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Assessment of the Cod Stock in NAFO Division 3M

by

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Abstract

An assessment of the cod stock in NAFO Division 3M is performed. A Bayesian SCAA (statistical catch-at-age) model was used to perform the analysis. The STACFIS estimations have been used as catch estimations. During the SC meeting in January 2019, B_{lim} was set as the SSB of 2007, which median is 20 000 t with the results of this assessment. Results indicate a general increase in SSB since 2005 to the highest value in 2017, with a slight decrease in 2018, reaching a value above B_{lim} since 2008. After 2012 recruitment has decreased substantially and in 2016 is among the lowest of the series; as a consequence, 5-year projections indicate that total biomass and SSB will decrease sharply during the projected years and there is a high probability of the SSB being below B_{lim} with a more than 10% probability by 2022.

Introduction

The 3M cod stock was on fishing moratorium from 1999 to 2009 following its collapse, which has been attributed to three simultaneous circumstances: a stock decline due to overfishing, an increase in catchability at low abundance levels and a series of very poor recruitments starting in 1993. The assessments performed after the collapse of the stock confirmed the poor situation, with SSB at very low levels, well below B_{lim} (Vázquez and Cerviño, 2005). Nevertheless, recruitment was estimated above the historical average in 2005 and 2006, which in turn caused an increase of SSB that allowed the reopening of the fishery in 2009. Recruitment estimates from 2010 to 2012 (2009-2011 year-classes) have been the highest since 1992 (González-Troncoso *et al.*, 2018) and have resulted in a very high stock biomass level at present; however, they have been followed by low recruitments and, as a consequence, a strong decrease in stock biomass is expected in the near future.

Since 1974, when a TAC was established for the first time, estimated catches ranged from 48 000 tons in 1989 to a minimum value of 5 tons in 2004. Annual catches were about 30 000 tons in the late 1980's (notwithstanding the fact that the fishery was under moratorium in 1988-1990) and diminished since then as a consequence of the stock decline. Since 1998 yearly catches have been below 1 000 tons and from 2 000 to 2005 they were lower than 100 tons, mainly attributed to by-catches from other fisheries. Estimated commercial catches in 2006-2009 were between 339 and 1 161 tons (Table 1 and Figure 1), which represent more than a ten-fold increase over the average yearly catch during the period 2000-2005. The results of the 2009 assessment led to a reopening of the fishery with 5 500 tons of catch in 2010. With the results of the 2010-2015 assessments TACs for 2011-2018 of 10 000, 9 280, 14 113, 14 521, 13 795, 13 931, 13 931 and 11 145 tons were established. The STACFIS estimated catches for 2010 was 9 291 tons, which almost doubled the TAC. The STACFIS estimated catches for 2011-2018 were 12 836, 12 836, 13 985, 14 290, 13 785, 14 023, 13 928 and 11 481tons, respectively.

A VPA based assessment of the cod stock in Flemish Cap was approved by NAFO Scientific Council (SC) in 1999 for the first time and was annually updated until 2002. However, catches between 2002 and 2005 were very small undermining the VPA based assessment, as its results are quite sensitive to assumed natural mortality when catches are at low levels. Cerviño and Vázquez (2003) developed a method which combines survey abundance indices at age with catchability at age, the latter estimated from the last reliable accepted XSA. The method estimates abundances at age with their associated uncertainty and allows calculating the SSB distribution and, hence, the probability that SSB is above or below any reference value. The method was used to assess the stock since 2003. In 2007 results from an alternative Bayesian model were also presented (Fernández *et al.*, 2007) and in 2008 this Bayesian model was further developed and approved by the NAFO SC (Fernández *et al.*, 2008), being used between 2008 and 2017 in the assessment of this stock.

In April 2018 a benchmark on the 3M cod was carried out by the NAFO Scientific Council. During that meeting it was decided to replace the Bayesian XSA used to assess this stock between 2008 and 2017 with a Bayesian SCAA (statistical catch-at-age). Another important change introduced at the benchmark is the value of the natural mortality, which the benchmark agreed to base on biological and multi-species considerations; this has resulted in considerably higher values of M than estimated in previous assessments. The results of the Bayesian SCAA model are presented here, including the updated data until 2018.

Material and Methods

Data used

Commercial data

Total Catch

In 2018 there were catches of 3M cod from EU-Estonia, EU-Portugal, EU-Spain, Faroe Islands (Denmark), Japan, Norway, Russia and United States with a total amount of 11 481 tons from the Secretariat estimates (Table 1, Figure 1).

In 2010 the fishery on this stock was reopened. Since then, STACFIS estimated catches were used for the stock assessment. To know more details, see González-Costas *et al.* (2018) and NAFO (2018b).

Length distributions

In 2018 length sampling of catch was conducted by EU-Estonia (SCS 19/06), EU-Portugal (SCS 19/09), EU-Spain (SCS 19/10), Faroe Islands (SCS 19/07) and Norway (Kjell, personal communication). Length frequency distributions from the commercial catch and from the EU survey (González-Troncoso *et al.*, 2019) are shown in Figure 2A.

EU-Estonia has measured 1331 individuals in a range of 27-104 cm, with mean in 58 cm and mode in 65 cm. The sample of EU-Portugal contains 8314 individuals measured within 39-105 cm, mean 62 cm and mode in the range 63-65 cm. EU-Spain has a 235 individuals sample in a range of 44-126 with a mode in 70 cm and mean in 69 cm. Faroe Islands has catch only with longliners, measuring 3543 individuals with lengths between 29 and 133 cm. The modal length is 68 cm and the mean length 71 cm. For Norway, that used only longliners too, a mode in 69 and a median in 74 cm over a range of 43-131 cm can be seen. The mean length of the total commercial catch is at 64 cm and the mode at 63. The EU survey has two modes, one at 30 cm and another one at 54 cm. The recruitment is very low. The range is from 9 to 132 cm and the mean is at 55 cm.

It is remarkable the difference in the 2017 and 2018 length distributions with regards to the period 2010-2016 (Figure 2B). While between the reopening of the fishery and 2016 the bulk of the commercial length distribution was between 40 and 60 cm, in 2017 and 2018 most of the catches are between 55 and 75 cm. In fact, the mean length in 2010-2016 was between 47 and 59 cm, whereas in 2017 and 2018 was 64 cm. While during the period 2010-2012 the mode of the commercial length distribution was around 54 cm, in 2013 that mode was decreased substantially, being around 42 cm. In 2014 and 2015 the first mode is about 51 and 54 cm respectively, but in both years there is a second mode around 39-42 cm. In 2016 the mode is at 39 cm, whereas in 2017 and in 2018 is at 63 cm, which represents a big change.

In order to see if this behaviour of the fleets is because the fish is bigger or if it is due to commercial reasons, the survey length distribution during all the period is plot in Figure 2C. It can be seen that the percentage of individuals of more than 60 cm (which come probably from the good cohorts of 2010-2011) is slightly higher in 2017 and 2018 than in past years, although in less extent than in the commercial length distribution.

Indices by age

As no age-length keys (ALK) were available for commercial catch from 1988 to 2008, each year the corresponding ALKs from the EU survey (read by the IIM in Vigo) were applied in order to calculate annual catch-at-age. A commercial ALK was available for 2009-2011 only from the Portuguese commercial data and was applied to the total commercial length distribution. In 2012 otoliths were not collected by the Portuguese fleet, and although a commercial ALK from the Spanish fleet was available, it was not used because it was no validated, so the commercial 2011 ALK was applied to the total commercial length distribution. In 2013-2016 there were two available ALKs for commercial length distribution, one from Portugal and the other from Spain, but as they have not been validated yet, the 2013-2016 survey ALKs were used respectively. Much progress in understanding where the differences between the commercial and survey ALKs come from were made but still need more research to completely know the problem.

Last year, due to administrative problems, the 2017 survey ALK was not available, and the 2016 ALK was used for generate the input data of the last assessment. This year the 2017 survey ALK is available, so the 2017 indices were updated, both for commercial and survey length distributions. Although an ALK from the Spanish commercial fleet in 2017 is available, it has not been validated. In 2018, only the survey ALK is available, and it was used for both commercial and survey indices.

The differences between the 2017 indices used in the last assessment (with the 2016 ALK) and the ones used this year (with the 2017 ALK), are displayed in Figure 2.5. It can be seen that, although the mean length at age and the mean weight at age have not changed considerably, in the case of the numbers the modes have changed, more in the survey indices than in the commercial indices. In both cases the numbers at age 4 and age 5 changed, increasing the first one and decreasing the second. Age 3 decreased too, but in a less extent than age 5.

Catch-at-age

Catch-at-age is presented in Table 2. The range of ages in the catch goes from 1 to 8+. No catch-at-age was available for 2002-2005 due to the lack of length distribution information because of low catches. Figure 3A shows a bubble plot of catch proportions at age over time (with larger bubbles corresponding to larger values), indicating that the bulk of the catch is comprised of 3-5 years age cod, although in the last three years a shift to the oldest ages can be seen. Between years 2006 and 2014, in general the catches contain mostly age 3 and 4 individuals. In 2015 and 2017 age 6 was the most fished and in 2016 age 5, while in 2018 were ages 7 and 8+. These ages correspond to the strong cohorts of 2009-2011.

Figure 3B shows standardised catch proportions at age (each age standardised independently to have zero mean and standard deviation 1 over the range of years considered). Assuming that the selection pattern at age is not too variable over time, it should be possible to follow cohorts from such figure. Some strong and weak cohorts can be followed, although the pattern is not too evident. It is remarkable the catch over the recruitment in 2010-2012. In 2013, all the values for ages younger than 7 are negative except age 3, with a quite large positive value. In 2014 the biggest value is at age 4, being the values at ages 1-3 large and negative and at ages 5-8 very small. In 2015 ages 2-4 are negative and 6-8+ values quite large. In 2016, the first positive value is at age 5, and the values increase by age, being 8+ the largest in that year. In 2017 the first positive is at age 6, being 6-8+ values quite large. We can follow the cohort in 2018, being the first positive value at age 7. The consequence of the poor recruitments of the last 6 years can be seen in the failure of all the ages below 6 years old (included).

Mean weight-at-age

For 2018, mean weight-at-age has been computed using length-weight relationships from the commercial sampling. For this year, for the commercial case, there are four length-weight relationships available: EU-Estonia, EU-Portugal, EU-Spain and Faroes. All of them are presenting in Figure 4 besides the 2018 EU survey one. The EU survey relationship gives the highest weight for the higher lengths, while the Faroese one gives the highest for the younger lengths. The Portuguese relationship gives the smallest weight to the same length, and the behaviour is quite different as the rest. As the Portuguese relationship is a bit strange, the Estonian length-weight relationship was applied to the trawl commercial data to calculate the mean weight-at-age in the catch. The Faroese longliner is considered separated in order to get the total length distribution, but age distribution was obtained by applying the trawl EU survey ALK to the total length distribution.

Mean weight-at-age for 1988-2018 is showed in Table 3 and Figure 5. Since 2007 there is a general decrease in the trend of the mean-weight for the ages older than 2, especially since 2010. In 2018 a slight increase with regards 2017 can be seen in all ages until 6 years old (included). It is remarkable the decrease of the mean weight in ages 7 and 8.

An inconsistence was detected in the series of mean weights in catch, due to anomalously low weights at age 1 in 2013. It was replaced using the mean of the previous year and the following year and was incorporated to Table 3 in red.

The SoP (sum over ages of the product of catch weight-at-age and numbers at age) for the commercial catch differs 3% from the estimated total catch both in 2017 and 2018.

EU survey data

The EU bottom trawl survey on Flemish Cap has been carried out since 1988 using a *Lofoten* type gear, targeting the main commercial species down to 730 m of depth. The surveyed zone includes the complete distribution area for cod, which rarely occurs deeper than 500 m. The survey procedures have been kept constant throughout the entire period, although in 1989 and 1990 a different research vessel was used. Since 2003, the survey has been carried out with a new research vessel (R/V *Vizconde de Eza*, replacing R/V *Cornide de Saavedra*) and conversion factors to transform the values from the years before 2003 have been implemented (González-Troncoso and Casas, 2005). The results of the survey for the years 1988-2018 are presented in González-Troncoso *et al.* (2019).

The survey abundance indices besides the total biomass are presented in Table 4. Figure 6 displays the estimated biomass and abundance indices over time. Biomass and abundance show a high increase since 2005, higher in biomass than in abundance except for 2011, following an extremely low period starting in the mid 1990's. The large number in 2011 is due to a big presence of individuals of age 1. From 2009 biomass is higher than the level of the first years of the assessment (is approximately twice the mean of the EU series), but it must be noted that abundance in these years is roughly the same as the pre-collapse years (it is below the mean abundance of the EU entire series). In 2010 the biomass has suffered a slight decrease, probably due to the opening of the fishery, but a new huge increase can be seen in 2011 and 2012. The abundances in 2011-2012 are, by far, the highest of the time series of this survey. In 2013 a new decrease in abundance and biomass occurred, both reaching the level of 2009-2010. In 2014 the biomass increased again reaching the maximum of the time series by a long way. The abundance increased too but much less, being well below the maximum observed during years 2011-2012. The increase in biomass is due to a big increase in the number of individuals of 3 and 4 years old, those from the 2010-2011 cohorts, and the decrease in abundance to a less presence of individuals of ages 1 and 2 (González-Troncoso *et al.*, 2019). Since 2013, taking out the 2014 and 2015 values, the biomass has been quite stable, but a general decrease can be seen in abundance, due mainly to the fail of the recruitment.

Figure 7 shows a bubble plot of the abundances at age, in logarithmic scale, with each age standardised separately (each age to have mean 0 and standard deviation 1 over the range of survey years). Grey and black bubbles indicate values above and below average, respectively, with larger sized bubbles corresponding to larger magnitudes. The plot indicates that the survey is able to detect strength of recruitment and to track cohorts through time very well. It clearly shows a series of consecutive recruitment failures from 1996 to 2004, leading to very weak cohorts. Cohorts recruited from 2005 to 2014 appear to be above average. In 2010-2012 a good recruitment can be seen, especially in 2011, lead to two reasonably good cohorts. 2013 and 2014 recruitment were not as good as in those years, but it is still at the level of the beginning of the recovery of the stock. 2015-2018, especially 2016 recruitments, have failed. The 2015 cohort is the worst since the 2003 one. Age 8+ in 2014-2018 presented a high value, which indicates the strength of the 2006-2009 cohorts.

<u>Mean weight-at-age</u>

Results are showed in Table 5 and Figure 8. An inconsistence was detected in the series of mean weights in stock, due to anomalously low weights at age 1 in year 2004. It was replaced using the mean of the previous year and the following year and was incorporated to Table 5 in red. For 2017, length-weight relationship from the EU survey (Figure 4) was used to calculate the mean weight-at-age in stock.

Mean weight-at-age in the stock showed a strong increasing trend from the late 1990's until 2007, being much higher than at the beginning of the series. Since 2008 to 2017 a deceasing trend was observed for all age groups, being very steep in some cases. In those years the mean weights in stock for ages 1-7 decreased among 38% and 75% and all of them are among the minimum of the entire series. The biggest difference is from 2011 to 2012, when the weight-at-age for ages 1-2 increased, but decreased substantially for ages 3-8+. It is remarkable the low value of weight at age 3 (0.35 kg) in 2014, which is the lowest since 1990. In 2018 an increase with regards 2017 can be seen in all ages until 7 years old (included), being quite important in some of the ages, as age 3 (from 385 grams in 2017 to 656 gram in 2018). For age 8, a rather decrease occurs.

<u>Maturity at age</u>

Maturity ogives are available from the EU survey for years 1990-1998, 2001-2006 and 2008-2018. For those years a Bayesian logistic regression models for proportion mature at age with 1000 iterations have been fitted independently for each year. For 1988 and 1989 the 1990 maturity ogive was applied. For 1999 and 2000 maturity ogive was computed as a mixture of 1998 and 2001 data, and for 2007 as a mixed of 2006 and 2008 maturity ogive. Maturity data for 1991 were of poor quality and did not allow a good fit, so a mixture of the ogives for 1990 and 1992 was used.

Last year, the 2017 maturity ogive was not available due to different problems, so the 2016 one was applied to the 2017 data. This year, the actual 2017 maturity ogive is available, so it was applied to the data.

The median of the maturity ogives for the whole period are presented in Table 6 and Figure 9A. It can be seen that the percentage of matures in all ages decreased since 2006 to 2011, especially in 2011. This fact, along with the decreasing mean weight at age, is consistent with a stock in a recovery process, with a slower growth and maturing. In 2012 the percentage in ages 4 and 5 increased, as in all ages in 2013 (especially for ages 3 and 4). This is not consistent with the decrease in the mean weight for all ages. Maturity for all age groups declined sharply from 2013 to 2018, interrupted by an increase in 2017 for ages 5 and 6 and an increase in 2018 for age 4.

If we compare the maturity ogive applied last year for the 2017 data (the 2016 maturity at age), and the one applied this year (the 2017 maturity at age), we can see that there are some important differences, specially at ages 5 and 6. This fact could affect the results in SSB given last year.

Figure 9B displays the evolution of the a50 (age at which 50% of fish are mature) through the years (estimate and 90% uncertainty limits) and the median value is presented in Table 6. The figure shows a continuous decline of the a50 through time, from above 5 years old in the late 1980's to below 3 years old in 2002 and

2003. An upward trend is present in a50 since 2005. From 2005 to 2011 a50 increased monotonously from 3 to 4.13 years respectively and it declined in 2012 and again in 2013 to 3.39 years due to the increase in the percentage of maturation on all the ages. In 2014-2016 it increased substantially to 5.17 years old in 2016, around the maximum in the time series, being the 2017 almost the same despite the differences in the maturity at age.

Assessment methodology

A Bayesian SCAA model was applied to the data. Ages are from 1 to A+=8+ and years are from 1988 to 2018. The cohorts are modelled forwards in time, starting from the recruits (age 1) in each year and abundance of each age 2-8+ in the first assessment year, taking into account the natural and fishing mortality. The model equations are listed in Annex I. The model run was made in Jags called from R via the package rjags.

The input data, configuration and settings of this model were chosen during the 2018 benchmark on 3M cod (NAFO, 2018b). The natural mortality, M, is estimated by the model via a prior to be constant by year but variable through the ages.

Given the very low catch numbers observed at age 1 (Table 2), the catch at age 1 data was set equal to zero in all years and it was assumed in the model that F at age 1 is equal to zero. The zeros observed in the survey abundance indices at age and those observed in the catch at age matrix for ages > 1 are treated as NAs.

The inputs of the assessment of this year are as follow:

Catch data for 31 years, from 1988 to 2018

Catch in tonnes in all years; Years with catch-at-age: 1988-2001, 2006-2018

Tuning with EU survey for 1988 to 2018

Ages from 1 to 8+ in all cases (catch-at-age and survey indices at age)

Catchability analysis

Survey catchability dependent on stock size for age 1

Priors over parameters: See Annex I to know the details. The values used in the priors are:

Recruitment: *medrec* = 45000, *cvrev* = 10

N in the first assessment year: *medF*[a] = c(0.0001,0.1,0.5,0.7,0.7,0.7,0.7,0.7), cvyear1 = 10

f: *medf* = 0.2, *cvf* = 4

rC: *aref* = 5, *medrC*[a] = c(0.001,0.3,0.6,0.9,1,1,1), *cvrC*[a] = c(4,4,4,4,4,4,4), *cvrCcond*=0.2

Catch in tonnes: *cvCW* = 0.077 (95% probability of no more than 15% deviation)

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

Survey index: *psi.EU* corresponds to CV=0.3 on abundance index at age (in original, not log-scale)

Survey catchability: *medlogphi* = 0, *taulogphi* = 1/5

Survey catchability exponent at age 1: *medgama* = 1, *taugama* = 1/0.25

M: *medM*[a]= c(1.26,0.65,0.44,0.35,0.30,0.27,0.24,0.24), *cvM* = 0.15

A five year retrospective plot was made. Five years projections were made with three different scenarios, as later described, in order to see the possible evolution of the stock. The settings and the results are explained above.

Results

Assessment results regarding total biomass, SSB, recruitment and F_{bar} (ages 3-5) are presented in Table 7 and Figure 10. SSB in 2019 was calculated using the numbers estimated by the assessment at the beginning of 2019, applying the maturity ogive and mean weight at age in stock from 2018.

Total biomass had a sharp increasing trend during 2006-2012, reaching a higher level than before the collapse of the stock in the mid 1990´s. After 2012, a decreasing trend can be observed, and in 2018 the biomass is hardly above the level at the beginning of the series.

The results for SSB indicate that there has been a substantial increase in SSB in the last few years, with the largest increase occurring from 2007 onwards. After a small decrease in 2011 and 2012, the SSB between 2013 and 2018 was stable. A substantial decrease in the 2019 point is displayed, although the SSB is still at the highest level of the historical series (starting in 1988). The high values of SSB in the last years are probably due to the incorporation of the strong 2009-2011 year classes which leads in a higher number of individuals.

