used as we do not have value of the residual of the R.

Projection years: y_{proj}=2018-2037 (20 years)

<u>For each iteration, i:</u>

y_1: 2017.

y_2: Sample of one year in a window of 5 years around y_1, $[y_1-2:y_1+2]$

y_3: Sample of one year in a window of 5 years around y_2, $[y_2-2:y_2+2]$

$y_4,\ldots,y_{20}$: as y_2-y_3.

This is repeated for each iteration, so at the end we have 1000 values of each projected parameter. In the case of the parameters that have iterations *per se* (mat, M, PR and resR), the iterations match.

Projection Mean last three years (*projmean*)

Historical years: y_{hist}=1988-2017 (30 years). Used years: $y_{histused}$=2015-2017 (3 years)

Projection years: y_{proj}=2018-2037 (20 years)

<u>For each iteration, i:</u>

$y_1,\ldots,y_{20}$: Mean of years 2015-2017 used.

This is repeated for each iteration, so at the end we have 1000 values of each projected parameter. In the case of the parameters that have iterations *per se* (mat, M, PR and resR), the iterations match.

Projection Density Dependent model (*projden*)

Explained in Brunel, 2019.

Stock-Recruitment relationships:

The Spawning Stock Biomass (SSB) is calculated as:

$$SSB_y = \sum_{a=1}^{8+} N_y^a * matproj_y^a * wstockproj_y^a$$

Four different stock-recruitment relationships were considered for calculating the future recruitment:

1. *SegRegB_{lim}*: A Segmented-Regression stock-recruitment relationship to the historical data (y=1988-2017) assuming that the break point is B_{lim}:

$$ln(\hat{R}_y) = \begin{cases} ln(alfa * SSB_y), \; if \; SSB_y \leq B_{lim} \\ ln(alfa * B_{lim}), \; if \; SSB_y > B_{lim} \end{cases}$$

2. *Ricker*: A Ricker stock-recruitment relationship to the historical data (y=1988-2017):

$$ln(\hat{R}_y) = ln(\propto * SSB_y * exp^{-\beta * SSB_y})$$

3. *RickerR*: A Ricker stock-recruitment relationship excluding years with very low recruitment values (R>50000):

$$ln(\hat{R}_y) = ln(\propto * SSB_y * exp^{-\beta * SSB_y}) \text{ , } y \text{ where } R_y > 50000$$

4. *RickerB*: A Ricker stock-recruitment relationship truncated at the SSB_{1997} values (points below SSB_{1997} are not used in the fitting):

$$ln(\hat{R}_y) = ln(\propto * SSB_y * exp^{-\beta * SSB_y}) \text{ , } y \text{ where } SSB_y > SSB_{1997}$$

In all the cases, an error is added to the recruitment obtained for these stock-recruitment relationships:

$$ln(R_y) = ln(\hat{R}_y) + resRproj_y^a \quad => \quad R_y = \hat{R}_y * e^{resRproj_y^a}$$

Projection alternative for the residuals of the R (*resRbin*)

Historical years: y_{hist}=1988-2017 (30 years). Used years: $y_{histused}$=1988-2017 (30 years)

Projection years: y_{proj}=2018-2037 (20 years)

<u>For each iteration, i:</u>

<u>If a Ricker stock-recruitment relationship is used:</u>

$$y_1,\dots,y_{20}: resR^{a,i}_{y_j} = \begin{cases} bootstrap\ over\ resR^{a,i}_{1988-1997}, & if\ SSB_{y_j} \le SSB_{1997} \\ bootstrap\ over\ resR^{a,i}_{1998-2007}, & if\ SSB_{1997} < SSB_{y_j} \le SSB_{2007} \\ bootstrap\ over\ resR^{a,i}_{2008-2010}, & if\ SSB_{2007} < SSB_{y_j} \le SSB_{2010} \\ bootstrap\ over\ resR^{a,i}_{2011-2017}, & if\ SSB_{y_j} > SSB_{2010} \end{cases}$$

If a Segmented Regression stock-recruitment relationship is used:

$$y_1,\dots,y_{20}: resR^{a,i}_{y_j} = \begin{cases} bootstrap\ over\ resR^{a,i}_{yy}, & if\ SSB_{y_j} \le B_{lim},\ being\ yy\ the\ years\ where\ SSB \le B_{lim} \\ bootstrap\ over\ resR^{a,i}_{yy}, & if\ SSB_{y_j} > B_{lim},\ being\ yy\ the\ years\ where\ SSB > B_{lim} \end{cases}$$

So, we take as inputs in the projections:

$$resRproj^{a}_{y_{proj}} = \left(resR^{a,i}_{y_1}, resR^{a,i}_{y_2}, \dots, resR^{a,i}_{y_{20}}\right)$$

This is repeated for each iteration, so at the end we have 1000 *resR* values.

