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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 catch estimations and the Flemish Cap survey indices have been used to fit the model. B_{lim}, estimated as the SSB of 2007, gives a median of 15 271 t with the results of this assessment. Results indicate a general increase in SSB since 2005 to the highest value in 2017, decreasing sharply since then. SSB has been above B_{lim} since 2008. Between 2013 and 2018 recruitment was at very low levels, being in 2016 and 2018 among the lowest of the series; as a consequence, 5-year projections indicate that total biomass will decrease during the projected years, while the SSB could increase under some scenarios in the final projected year. Depending on the projected scenario, probability of SSB being below B_{lim} in 2022 and 2023 is very high (≥24%) or very low (≤10%). An increase in recruitment occurred in 2019, reaching the 2008 level.

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.*, 2019) 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 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. Between 1998 and 2008, almost coinciding with the fishing moratorium, yearly catches were below 1 000 tons, being lower than 100 tons from 2000 to 2005, mainly attributed to by-catches from other fisheries. Estimated commercial catches in 2006-2009 were between 339 and 1 161 tons, 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 following years assessments TACs for 2011-2019 between 9 280 and 17 500 tons were established. The STACFIS estimated catches for 2010-2019 were between 9 291 and 17 520 tons (Table 1A and Figure 1).

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 in the period 2003-2007. 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 with a Bayesian SCAA (statistical catch-at-age), that has been being used since then. Another important change introduced at the benchmark is the prior median 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 input data until 2019.

Material and Methods

<u>Data used</u>

<u>Commercial data</u>

<u>Total Catch</u>

In 2019 there were catches of 3M cod from EU-Estonia, EU-Portugal, EU-Spain, Faroe Islands (Denmark), Japan, Norway, Russia and St Pierre and Miquelon (France) with a total amount of 17 520 tons from the WG-CESAG estimates (Table 1A, Figure 1).

In 2010 the fishery on this stock was reopened after the moratorium period between 1999 and 2009. Since then, STACFIS estimated catches were used for the stock assessment. To know more details, see González-Costas *et al.* (2018) and NAFO (2018b). Between 2010 and 2012, only trawler vessels were present in the fishery; since 2013, longliners from Faroes and Norway were incorporated to the direct fishery with a variable presence depending on the year. Since 2017, the Faroese fishery has been exclusively conducted by longliners. Since 2016, Norwegian vessels alternate both gears between years, going one year only with trawl and the next year only with longline. This makes that the proportion of trawlers and longliners is variable among the years, ranking since 2013 between 16% and 49% (Table 1B).

<u>Length distributions</u>

In 2019 length sampling of catch was conducted by EU-Estonia (SCS 20/06), EU-Portugal (SCS 20/09), EU-Spain (SCS 20/07), Faroe Islands (SCS 20/08) and Norway (Kjell, personal communication). Length frequency distributions from the commercial catch and from the EU survey (González-Troncoso *et al.*, 2020) are shown in Figure 2A.

EU-Estonia has measured 1479 individuals in a range of 35-126 cm, with mean in 62 cm and mode in 64 cm. The sample of EU-Portugal contains 6324 individuals measured within 36-96 cm, mean 57 cm and mode in the range 60-63 cm. EU-Spain has a 2297 individuals sample in a range of 38-130 with a mode in 64 cm and mean in 65 cm. Faroe Islands has catch only with longliners, measuring 4552 individuals with lengths between 39 and 135 cm. The mean and modal length are at 74 cm. For Norway, a mode in 58 and a mean in 63 cm over a range of 30-115 cm can be seen for a total of 1631 measured individuals. The mean length of the total commercial catch is at 62 cm and the mode at 60. The EU survey has a clear mode at 19-23 cm, following with two lower modes around 60 and 44 cm. The range is from 13 to 126 cm and the mean is at 44 cm.

It is remarkable the difference in the length distributions from 2017 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 2019 the mode and the mean decreased a little bit, being 60 and 62 cm respectively, but they are still higher than before 2016.

<u>Indices by age</u>

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. In 2017, ALKs from the survey and from the Spanish commercial fleet were available, but the survey one was used for the same reason stated above. In 2018 and 2019, only the survey ALK was available, and it was used for both commercial and survey indices.

<u>Catch-at-age</u>

Catch-at-age in numbers is presented in Table 2. To get this numbers, the available length distributions for trawlers weighted to the total trawl catch, on one hand, and the length distribution for the longliners weighted to the total longliner catch, on the other hand, were added to get the total commercial length distribution, and age distribution was obtained by applying the trawl EU survey ALK to this total length distribution.

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 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 the period 2015-2019, ages 5 to 7 were the most abundant in the catches.

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. We can follow easily the 2009-2011 cohorts, reaching age 8+ in 2019. The catch of the cohorts from 2012 was very poor. As a consequence, since 2015 all the values of the ages less than 4 are negative. It is remarkable the big catch at age 6 in 2019, that corresponds to the 2013 cohort, that was the first of the weak cohorts, and that had never appeared before. Something similar can be seen in the 2011 cohort, that started with a good recruitment in 2012 but then disappeared until age 5, in 2016.

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

For 2019, mean weight-at-age has been computed using length-weight relationships from the commercial sampling. For this year, there are four commercial length-weight relationships available: EU-Estonia, EU-Portugal, EU-Spain and Faroes. All of them are presenting in Figure 4 besides the 2019 EU survey one. The EU-Spain relationship gives the highest weight for the higher lengths. The Portuguese relationship gives the smallest weight to the same length, and the behaviour is quite different as the rest, being more similar to the longliner Faroese one. The Estonian length-weight relationship was applied to the commercial data to calculate the mean weight-at-age in the catch, giving a status-quo vision.

Mean weight-at-age for 1988-2019 is showed in Table 3 and Figure 5. In the period 2007-2017 there is a general decrease in the trend of the mean-weight for the ages older than 2, especially since 2010. In 2018 and 2019 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.

The SoP (sum over ages of the product of catch weight-at-age and numbers at age) for the commercial catch differs 1% from the estimated total catch in 2019.

<u>EU survey data</u>

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 of this stock, 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 1988-2019 are presented in González-Troncoso *et al.* (2020).

The survey abundance indices besides the total biomass are presented in Table 4. Figure 6 displays the estimated survey biomass and abundance indices over time. Biomass and abundance showed 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.*, 2020). Since 2012, taking out the 2014 and 2015 values, both biomass and abundance have decreased, due mainly to the failure of the recruitment. In 2019, the decrease in biomass is higher than in abundance, because an increase in the recruitment in the survey.

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 2014-2019 presented a high value, which indicates the strength of the 2006-2010 cohorts. In 2019, a good signal of recruitment can be seen, being the best value since 2012, at the level of the 2006 recruitment, that allowed the recovery of the stock.

Mean weight-at-age

Results are showed in Table 5 and Figure 8. The 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 and 2019 an increase with regards 2017 can be seen in all ages until 6 years old (included), being quite important in some of the ages, as age 3 (from 385 grams in 2017 to 776 gram in 2019). For age 8, a rather decrease occurs, being in 2019 the lowest of the time series.

Maturity at age

Maturity ogives are available from the EU survey for years 1990-1998, 2001-2006 and 2008-2019. 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.

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 2016, being since then quite irregular for ages 5-6 and increasing for age 4.

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 since then quite stable with ups and downs.

Assessment methodology

A Bayesian SCAA model was applied to the data. Ages are from 1 to A+=8+ and years are from 1988 to 2019. 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, 2018a). 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 32 years, from 1988 to 2019

Catch in tonnes in all years; Years with catch-at-age: 1988-2001, 2006-2019

Tuning with EU survey for 1988 to 2019

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 in the medium term. 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 2020 was calculated using the numbers estimated by the assessment at the beginning of 2020, applying the maturity ogive and mean weight at age in stock from 2019.

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 2019 the biomass is at the level of the beginning of the series.

The results for SSB indicate that there was a substantial increase in SSB from 2007. After a small decrease in 2011 and 2012, the SSB between 2013 and 2017 was stable. A substantial decrease since 2018 is displayed, mainly in 2020, although the SSB is still at the highest level of the historical series (starting in 1988) and above B_{lim}. The high values of SSB in the period 2013-2017 were 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. In 2019 an increase can be seen, reaching the level of 2008 recruitment.

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 and it was below F_{lim}. Since then until 2018, fishing mortalities slightly decreased. A considerable increase occurred in 2019, reaching the level of the pre-collapse period and being above F_{lim}. Table 8 and Figure 11 provide more detailed information on the estimated F-at-age values. Since 2010 the F-at-age has increased for all the ages, and with the age. In 2019, high F values at ages 4-6 can be seen. Figure 12 shows the PR along the years, calculated as the ratio of fishing mortalities to F_{bar}. Figure 13A shows the median PR for the years since the reopening of the fishery (2010-2019) and Figure 13B the mean of the three last years (2017-2019) PR *versus* the 2019 PR. In general, except 2018 and 2019 PRs, all the years have a similar and increasing PR. In the case of the 2018 and 2019 PRs, age 6 was the most caught age. The difference between both years is that in 2018 ages 7 and 8+ are the second most caught, being age 4 in the case of 2019. The mean PRs of the last three years is slightly different to the 2019 one, mostly 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 2019, the level of *f* is similar to that in 1999. 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 variable since then, reaching in 2019 a value comparable to the first years of the observed period. For ages 6 and 7 an increasing trend can be observed since 2006, broken for age 7 in the last two years.

Figure 15 shows total biomass and abundance by year. In general, there is a good concordance between biomass and abundance, although between 2012 and 2018 abundance decreased in a more extent than biomass. In 2019, the decrease in biomass continues, but an increase in the abundance can be seen. Both total biomass and abundance are in 2019 close to the mean values of the series.

Estimates of stock abundance at age for 1988-2019 are presented in Table 9 and Figure 16. It can be seen a general increasing trend in the total number of matures until 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 and 2019), followed by the 2011 cohort (reaching 8 years old in 2019). 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 2014-2016, which is the driver to the huge increase in the SSB in those years. The failure in recruitment since 2013 gave low numbers in ages 2-5 in the most years, which led to the decrease in the SSB.

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

The stock-recruit scatter plot can be seen in Figure 23. 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 (NAFO, 2019).

In this way, for the present assessment 1000 values of B_{lim}, one for each iteration, are considered, with a median value of 15 271 tons, and an 80% confidence interval between 13 551 and 17 611 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 2017-2019 data as 0.191. 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 2017-2019 as well as the value of F_{lim} and $F_{statusquo}$ (defining the latter as the mean fishing mortality over 2017-2019).

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. Between 2007 and 2018 a decreasing trend can be seen, reaching since 2013 very low values. The 2019 value is the highest since 2013, although it is much lower than those between 2005 and 2012.

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 2020 to 2024 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 2020: estimated from the assessment.

Recruitments for 2020-2023: Recruits per spawner were drawn randomly from 2016-2018. The 2019 value of recruits per spawner was omitted due to uncertainty in estimating the recruitment.

Maturity ogive for 2020-2023: Mean of the last three years (2017-2019) maturity ogive.

Natural mortality for 2020-2023: Natural mortality from the 2019 assessment results.

Weight-at-age in stock and weight-at-age in catch for 2020-2023: Mean of the last three years (2017-2019) weight-at-age.

PR at age for 2020-2023: Mean of the last three years (2017-2019) PRs.

F_{bar}(ages 3-5): Four scenarios were considered:
(*Scenario 1*) $F_{bar}=3/4F_{lim}$ (median value = 0.143).
(*Scenario 2*) $F_{bar}=0$ (no catch).
(*Scenario 3*) Catch in 2021-2023=1000 tons.
(*Scenario 4*) Catch in 2021-2023=3000 tons.

All scenarios assumed that the Yield for 2020 is the established TAC (8 531 t).

Results for the four options are presented in Tables 11-18 and Figure 28. They indicate that under all scenarios, total biomass during the projected years will decrease sharply, while the SSB will increase slightly in 2023 and 2024 with the F=0 and the Catch=1000 tons scenarios. The probability of SSB being below B_{lim} in 2022 and 2023 is very high (≥24%) in the scenarios with $F_{bar}=3/4F_{lim}$ and Catch=3000 tons, being very low (≤10%) in the rest of the cases. The probability of SSB in 2024 being above that in 2020 is <1%.

Under all scenarios, the probability of F exceeding F_{lim} is less than or equal to 6% in 2022 and 2023, and less or equal to 11% in 2024.

Under $3/4F_{lim}$, the projected Yield has a decreasing trend in the projected years (2021-2023).

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Table 1A. Total commercial cod catch in Division 3M. Reported nominal catches since 1960 and estimated total catch from 1988 to 2019 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	726		2972			1043			1040	11176
2019	17520	6319	1132	2296	13				1643			1607	13010

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

Table 1B. Trawlers and longliners catches since the reopening of the fishery in 2010

Year	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Total catch	9192	9794	9003	13985	14290	13785	14023	13928	6447	17520
Total trawler	9192	9794	9003	10095	12034	10125	10208	10762	4210	12968
Total longliner	0	0	0	3889	2256	3659	3814	3166	3166	4552
% longliner	0	0	0	28	16	27	27	23	49	26

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
2019	0	2	676	191	1752	2656	188	2044

Table 3. Weight-at-age (kg) in catch.

	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
2019	0.078	0.365	0.802	1.158	1.528	1.940	2.150	4.056

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	18	19	Total Abundance	Total Biomass
1988	4868	79905	49496	13448	1457	211	225	72	0	0	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	0	0	198363	114050
1990	2303	12348	5121	16952	15834	4492	340	146	77	25	0	0	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	0	0	183181	40248
1992	71533	41923	5578	2385	385	1398	244	14	0	0	8	0	0	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	0	0	176693	60963
1994	3017	4130	27756	5097	130	67	7	111	0	5	0	0	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	0	0	19567	9695
1996	36	3121	6659	892	2407	192	8	5	0	0	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	0	0	9837	9966
1998	23	83	95	1256	1572	78	146	0	6	0	0	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	0	0	1507	2854
2000	178	16	327	198	96	446	172	11	17	0	0	5	0	5	0	0	0	0	0	1470	3062
2001	473	1990	13	122	79	15	142	99	6	6	6	0	0	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	0	0	2261	2496
2003	684	54	628	134	22	42	7	8	39	24	0	0	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	0	0	4226	4071
2005	8069	16	1118	78	709	136		17	16	8	0	0	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	0	0	25965	12505
2007	3917	11620	5022	21	1138	58	425	74	13	20	0	0	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	0	0	41124	43676
2009	5139	7479	16150	14310	4154	26	1091	0	335	0	0	14	0	0	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	0	0	117810	69295
2011	347674	142999	16993	6309	7739	3089	1191	0	215	0	89	0	0	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	0	0	266720	113227
2013	5525	67521	32339	4776	4185	2782	1807	963	278	40	29	32	5	0	0	0	0	0	0	120280	72289
2014	7282	2372	48564	43168	17861	6842	3447	1931	1551	600	79	54	8	0	0	0	0	0	0	133760	159939
2015	1141	12952	7250	25614	14107	21854	3434	1426	762	366	194	14	21	21	0	7	0	0	0	89164	114807
2016	56	4485	14356	2230	14540	12375	4814	1157	522	303	145	28	20	0	0	0	0	0	0	55032	80583
2017	2010	314	6516	16645	3267	15842	8519	2765	789	345	137	53	27	6	7	0	0	0	0	57241	89414
2018	366	4308	309	6082	12996	3447	7090	3933	1046	306	165	59	10	0		11	8	0	0	40139	75795
2019	11896	1737	5213	295	3252	5733	417	1495	1956	822	122	33	14	7	0	0	0	0	8	33002	42460

Table 5. Weight-at-age (kg) in stock.