Recruitment had an increasing trend from 2005 to 2012, being above the mean recruitment of the period between 2007 and 2012. The 2010-2012 values are the highest of the series. Since 2012 the recruitment has been decreased substantially and in 2016 is among the lowest of the series.

F_{bar} (mean for ages 3-5) was estimated at very low levels in the period 2001-2009. In 2010, when the fishery was reopened, the F_{bar} increased although it did not reach the level of the pre-collapse years. Since then fishing mortalities has slightly decreased and they are well below the values of the pre-collapse period. Table 8 and Figure 11 provide more detailed information on the estimated F-at-age values. Since 2010 the F-at-age increases for all the ages, and with the age. Figure 12 shows the PR along the years, calculated as the ratio of fishing mortalities to F_{bar}. Figure 13A shows the PR for the years since the reopening of the fishery (2010-2018) and Figure 13B the mean of the three last years (2016-2018) PR *versus* the 2018 PR. In general, except 2010 and 2018 PRs, all the years have a similar and increasing PR. In the case of the 2018 PR, age 6 was the most caught age, and after ages 7 and 8+. The mean PRs of the last three years is slightly different to the 2018 one, disagreeing in the last two ages.

The results for the two components of F, the year effect (*f*) and the selectivity by year and age (*rC*), are presented in Figure 14. It can be seen a clear different level of *f* before and after year 2000. In the case of *rC*, for age 1 was set as 0, the age of reference is 5 and for age 8+ is the same as for age 7. During the period on which the fishery was closed (1999-2009) *rC* of ages 2 and 3 increased to high levels probably because the catches came from by catches of other fisheries. Age 4 shows a decreasing trend until 2009, being stable since then, while for ages 6 and 7 an increasing trend can be observed (with a decrease in the last three years).

Figure 15 shows total biomass and abundance by year. In general, there is a good concordance between biomass and abundance, although in last years abundance has decreased in a more extent than biomass. It must be noted that, although SSB in last years has been stable (Figure 10), total biomass and abundance have been decreased since 2011-2012. Total biomass is at the highest levels of the total period biomass, but abundance is below the mean.

Estimates of stock abundance at age for 1988-2018 are presented in Table 9 and Figure 16. It can be seen a general increasing trend in the total number of matures, especially in 2013, due probably to the decreasing in the age of maturity. Since then it has decreased. The maximum numbers-at-age since 2005 in all the ages correspond to the 2010 cohort (reaching 7 years old in 2017 and being incorporated to the 8+ group in 2018), followed by the 2011 cohort (reaching 7 years old in 2018). Since those cohorts, all the numbers at age have decreased (ages 1 to 6). It is remarkable the big value of ages 6+ in the last years, which is the driver to the huge increase in the SSB in those years. But as no new good recruitment is entering in the stock, it is feasible that the SSB starts to decrease in the next years.

Figure 17 depicts the prior and posterior distributions of the recruitment in all the years. Although in some years there has been substantial updating on the prior distribution for recruitment, in general the posterior is among the prior distribution.

Figure 18 displays prior and posterior distributions for the numbers in the first year (1988) for ages 2 to 8+. Whereas the prior distribution is the same every year, posterior distributions vary depending on the year. For all the ages, the update posterior numbers is to higher values than the prior median.

In Figure 19 observed versus estimated total catches by year are presented. Before 2001 the discrepancies seem to be more variable than after that year. No clear patterns can be observed in the whole period.

Figure 20 shows the prior and the posterior distributions of the natural mortality, M, by age. The prior and posterior medians can be seen in Table 10. For ages 1 and 6+, the posterior median of M is higher than the prior median. Overall, the priors on M are not much updated by the posteriors for any of the ages; this is as intended by the Benchmark, who considered the stock assessment has little ability to estimate M and decided to use a relatively tight prior distribution (CV=15%) around median values of M derived from biological considerations, including multi-species interactions. This has resulted in much higher values of M than estimated in the XSA assessments prior to 2017 (where the posterior median of M did not exceed 0.2). A higher M can be expected to result in the stock abundance changing more rapidly from year to year, because it generally results in higher estimates of recruitment but, at the same time, the fish disappear more quickly from the population ("killed by M") than with a lower M.

Bubble plot of standardised residuals (observed minus fitted values divided by estimated standard deviations and in logarithmic scale) for the catch number-at-age and the EU survey abundance at age indices are displayed in Figure 21. This graph should highlight year effects, identified as years in which most of the residuals are above or below zero. No clear trends can be seen in the graphs. In general, the residuals are quite high both in the catch numbers at age and in the EU survey indices. In the case of the EU survey indices, in year 2004 all the residuals are negative, i.e. survey catchabilities are below average.

Figure 22 illustrates the distribution of the catchabilities for the EU survey by group of ages (1, 2, 3, 4+). The catchability at age 1 is very low. Age 2 catchability is lower than age 3 catchability, which is quite similar to the catchabilities of ages 4+.

Biological Referent Points

Last year the assessment results were used to estimate the limit reference points, both for the SSB and for the F.

The stock-recruit scatter plot was visually examined in June 2018 to find an SSB below which no good recruitments have been observed (Figure 23). This SSB (20 000 t) was set last year as B_{lim}. During the January 2019 June meeting regarding the 3M cod MSE, the meeting agreed to use the 2007 SSB as B_{lim}, as this is the highest SSB value of the three years (2005-2007) in which good recruitment leading to stock recovery was observed in the past. The highest value, rather than the mean of the three, was chosen to give a degree of security.

In this way, for the present assessment 1000 values of B_{lim}, one for each iteration, are considered, with a median value of 15 142 tons, and a 90% confidence interval between 13 196 and 18 406 tons (Table 7). This value is displayed in Figure 23, showing that this value is rather consistent. SSB is well above B_{lim} in recent years.

Figure 24 shows the SSB-F_{bar} scatter plot. F_{lim} for this stock was estimated based on $F_{30\%SPR}$ calculated with the 2016-2018 data as 0.167. This period was chosen due to the rapid change in biological parameters in the stock.

Figure 26 shows the Yield per Recruit versus F_{bar} curve calculated with the data of years 2016-2018 as well as the value of F_{lim} and $F_{statusquo}$ (defining the latter as the mean fishing mortality over 2016-2018).

Retrospective pattern

A retrospective analysis of five years was made (Figure 25). The analysis shows revisions in the recruitment, mainly regarding the highest values of recruitment in years 2011 and 2012, but no patterns are evident in recent years. The downwards revision of these two recruitment estimates results in a tendency to over-estimate total biomass and SSB in recent years. No retrospective pattern is evident in the F estimates.

Recruits per Spawner

Figure 27 displays the Recruits per Spawner. The variability over the years of the assessment is very high. Since 2007 a decreasing trend can be seen, reaching since 2013 very low values.

Projections

The same method as last year was used to calculate the projections and the risk. To know more details about the projection method, see Fernández *et al.* (2017). Stochastic projections of the stock dynamics from 2019 to 2023 were conducted. The variability in the input data is taken from the results of the Bayesian assessment. Input data for the projections are as follows:

Numbers aged 2 to 8+ in 2019: estimated from the assessment.

Recruitments for 2019-2023: Recruits per spawner were drawn randomly from 2015-2017. The 2018 value of recruits per spawner was omitted due to uncertainty in estimating the recruitment.

Maturity ogive for 2019-2023: 2018 maturity ogive.

Natural mortality for 2019-2023: Natural mortality from the 2018 assessment results.

Weight-at-age in stock and weight-at-age in catch for 2019-2023: 2018 weight-at-age.

PR at age for 2019-2023: Mean of the last three years (2016-2018) PRs.

F_{bar}(ages 3-5): Four scenarios were considered:
(*Scenario 1*) $F_{bar}=F_{lim}$ (median value = 0.167).
(*Scenario 2*) $F_{bar}=3/4F_{lim}$ (median value = 0.125).
(*Scenario 3*) $F_{bar}=F_{statusquo}$ (median value = 0.079).
(*Scenario 4*) $F_{bar}=0$ (no catch).

All scenarios assumed that the Yield for 2019 is the established TAC (17 500 t). $F_{statusquo}$ was established as the mean fishing mortality over 2016-2018.

Results for the four options are presented in Tables 11-18 and Figure 28. They indicate that under all scenarios total biomass and SSB during the projected years will decrease sharply. The probability of SSB being below B_{lim} in 2020 is very low (<1%) in all cases. For $F_{2016-2018}$, ¾F_{lim} and F=0 the probability of SSB being below B_{lim} in 2021 is very low (≤1%). However, the probability of being below B_{lim} is 5% if F = F_{lim}. And in 2022, in all the cases except F=0 the probability of being below B_{lim} is more than the acceptable risk of 10%, which implies that the stock would be in moratorium. The probability of SSB in 2022 being above the SSB in 2019 is <1%.

Under ¾F_{lim} and$F_{2016-2018}$, the probability of F exceeding F_{lim} is less than 20% for all the projected years.

Under all scenarios, the projected Yield decreases sharply in 2020 relative to the Yield in 2019.

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Table 1. Total commercial cod catch in Division 3M. Reported nominal catches since 1960 and estimated total catch from 1988 to 2018 in tons.

Year	Estimated[2]	Portugal	Russia	Spain	France	Faroes	UK	Poland	Norway	Germany	Cuba	Others	Total[1]
1960		9	11595	607					46	86		10	12353
1961		2155	12379	851	2626		600	336		1394		0	20341
1962		2032	11282	1234			93	888	25	4		349	15907
1963		7028	8528	4005	9501		2476	1875				0	33413
1964		3668	26643	862	3966		2185	718	660	83		12	38797
1965		1480	37047	1530	2039		6104	5073	11	313		458	54055
1966		7336	5138	4268	4603		7259	93		259		0	28956
1967		10728	5886	3012	6757		5732	4152		756		46	37069
1968		10917	3872	4045	13321		1466	71				458	34150
1969		7276	283	2681	11831					20		52	22143
1970		9847	494	1324	6239		3	53				35	17995
1971		7272	5536	1063	9006			19		1628		25	24549
1972		32052	5030	5020	2693	6902	4126	35	261	506		187	56812
1973		11129	1145	620	132	7754	1183	481	417	21		18	22900
1974		10015	5998	2619		1872	3093	700	383	195		63	24938
1975		10430	5446	2022		3288	265	677	111	28		108	22375
1976		10120	4831	2502	229	2139		898	1188	225		134	22266
1977		6652	2982	1315	5827	5664	1269	843	867	45	1002	553	27019
1978		10157	3779	2510	5096	7922	207	615	1584	410	562	289	33131
1979		9636	4743	4907	1525	7484		5	1310		24	76	29710
1980		3615	1056	706	301	3248		33	1080	355	1	62	10457
1981		3727	927	4100	79	3874			1154			12	13873
1982		3316	1262	4513	119	3121	33		375			14	12753
1983		2930	1264	4407		1489			111	3		1	10205
1984		3474	910	4745		3058			47	454	5	9	12702
1985		4376	1271	4914		2266			405	429	9	5	13675
1986		6350	1231	4384		2192				345	3	13	14518
1987		2802	706	3639	2300	916						269	10632
1988	28899	421	39	141		1100					3	14	1718
1989	48373	170	10	378								359	917
1990	40827	551	22	87		1262						840	2762
1991	16229	2838	1	1416		2472	26		897		5	1334	8989
1992	25089	2201	1	4215		747	5				6	51	7226
1993	15958	3132	0	2249		2931						4	8316
1994	29916	2590	0	1952		2249			1			93	6885
1995	10372	1641	0	564		1016						0	3221
1996	2601	1284	0	176		700	129			16		0	2305
1997	2933	1433	0	1			23					0	1457
1998	705	456	0									0	456
1999	353	2	0									0	2
2000	55	30	6									0	36
2001	37	56	0									0	56
2002	33	32	1									0	33
2003	16	7	0									9	16
2004	5	18	2									3	23
2005	19	16	0			7						3	26
2006	339	51	1	16								55	123
2007	345	58	6	33								28	125
2008	889	219	74	42	3	0						63	401
2009	1161	856	87	85		22						122	1172
2010	9291	1345	374	921		1183	761		514			147	5245
2011	12836	2412	655	1610	200	2211	1063		1301		185	340	9977
2012	12836	2593	745	1597	131	2045	868		809		172	108	9068
2013	13985	4427	896	2380		2723	1328		1322			445	13521
2014	14290	5345	950	2099		3370		393	1344			855	14356
2015	13785	4680	893	1999		3319			1296			641	12828
2016	14023	5484	893			3124	1198		1336			72	12107
2017	13928	5245	900	900		3165	1148		1240			1322	13920
2018	11481	4690	705			2972			1043			1040	10450

[1] Recalculated from NAFO Statistical data base using the NAFO 21A Extraction Tool
[2]STACFIS estimates

Table 2. Catch-at-age (thousands).

	1	2	3	4	5	6	7	8+
1988	1	3500	25593	11161	1399	414	315	162
1989	0	52	15399	23233	9373	943	220	205
1990	7	254	2180	15740	10824	2286	378	117
1991	1	561	5196	1960	3151	1688	368	76
1992	0	15517	10180	4865	3399	2483	1106	472
1993	0	2657	14530	3547	931	284	426	213
1994	0	1358	28303	9218	430	206	16	203
1995	0	0	192	4773	2003	474	98	169
1996	0	81	714	311	1072	88	0	0
1997	0	0	1016	956	179	359	60	0
1998	0	0	8	170	286	30	19	2
1999	0	0	15	15	96	60	3	1
2000	0	0	54	1	1	4	1	0
2001	0	9	0	4	2	0	2	2
2002								
2003								
2004								
2005								
2006	0	22	19	81	2	10	2	0
2007	0	2	30	1	27	1	14	5
2008	1	89	136	133	3	40	1	3
2009	0	23	51	210	108	0	32	7
2010	34	452	1145	1498	808	388	4	103
2011	18	537	1608	701	1144	961	354	275
2012	39	389	1443	834	1013	739	357	344
2013	22	646	4169	962	1124	755	521	388
2014	7	13	730	4131	1464	871	556	405
2015	0	94	402	1548	1457	2596	602	480
2016	0	40	883	731	1822	1167	939	757
2017	1	2	73	407	256	1954	1553	961
2018	0	77	33	206	800	408	1392	1357

Table 3. Weight-at-age (kg) in catch. In red, the 2013 replaced value.

	1	2	3	4	5	6	7	8+
1988	0.058	0.198	0.442	0.821	2.190	3.386	5.274	7.969
1989	0.069	0.209	0.576	0.918	1.434	2.293	4.721	7.648
1990	0.080	0.153	0.500	0.890	1.606	2.518	3.554	7.166
1991	0.118	0.229	0.496	0.785	1.738	2.622	3.474	6.818
1992	0.115	0.298	0.414	0.592	1.093	1.704	2.619	3.865
1993	0.115	0.210	0.509	0.894	1.829	2.233	3.367	4.841
1994	0.112	0.248	0.649	0.973	1.686	2.331	3.008	4.898
1995	0.112	0.248	0.649	0.973	1.686	2.331	3.008	4.898
1996	0.110	0.286	0.789	1.051	1.543	2.429	2.730	4.653
1997	0.107	0.360	0.754	1.038	1.506	2.115	2.451	4.408
1998	0.098	0.472	0.719	1.024	1.468	1.800	2.252	3.862
1999	0.098	0.472	0.920	1.298	1.848	2.436	3.513	4.893
2000	0.098	0.583	0.672	1.749	2.054	2.836	3.618	5.055
2001	0.098	0.481	0.998	1.696	2.560	3.303	3.905	5.217
2002	0.098	0.588	1.323	1.388	2.572	3.770	5.158	5.603
2003	0.098	0.462	1.063	1.455	2.978	3.696	5.859	6.120
2004	0.098	0.839	1.677	2.009	3.353	5.576	6.241	8.273
2005	0.098	0.895	1.618	2.368	3.259	4.767	6.177	6.553
2006	0.098	1.081	1.462	2.283	3.966	5.035	6.332	7.997
2007	0.098	0.974	1.858	3.388	4.062	6.128	6.809	9.440
2008	0.088	0.448	1.364	3.037	3.498	5.248	6.643	8.251
2009	0.172	0.507	1.026	2.087	3.727	4.810	5.900	9.534
2010	0.162	0.700	1.279	1.829	2.764	4.372	4.199	8.575
2011	0.086	0.396	0.939	1.522	2.228	3.560	5.980	8.753
2012	0.086	0.374	0.990	1.491	2.136	3.583	6.183	9.183
2013	0.097	0.284	0.762	1.305	2.112	2.990	4.530	8.564
2014	0.108	0.203	0.538	1.108	1.809	2.874	4.087	7.671
2015	0.085	0.261	0.531	0.857	1.370	1.938	3.570	6.252
2016	0.082	0.191	0.550	0.787	1.237	2.157	3.439	6.719
2017	0.078	0.192	0.399	0.813	1.348	1.949	2.784	5.080
2018	0.078	0.313	0.561	0.942	1.571	1.974	2.550	4.166

Table 4. EU bottom trawl survey abundance at age and total (thousands) and total biomass (tons).

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	Total Abundance	Total Biomass
1988	4868	79905	49496	13448	1457	211	225	72	0	0	0	0	0	0	0	0	0	149683	40839
1989	19604	10800	91303	54613	20424	1336	143	126	6	7	0	0	0	0	0	0	0	198363	114050
1990	2303	12348	5121	16952	15834	4492	340	146	77	25	0	0	0	0	0	0	0	57637	59362
1991	129032	26220	16903	2125	6757	1731	299	68	32	4	10	0	0	0	0	0	0	183181	40248
1992	71533	41923	5578	2385	385	1398	244	14	0	0	8	0	0	0	0	0	0	123468	26719
1993	4075	138357	31096	1099	1317	173	489	87	0	0	0	0	0	0	0	0	0	176693	60963
1994	3017	4130	27756	5097	130	67	7	111	0	5	0	0	0	0	0	0	0	40319	26463
1995	1425	11901	1338	3892	928	33	23	0	21	5	0	0	0	0	0	0	0	19567	9695
1996	36	3121	6659	892	2407	192	8	5	0	0	0	0	0	0	0	0	0	13320	9013
1997	37	150	3478	4803	391	952	21	0	0	0	0	4	0	0	0	0	0	9837	9966
1998	23	83	95	1256	1572	78	146	0	6	0	0	0	0	0	0	0	0	3259	4986
1999	5	84	116	117	717	444	19	5	0	0	0	0	0	0	0	0	0	1507	2854
2000	178	16	327	198	96	446	172	11	17	0	0	5	0	5	0	0	0	1470	3062
2001	473	1990	13	122	79	15	142	99	6	6	6	0	0	0	0	0	0	2951	2695
2002	0	1330	641	29	70	33	26	96	30	0	5	0	0	0	0	0	0	2261	2496
2003	684	54	628	134	22	42	7	8	39	24	0	0	0	0	0	0	0	1642	1593
2004	14	3380	25	600	168	5	10	3	5	15	0	0	0	0	0	0	0	4226	4071

2005	8069	16	1118	78	709	136		17	16	8	0	0	0	0	0	0	0	10166	5242
2006	19709	3886	62	1481	85	592	115	7	0	7	14	0	7	0	0	0	0	25965	12505
2007	3917	11620	5022	21	1138	58	425	74	13	20	0	0	0	0	0	0	0	22308	23886
2008	6096	16671	12433	4530	72	946	56	231	76	0	14	0	0	0	0	0	0	41124	43676
2009	5139	7479	16150	14310	4154	26	1091	0	335	0	0	14	0	0	0	0	0	48697	75228
2010	66370	27689	8654	7633	4911	1780	8	442	46	251	26	0	0	0	0	0	0	117810	69295
2011	347674	142999	16993	6309	7739	3089	1191	0	215	0	89	0	0	0	0	0	0	526300	106151
2012	103494	128087	10942	11721	4967	4781	1630	832	24	93	30	101	0	17	0	0	0	266720	113227
2013	5525	67521	32339	4776	4185	2782	1807	963	278	40	29	32	5	0	0	0	0	120280	72289
2014	7282	2372	48564	43168	17861	6842	3447	1931	1551	600	79	54	8	0	0	0	0	133760	159939
2015	1141	12952	7250	25614	14107	21854	3434	1426	762	366	194	14	21	21	0	7	0	89164	114807
2016	56	4485	14356	2230	14540	12375	4814	1157	522	303	145	28	20	0	0	0	0	55032	80583
2017	2010	314	6516	16645	3267	15842	8519	2765	789	345	137	53	27	6	7	0	0	57241	89414
2018	366	4308	309	6082	12996	3447	7090	3933	1046	306	165	59	10	0		11	8	40139	75795

Table 5. Weight-at-age (kg) in stock. In red, the 2004 replaced value.