Annex IIB: Specification of the projections

Projections into the future are performed following the standard survivor equation and the catch equation.

All this process is made by iteration independently (1000 iterations), as well as by OM.

1. Numbers-at-age in the first year of projection: From the last year of the OM (2017) numbers-at-age, the numbers-at-age at the beginning of the next year (2018) are calculated, for all the ages but recruitment (age 1) by the survivor equation:

$$N^{1}_{2018} = R_{2018}$$

$$N^{a+1}_{2018} = N^{a}_{2017} * e^{-Z^{a}_{2017}},\ a=2,\dots,7$$

$$N^{8+}_{2018} = N^{8+}_{2017} + N^{7}_{2017} * e^{-Z^{7}_{2017}}$$

$$Z^{a}_{2017} = F^{a}_{2017} + M^{a}_{2017},\ a=1,\dots,8+$$

In the case of the recruitment, it is generated from a segmented regression adding an error, as it is explained in point 5.

2. Catch

The catch for the first year of the projection (2018) is assumed as the TAC of year 2018 (11 145 tons). In the subsequent years, the catch C_y is obtained from the Harvest Control Rule (HCR).

3. Fishing mortality in the subsequent years

The fishing mortality in the subsequent years is calculated solving the catch equation. This equation postulates that the catch at age C^{a}_{y} is estimated from the numbers-at-age of this year and the PR and M estimated as inputs of this year:

$$C_y^a = N_y^a * \left(1 - e^{-(PRproj_y^a * F_y^a + Mproj_y^a)}\right) * \frac{PRproj_y^a * F_y^a}{(PRproj_y^a * F_y^a + M_y^a)}$$

So, the total catch by year, C_y, can be estimated from:

$$\hat{C}_y = \sum_{a=1}^{8+} C_y^a * wstockproj_y^a$$

And F_y^a can be calculated by solving: $C_y - \hat{C}_y = 0$

4. Numbers-at-age in subsequent years, y=2019,…,2037

$$N_{y+1}^1 = R_{y+1}$$

$N_{y+1}^{a+1} = N_y^a * e^{-Z_y^a}$, a=2,…,7

$N_{y+1}^{8+} = N_y^{8+} * e^{-Z_y^{8+}} + N_y^7 * e^{-Z_y^7}$ for the plus group, 8+

$Z_{2017}^a = F_y^a + M_y^a$, a=1,…,8+

5. Recruitment in subsequent years, y=2018,…,2037

The Recruitment in the future is generated from the fit of a stock-recruitment relationship, adding a residual to the result:

$\hat{R}_y = f(SSB_y)$, f a stock-recruitment relationship

where SSB, the Spawning Stock Biomass, is calculated as:

$$SSB_y = \sum_{a=1}^{8+} N_y^a * matproj_y^a * wstockproj_y^a$$

And the final result, after adding the residual, is:

$$R_y = \hat{R}_y * e^{resRproj_y^a}$$

6. Survey indices in subsequent years, y=2018,…,2037

The Total Biomass in weight of the OM is calculated as:

$$B_y = \sum_{a=1}^{8+} N_y^a * wstockproj_y^a$$

and the Total Biomass in weight in the survey as:

$$I_y = \sum_{a=1}^{8+} q^a * N_y^a \; wstockproj_y^a * e^{\varepsilon_y}$$

being q^a catchability of the survey estimated in the OM (q is constant over years).

The method to estimate e^{ε_y} is method 1 in Fernández *et al.* (2019).

The model-free HCRs use an estimation of the Recruitment of the survey, R_y^{surv}, to calculate the catch for the next year. We obtain R_y^{surv} from R_y this way:

$$ln(R_y^{surv}) = ln(R_y) + ln(q^1) + \varepsilon_y^1$$

being ε_y^1 the error for age 1 of method 2 in Fernández *et al.* (2019) (SCR about the indices of the survey).

7. Catch in subsequent years, y=2018,…,2037.

The catch in year y+1 is calculated as the chosen HCR and we repeat all the process from Step 3 for y+1.