	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
2019	0.076	0.278	0.776	1.275	1.733	2.151	2.389	4.043

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

	1	2	3	4	5	6	7	8+	a50
1988	0.053	0.097	0.172	0.286	0.438	0.599	0.742	0.878	5.385
1989	0.053	0.097	0.172	0.286	0.438	0.599	0.742	0.878	5.385
1990	0.053	0.097	0.172	0.286	0.438	0.599	0.742	0.878	5.385
1991	0.019	0.046	0.110	0.246	0.461	0.673	0.829	0.939	5.179
1992	0.002	0.011	0.046	0.181	0.499	0.818	0.953	0.993	5.004
1993	0.001	0.006	0.047	0.280	0.750	0.959	0.995	1.000	4.467
1994	0.000	0.001	0.049	0.655	0.986	1.000	1.000	1.000	3.823
1995	0.000	0.000	0.005	0.801	1.000	1.000	1.000	1.000	3.788
1996	0.000	0.000	0.028	0.666	0.993	1.000	1.000	1.000	3.839
1997	0.000	0.007	0.109	0.670	0.972	0.998	1.000	1.000	3.749
1998	0.000	0.001	0.087	0.872	0.998	1.000	1.000	1.000	3.552
1999	0.000	0.001	0.118	0.898	0.999	1.000	1.000	1.000	3.477
2000	0.000	0.001	0.146	0.959	1.000	1.000	1.000	1.000	3.382
2001	0.000	0.000	0.271	0.997	1.000	1.000	1.000	1.000	3.151
2002	0.000	0.010	0.633	0.997	1.000	1.000	1.000	1.000	2.896
2003	0.000	0.022	0.515	0.979	1.000	1.000	1.000	1.000	2.985
2004	0.000	0.000	0.092	0.966	1.000	1.000	1.000	1.000	3.408
2005	0.038	0.165	0.500	0.830	0.959	0.991	0.998	1.000	2.999
2006	0.000	0.013	0.354	0.959	0.999	1.000	1.000	1.000	3.160
2007	0.000	0.012	0.262	0.916	0.997	1.000	1.000	1.000	3.297
2008	0.000	0.012	0.232	0.883	0.995	1.000	1.000	1.000	3.373
2009	0.000	0.010	0.181	0.829	0.991	1.000	1.000	1.000	3.489
2010	0.000	0.009	0.164	0.810	0.989	1.000	1.000	1.000	3.533
2011	0.001	0.008	0.071	0.424	0.877	0.986	0.999	1.000	4.136
2012	0.000	0.000	0.016	0.572	0.991	1.000	1.000	1.000	3.935
2013	0.003	0.035	0.283	0.802	0.977	0.998	1.000	1.000	3.400
2014	0.000	0.003	0.044	0.397	0.901	0.992	0.999	1.000	4.158
2015	0.000	0.000	0.004	0.113	0.790	0.991	1.000	1.000	4.605
2016	0.000	0.000	0.004	0.046	0.388	0.892	0.991	1.000	5.177
2017	0.000	0.000	0.000	0.017	0.829	0.999	1.000	1.000	4.720
2018	0.000	0.001	0.007	0.067	0.425	0.880	0.986	0.999	5.132
2019	0.000	0.000	0.005	0.083	0.615	0.966	0.998	1.000	4.837

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

	B quantiles			SSB quantiles			R quantiles			F_{bar} quantiles		
Year	**50%**	**10%**	**90%**	**50%**	**10%**	**90%**	**50%**	**10%**	**90%**	**50%**	**10%**	**90%**
1988	86443	82004	91502	23435	19727	27997	64382	49253	86085	0.517	0.474	0.561
1989	97515	92315	102747	29532	25038	34790	127697	98008	168359	0.622	0.578	0.668
1990	89038	84266	93980	32607	28763	36947	114236	87568	151604	0.728	0.680	0.782
1991	75706	70116	83578	24938	22141	28362	387660	301538	519474	0.436	0.397	0.478
1992	88637	82499	96603	25570	23010	28499	314293	239538	417466	1.403	1.305	1.495
1993	62092	58272	66832	10372	9227	11843	21008	16242	27632	0.959	0.894	1.031
1994	54684	51318	58211	21299	18912	24047	38722	30268	50820	1.369	1.294	1.443
1995	19849	18715	21110	13574	12568	14630	16529	12768	21924	1.297	1.214	1.377
1996	7339	6944	7747	3613	3305	3936	1013	780	1351	0.475	0.435	0.518
1997	6215	5867	6573	3995	3694	4302	893	684	1185	0.916	0.840	0.996
1998	3085	2847	3376	2668	2450	2927	1505	1129	1997	0.323	0.285	0.364
1999	2491	2225	2783	2218	1968	2511	222	168	304	0.208	0.18	0.241
2000	2779	2470	3137	2142	1883	2456	4186	3174	5589	0.064	0.054	0.075
2001	3517	3140	3972	2121	1890	2399	9837	7560	13276	0.075	0.061	0.094
2002	3799	3455	4201	2406	2165	2676	941	709	1256	0.020	0.017	0.024
2003	5080	4551	5734	2858	2600	3148	26104	20067	34451	0.006	0.005	0.007
2004	8647	7837	9639	4313	3927	4736	782	607	1039	0.002	0.002	0.002
2005	13610	12156	15436	6550	5884	7393	57351	44040	75720	0.002	0.002	0.002
2006	30239	27003	34826	10685	9801	11737	92470	71884	123731	0.053	0.046	0.061
2007	45198	41106	50169	15271	13551	17611	124907	96600	166591	0.014	0.013	0.016
2008	60970	56042	66981	26720	24690	28938	112222	84915	146288	0.027	0.024	0.031
2009	82210	76031	89814	41661	38614	44958	157699	122556	210698	0.020	0.018	0.023
2010	110805	102528	120266	60689	55915	65978	279370	214102	369261	0.127	0.113	0.141
2011	114435	106207	124198	53173	48874	57388	448234	339592	584405	0.136	0.122	0.152
2012	157532	143841	174315	55602	51280	60506	353125	269933	466687	0.092	0.082	0.104
2013	144393	133711	155692	89851	82769	97786	49710	37771	66127	0.093	0.082	0.105
2014	140542	129967	151786	87884	80074	95471	134083	103811	178036	0.071	0.063	0.082
2015	121196	112101	130516	81973	74395	89855	43591	33496	59287	0.081	0.071	0.092
2016	124576	114785	135335	89152	80704	98448	4184	3126	5549	0.088	0.077	0.101
2017	104070	95380	113616	90145	81710	98923	52636	38910	70033	0.058	0.050	0.066
2018	94605	85559	103382	78010	70284	86387	5210	3761	7427	0.099	0.086	0.112
2019	80172	71765	88531	62397	55192	69233	115337	78662	173384	0.289	0.246	0.344

Table 8. F at age (posterior median).

Year				F at age				
	1	2	3	4	5	6	7	8+
1988	0.000	0.018	0.332	0.584	0.628	0.647	0.780	0.780
1989	0.000	0.011	0.355	0.791	0.715	0.782	0.856	0.856
1990	0.000	0.018	0.378	0.905	0.898	1.220	1.031	1.031
1991	0.000	0.023	0.295	0.471	0.536	0.561	0.662	0.662
1992	0.000	0.140	0.978	1.471	1.753	1.421	1.970	1.970
1993	0.000	0.084	0.666	1.131	1.070	1.523	0.857	0.857
1994	0.000	0.188	0.979	1.745	1.379	1.333	0.988	0.988
1995	0.000	0.178	0.533	1.497	1.861	2.296	2.162	2.162
1996	0.000	0.046	0.241	0.491	0.688	0.910	0.819	0.819
1997	0.000	0.107	0.560	0.829	1.353	2.003	1.830	1.830
1998	0.000	0.041	0.192	0.316	0.453	0.534	0.393	0.393
1999	0.000	0.023	0.221	0.179	0.224	0.222	0.080	0.080
2000	0.000	0.005	0.124	0.026	0.042	0.032	0.010	0.010
2001	0.000	0.007	0.136	0.036	0.053	0.040	0.013	0.013
2002	0.000	0.002	0.034	0.010	0.015	0.011	0.004	0.004
2003	0.000	0.000	0.010	0.003	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	0.074	0.038	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	0.030	0.030
2009	0.000	0.001	0.007	0.025	0.029	0.029	0.033	0.033
2010	0.000	0.011	0.068	0.129	0.182	0.192	0.210	0.210
2011	0.000	0.010	0.086	0.110	0.211	0.275	0.367	0.367
2012	0.000	0.006	0.058	0.074	0.144	0.195	0.286	0.286
2013	0.000	0.006	0.063	0.074	0.142	0.205	0.277	0.277
2014	0.000	0.003	0.033	0.083	0.097	0.163	0.224	0.224
2015	0.000	0.003	0.049	0.083	0.110	0.190	0.223	0.223
2016	0.000	0.004	0.046	0.106	0.113	0.138	0.212	0.212
2017	0.000	0.003	0.026	0.057	0.089	0.150	0.181	0.181
2018	0.000	0.004	0.054	0.093	0.147	0.271	0.186	0.186
2019	0.000	0.004	0.127	0.377	0.362	0.662	0.322	0.322

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	64382	144614	98165	30684	4373	970	708	283	344179	46451
1989	127697	16111	77246	48862	13091	1776	346	325	285452	42968
1990	114236	31996	8623	37444	16936	4872	555	199	214861	32239
1991	387660	28634	17066	4092	11594	5252	983	190	455470	21850
1992	314293	97117	15121	8774	1954	5138	2052	430	444879	11658
1993	21008	79025	45438	3940	1533	258	853	245	152300	6261
1994	38722	5256	39082	16197	968	398	38	329	100989	14220
1995	16529	9780	2334	10231	2190	186	72	93	41415	10716
1996	1013	4113	4389	950	1753	258	13	13	12502	2779
1997	893	254	2126	2396	447	666	70	8	6862	3009
1998	1505	225	123	836	796	88	61	9	3643	1691
1999	222	375	115	70	469	383	35	34	1704	998
2000	4186	56	197	64	45	286	209	45	5087	673
2001	9837	1044	30	121	48	33	189	180	11481	576
2002	941	2475	562	18	89	34	22	255	4397	796
2003	26104	235	1331	375	14	67	23	188	28338	1351
2004	782	6518	127	917	287	10	46	145	8832	1381
2005	57351	196	3506	88	702	218	7	131	62200	5082
2006	92470	14367	106	2417	67	535	149	94	110206	3411
2007	124907	23240	7719	68	1790	49	353	167	158294	4816
2008	112222	31307	12582	5313	52	1340	33	360	163208	9795
2009	157699	27789	16880	8573	3945	38	888	261	216073	15590
2010	279370	39604	15022	11639	6443	2921	25	788	355813	22383
2011	448234	69259	21184	9742	7855	4069	1653	448	562445	19479
2012	353125	111445	37112	13466	6685	4836	2120	1028	529816	22872
2013	49710	88396	59860	24245	9579	4402	2722	1673	240587	57474
2014	134083	12353	47336	38877	17245	6324	2465	2341	261025	44002
2015	43591	33880	6686	31820	27318	11898	3688	2692	161573	43316
2016	4184	11067	18091	4413	22462	18672	6746	3592	89227	35810
2017	52636	1036	5938	12042	3038	15232	11137	5923	106982	34948
2018	5210	13085	560	4012	8704	2112	9024	10073	52780	24733
2019	115337	1301	7041	369	2813	5713	1104	11071	144749	19442

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	1.38	0.61	0.36	0.26	0.27	0.38	0.33	0.39

Table 11. N-at-age in prediction years (medians) with F_{bar}=3/4F_{lim}=0.143 including total number and number of matures.

Year/Age	1	2	3	4	5	6	7	8+	Total	Matures
2020	3065	28711	704	4279	192	1491	2001	6028	52281	9870
2021	1467	745	15521	452	2778	118	691	4081	30859	6745
2022	1020	357	394	10221	305	1809	60	2600	20841	5244
2023	797	248	191	259	6937	198	925	1448	14595	6957
2024	1118	195	133	125	176	4506	102	1318	11018	6132

Table 12. Projections results (median and 80% CI) with F_{bar}=3/4F_{lim}=0.143.

Year	Total Biomass		SSB		P(SSB<B_{lim})	P(SSB_{24} >SSB_{19})	Yield	P(F>F_{lim})
2020	48777	(42258 - 55350)	35725	(30140 - 41365)	<1%		8531	4%
2021	35857	(30252 - 41757)	23121	(18576 - 27867)	1%		5595	5%
2022	26786	(21764 - 32499)	15472	(11920 - 19144)	50%	<1%	4622	6%
2023	19902	(15130 - 25556)	14280	(10838 - 18316)	62%		3494	11%
2024	15396	(10877 - 21078)	13556	(9424 - 18349)	69%			

Table 13. 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
2020	3065	28711	704	4279	192	1491	2001	6028	52281	9870
2021	1467	745	15521	452	2778	118	691	4081	30859	6745
2022	1020	357	395	10825	346	2134	81	3273	22508	6283
2023	956	248	191	274	8313	264	1453	2288	17960	9226
2024	1458	235	134	132	212	6302	181	2619	15032	9306

Table 14. Projections results (median and 80% CI) with F_{bar}=0.

Year	Total Biomass		SSB		P(SSB<B_{lim})	P(SSB_{24} >SSB_{19})	Yield	P(F>F_{lim})
2020	48777	(42258 - 55350)	35725	(30140 - 41365)	<1%		8531	4%
2021	35857	(30252 - 41757)	23121	(18576 - 27867)	1%		0	0%
2022	32245	(27255 - 37930)	20159	(16445 - 23914)	6%	<1%	0	0%
2023	28937	(24157 - 34759)	22321	(18764 - 26370)	1%		0	0%
2024	27386	(22667 - 33174)	25006	(20842 - 29872)	<1%			

Table 15. N-at-age in prediction years (medians) with Catch=1000 tons including total number and number of matures.

Year/Age	1	2	3	4	5	6	7	8+	Total	Matures
2020	3065	28711	704	4279	192	1491	2001	6028	52281	9870
2021	1467	745	15521	452	2778	118	691	4081	30859	6745
2022	1020	357	395	10704	337	2060	76	3119	22136	6047
2023	917	248	191	271	7990	248	1323	2077	17120	8692
2024	1383	225	134	130	203	5839	159	2254	14035	8473

Table 16. Projections results (median and 80% CI) with Catch=1000 tons.

Year	Total Biomass		SSB		P(SSB<B_{lim})	P(SSB_{24} >SSB_{19})	Yield	P(F>F_{lim})
2020	48777	(42258 - 55350)	35725	(30140 - 41365)	<1%		8531	4%
2021	35857	(30252 - 41757)	23121	(18576 - 27867)	1%		1000	<1%
2022	31265	(26251 - 36956)	19317	(15655 - 23065)	10%	<1%	1000	<1%
2023	27176	(22347 - 32982)	20743	(17192 - 24760)	4%		1000	<1%
2024	24680	(19993 - 30474)	22430	(18278 - 27230)	2%			

Table 17. N-at-age in prediction years (medians) with Catch=3000 tons including total number and number of matures.

Year/Age	1	2	3	4	5	6	7	8+	Total	Matures
2020	3065	28711	704	4279	192	1491	2001	6028	52281	9870
2021	1467	745	15521	452	2778	118	691	4081	30859	6745
2022	1020	357	394	10427	319	1913	67	2817	21375	5587
2023	845	248	191	263	7324	217	1063	1670	15506	7565
2024	1216	207	134	126	182	4839	116	1565	11870	6737

Table 18. Projections results (median and 80% CI) with Catch=3000 tons.