	1	2	3	4	5	6	7	8+
1988	0.032	0.106	0.308	0.664	1.970	3.500	5.742	6.954
1989	0.036	0.101	0.330	0.836	1.293	2.118	4.199	7.360
1990	0.043	0.181	0.354	0.868	1.566	2.507	4.132	6.572
1991	0.056	0.171	0.501	0.865	1.594	2.593	3.423	6.182
1992	0.056	0.247	0.485	1.394	1.723	2.578	3.068	9.406
1993	0.043	0.227	0.657	1.216	2.279	2.381	3.373	5.731
1994	0.063	0.214	0.599	1.321	2.132	4.054	4.119	6.555
1995	0.048	0.243	0.479	0.969	1.851	2.680	5.532	7.309
1996	0.044	0.260	0.544	0.813	1.331	2.252	4.079	5.118
1997	0.081	0.333	0.652	1.020	1.327	2.092	1.997	9.717
1998	0.073	0.371	0.773	1.206	1.684	2.015	3.070	7.525
1999	0.108	0.398	0.946	1.329	1.866	2.444	3.461	4.987
2000	0.106	0.606	0.971	1.638	1.940	2.860	3.461	7.985
2001	0.084	0.493	1.281	1.724	2.588	3.488	3.893	5.137
2002	0.071	0.440	1.191	1.540	2.661	3.916	5.302	5.672
2003	0.058	0.337	0.926	1.566	3.047	3.769	5.721	6.451
2004	0.071	0.620	1.488	2.098	3.332	4.808	6.207	7.886
2005	0.084	0.580	1.256	2.242	2.875	4.187	6.033	8.148
2006	0.096	0.720	1.096	2.549	3.644	4.777	5.858	9.691
2007	0.053	0.609	1.640	3.478	4.097	5.787	6.373	8.315
2008	0.068	0.382	1.344	2.695	3.191	5.015	6.324	7.938
2009	0.078	0.407	0.976	2.072	3.881	6.958	6.583	9.461
2010	0.061	0.384	1.089	1.677	2.956	5.379	7.616	9.144
2011	0.038	0.211	0.913	1.618	2.339	3.594	6.050	9.396
2012	0.074	0.369	0.726	1.349	1.988	2.656	4.933	7.812
2013	0.071	0.175	0.687	1.159	2.004	2.750	4.206	7.614
2014	0.048	0.169	0.354	1.059	1.623	2.536	3.846	8.444
2015	0.049	0.156	0.469	0.747	1.216	1.847	3.434	6.775
2016	0.044	0.169	0.412	0.783	1.304	2.024	2.883	6.905
2017	0.044	0.205	0.385	0.709	1.204	1.831	2.573	5.111
2018	0.049	0.277	0.656	0.981	1.497	1.937	2.646	4.493

Table 6. Maturity at age and age of first maturation (median values of ogives).

	1	2	3	4	5	6	7	8+	a50
1988	0.054	0.099	0.175	0.292	0.440	0.601	0.743	0.879	5.37
1989	0.054	0.099	0.175	0.292	0.440	0.601	0.743	0.879	5.37
1990	0.054	0.099	0.175	0.292	0.440	0.601	0.743	0.879	5.37
1991	0.015	0.041	0.107	0.242	0.464	0.704	0.882	0.969	5.15
1992	0.002	0.011	0.046	0.181	0.500	0.819	0.953	0.993	5.00
1993	0.001	0.006	0.048	0.282	0.750	0.958	0.994	1.000	4.47
1994	0.000	0.001	0.049	0.658	0.986	1.000	1.000	1.000	3.82
1995	0.000	0.000	0.006	0.803	1.000	1.000	1.000	1.000	3.79
1996	0.000	0.000	0.030	0.670	0.993	1.000	1.000	1.000	3.84
1997	0.000	0.007	0.109	0.670	0.971	0.998	1.000	1.000	3.75
1998	0.000	0.002	0.097	0.873	0.998	1.000	1.000	1.000	3.55
1999	0.000	0.001	0.125	0.899	0.999	1.000	1.000	1.000	3.47
2000	0.000	0.001	0.162	0.970	1.000	1.000	1.000	1.000	3.39
2001	0.000	0.001	0.280	0.997	1.000	1.000	1.000	1.000	3.14
2002	0.000	0.010	0.634	0.997	1.000	1.000	1.000	1.000	2.89
2003	0.001	0.023	0.513	0.979	1.000	1.000	1.000	1.000	2.99
2004	0.000	0.000	0.102	0.967	1.000	1.000	1.000	1.000	3.39
2005	0.038	0.165	0.503	0.833	0.961	0.992	0.998	1.000	2.99
2006	0.000	0.013	0.362	0.960	0.999	1.000	1.000	1.000	3.15
2007	0.000	0.012	0.262	0.921	0.997	1.000	1.000	1.000	3.31
2008	0.000	0.011	0.230	0.883	0.995	1.000	1.000	1.000	3.37
2009	0.000	0.010	0.180	0.830	0.991	1.000	1.000	1.000	3.49
2010	0.000	0.009	0.166	0.811	0.989	0.999	1.000	1.000	3.53
2011	0.001	0.008	0.072	0.429	0.878	0.986	0.999	1.000	4.13
2012	0.000	0.000	0.018	0.579	0.991	1.000	1.000	1.000	3.93
2013	0.004	0.036	0.284	0.805	0.978	0.998	1.000	1.000	3.40
2014	0.000	0.003	0.046	0.400	0.902	0.992	0.999	1.000	4.16
2015	0.000	0.000	0.004	0.115	0.789	0.991	1.000	1.000	4.61
2016	0.000	0.000	0.004	0.047	0.392	0.895	0.991	1.000	5.17
2017	0.000	0.000	0.000	0.018	0.836	0.999	1.000	1.000	5.17
2018	0.000	0.001	0.008	0.070	0.427	0.878	0.986	0.999	5.13

Table 7. Posterior results: total biomass, SSB, recruitment (tons) and F_{bar}.

	B quantiles			SSB quantiles			R quantiles			F_{bar} quantiles		
Year	**50%**	**5%**	**95%**	**50%**	**5%**	**95%**	**50%**	**5%**	**95%**	**50%**	**5%**	**95%**
1988	86902	80678	93382	23666	18853	29950	67446	47096	95957	0.517	0.463	0.575
1989	97570	91361	104455	29813	23820	36846	132545	93487	191691	0.623	0.565	0.683
1990	89092	83395	95295	32807	27652	38291	117320	82402	169869	0.731	0.669	0.803
1991	76484	68211	86145	25059	21186	29322	404298	285289	576993	0.436	0.382	0.486
1992	89824	80763	99813	25592	22305	29142	326156	233844	467256	1.395	1.279	1.513
1993	62341	57246	68262	10434	9035	12221	21926	15546	31025	0.958	0.872	1.051
1994	54668	50408	59510	21341	18165	24768	40543	28803	57357	1.360	1.265	1.466
1995	19878	18462	21626	13591	12251	15038	17031	12300	24566	1.296	1.199	1.402
1996	7346	6841	7939	3628	3239	4057	1062	738	1506	0.474	0.422	0.533
1997	6214	5751	6682	3996	3579	4418	924	643	1331	0.923	0.831	1.019
1998	3045	2763	3408	2627	2372	2965	1562	1087	2253	0.326	0.279	0.379
1999	2442	2143	2819	2169	1888	2532	232	157	342	0.211	0.174	0.251
2000	2757	2392	3204	2112	1798	2504	4334	3021	6216	0.064	0.052	0.08
2001	3542	3045	4119	2112	1823	2463	10217	7054	14731	0.075	0.056	0.101
2002	3812	3337	4354	2409	2110	2739	980	681	1469	0.020	0.017	0.025
2003	5106	4435	5964	2866	2522	3230	26515	18910	38181	0.006	0.005	0.007
2004	8649	7607	9969	4305	3829	4826	809	574	1170	0.002	0.001	0.002
2005	13675	11913	16260	6559	5706	7603	58869	42047	85230	0.002	0.002	0.003
2006	30564	26340	36552	10629	9514	11963	95417	68379	139416	0.054	0.045	0.064
2007	45284	40083	52119	15142	13196	18406	128971	92123	187783	0.015	0.012	0.017
2008	61053	54826	68407	26443	23831	29389	115991	80689	166278	0.028	0.024	0.032
2009	82569	74766	92384	41449	37516	45881	166063	117619	235603	0.021	0.018	0.024
2010	111069	101008	124226	60238	54475	66960	290981	208503	420597	0.127	0.109	0.146
2011	115672	104799	129163	52772	47620	58662	476734	342681	671711	0.135	0.117	0.158
2012	162271	143172	185947	55772	50144	62016	385242	272530	557927	0.091	0.077	0.108
2013	148019	133038	163163	91066	81592	101297	58652	41542	84990	0.090	0.077	0.105
2014	143769	129430	158901	89049	79375	100350	131277	92561	188666	0.067	0.057	0.08
2015	124134	111200	138049	84181	74666	95226	33585	23367	49265	0.075	0.063	0.087
2016	129004	114547	144762	93437	81968	106553	2803	1911	4232	0.082	0.068	0.098
2017	108198	95039	122864	95829	83626	110459	37549	24526	56768	0.056	0.047	0.068
2018	98246	85974	112251	84248	72609	97584	8357	5070	13891	0.097	0.078	0.119

Table 8. F at age (posterior median).

				F at age				
Year	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8+**
1988	0.000	0.018	0.332	0.583	0.635	0.654	0.782	0.782
1989	0.000	0.011	0.353	0.787	0.722	0.791	0.860	0.860
1990	0.000	0.018	0.379	0.906	0.910	1.227	1.037	1.037
1991	0.000	0.023	0.292	0.471	0.536	0.566	0.665	0.665
1992	0.000	0.141	0.968	1.461	1.755	1.440	1.961	1.961
1993	0.000	0.083	0.664	1.125	1.080	1.535	0.859	0.859
1994	0.000	0.186	0.978	1.744	1.370	1.345	0.991	0.991
1995	0.000	0.178	0.532	1.485	1.865	2.306	2.158	2.158
1996	0.000	0.046	0.239	0.488	0.691	0.906	0.823	0.823
1997	0.000	0.109	0.559	0.839	1.360	2.049	1.842	1.842
1998	0.000	0.042	0.192	0.319	0.463	0.548	0.397	0.397
1999	0.000	0.024	0.225	0.178	0.227	0.230	0.082	0.082
2000	0.000	0.005	0.123	0.026	0.042	0.032	0.010	0.010
2001	0.000	0.007	0.134	0.036	0.053	0.040	0.013	0.013
2002	0.000	0.002	0.034	0.011	0.016	0.012	0.004	0.004
2003	0.000	0.000	0.010	0.004	0.005	0.004	0.002	0.002
2004	0.000	0.000	0.003	0.001	0.002	0.001	0.001	0.001
2005	0.000	0.000	0.003	0.001	0.002	0.001	0.001	0.001
2006	0.000	0.002	0.075	0.039	0.046	0.032	0.028	0.028
2007	0.000	0.000	0.010	0.015	0.018	0.017	0.023	0.023
2008	0.000	0.002	0.014	0.030	0.039	0.036	0.029	0.029
2009	0.000	0.001	0.008	0.025	0.029	0.030	0.032	0.032
2010	0.000	0.010	0.068	0.129	0.181	0.193	0.209	0.209
2011	0.000	0.010	0.086	0.111	0.210	0.277	0.369	0.369
2012	0.000	0.006	0.057	0.075	0.140	0.198	0.287	0.287
2013	0.000	0.006	0.061	0.073	0.135	0.205	0.276	0.276
2014	0.000	0.003	0.032	0.081	0.089	0.163	0.221	0.221
2015	0.000	0.004	0.048	0.078	0.098	0.184	0.218	0.218
2016	0.000	0.005	0.050	0.096	0.098	0.130	0.205	0.205
2017	0.000	0.005	0.034	0.056	0.077	0.133	0.173	0.173
2018	0.000	0.009	0.078	0.085	0.124	0.211	0.182	0.182

Table 9. N at age (posterior median), with the total number and number of matures (posterior median) by year.

	N at age									
Year	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8+**	**Total**	**Matures**
1988	67446	146949	98701	30827	4351	951	698	283	350206	47614
1989	132545	16406	76909	48688	13153	1752	344	321	290119	43920
1990	117320	32178	8640	37465	16956	4855	554	198	218168	32837
1991	404298	28502	16913	4078	11578	5168	988	190	471714	19475
1992	326156	98124	14910	8693	1946	5138	2037	437	457441	11634
1993	21926	80072	45718	3920	1537	255	847	247	154522	6323
1994	40543	5330	39186	16203	966	395	38	331	102993	14199
1995	17031	9896	2340	10221	2175	186	72	94	42015	10727
1996	1062	4146	4372	953	1771	253	13	13	12582	2791
1997	924	258	2102	2391	444	674	71	8	6872	3010
1998	1562	226	123	830	785	86	60	9	3682	1670
1999	232	381	115	70	459	374	35	34	1699	979
2000	4334	57	197	63	45	277	208	44	5225	666
2001	10217	1056	30	121	47	33	188	180	11871	575
2002	980	2479	554	18	89	34	22	256	4432	795
2003	26515	239	1325	372	14	66	23	189	28744	1348
2004	809	6502	128	906	284	10	46	146	8831	1375
2005	58869	196	3470	88	690	214	7	133	63668	5165
2006	95417	14368	105	2390	67	522	150	96	113115	3382
2007	128971	23469	7642	67	1764	49	353	170	162486	4803
2008	115991	31678	12524	5252	51	1314	33	364	167208	9679
2009	166063	28405	16869	8548	3897	37	885	265	224969	15493
2010	290981	40486	15070	11546	6371	2883	25	797	368160	22285
2011	476734	70965	21393	9668	7768	4016	1660	455	592658	19474
2012	385242	116913	37668	13512	6621	4772	2133	1044	567905	23019
2013	58652	94261	62019	24551	9587	4359	2728	1698	257855	58897
2014	131277	14338	49959	40171	17531	6352	2496	2374	264499	45168
2015	33585	32088	7619	33501	28261	12096	3778	2739	153666	44702
2016	2803	8231	17028	5026	23703	19532	7022	3714	87059	37682
2017	37549	676	4318	11202	3489	16260	11935	6190	91619	37451
2018	8357	9197	361	2901	8094	2449	9944	10824	52127	26399

Table 10. Prior and posterior median for M

	1	2	3	4	5	6	7	8+
Prior	1.26	0.65	0.44	0.35	0.30	0.27	0.24	0.24
Posterior	1.41	0.62	0.37	0.27	0.27	0.36	0.32	0.38

Table 11. N-at-age in prediction years (medians) with $F_{bar}=F_{lim}=0.167$ including total number and number of matures.

Year/Age	1	2	3	4	5	6	7	8+	Total	Matures
2019	5735	2054	4809	229	2040	5428	1387	12207	34448	19323
2020	4459	1399	1076	3011	151	1266	2776	6424	23223	10586
2021	2349	1087	742	660	1922	92	628	4236	14306	5819
2022	1312	571	572	452	424	1164	46	2200	8875	3562
2023	772	322	298	347	289	256	576	1002	5403	2139

Table 12. Projections results (median and 80% CI) with $F_{bar}=F_{lim}=0.167$.

Year	**Total Biomass**		**SSB**		**P(SSB<B$_{lim}$)**	**P(SSB$_{22}$ >SSB$_{19}$)**	**Yield**	**P(F>F$_{lim}$)**
2019	76891	(67817 - 86311)	69015	(60552 - 78262)	0%		17500	20%
2020	43969	(36989 - 51393)	38538	(32067 - 45573)	0%		10876	50%
2021	26256	(20590 - 32652)	22083	(17017 - 27722)	5%	<1%	6275	50%
2022	15086	(10689 - 20149)	12350	(8454 - 16718)	78%		3545	50%
2023	8803	(5242 - 13051)	6997	(4033 - 10442)	100%			

Table 13. N-at-age in prediction years (medians) with $F_{bar}=3/4F_{lim}=0.125$ including total number and number of matures.

Year/Age	1	2	3	4	5	6	7	8+	Total	Matures
2019	5735	2054	4809	229	2040	5428	1387	12207	34448	19323
2020	4459	1399	1076	3011	151	1266	2776	6424	23223	10586
2021	2349	1087	745	678	2012	97	686	4696	14951	6386
2022	1435	571	574	467	456	1288	52	2700	9735	4184
2023	919	355	300	363	312	294	692	1368	6259	2680

Table 14. Projections results (median and 80% CI) with $F_{bar}=3/4F_{lim}=0.125$.

Year	**Total Biomass**		**SSB**		**P(SSB<B$_{lim}$)**	**P(SSB$_{22}$ >SSB$_{19}$)**	**Yield**	**P(F>F$_{lim}$)**
2019	76891	(67817 - 86311)	69015	(60552 - 78262)	0%		17500	20%
2020	43969	(36989 - 51393)	38538	(32067 - 45573)	0%		8531	3%
2021	28637	(22958 - 34999)	24368	(19275 - 29993)	1%	<1%	5405	9%
2022	17653	(13236 - 22793)	14842	(10933 - 19242)	55%		3303	14%
2023	10933	(7370 - 15204)	9009	(6028 - 12496)	99%			

Table 15. N-at-age in prediction years (medians) with $F_{bar}=F_{2016-2018}=0.079$ including total number and number of matures.

Year/Age	1	2	3	4	5	6	7	8+	Total	Matures
2019	5735	2054	4809	229	2040	5428	1387	12207	34448	19323
2020	4459	1399	1076	3011	151	1266	2776	6424	23223	10586
2021	2349	1087	748	700	2115	103	757	5280	15747	7086
2022	1596	571	576	482	495	1450	61	3402	10930	5043
2023	1117	397	301	376	341	339	858	1944	7438	3472

Table 16. Projections results (median and 80% CI) with $F_{bar}=F_{2016-2018}=0.079$.

Year	Total Biomass		SSB		P(SSB<B_{lim})	P(SSB_{22} >SSB_{19})	Yield	P(F>F_{lim})
2019	76891	(67817 - 86311)	69015	(60552 - 78262)	0%		17500	20%
2020	43969	(36989 - 51393)	38538	(32067 - 45573)	0%		5619	0%
2021	31634	(25964 - 37966)	27230	(22125 - 32840)	0%	<1%	3953	0%
2022	21241	(16828 - 26434)	18302	(14356 - 22736)	20%		2645	0%
2023	14177	(10497 - 18490)	12106	(9069 - 15645)	86%			

Table 17. N-at-age in prediction years (medians) with $F_{bar}=0$ including total number and number of matures.

Year/Age	1	2	3	4	5	6	7	8+	Total	Matures
2019	5735	2054	4809	229	2040	5428	1387	12207	34448	19323
2020	4459	1399	1076	3011	151	1266	2776	6424	23223	10586
2021	2349	1087	753	738	2301	114	890	6422	17267	8444
2022	1892	571	580	513	570	1752	80	5013	13324	6941
2023	1553	470	303	397	395	429	1220	3464	10201	5473

Table 18. Projections results (median and 80% CI) with $F_{bar}=0$.

Year	Total Biomass		SSB		P(SSB<B_{lim})	P(SSB_{22} >SSB_{19})	Yield	P(F>F_{lim})
2019	76891	(67817 - 86311)	69015	(60552 - 78262)	0%		17500	20%
2020	43969	(36989 - 51393)	38538	(32067 - 45573)	0%		0	0%
2021	37465	(31837 - 43711)	32807	(27628 - 38492)	0%	<1%	0	0%
2022	29262	(24806 - 34479)	26096	(22110 - 30692)	0%		0	0%
2023	22406	(18583 - 26998)	20149	(16929 - 23775)	5%			

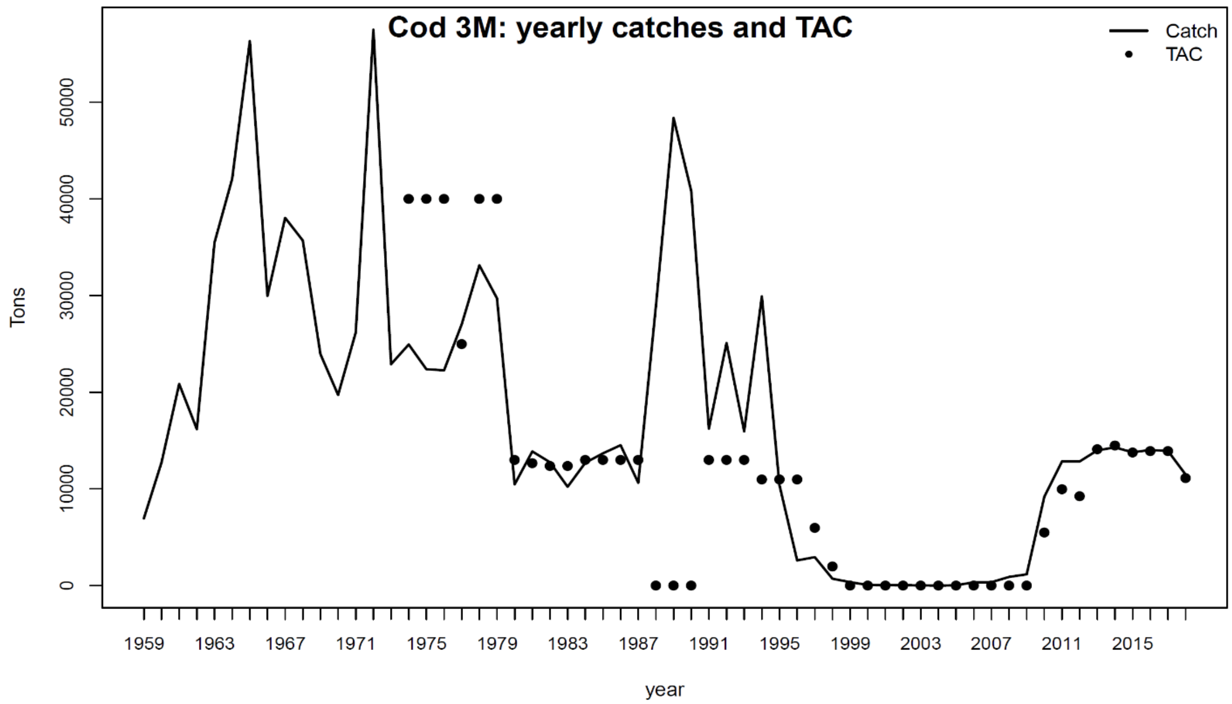


Figure 1. Catch and TAC of the 3M cod for the period 1959-2018.

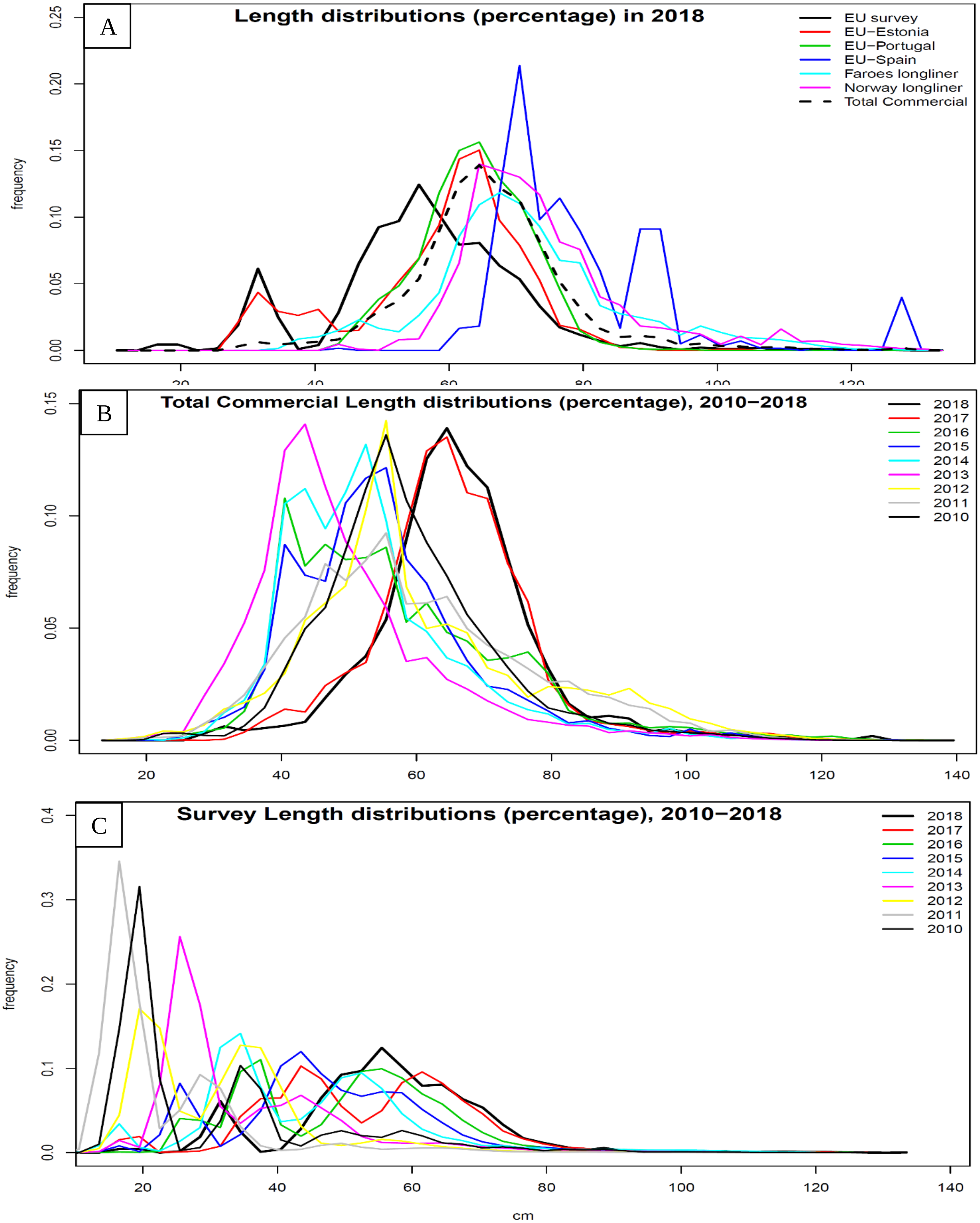


Figure 2. Length frequencies in commercial catches and EU survey in 2018 (A), and for the last fishery period (2010-2018), the total commercial (B) and the survey (C).

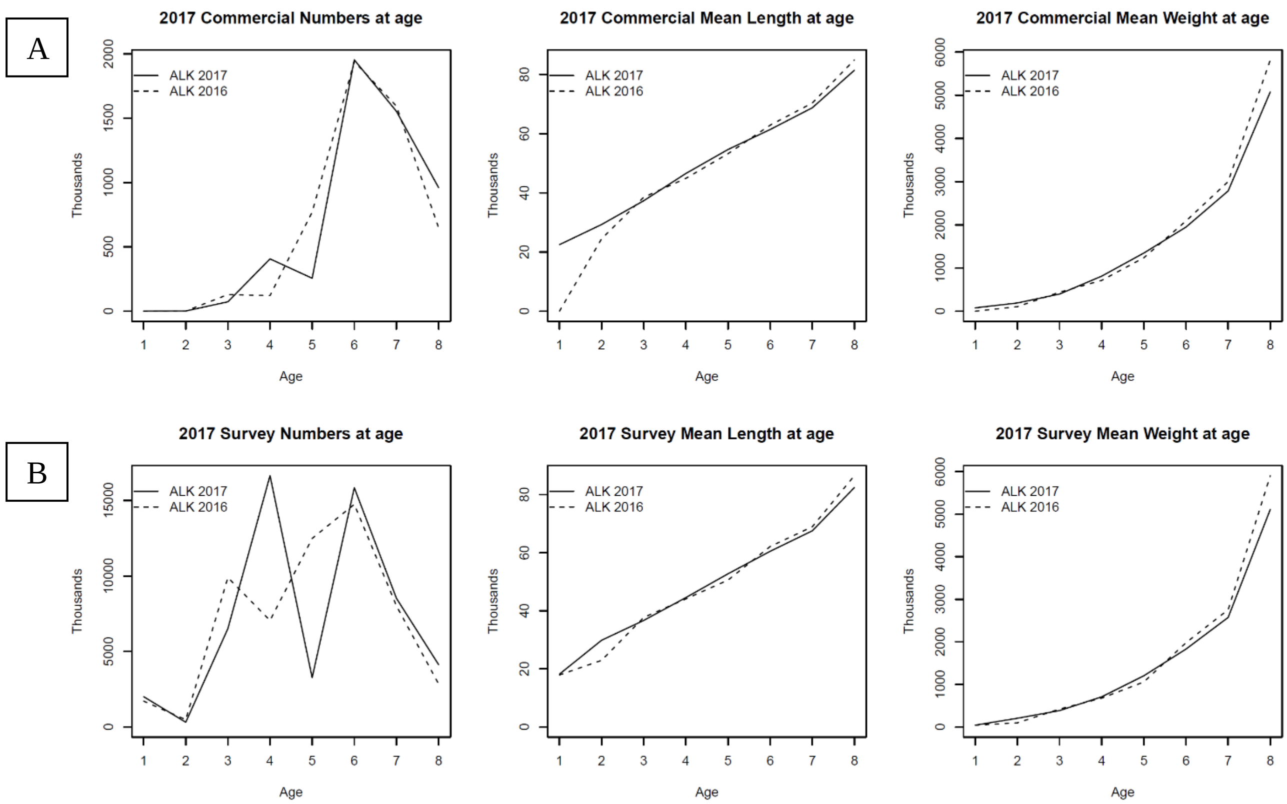
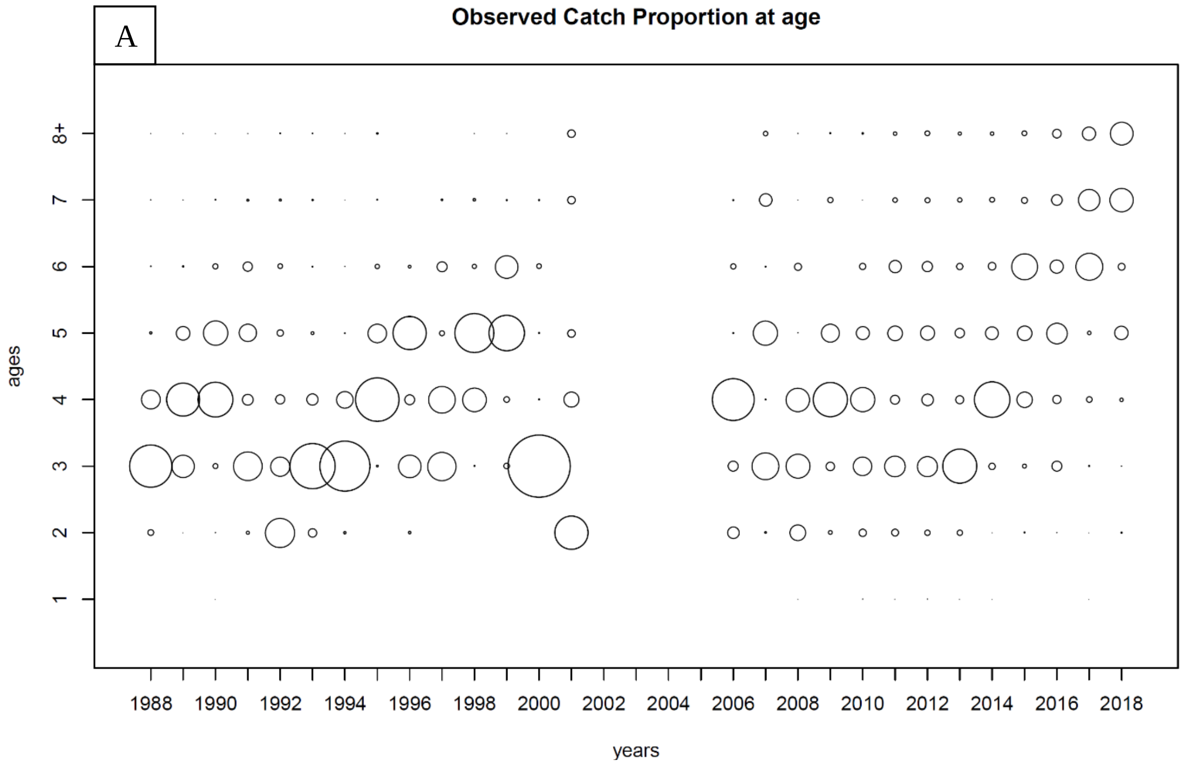


Figure 2.5. 2017 indices at age with the 2016 ALK (used in last assessment) and with 2017 ALK (used in the current assessment). Commercial indices (A) and survey indices (B).



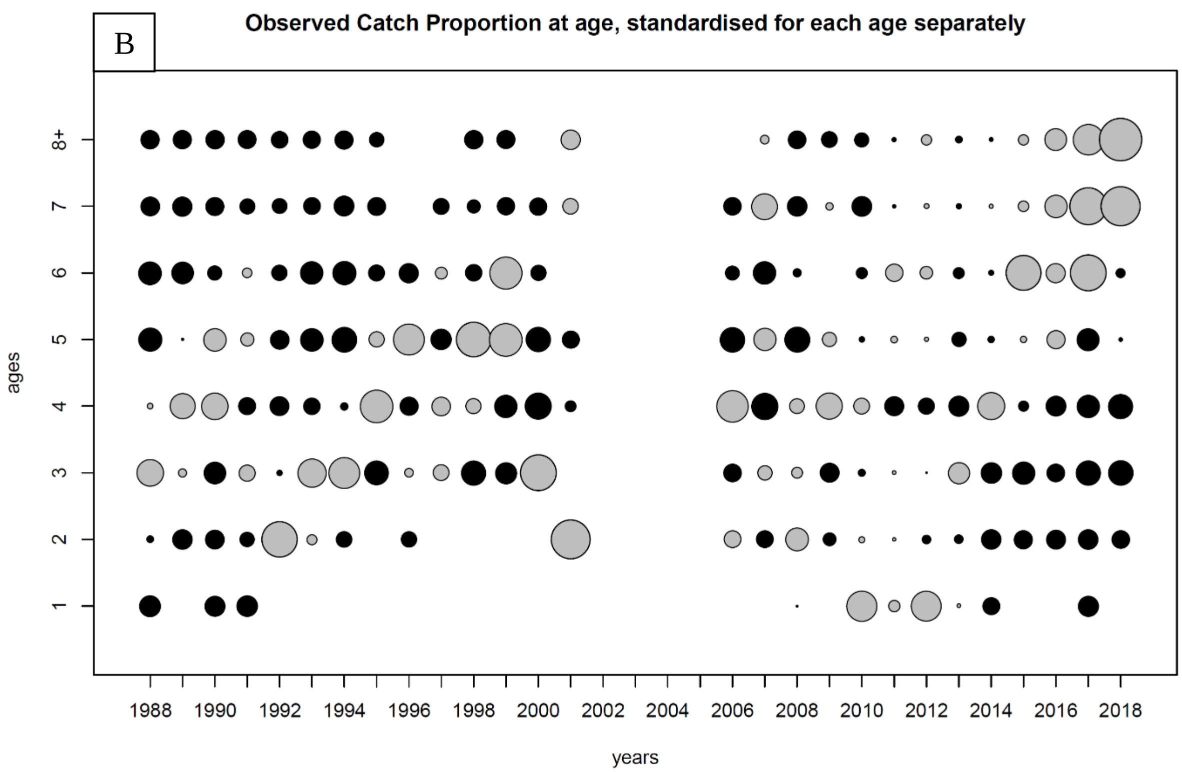


Figure 3. Commercial catch proportions at age (A) and standardised proportions at age (B). In B, grey and black values indicate values above and below the average. The larger the bubble size the larger the magnitude of the value.

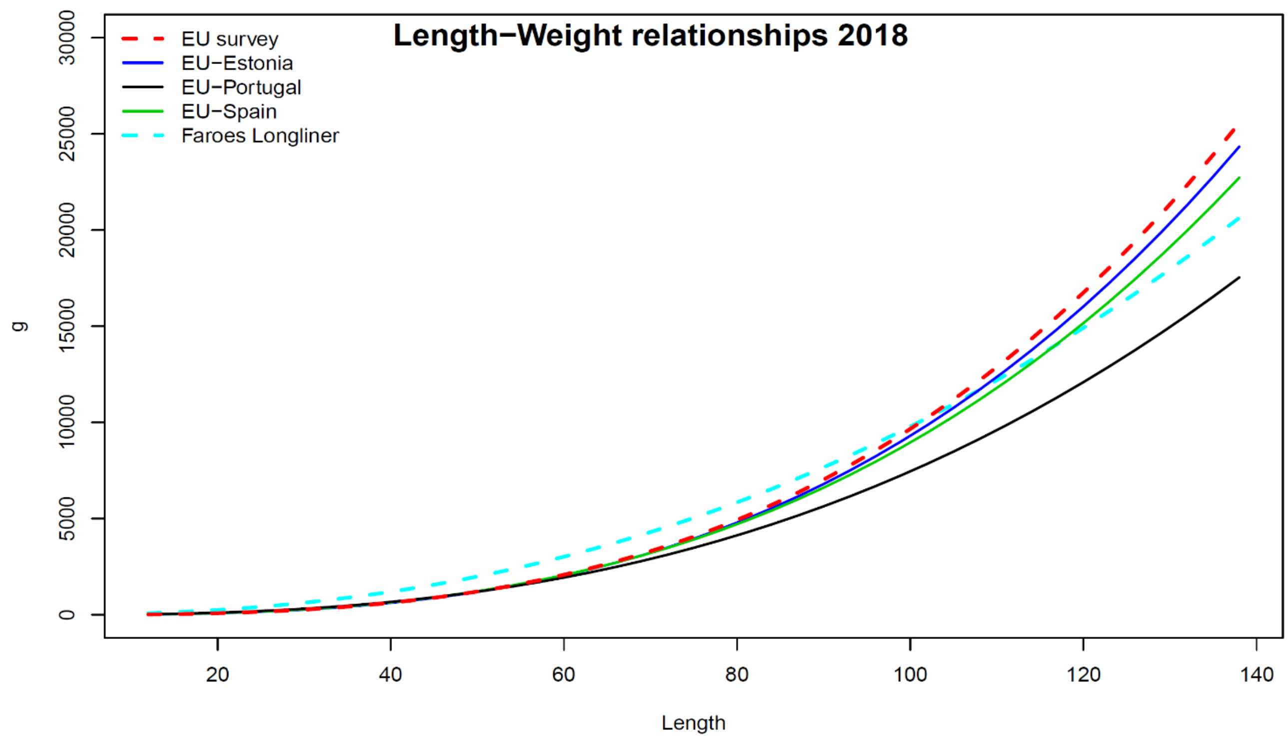


Figure 4. Length-weight relationships for commercial catches and EU survey in 2018.

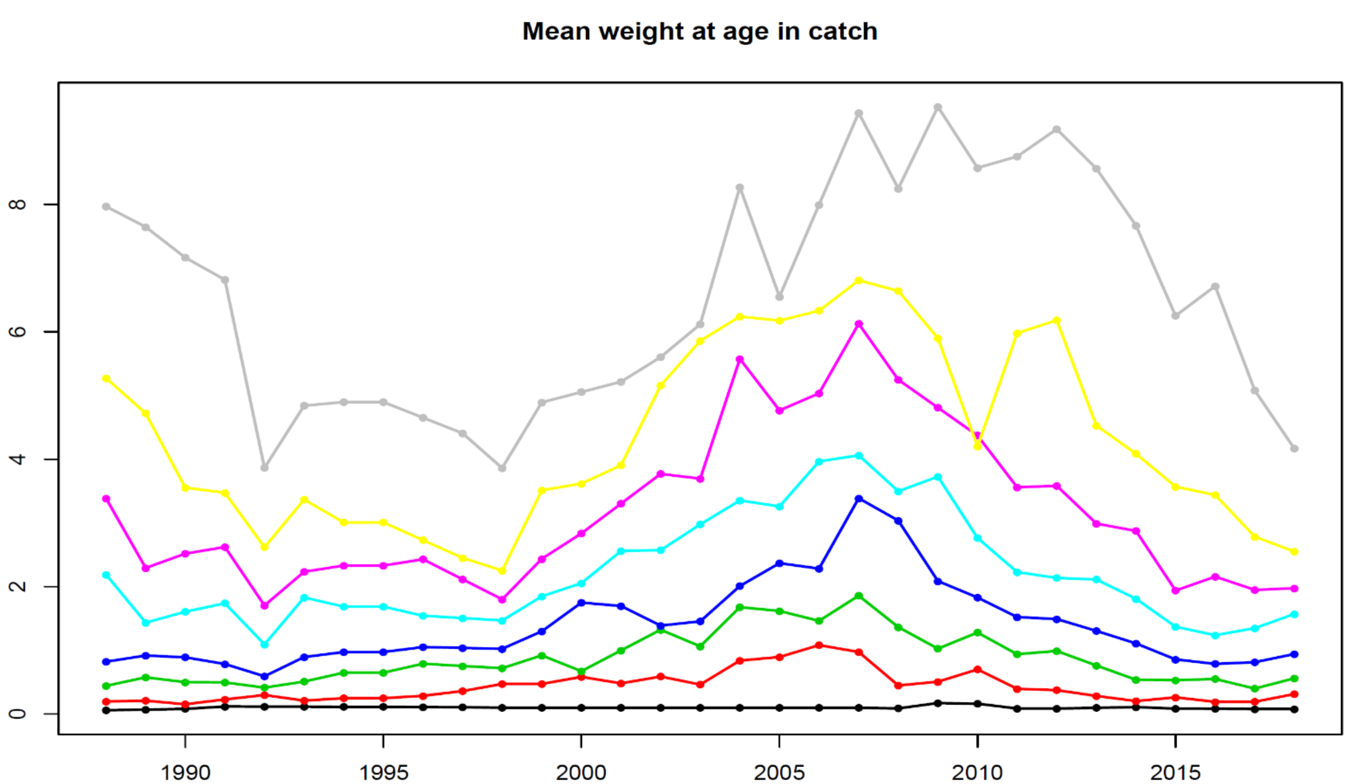


Figure 5. Catch mean weight at age.