Year	Total Biomass		SSB		P(SSB<B_{lim})	P(SSB_{24} >SSB_{19})	Yield	P(F>F_{lim})
2020	48777	(42258 - 55350)	35725	(30140 - 41365)	<1%		8531	4%
2021	35857	(30252 - 41757)	23121	(18576 - 27867)	1%		3000	<1%
2022	29305	(24278 - 35017)	17616	(13964 - 21334)	24%	<1%	3000	<1%
2023	23596	(18837 - 29285)	17549	(14040 - 21560)	24%		3000	<1%
2024	19249	(14646 - 24980)	17264	(13095 - 22048)	30%			

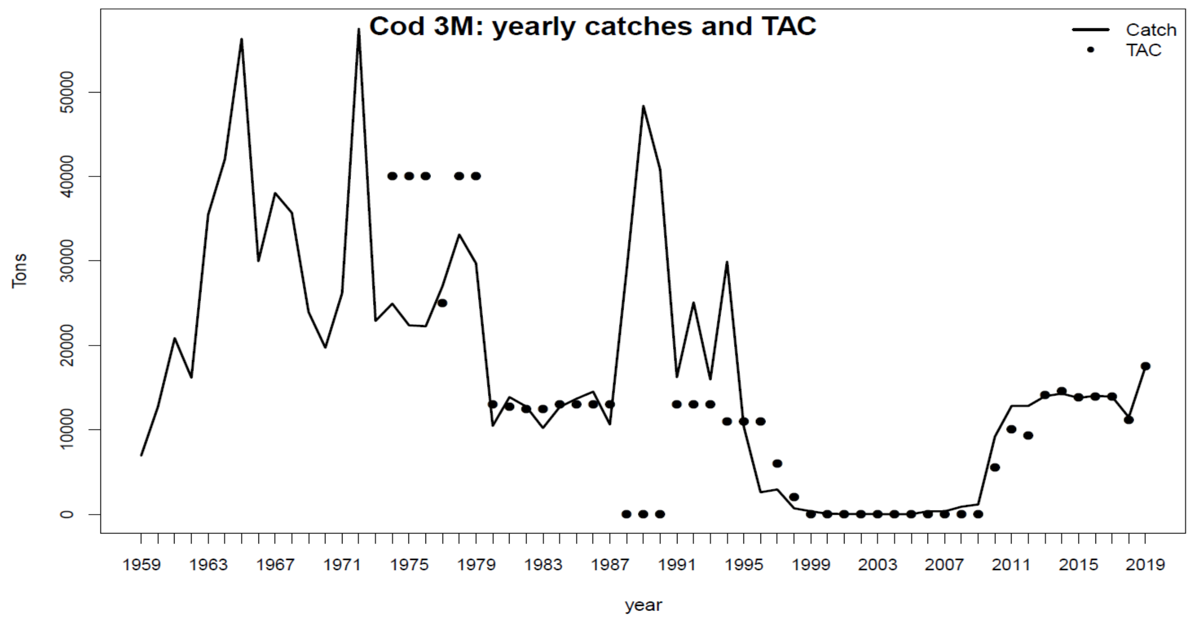
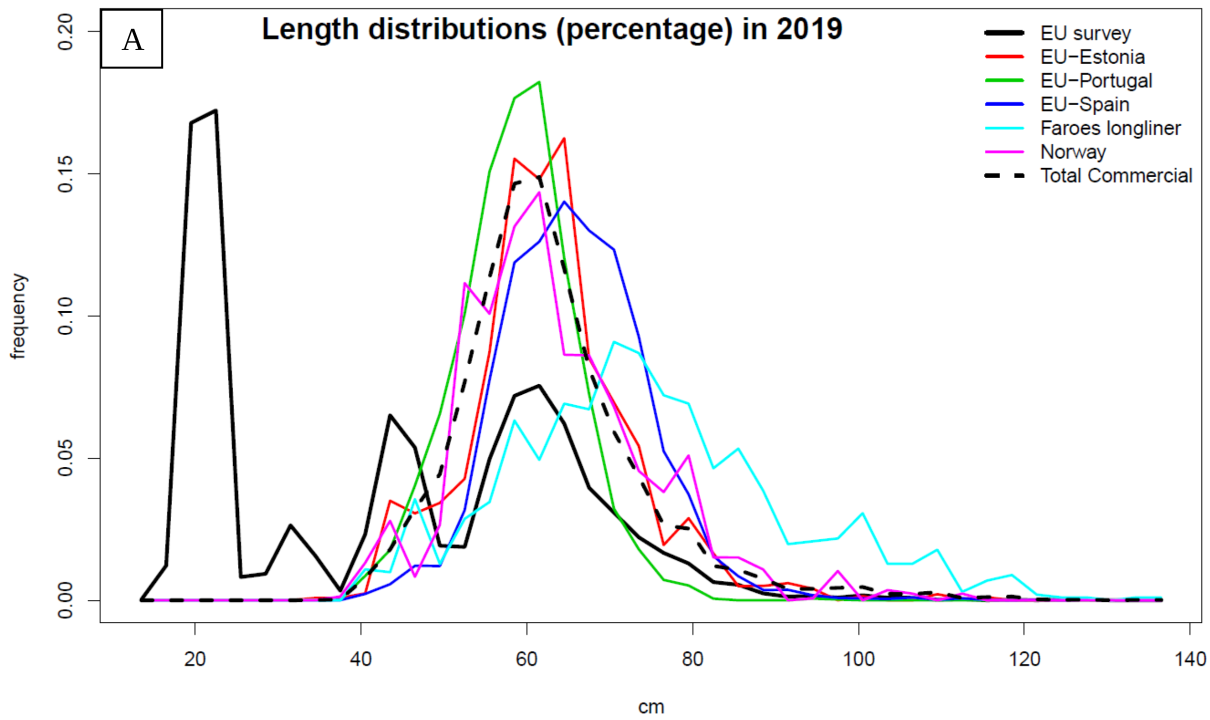


Figure 1. Catch and TAC of the 3M cod for the period 1959-2019.



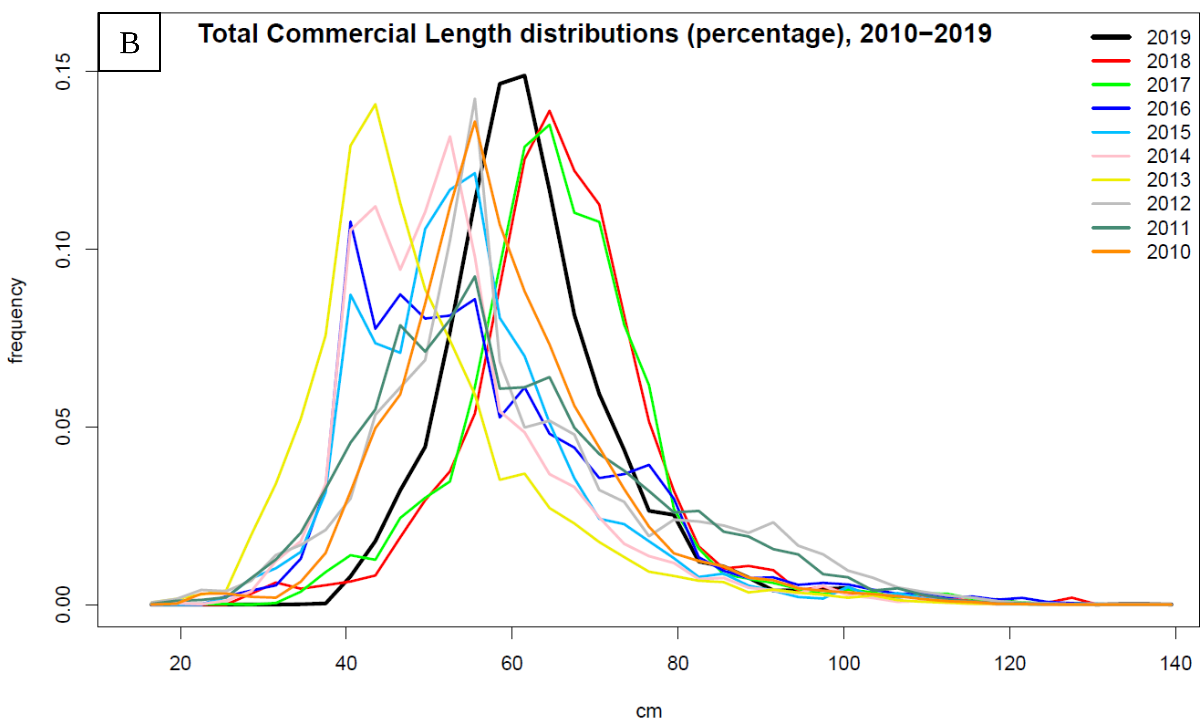


Figure 2. Length frequencies in commercial catches and EU survey in 2019 (A), and for the last fishery period (2010-2019) and the total commercial (B).

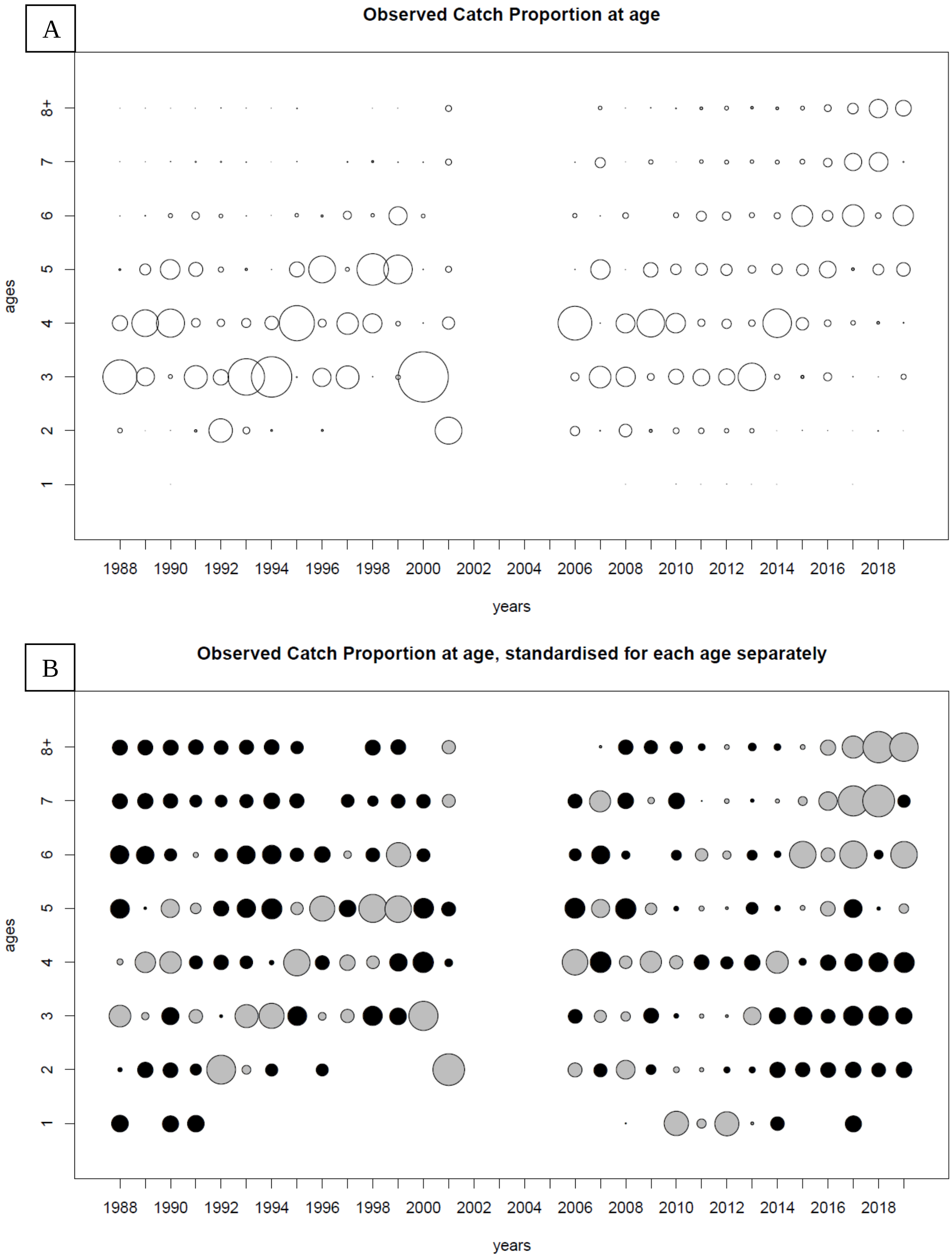


Figure 3. Commercial catch proportions at age (A) and standardised proportions at age (B). In B, grey and black values indicate values above and below the average. The larger the bubble size the larger the magnitude of the value.

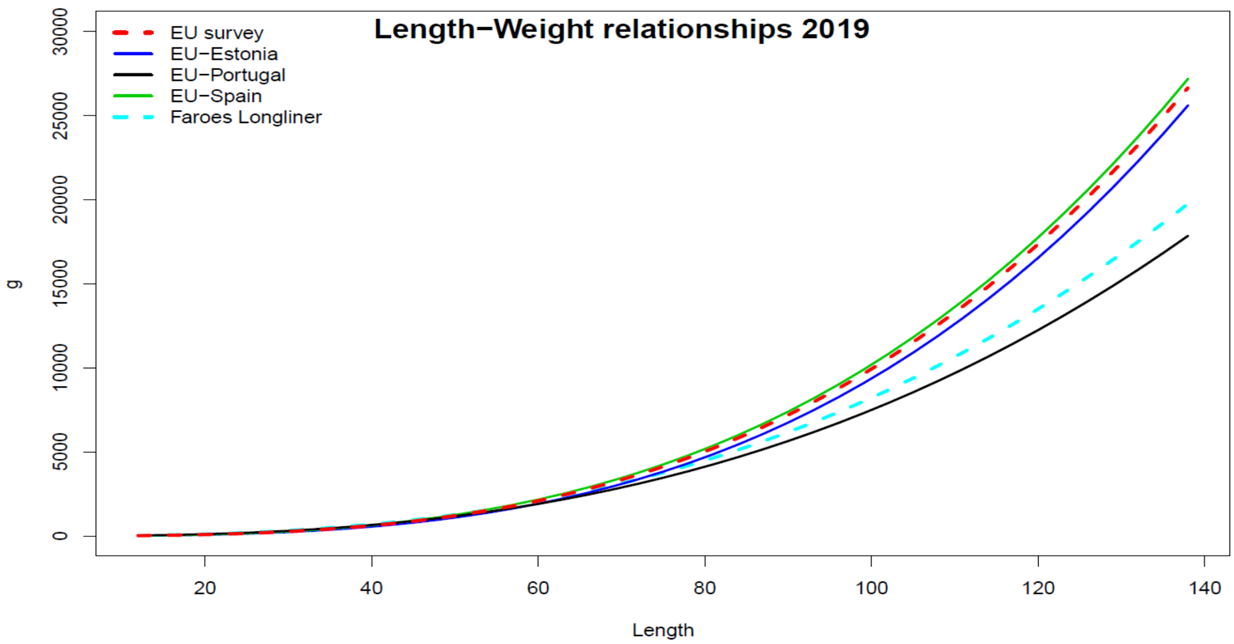


Figure 4. Length-weight relationships for commercial catches and EU survey in 2019.

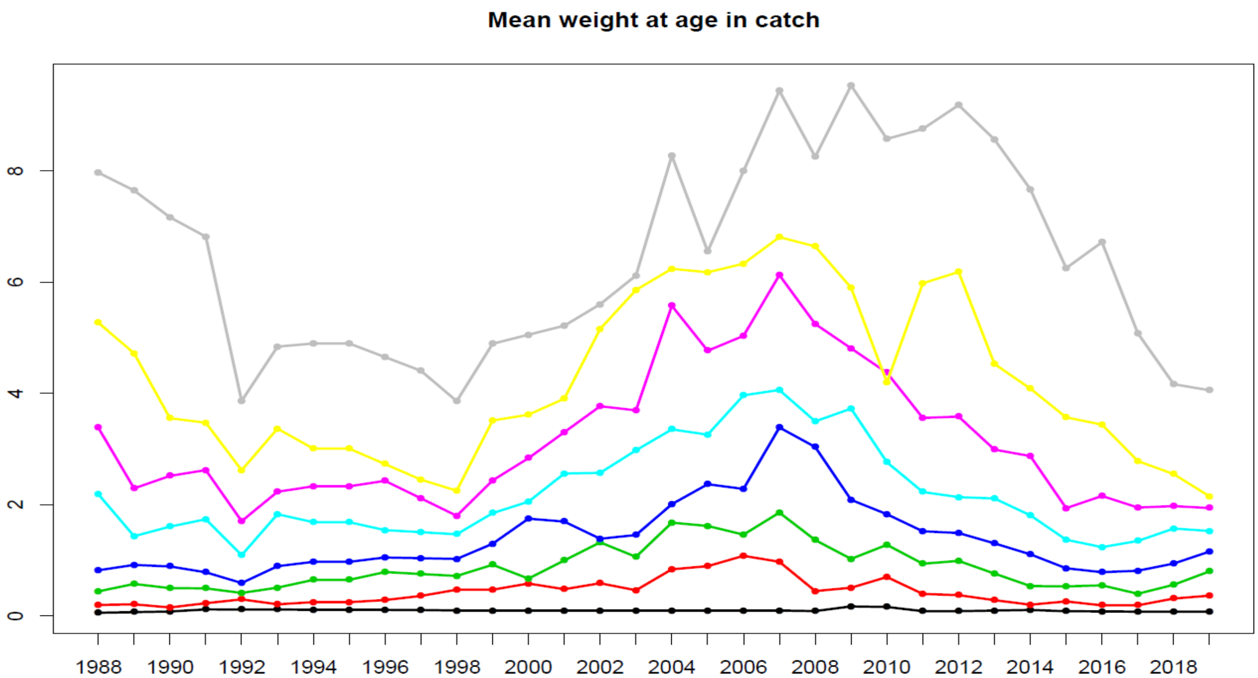


Figure 5. Catch mean weight at age.