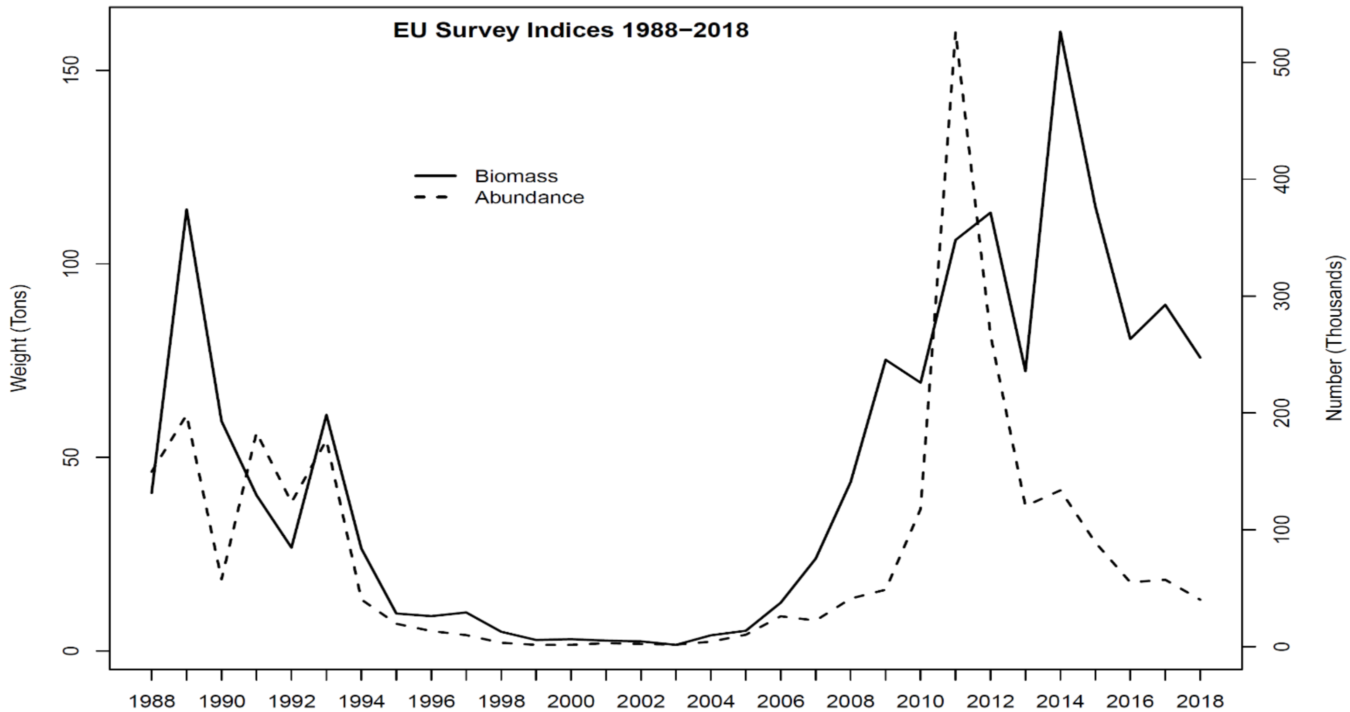


Figure 6. Biomass and abundance from EU surveys.

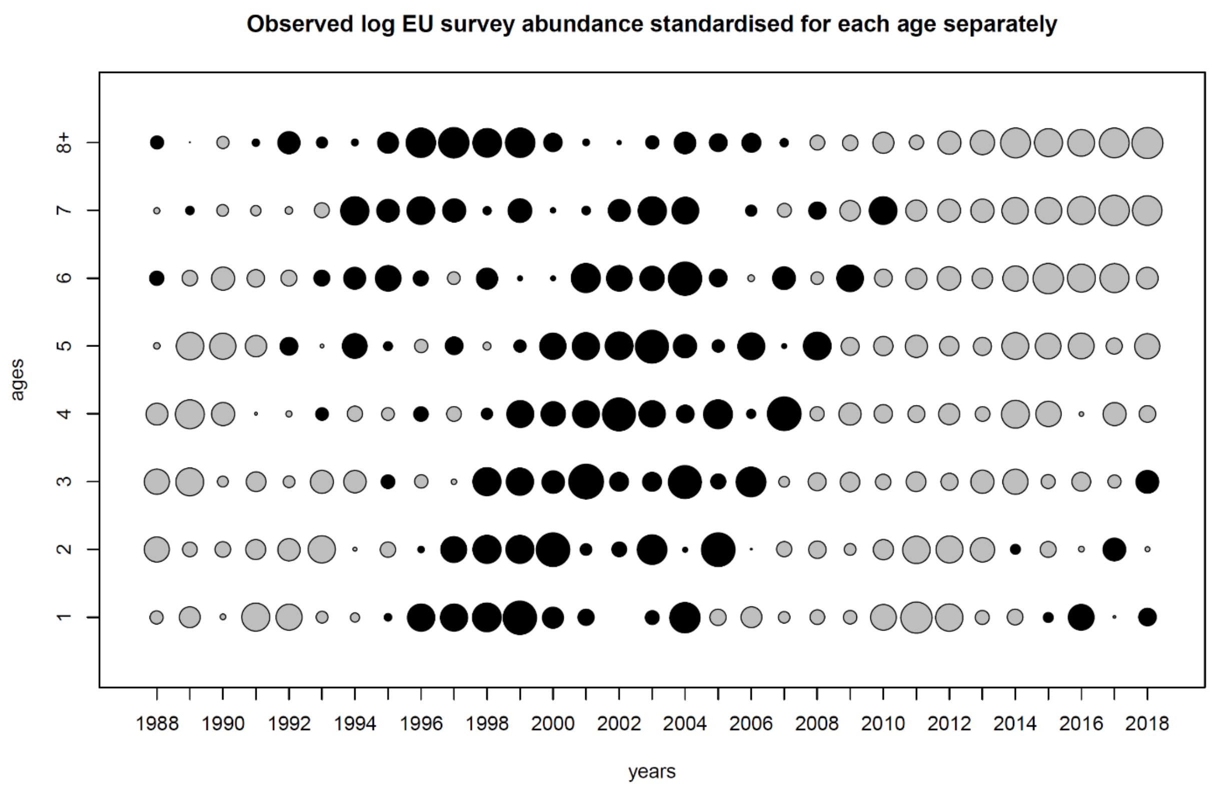


Figure 7. Standardised log(Abundance at age) indices from EU survey. Grey and black values indicate values above and below the average. The larger the bubble size the larger the magnitude of the value.

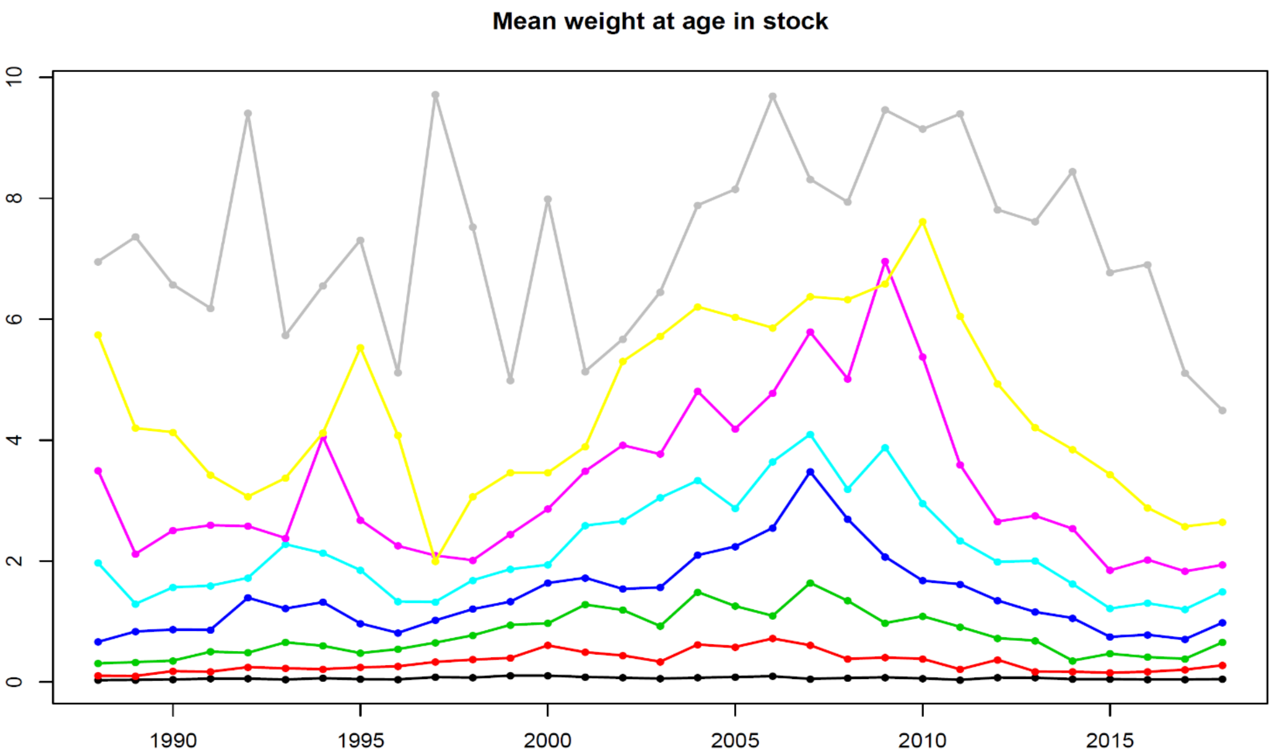


Figure 8. Stock mean weight at age.

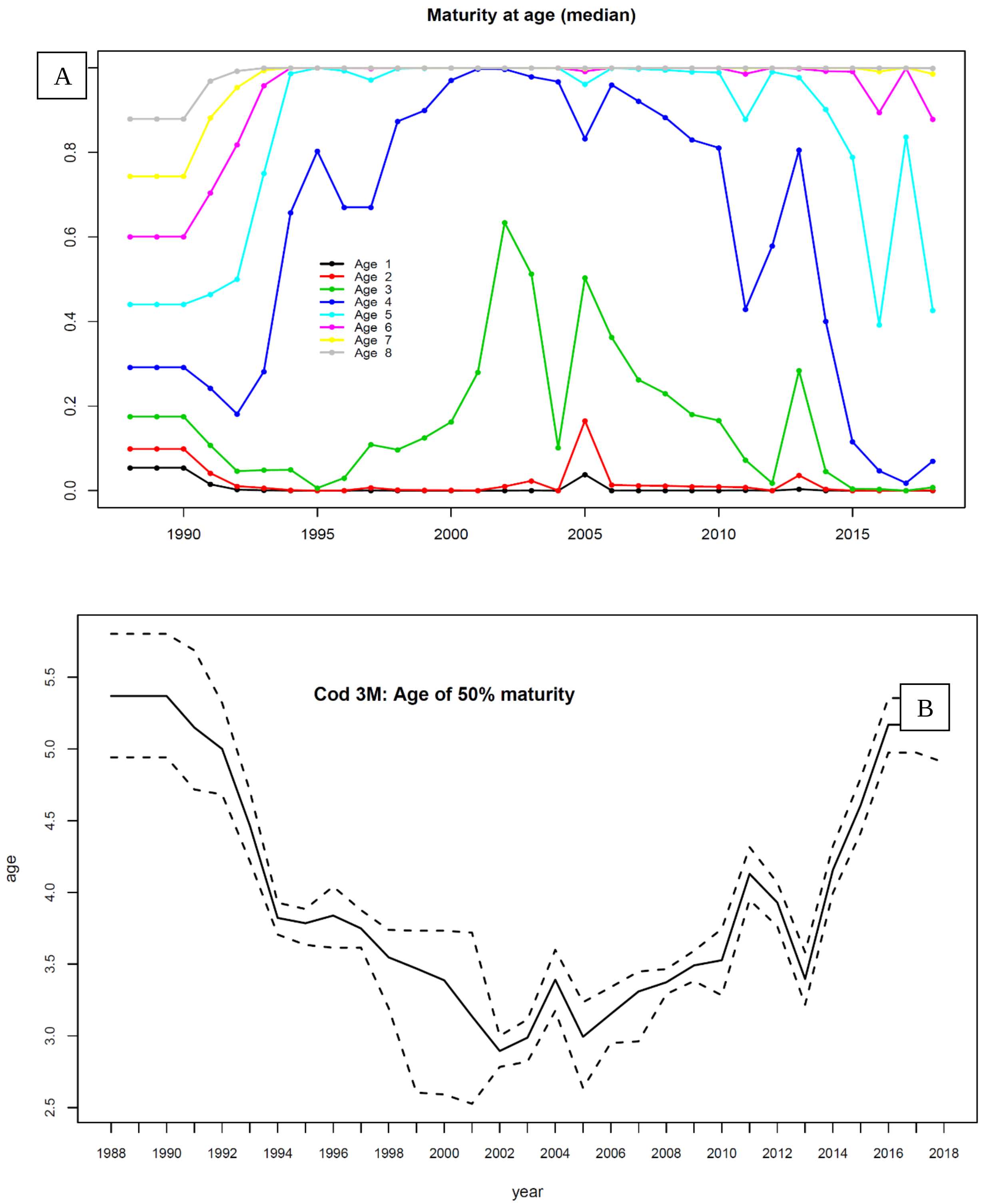


Figure 9. Maturity ogive by age (A) and age at which 50% of fish are mature (B).

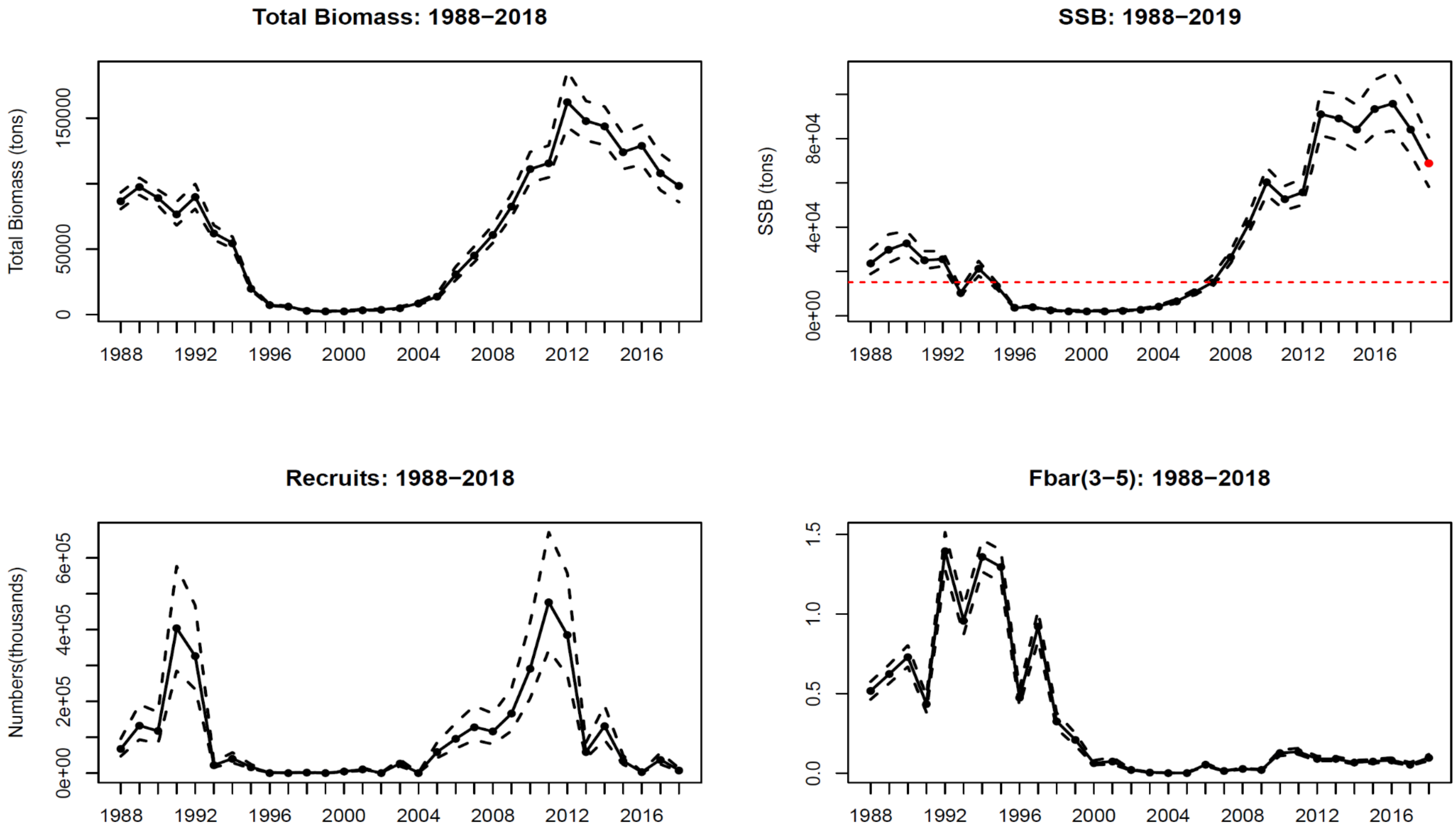


Figure 10. Estimated trends in biomass, SSB, recruitment and F_{bar}. The solid lines are the posterior medians and the dashed lines show the limits of 90% posterior credible intervals. Red point in the SSB plot indicates the SSB in 2019. Red horizontal line in the SSB graph represents median B_{lim} = medianSSB_{07} = 15 162 tons.

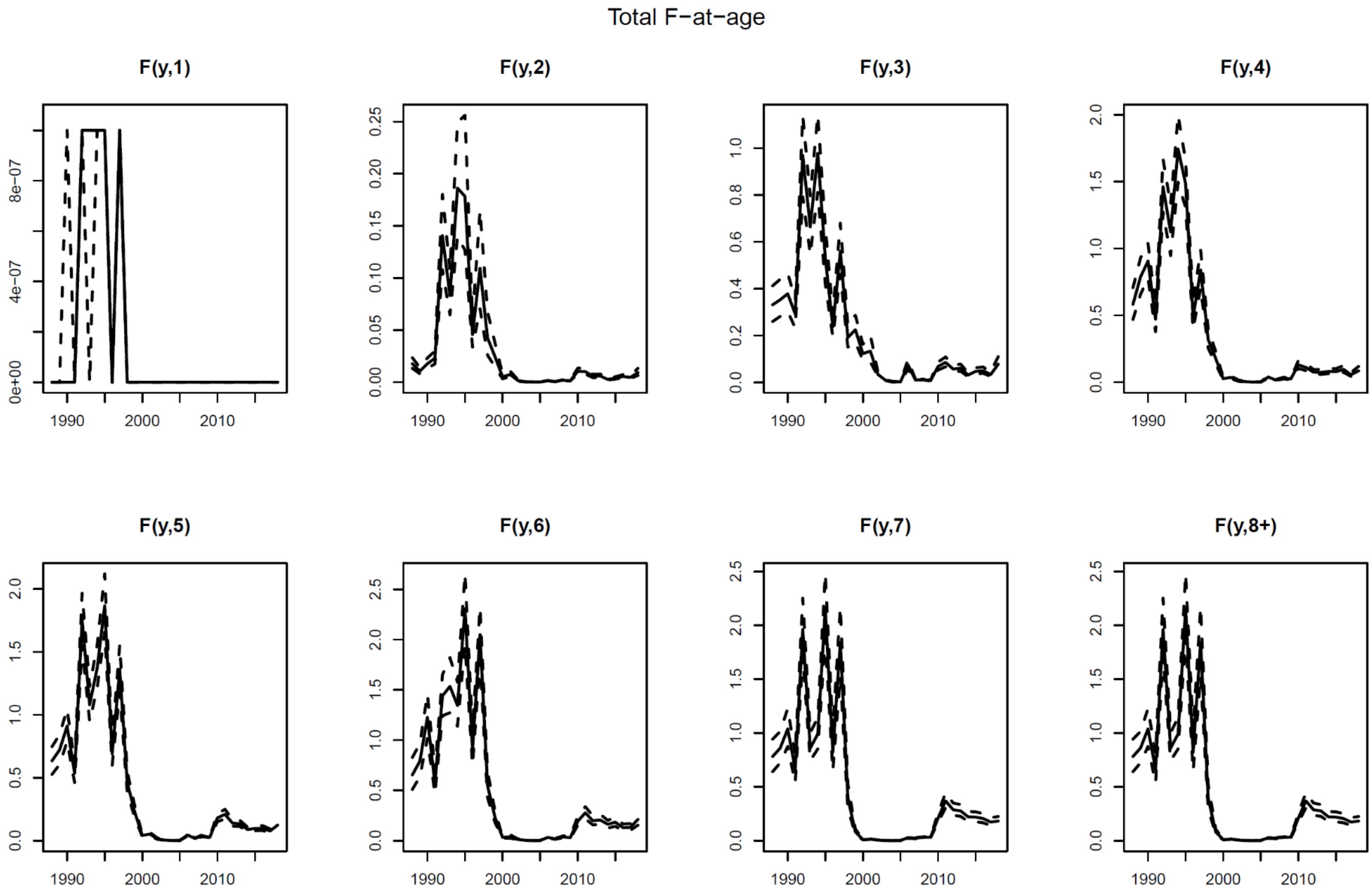


Figure 11. Estimated fishing mortality at age. The y-axis scale is different in all the graphs.

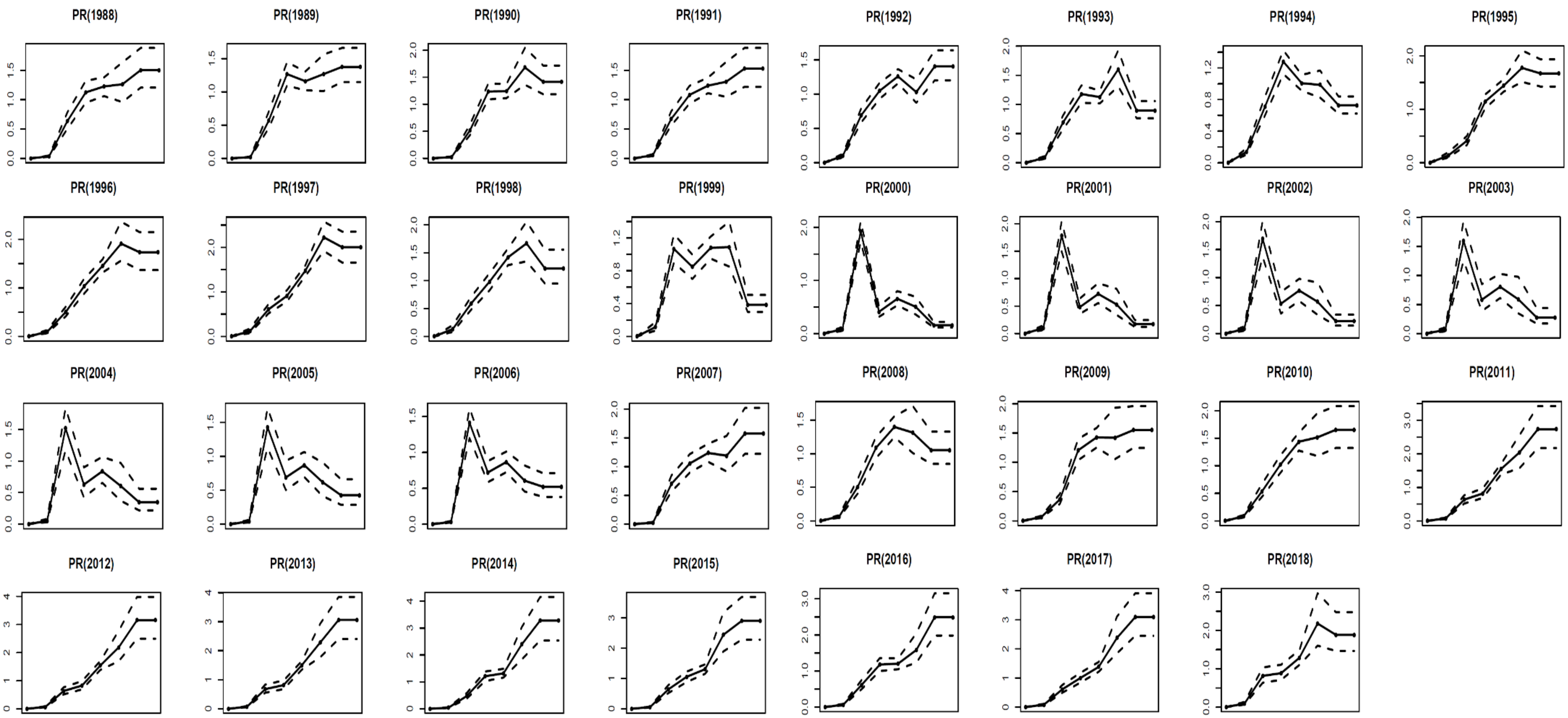
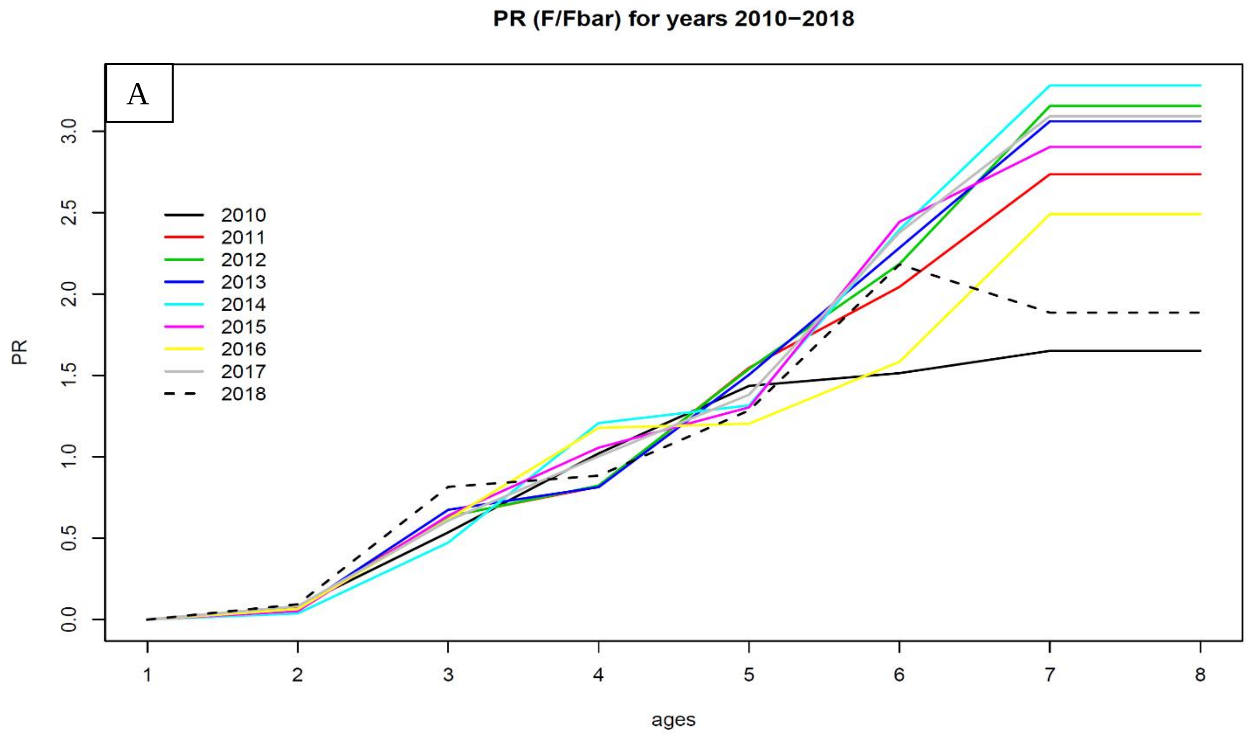


Figure 12. Estimated PR (F/F_{bar}) per age and year. Take into account the different y-axis between figures.



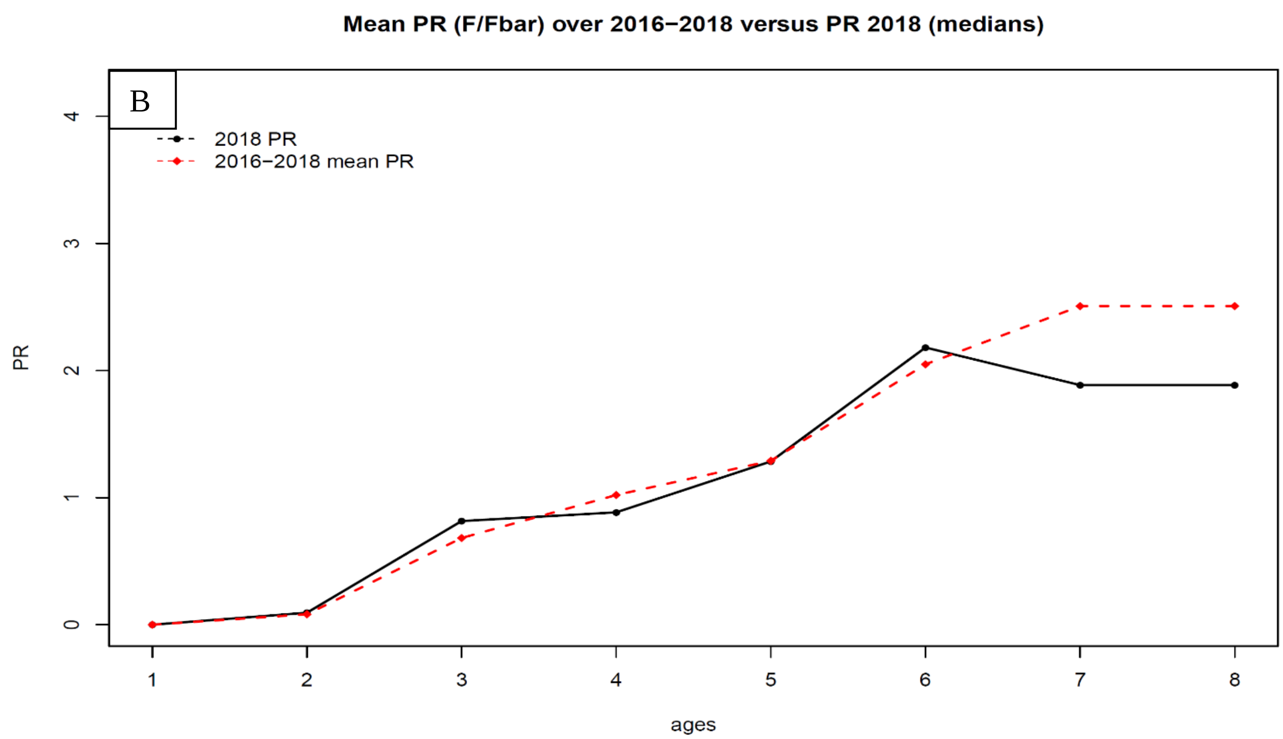


Figure 13. A) Estimated PR (F/F_{bar}) per age for the last six years and (B) mean of 2016-2018 PR versus 2018 PR (posterior medians). Bold line is the mean of the last three years PR.

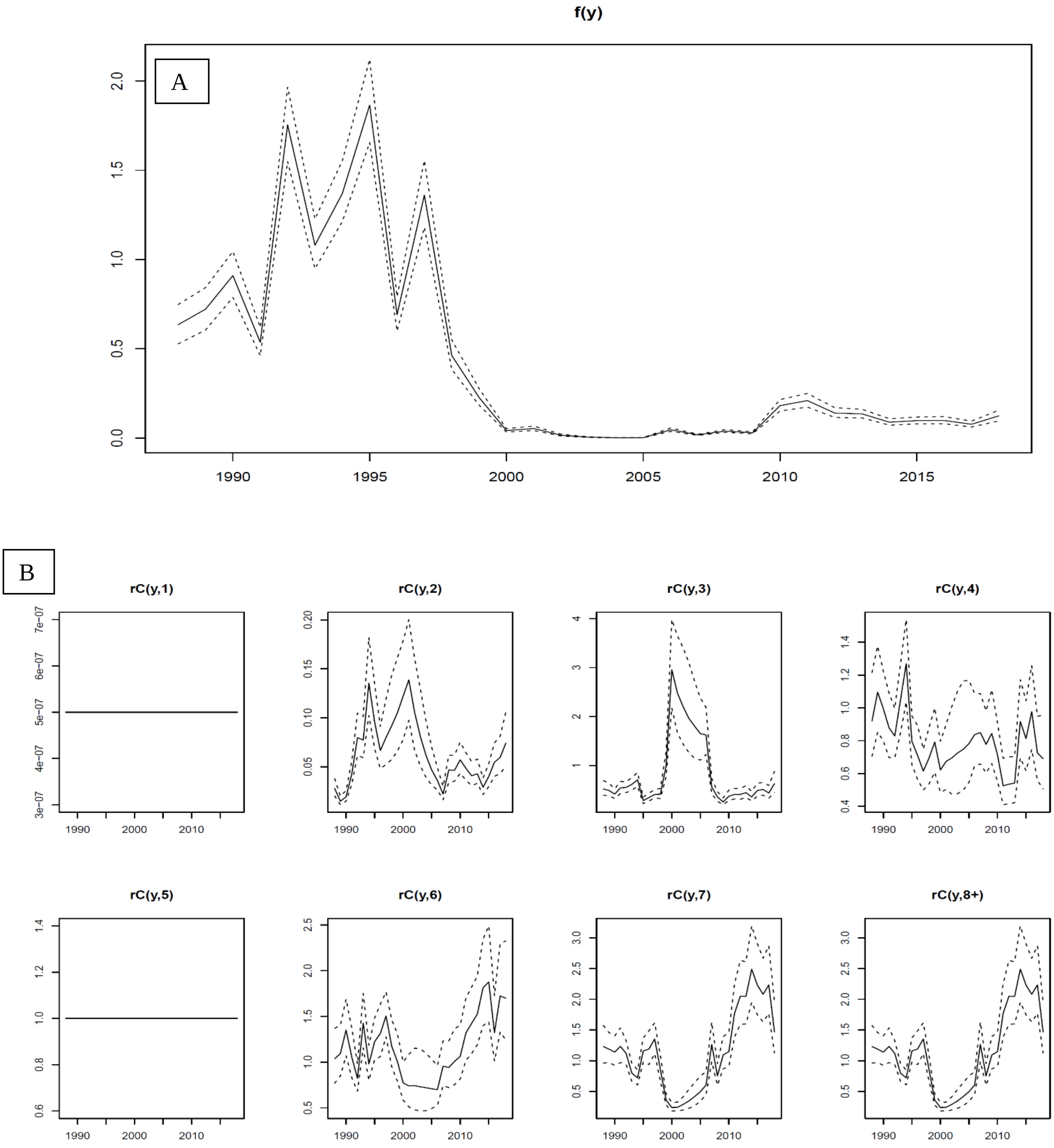


Figure 14. Components of the semi-separable model for Fishing Mortality: F[y,a]=*f*[y]**rC*[y,a].

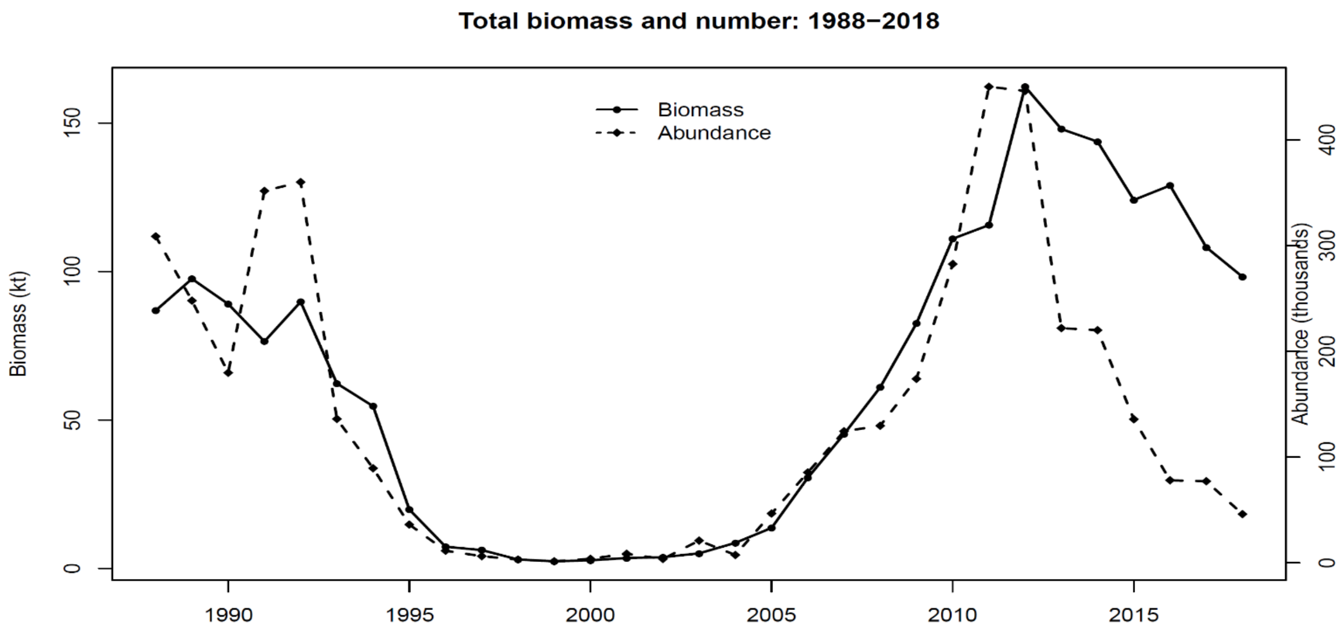


Figure 15. Estimated trends in biomass and abundance.

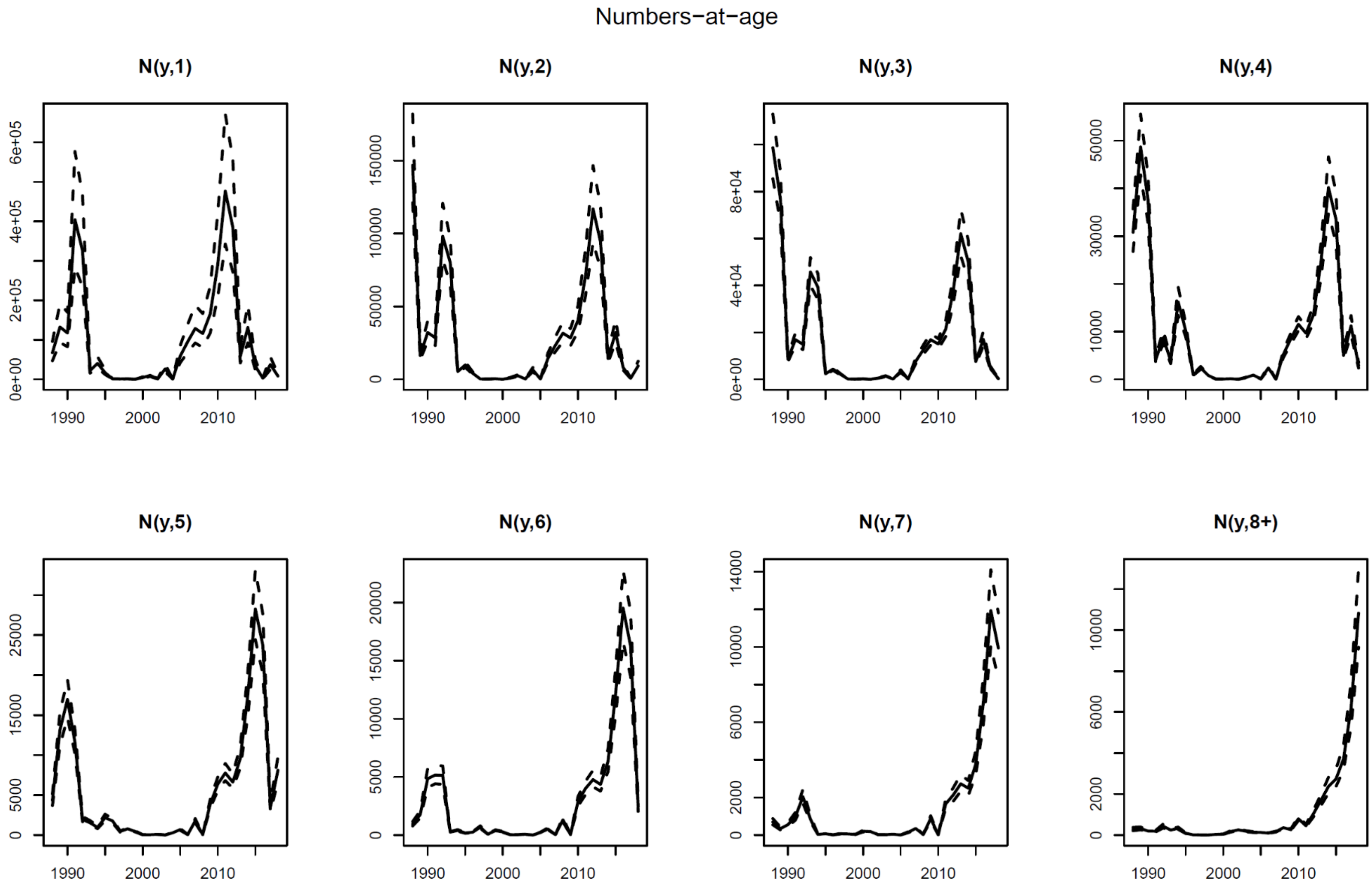


Figure 16. Estimated numbers at age. The y-axis scale is different in all the graphs.