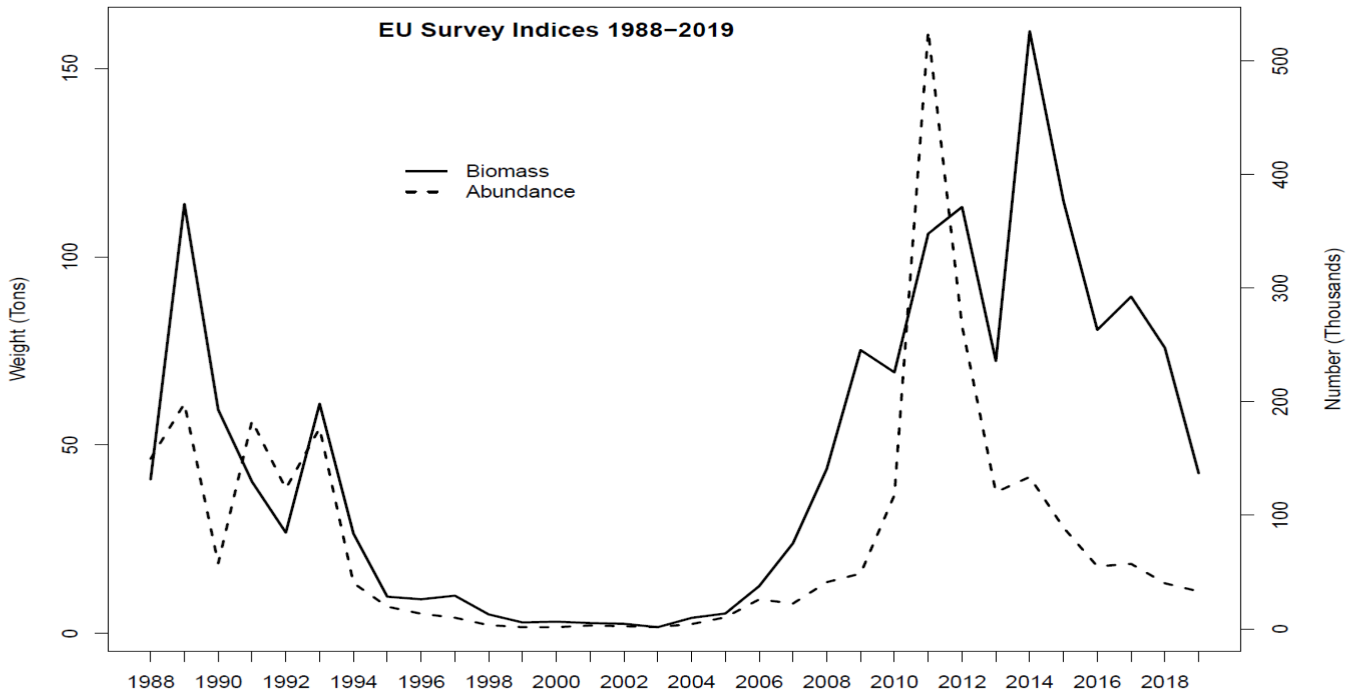


Figure 6. Biomass and abundance from EU surveys.

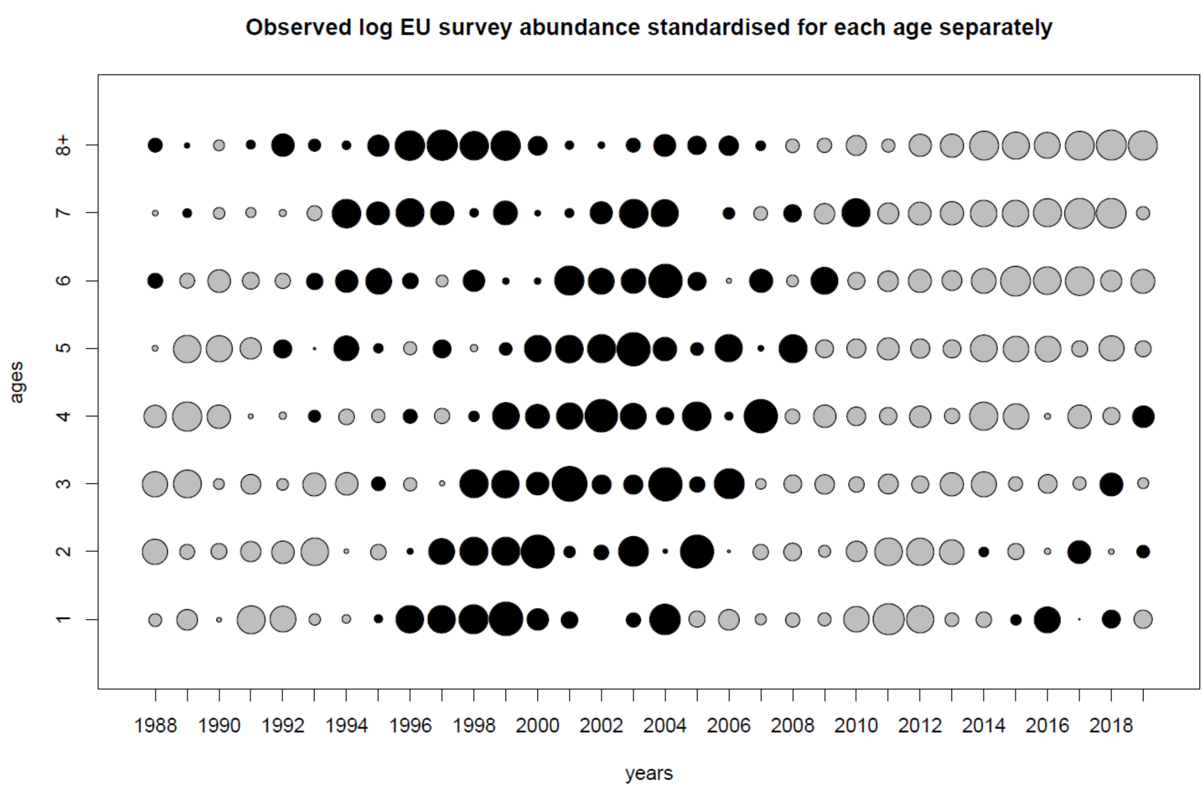


Figure 7. Standardised log(Abundance at age) indices from EU survey. Grey and black values indicate values above and below the average. The larger the bubble size the larger the magnitude of the value.

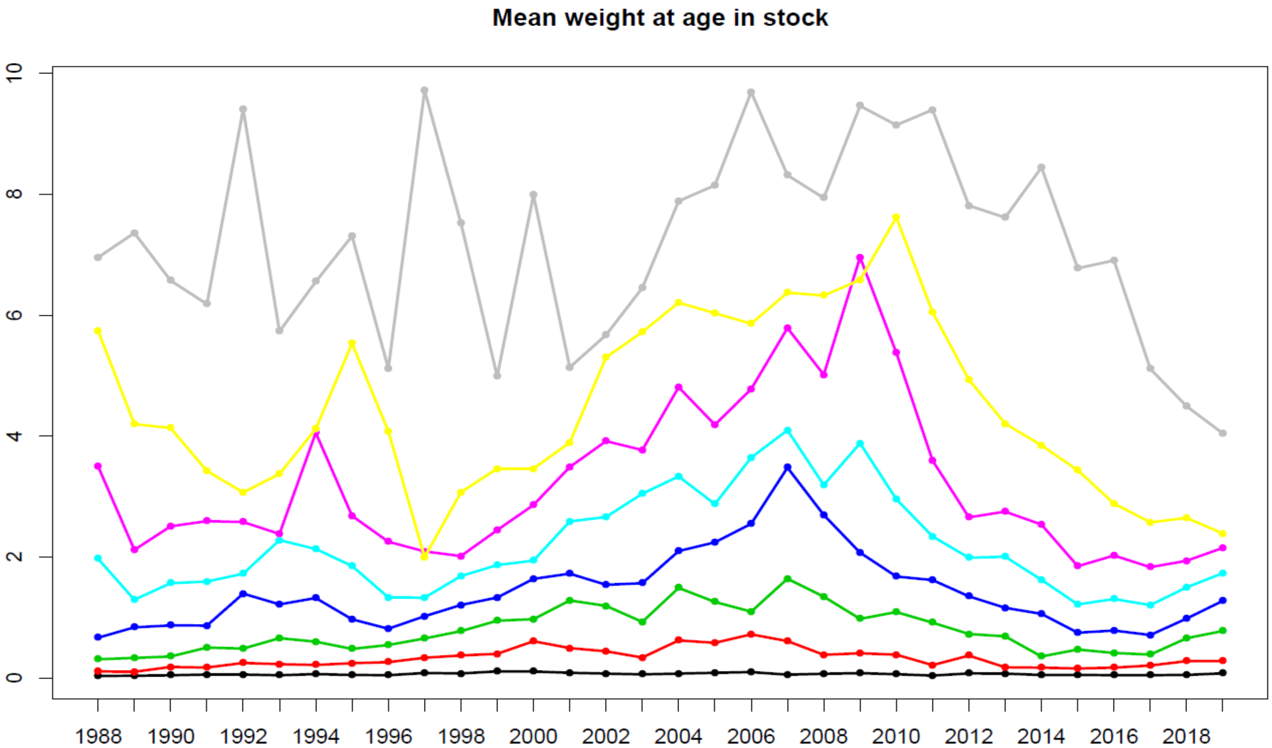
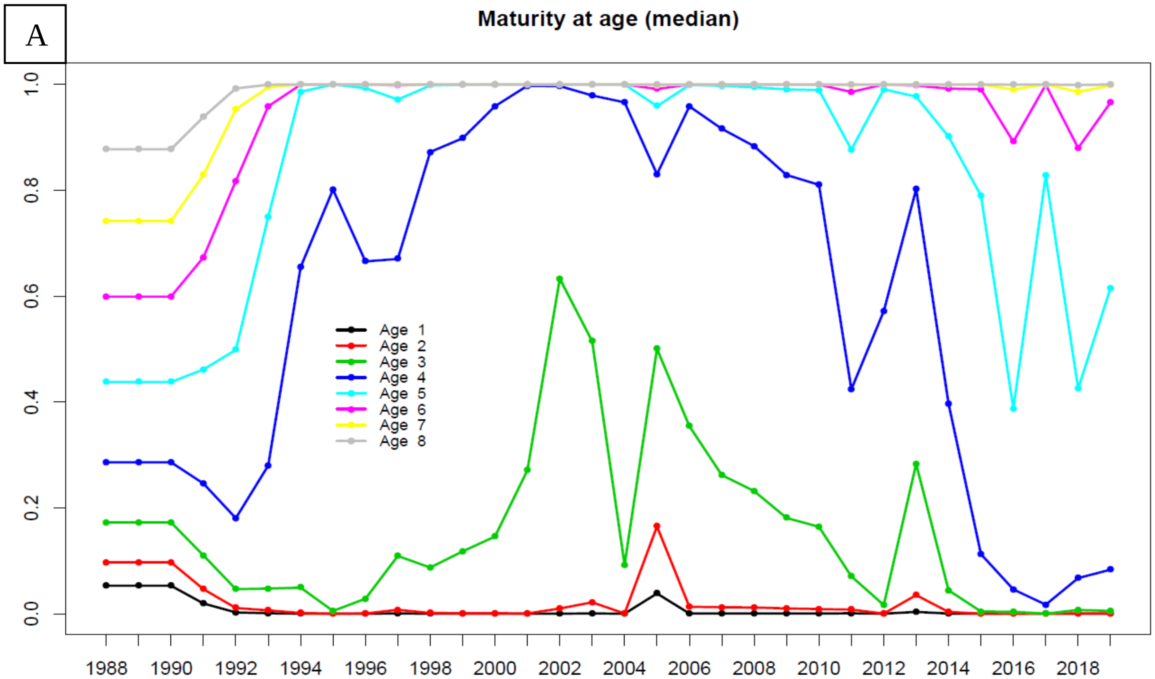


Figure 8. Stock mean weight at age.



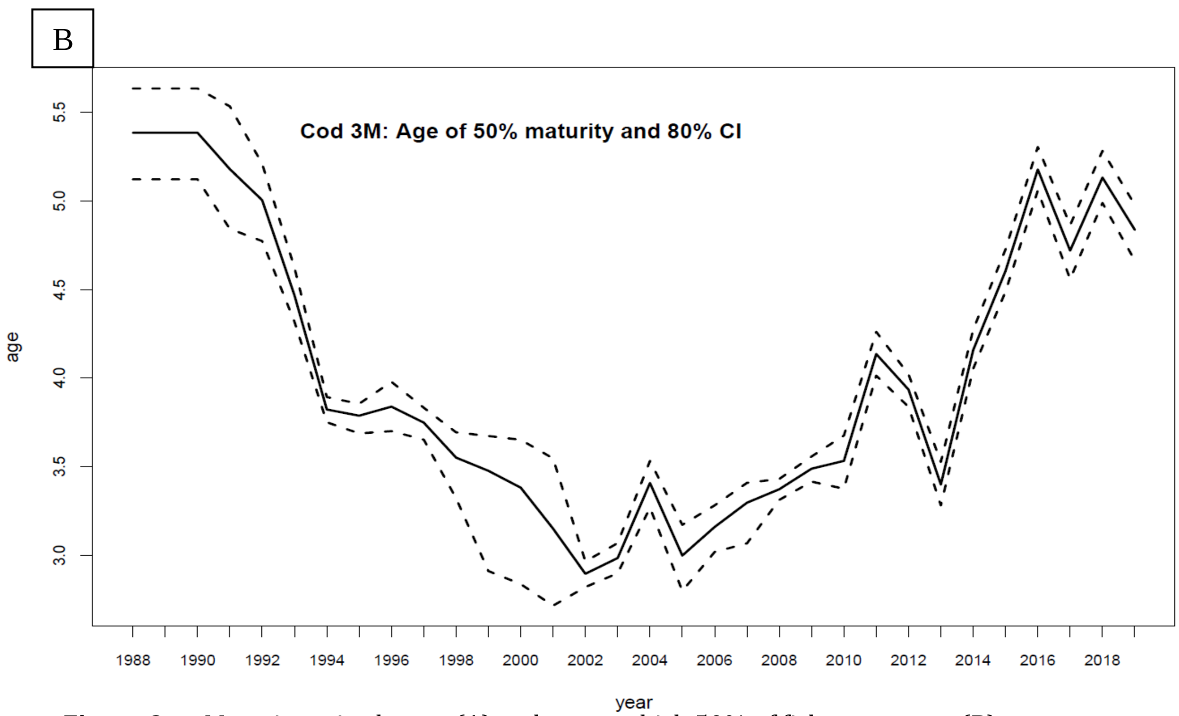


Figure 9. Maturity ogive by age (A) and age at which 50% of fish are mature (B).

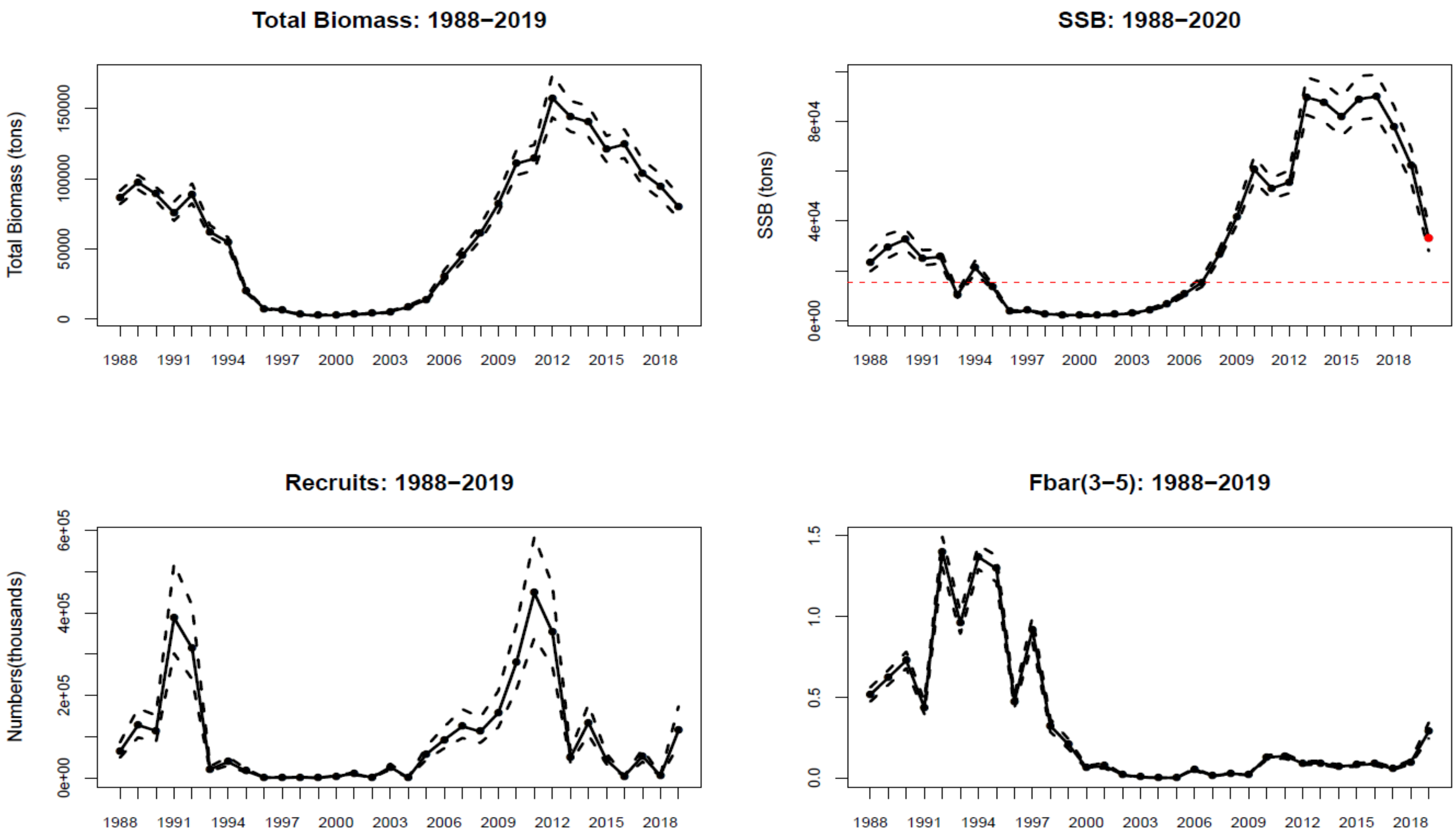


Figure 10. Estimated trends in biomass, SSB, recruitment and F_{bar}. The solid lines are the posterior medians and the dashed lines show the limits of 80% posterior credible intervals. Red point in the SSB plot indicates the SSB in 2020. Red horizontal line in the SSB graph represents median B_{lim} = medianSSB_{07} = 15 271 tons.

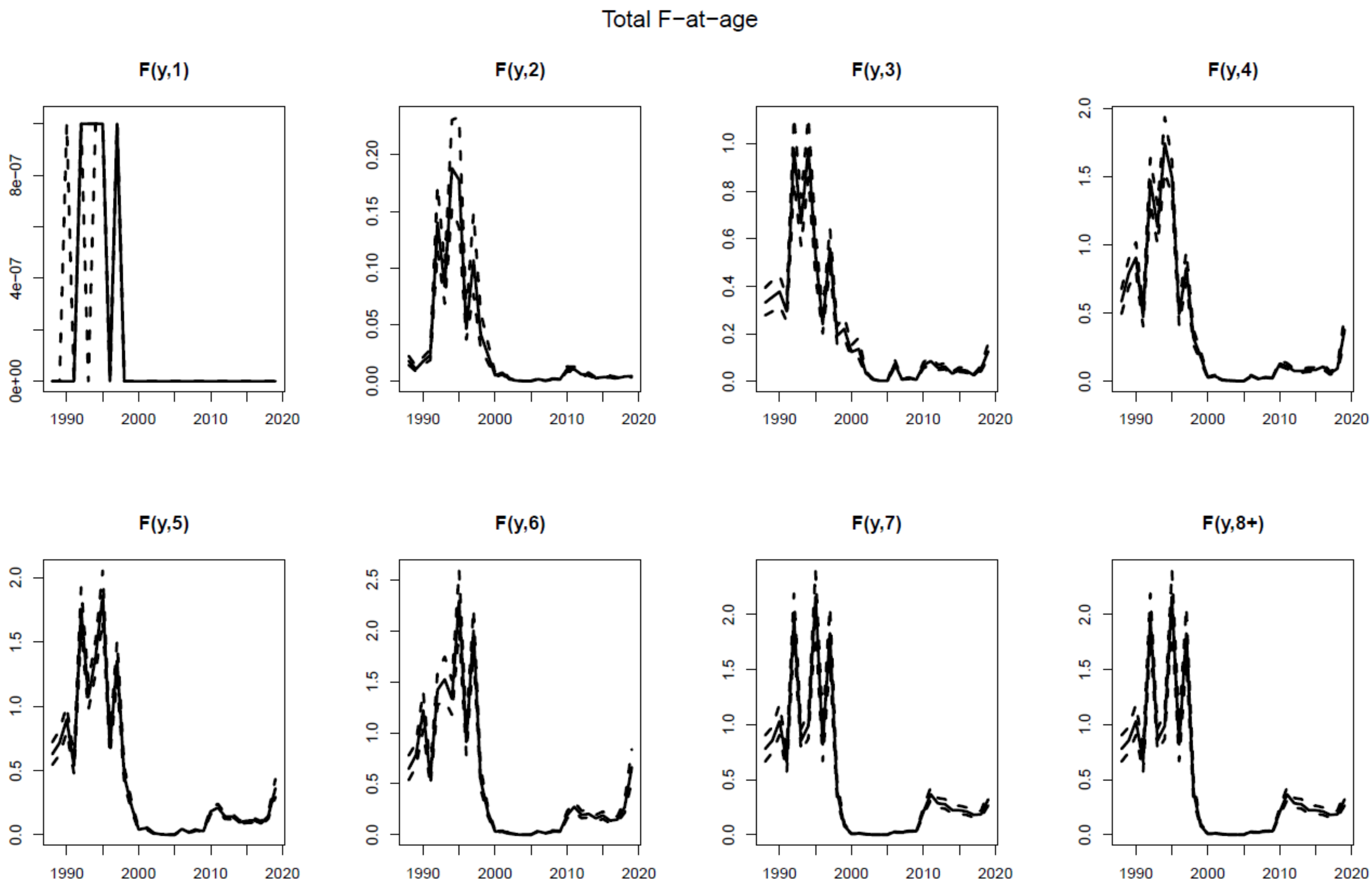


Figure 11. Estimated fishing mortality at age. The y-axis scale is different in all the graphs.

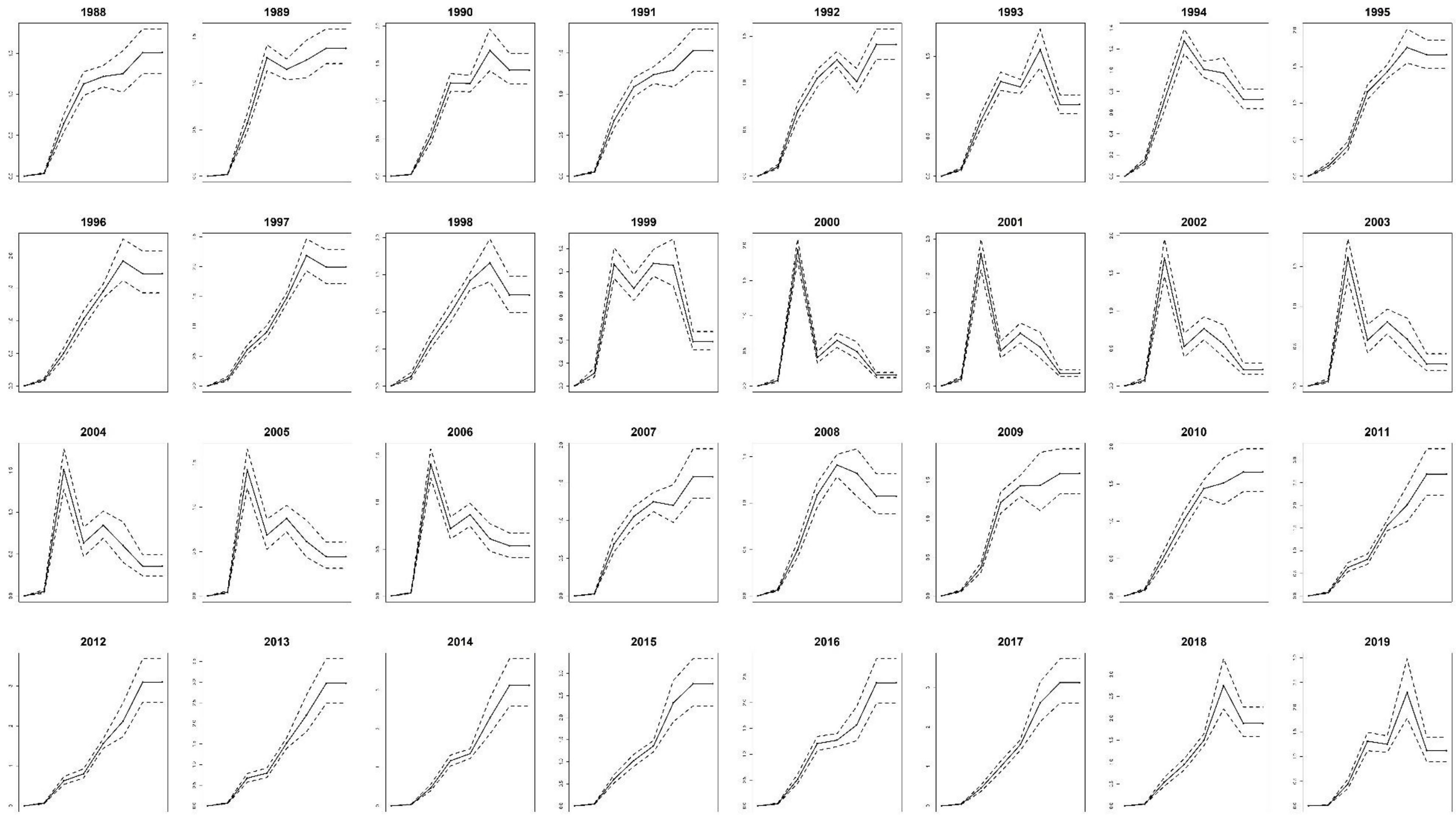


Figure 12. Estimated PR (F/F$_{bar}$) per age and year. The y-axis scale is different in all the graphs.

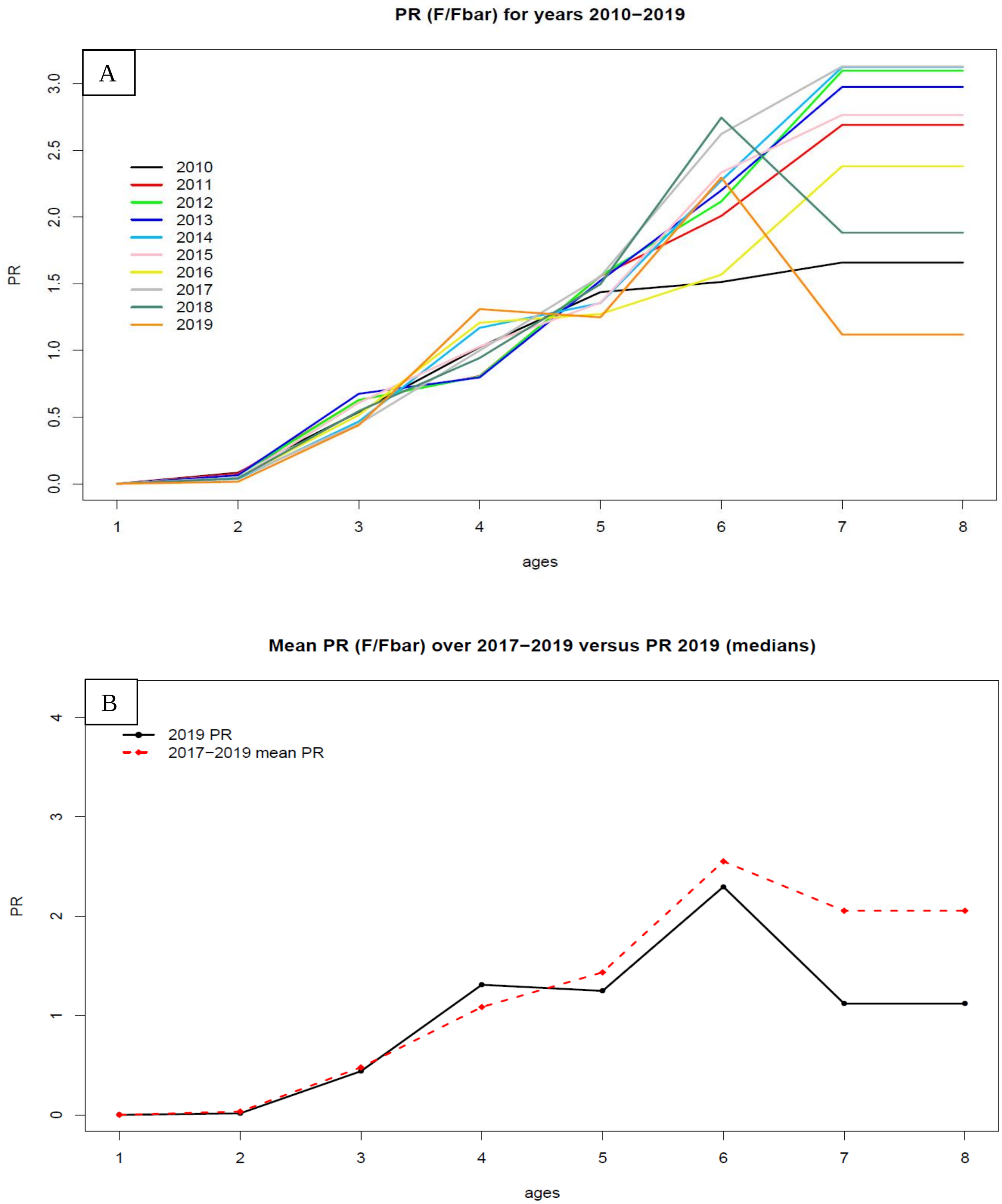


Figure 13. A) Estimated PR (F/F_{bar}) per age for the last ten years and (B) mean of 2017-2019 PR versus 2019 PR (posterior medians).