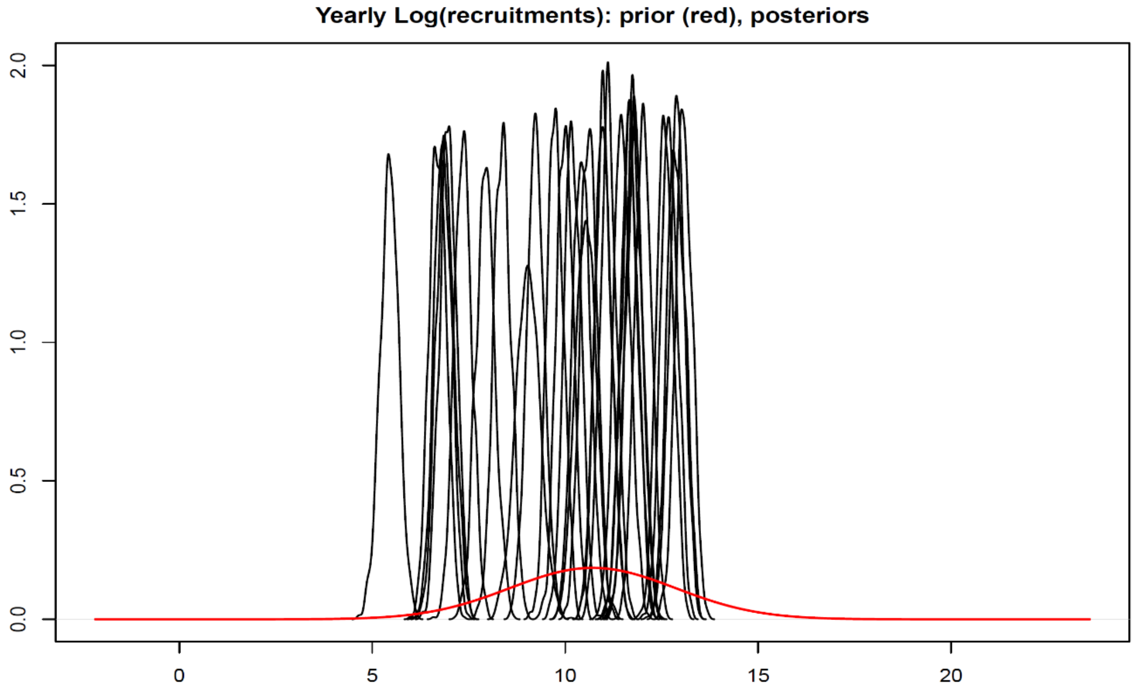


Figure 17. Prior and posterior of recruitment by year.

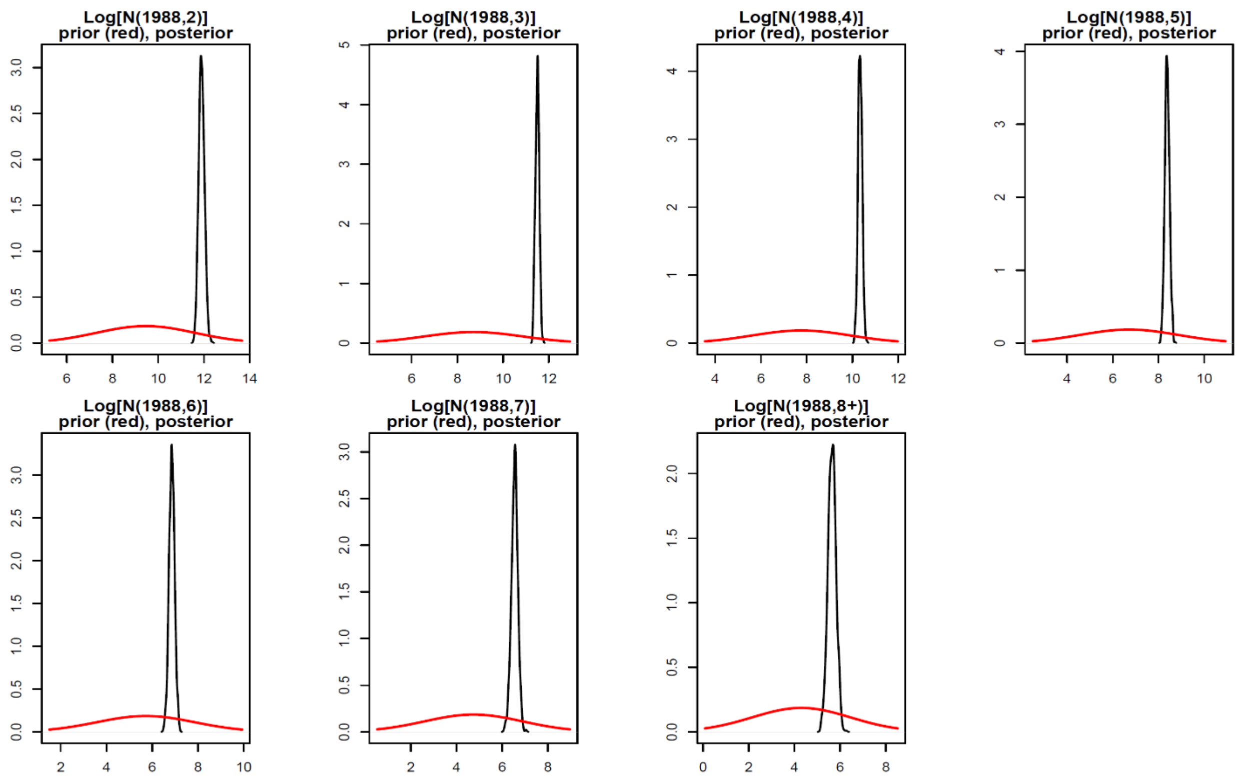


Figure 18. Prior and posterior of the numbers in the first year (1988) from age 2 to 8+.The x- and y-axis scales are different in all the graphs.

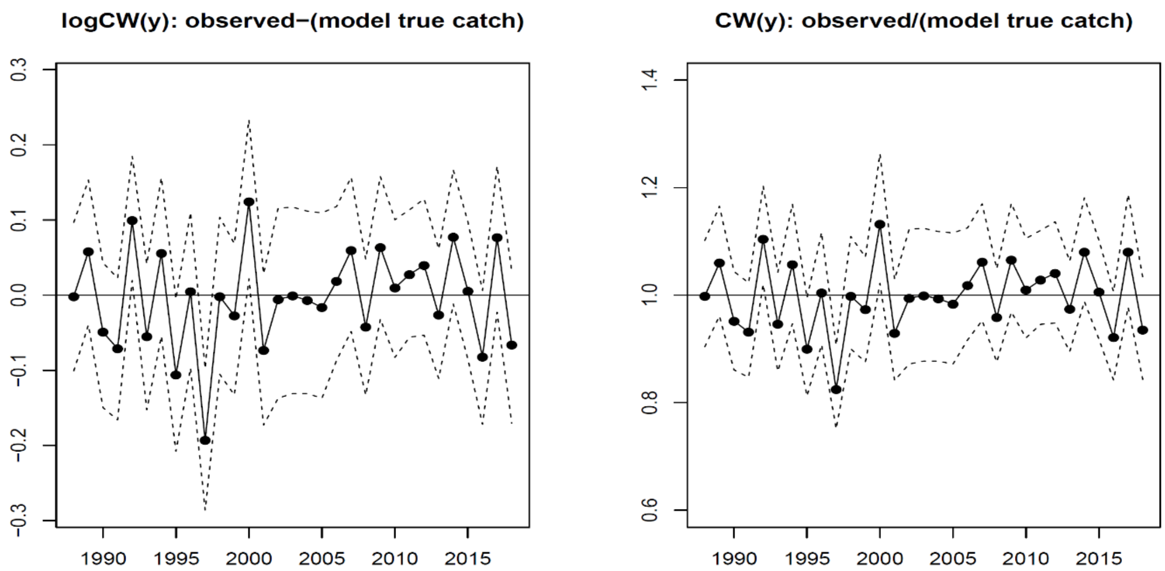


Figure 19. Observed versus estimated total catches by year.

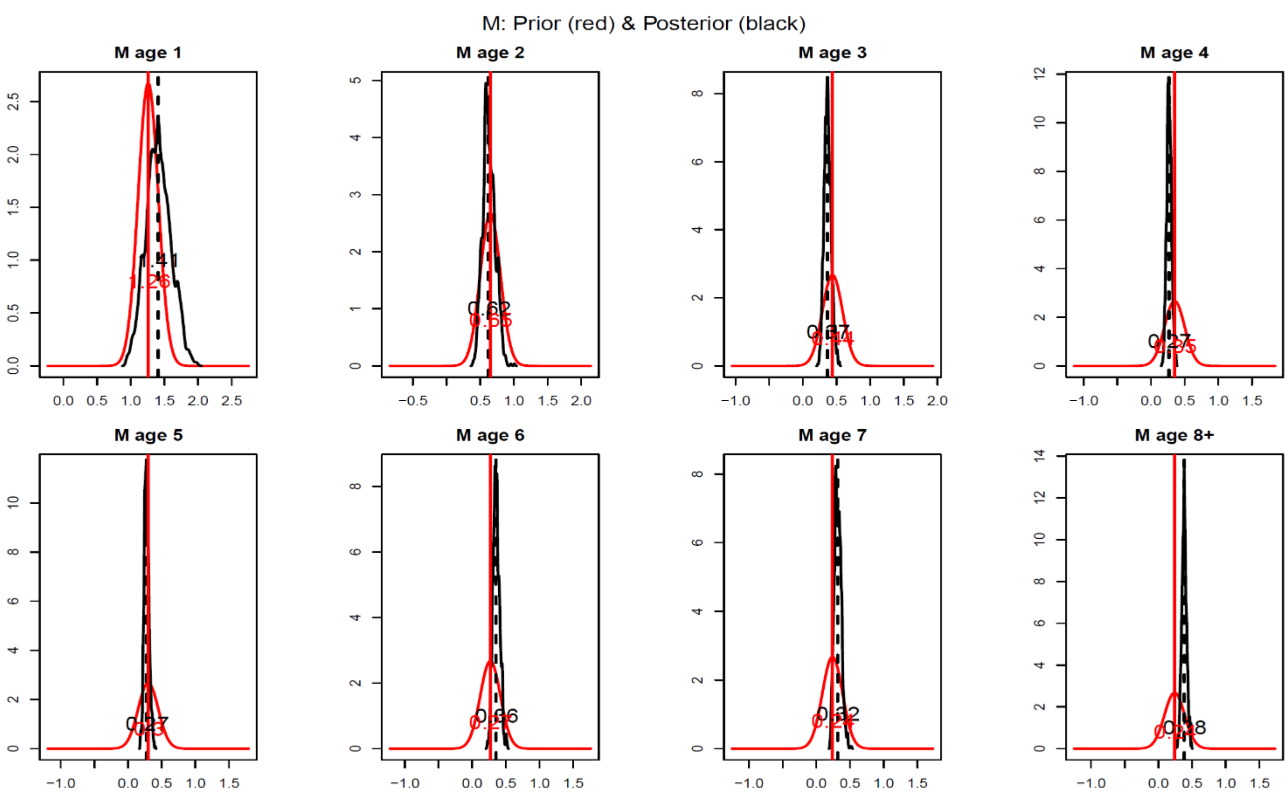


Figure 20. Estimated natural mortality by age in 2018.

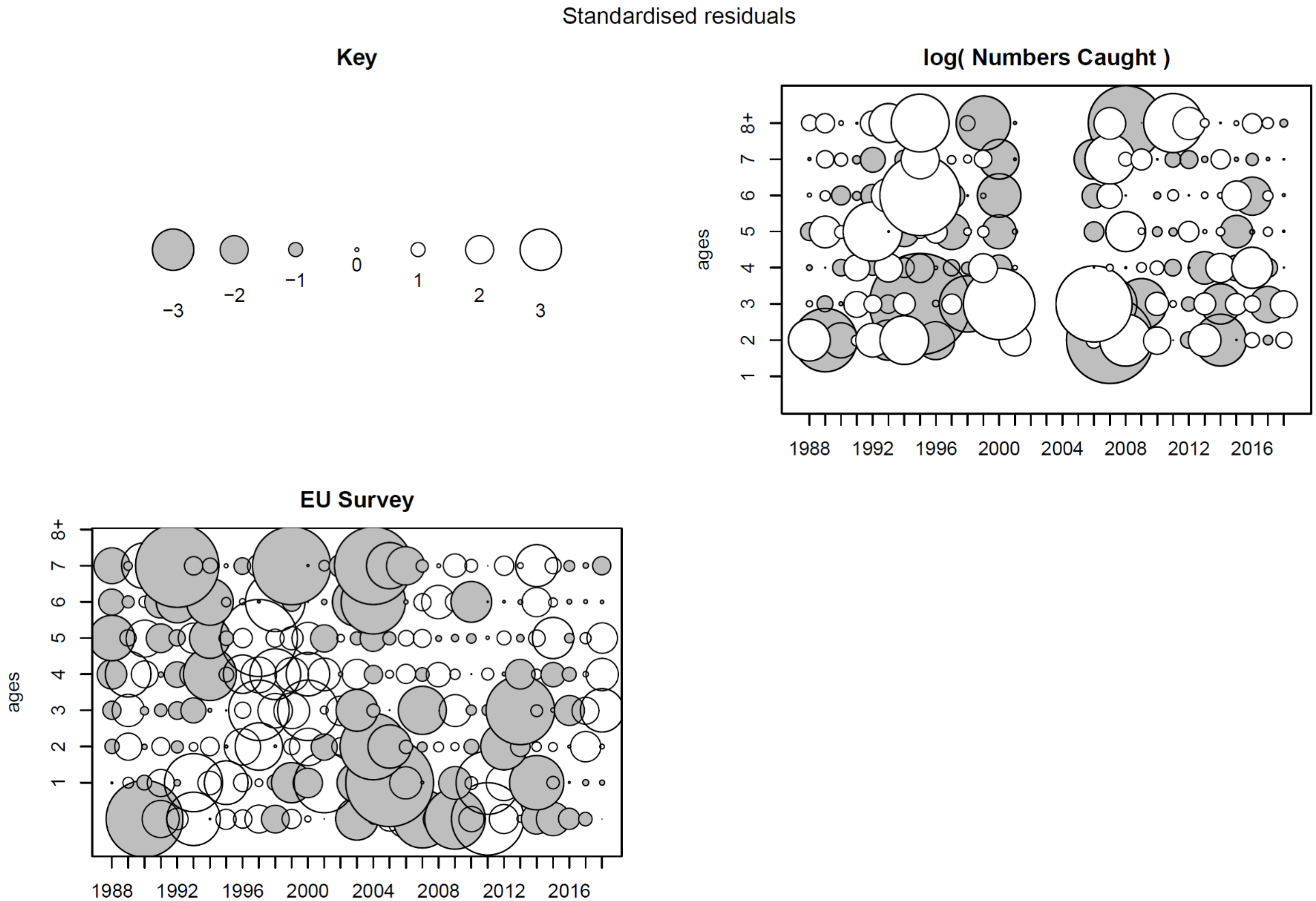


Figure 21. Standardised residuals (observed minus fitted value) in logarithmic scale of catch numbers at age and EU survey abundance indices at age. Grey and black values indicate values above and below the average. The larger the bubble size the larger the magnitude of the value.

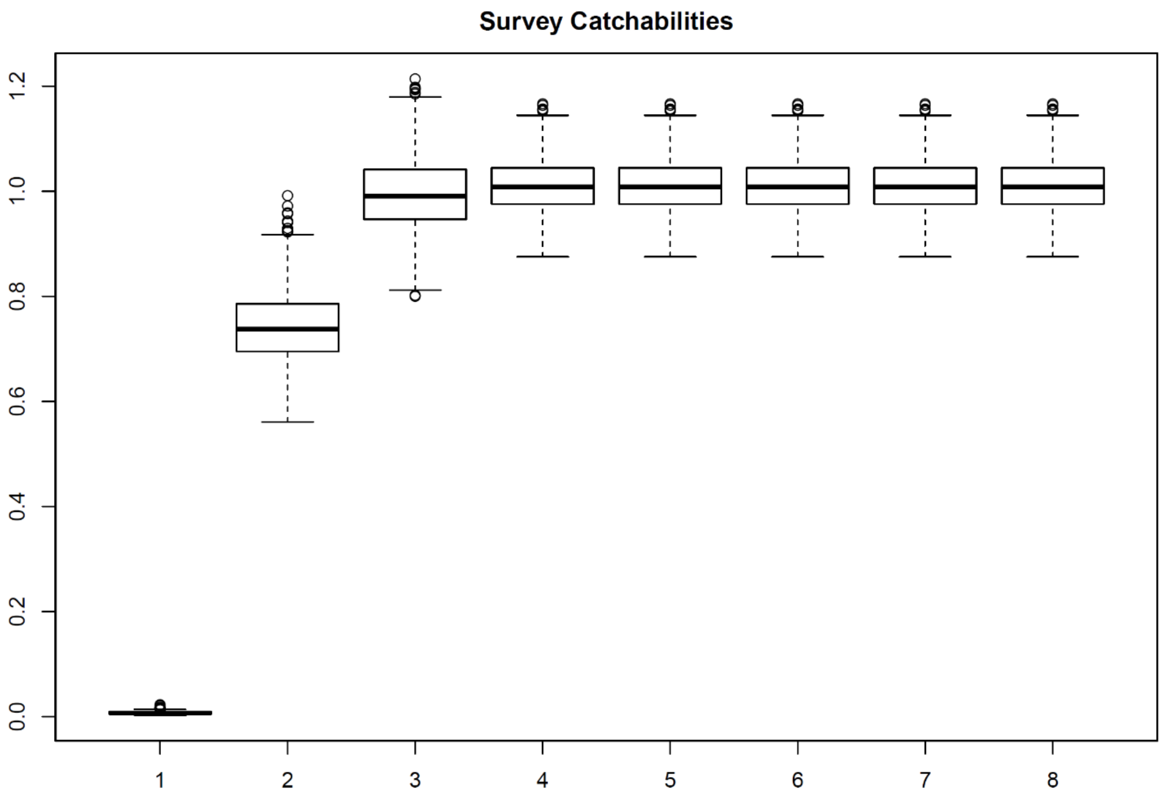


Figure 22. EU survey catchabilities distribution

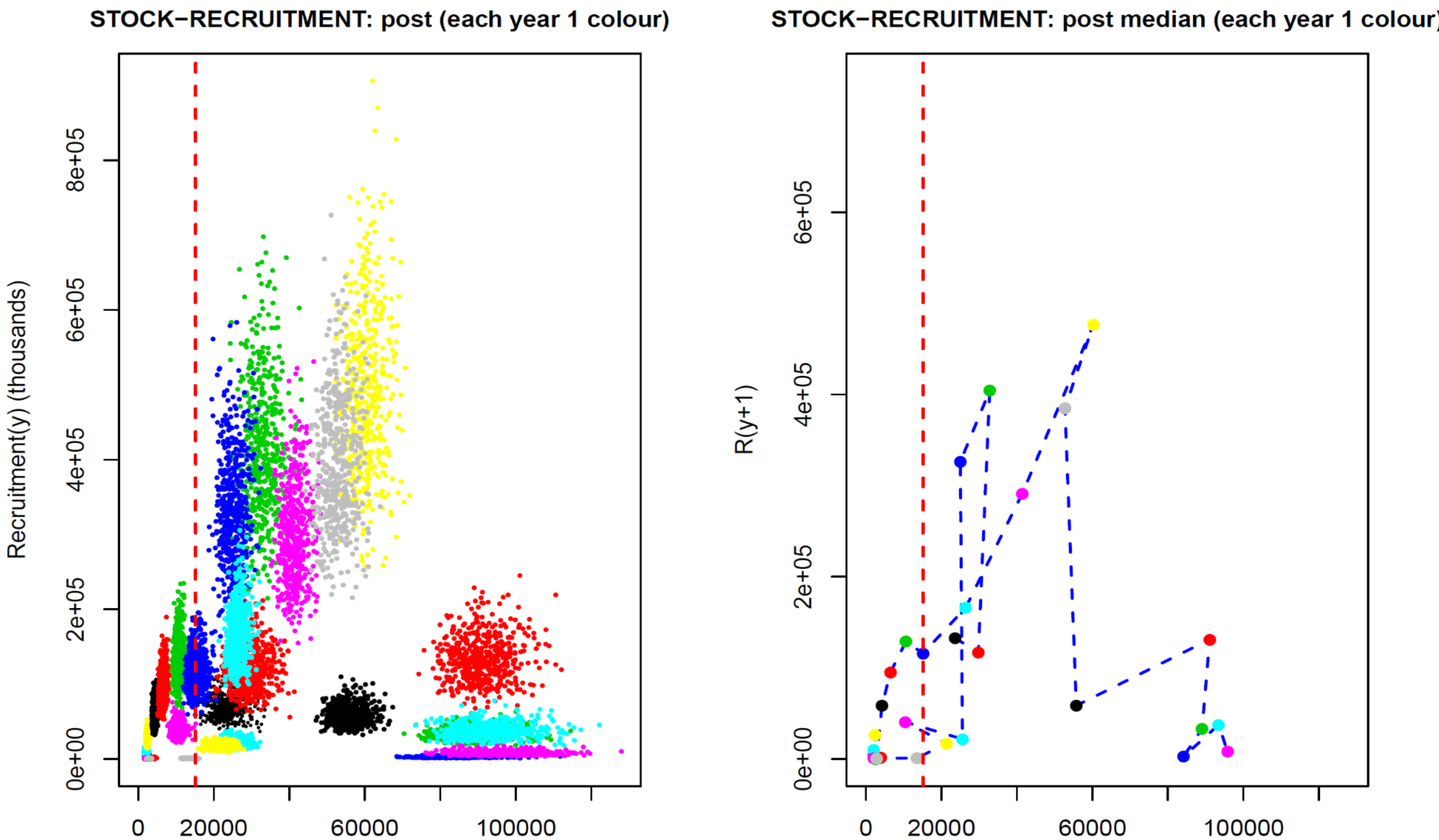


Figure 23. Stock-Recruitment plots. The value of median B_{lim}=medianSSB_{2007}=15 142 tons is shown as the red vertical line.