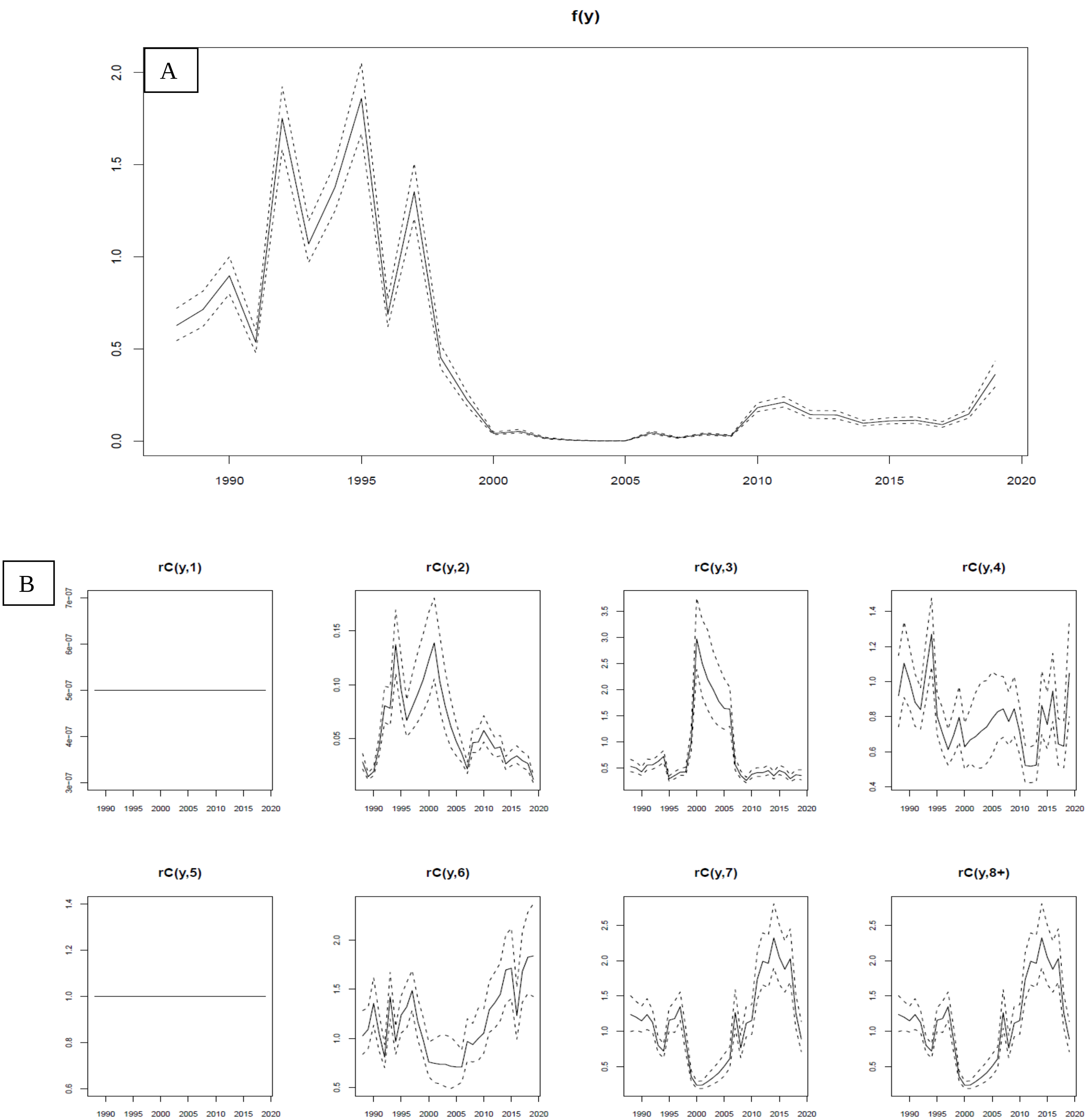


Figure 14. Components of the semi-separable model for Fishing Mortality: F[y,a]=*f*[y]**rC*[y,a].

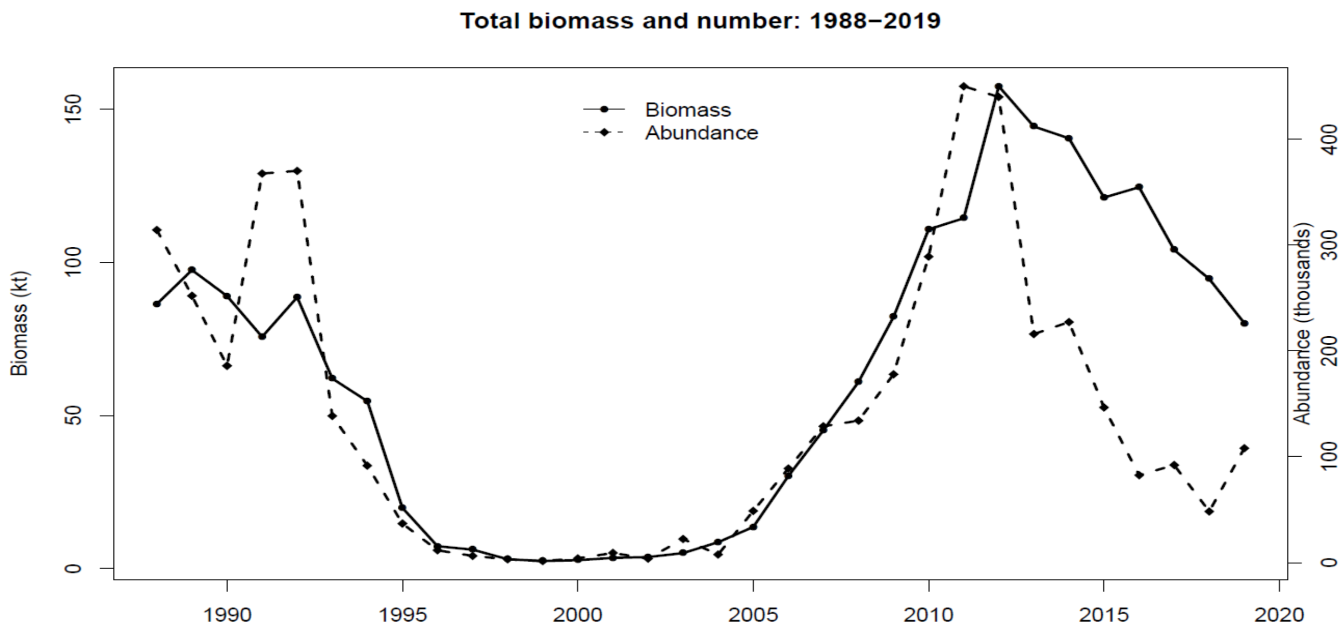


Figure 15. Estimated trends in biomass and abundance.

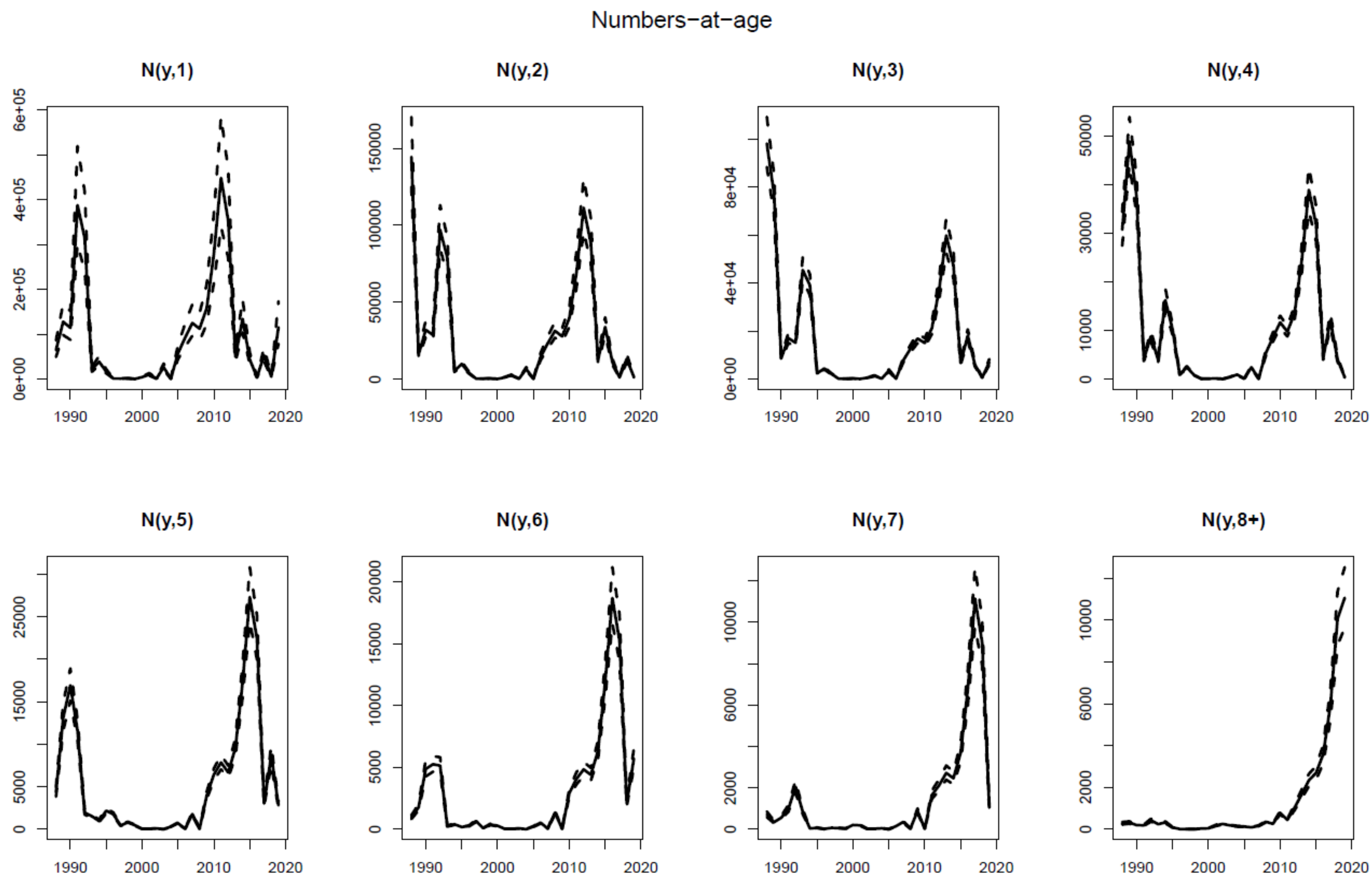


Figure 16. Estimated numbers at age. The y-axis scale is different in all the graphs.

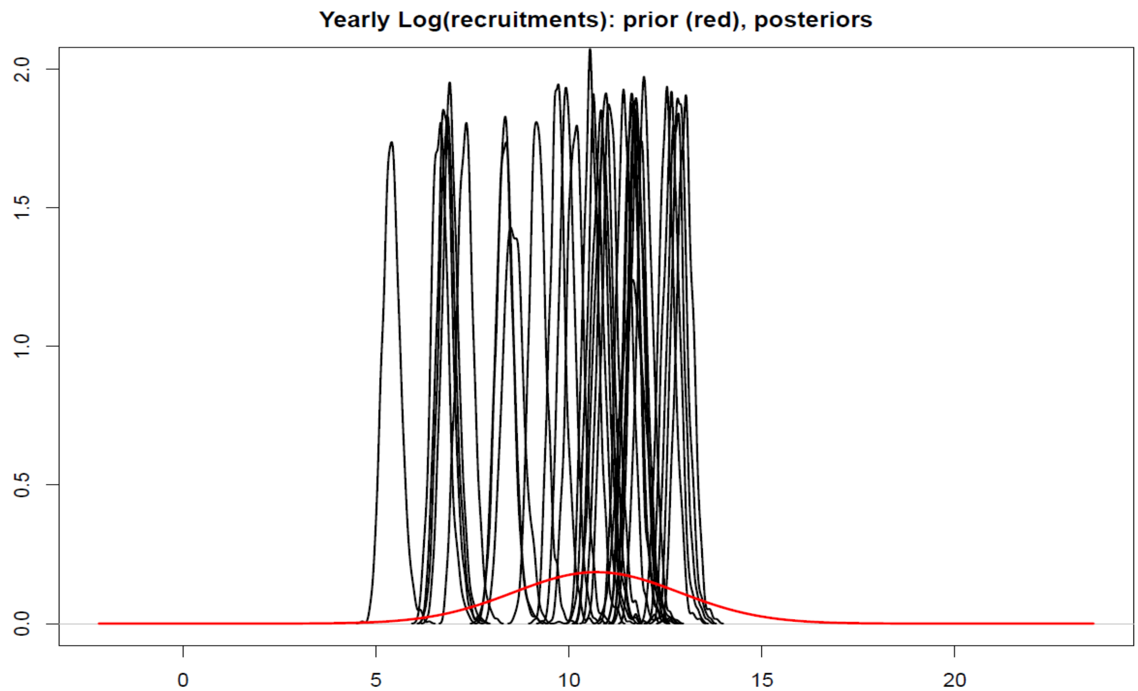


Figure 17. Prior and posterior of recruitment by year.

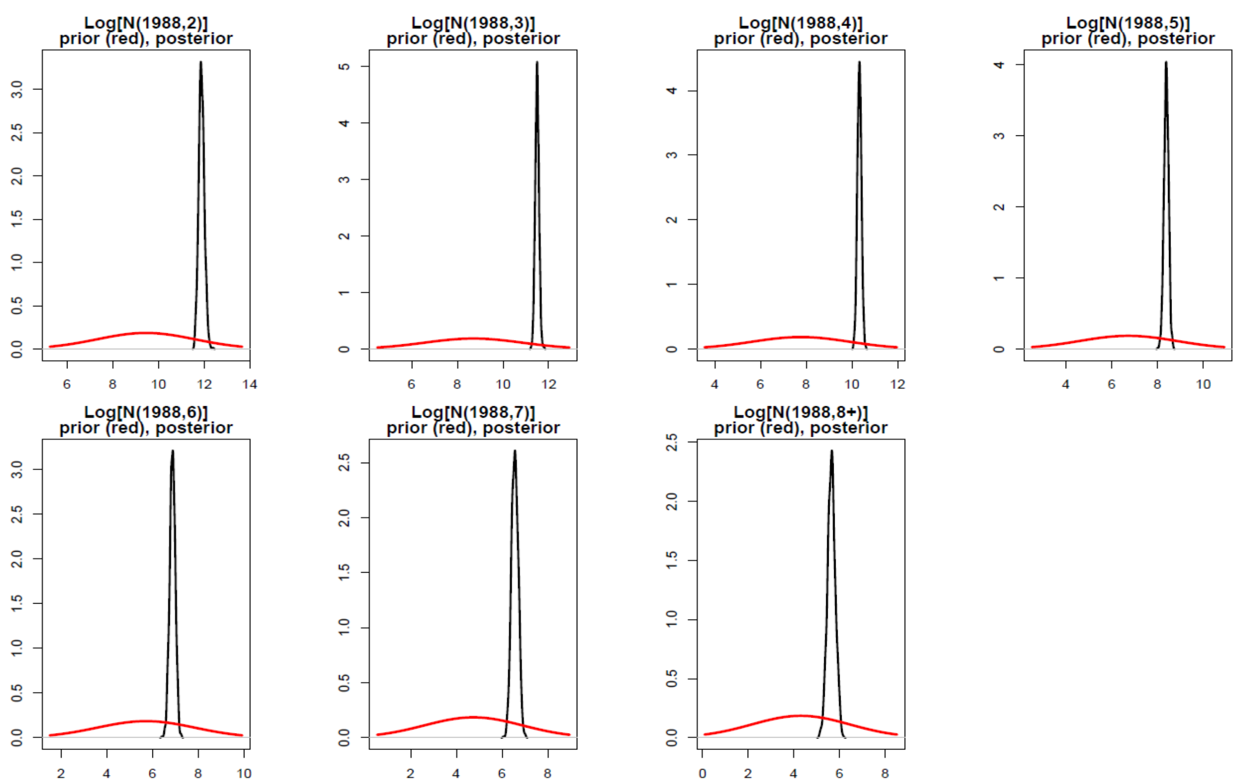


Figure 18. Prior and posterior of the numbers in the first year (1988) from age 2 to 8+.The x- and y-axis scales are different in all the graphs.

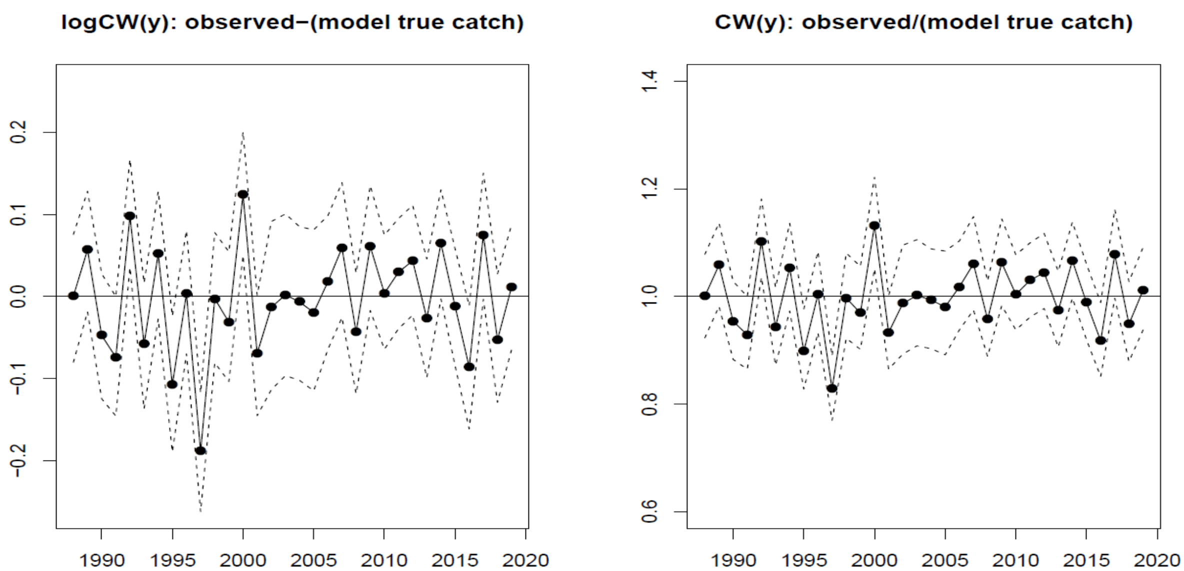


Figure 19. Observed versus estimated total catches by year.

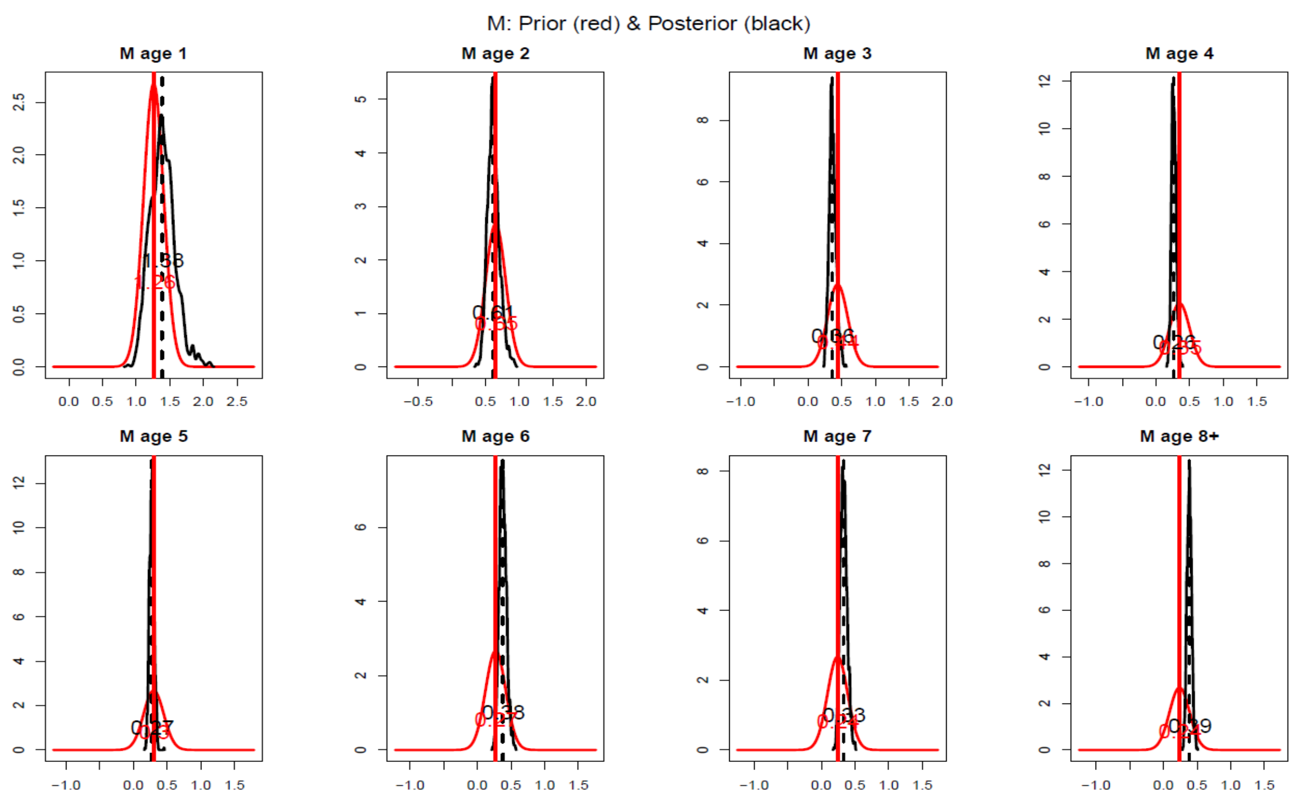


Figure 20. Estimated natural mortality by age in 2019.

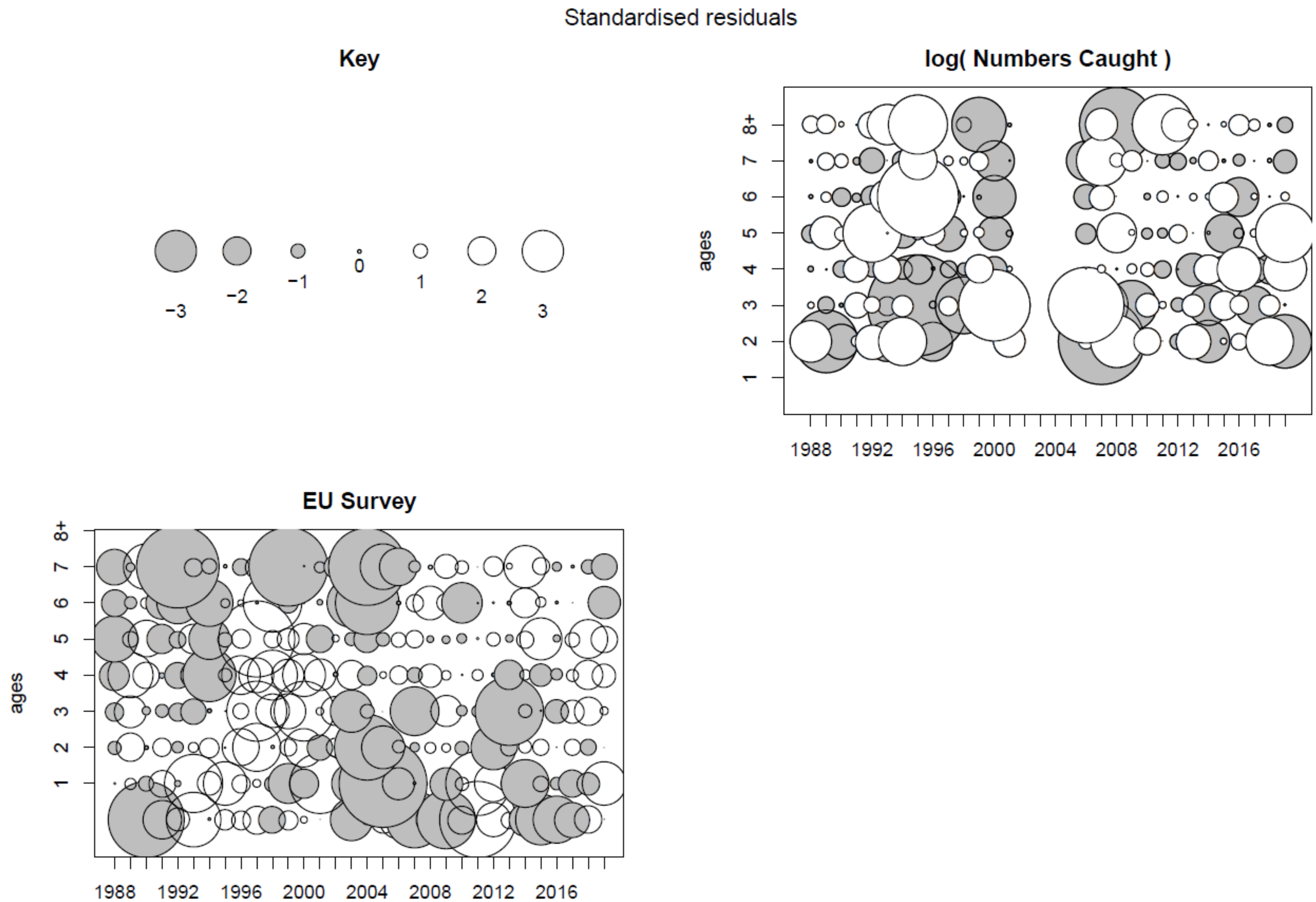


Figure 21. Standardised residuals (observed minus fitted value) in logarithmic scale of catch numbers at age and EU survey abundance indices at age. Grey and black values indicate values above and below the average. The larger the bubble size the larger the magnitude of the value.

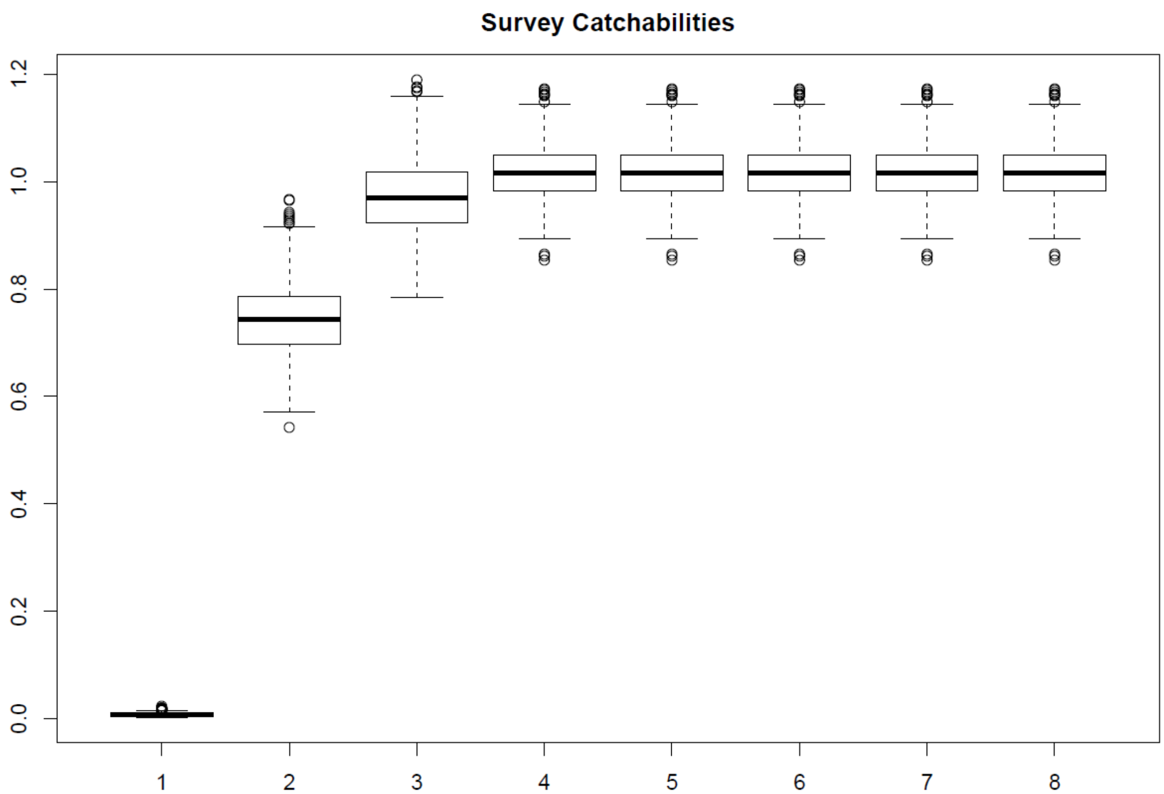


Figure 22. EU survey catchabilities distribution

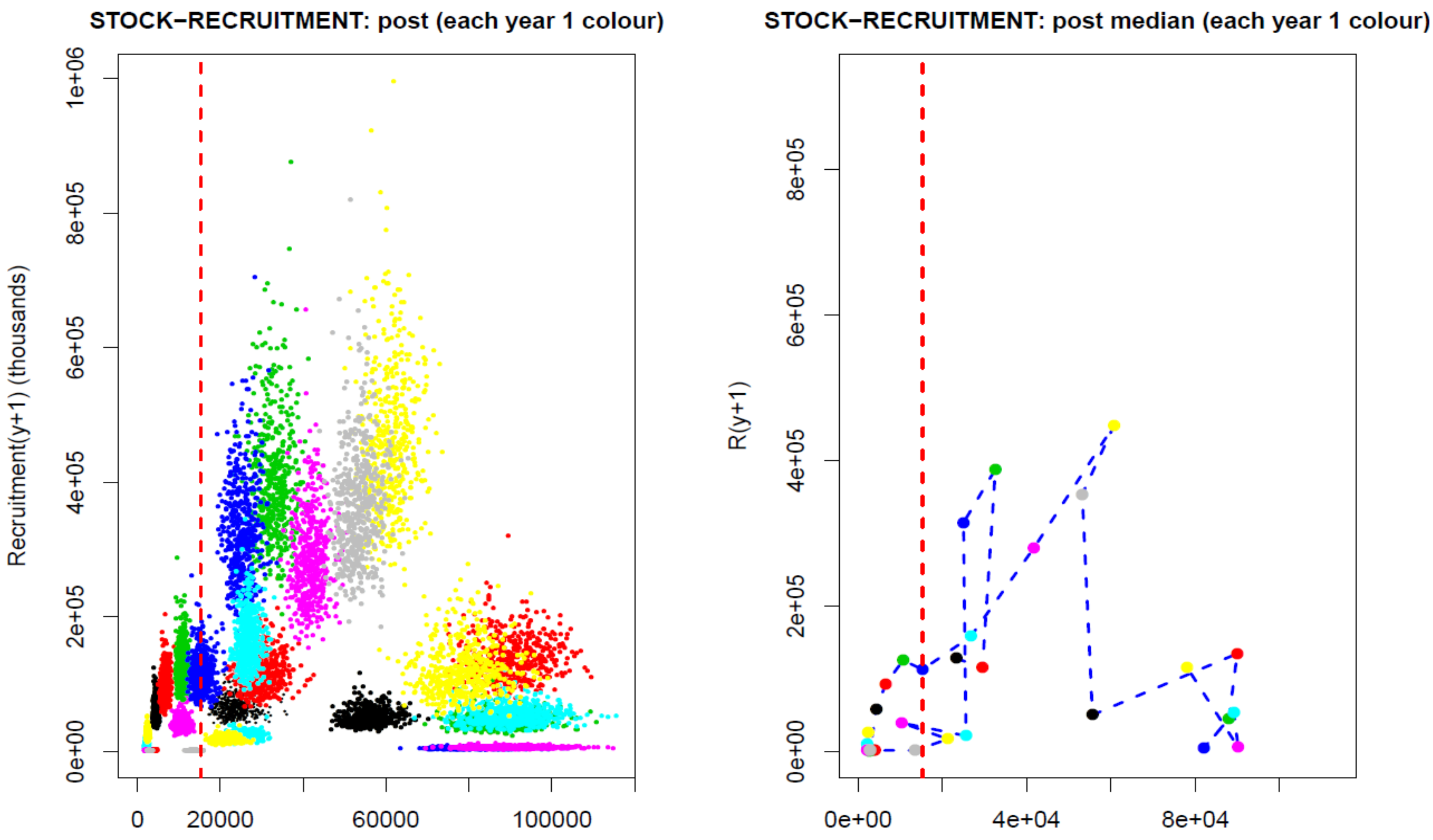


Figure 23. Stock-Recruitment plots. The value of median B_{lim}=medianSSB_{2007}=15 271 tons is shown as the red vertical line.