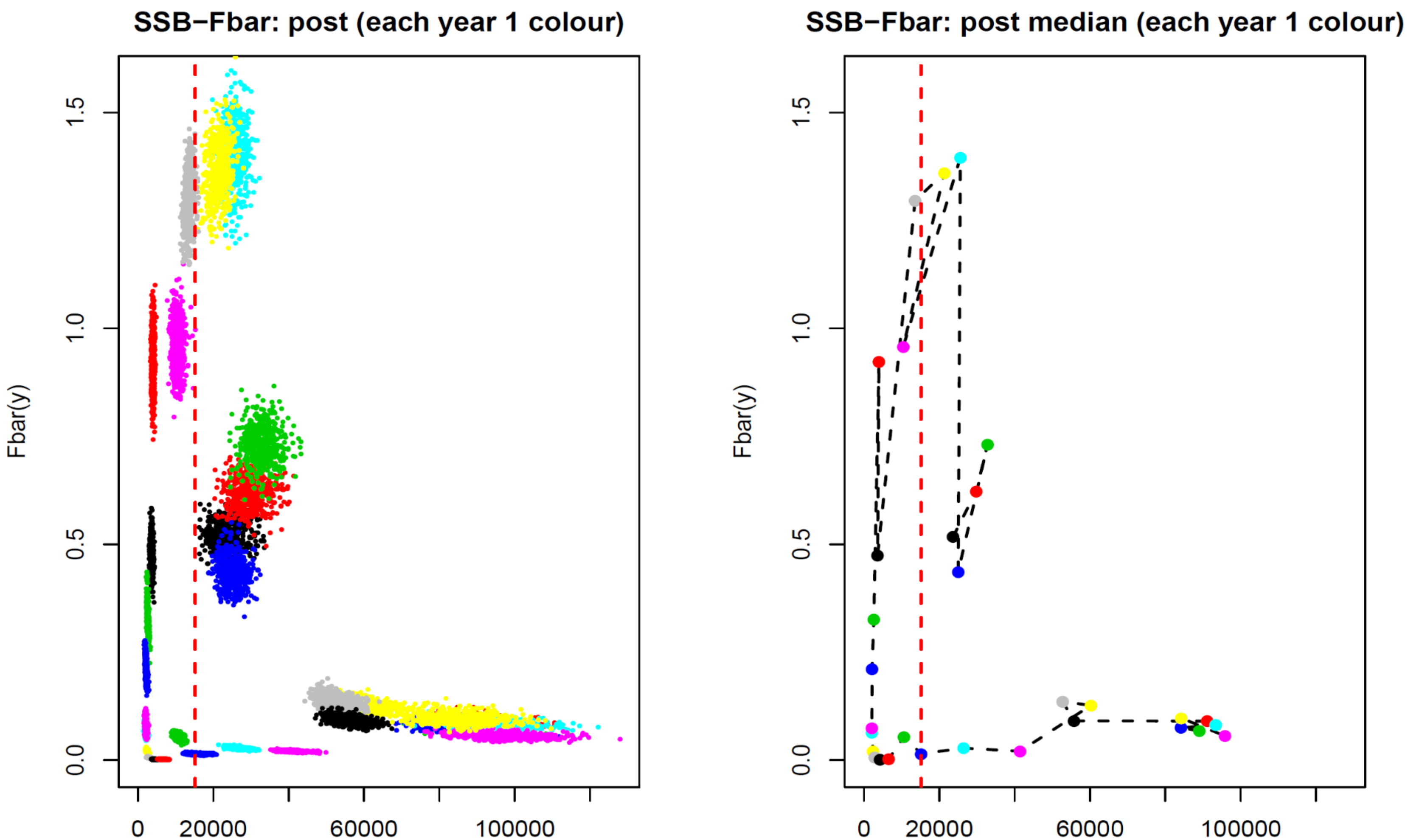


Figure 24. F_{bar} versus SSB plots. The value of median B_{lim}=medianSSB_{07}=15 162 tons is shown as the red vertical line.

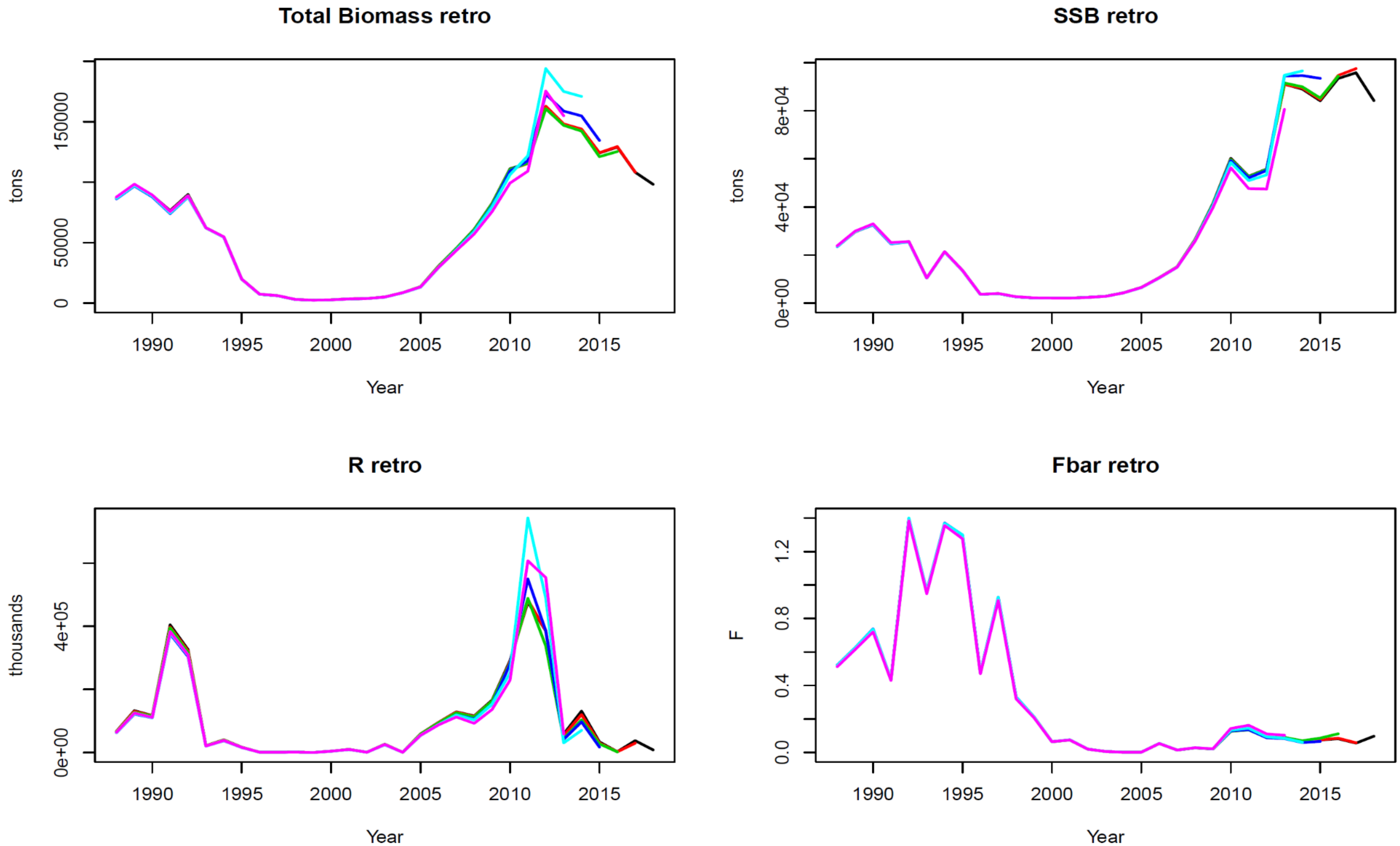


Figure 25. Retrospective patterns.

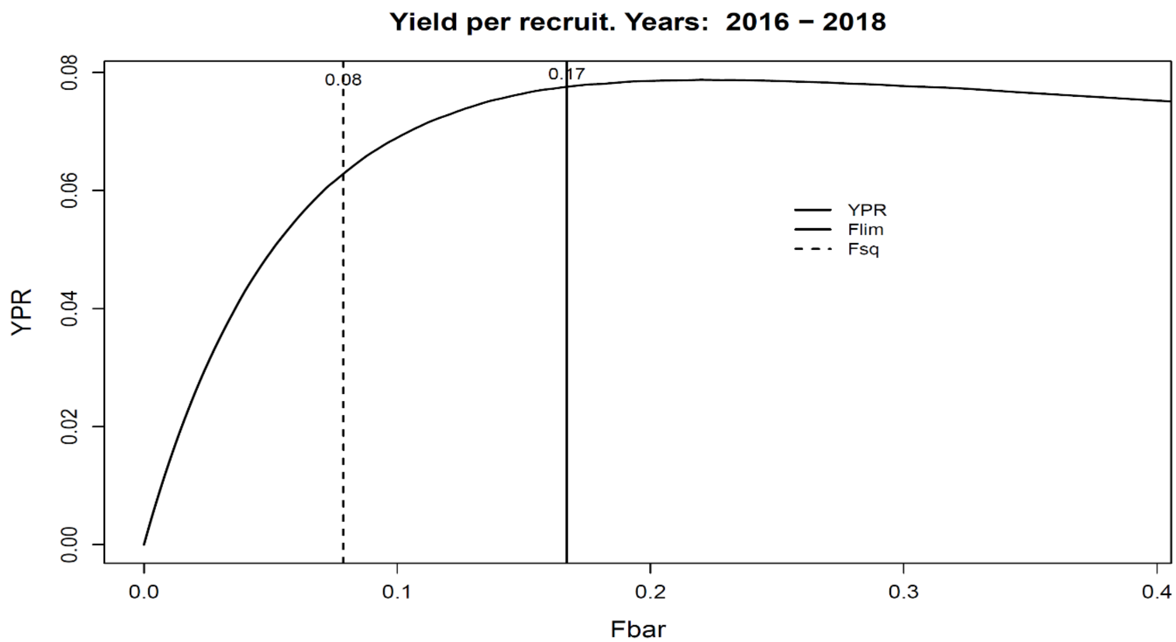


Figure 26. Yield per Recruit (2016-2018) versus F_{bar}. The values of F_{lim} ($F_{30\%SPR}$)and $F_{statusquo}$ (mean F over 2016-2018) are indicated.

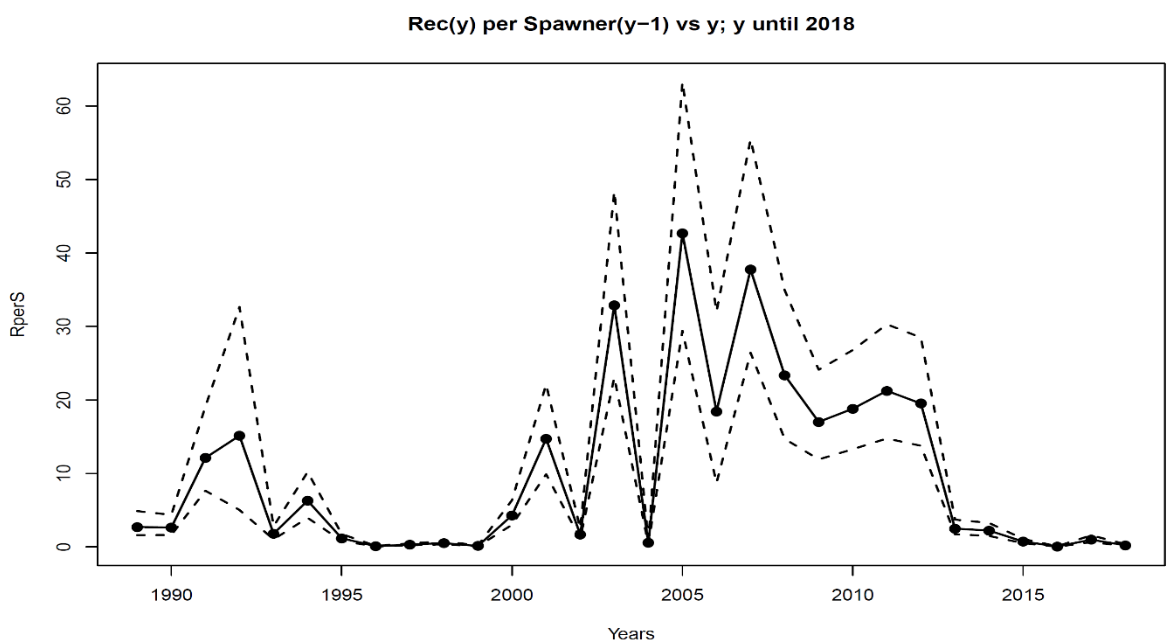


Figure 27. Estimated recruits (age 1) per spawner.

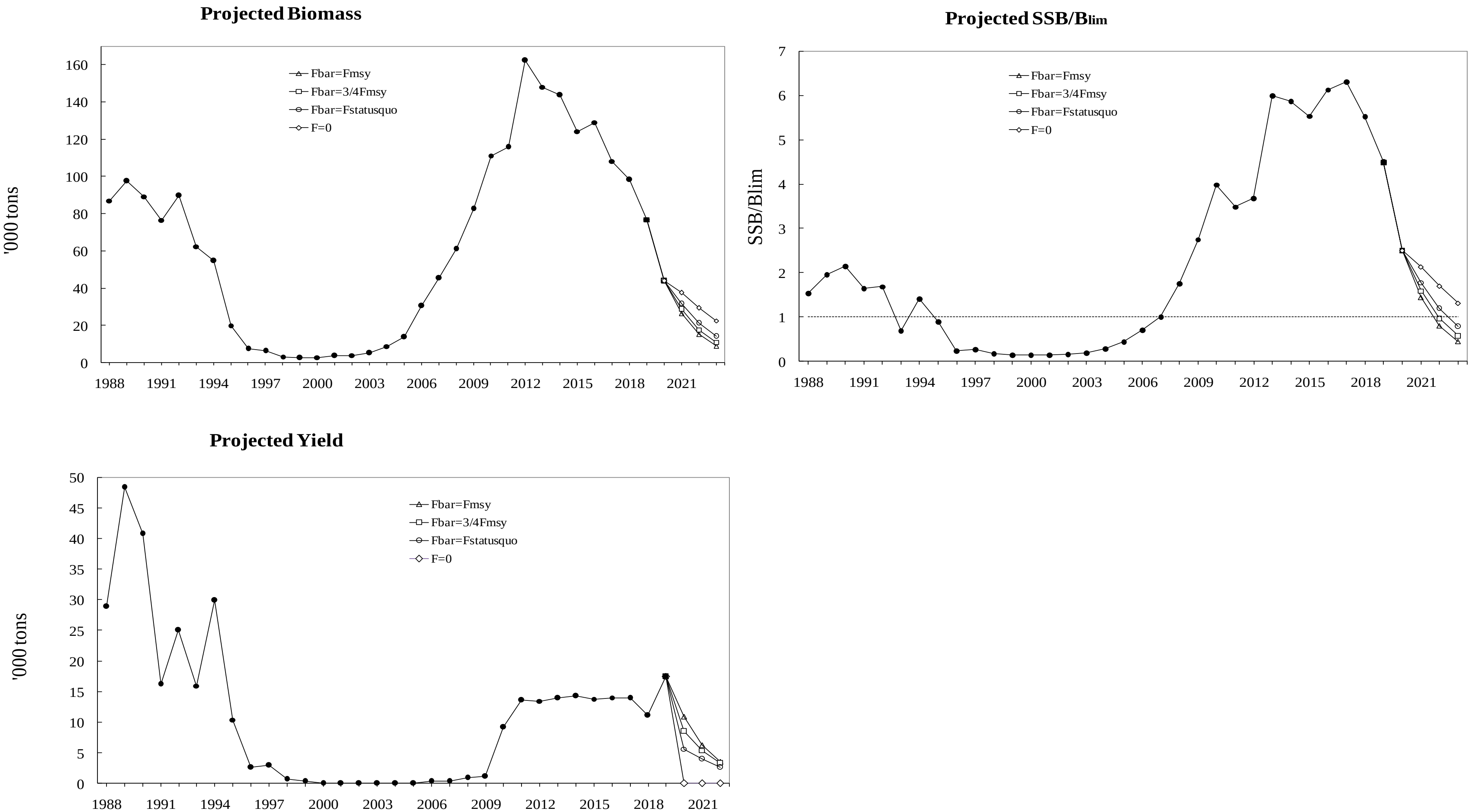


Figure 28. Projections for total Biomass, SSB/B_{lim} and Yield with different scenarios.

ANNEX I

The settings of the Bayesian SCAA model with ages *a* from 1 to A+ and years *y* from 1 (i.e. 1988) to Y (i.e. 2017) are:

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* and *cvrec* are some suitably chosen values.

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

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

$$N[1,A+] \sim LogN\ (\ median = medrec \times \frac{e^{-\sum_{i=1}^{A-1}(M[1,i]+medF[i])}}{1-e^{-(M[1,A+]+medF[A+])}}, CV = cvyear1\ ) \quad \text{for } a=A+,$$

   - *medF[a]*, a=1,…A+, and *cvyear1* are some suitably chosen values.

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

, for *a=2,…,A-1*, $$N[y,a] = N[y-1,a-1]\, e^{-Z[y-1,a-1]}$$

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

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

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, a=aref) =1*, for a chosen reference age *aref*.

   The factors *f[y]* and *rC(y,a)* are modelled as follows:

   a. ln(*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 a Uniform(0,1) prior distribution,
   - *medf* and *cvf* are some suitably chosen values

   b. For each age different from *aref* and A+, ln(*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:

$$rC[1,a] \sim LogN(median = medrC[a], CV = cvrC[a])$$

   - *medrC[a]* and *cvrC[a]* are some suitably chosen values.

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

$$\ln(\ rC[y,a]\ ) \sim N(mean = \ln(\ rC[y-1,a]\ ), CV = cvrCcond)$$

   - *cvrCcond*is a suitable chosen value.

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

$$Cton[y] \sim LogN\left(median = \sum_{a=1}^{A+} mu.C[y,a] \times wcatch[y,a]\,, CV = cvCW\,\right)$$

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

- *cvCW* is some suitably chosen value.

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

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

- *psi.C is some suitable value chosen*

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

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

where

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

,

- *alpha.EU=0.50* and *beta.EU=0.58* correspond to the timing of the survey (July),
- *psi.EU is some suitable value chosen*

<u>Prior on *phi.EU[a]*:</u>

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

- *medlogphi* and *taulogphi* are some suitably chosen values,

<u>Prior ongama.EU[a]:</u>

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* and *taugama*are some suitably chosen values

8. **Natural Mortality** is assumed to be age-dependent but the same in all years, i.e.*M[y,a]=M[a]*, a=1,…,A+, with the following prior distribution by age:

$$\ln(M[a]) \sim N(mean = \ln(medM[a]), CV = cvM)$$

- *medM* and *cvM* are some suitably chosen values