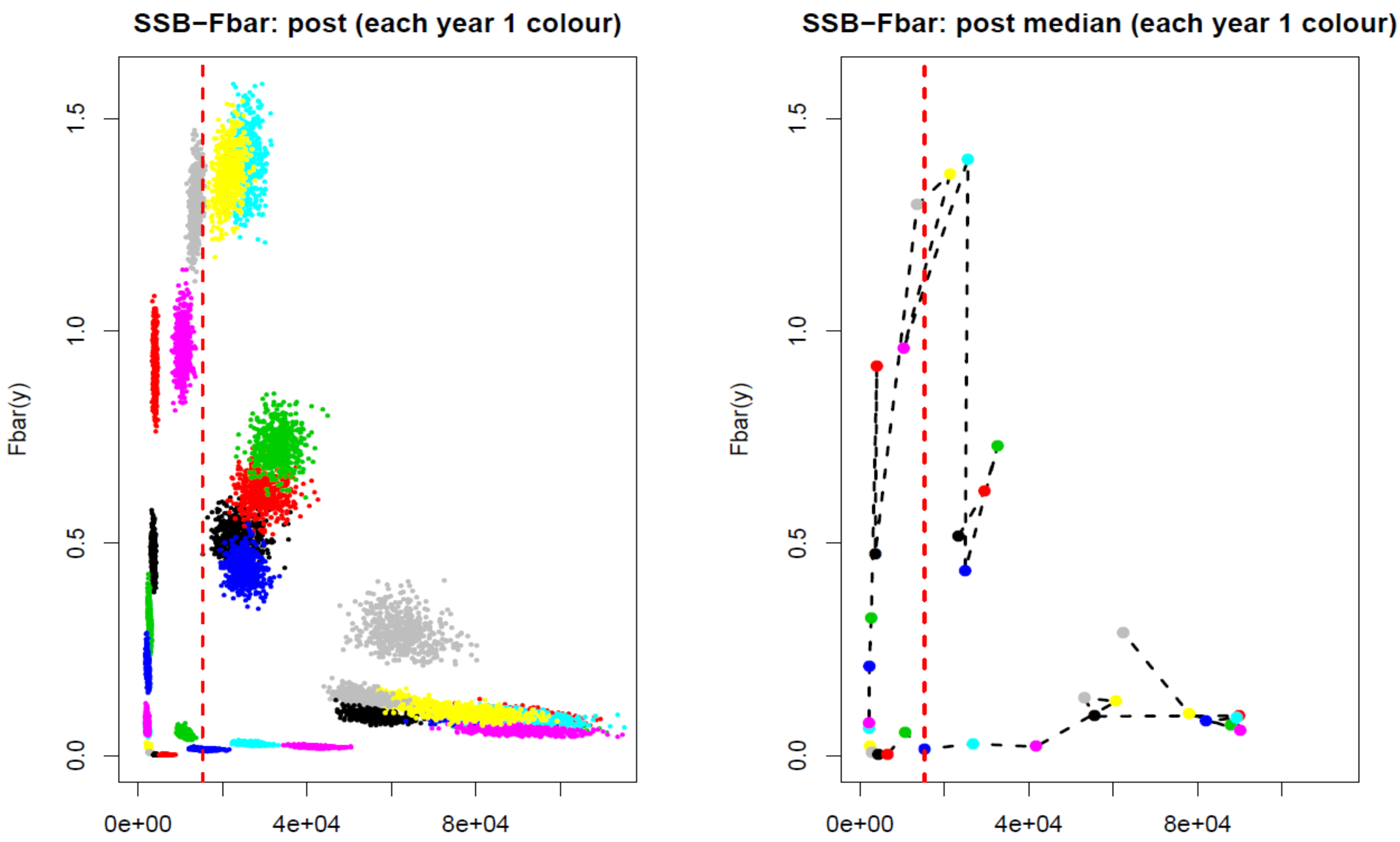


Figure 24. F_{bar} versus SSB plots. The value of median B_{lim}=medianSSB_{07}=15 271 tons is shown as the red vertical line.

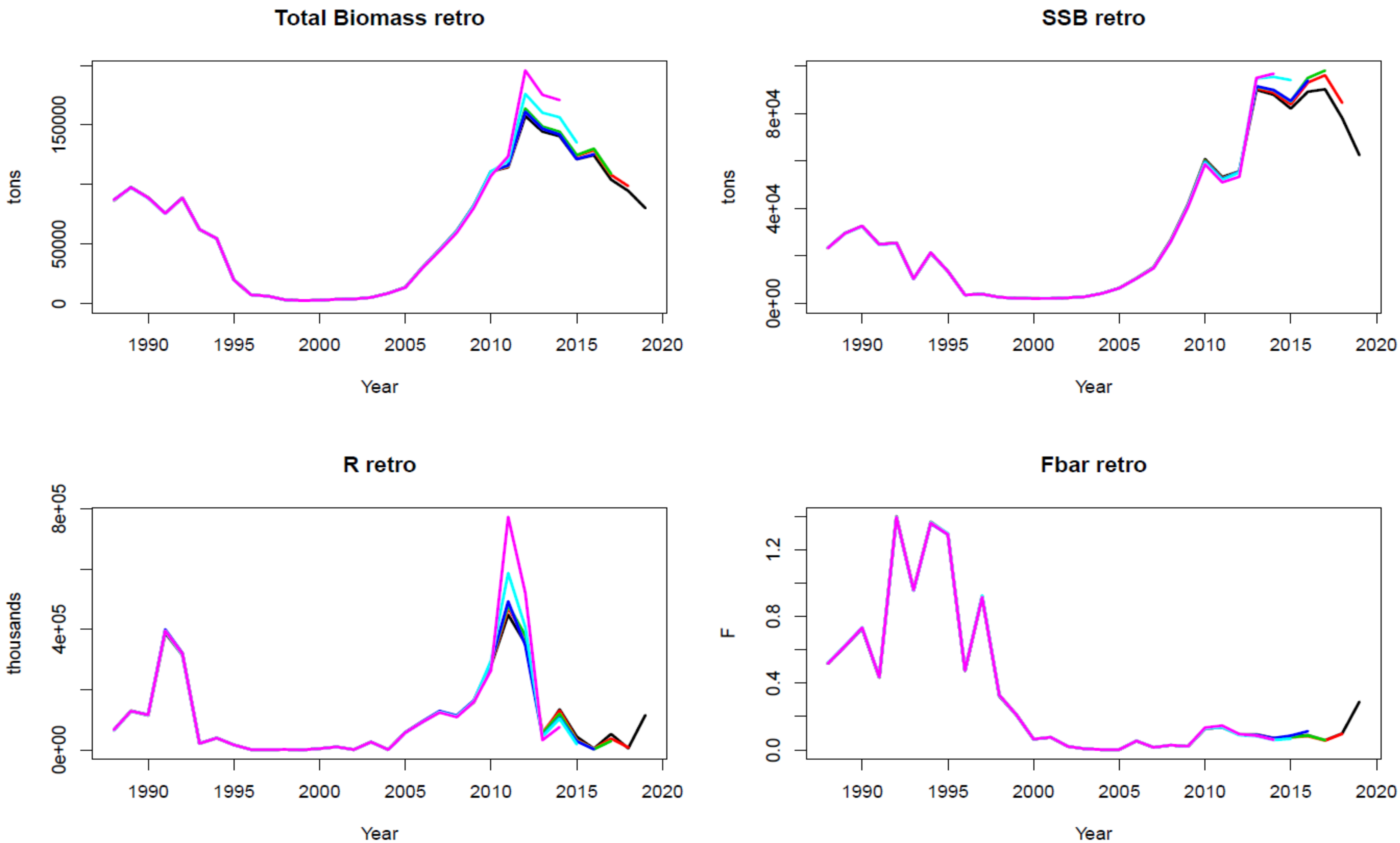


Figure 25. Retrospective patterns.

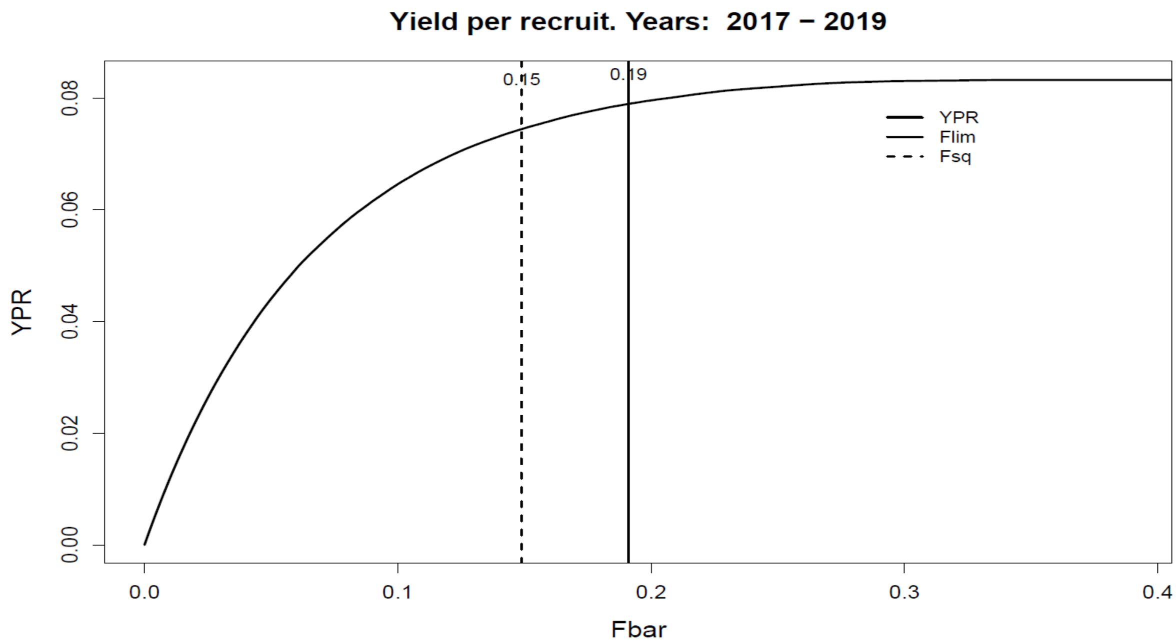


Figure 26. Yield per Recruit (2017-2019) versus F_{bar}. The values of F_{lim} ($F_{30\%SPR}$)and $F_{statusquo}$ (mean F over 2017-2019) are indicated.

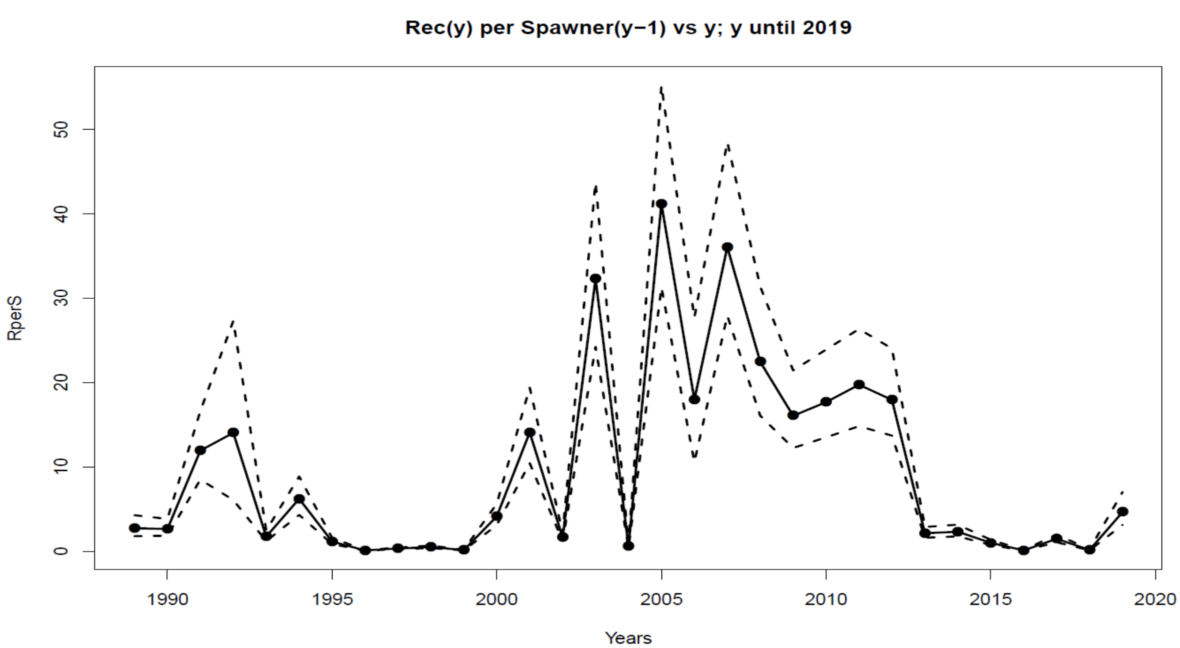


Figure 27. Estimated recruits (age 1) per spawner.

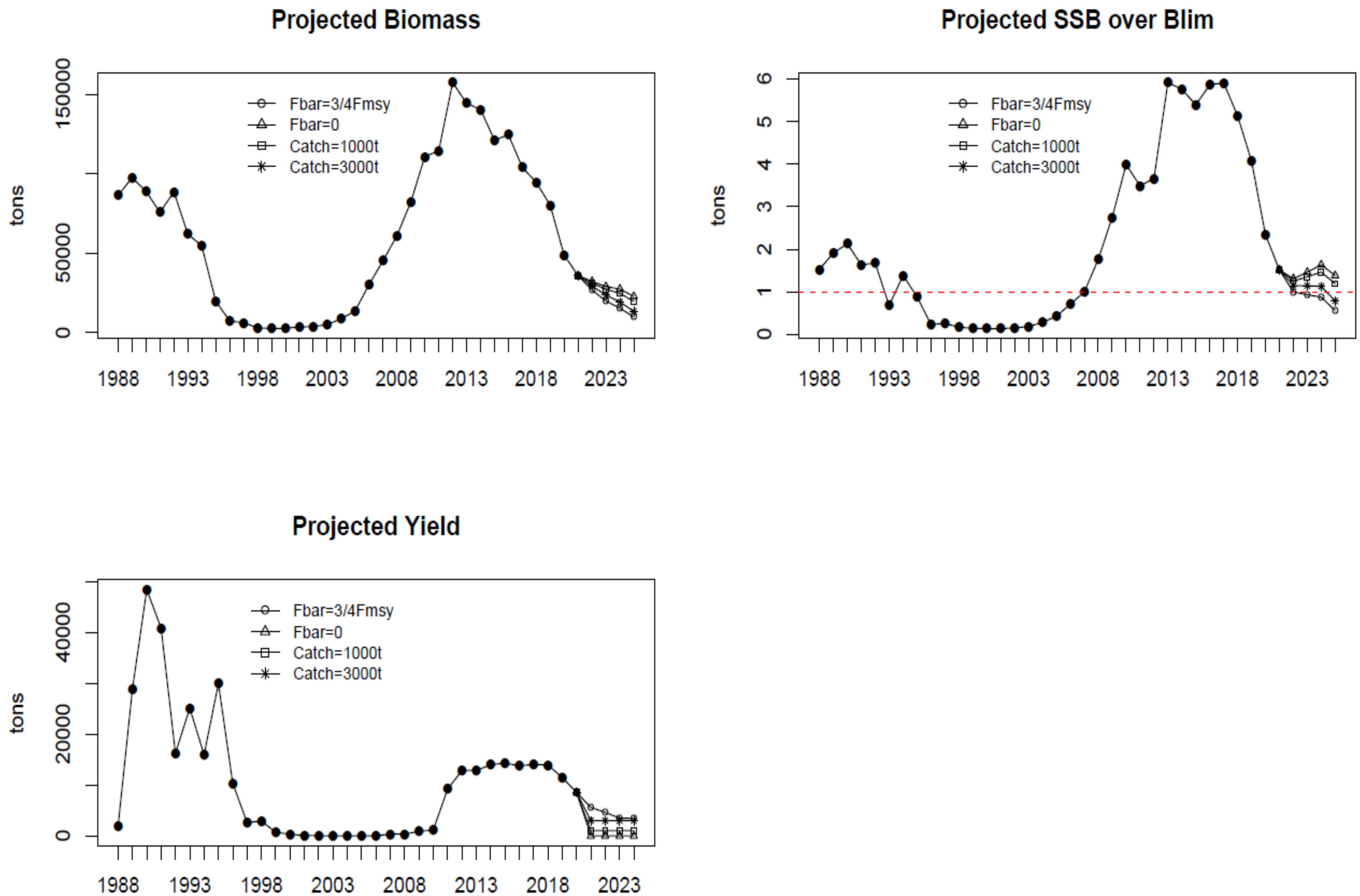


Figure 28. Projections for total Biomass, SSB/B_{lim} and Yield with different scenarios.

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. 2019) 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:

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

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

- *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:

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

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

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

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*

Prior on *phi.EU[a]*:

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

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

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* 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