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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 was conducted using a Bayesian SCAA (statistical catch-at-age) model. The STACFIS catch estimates and the Flemish Cap survey indices were used to fit the model. B_{lim}, defined as the SSB of 2007, was estimated at 15 408 t (median). 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; the 2016 and 2018 values were among the lowest of the series; as a consequence, 3-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 2023 and 2024 is high (≥12%) or very low (≤5%). An increase in recruitment occurred in 2019 and 2020, reaching the 2008 level.

Introduction

The 3M cod stock was under fishing moratorium from 1999 to 2009 following a decline to well below B_{lim} (Vázquez and Cerviño, 2005). The stocks collapse has been attributed to three simultaneous circumstances: 1) overfishing, 2) increased catchability at low abundance levels and 3) a series of very poor recruitments starting in 1993. 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 in the following years; 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 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 2011-2020 between 9 280 and 8 531 tons were established. The STACFIS estimated catches for 2010-2020 were between 9 291 and 8 458 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 2020.

Material and Methods

Data used

Commercial data

Total Catch

In 2020 catch data were available from EU-Estonia, EU-Portugal, EU-Spain, Faroe Islands (Denmark), Japan, Norway and Russia with a total amount of 8 458 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 (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 also periodically active. 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 (even years). This causes the proportion of trawlers and longliners to be variable among the years, ranging between 16% and 49% (Table 1B).

Length distributions

In 2020 length sampling of catch was conducted by EU-Estonia (SCS 21/13), EU-Portugal (SCS 21/05), Faroe Islands (SCS 21/10) and Norway (Nedreaas, personal communication). Length frequency distributions from the commercial catch and from the EU survey (González-Troncoso *et al.*, 2021) are shown in Figure 2A.

In general, the sampling effort in 2020 was less than in previous years, mostly due to the COVID-19. Table 1C shows the number of individuals measured as well as the length range, the mean and the mode for each of the countries with samples, for the total commercial length distribution and for the survey.

There is a noteworthy difference in the length distributions from the recent 2017 to 2020 period and the previous 2010-2016 period (Figure 2B). In the earlier period, following the reopening of the fishery, the bulk of the fish caught was between 40 and 60 cm, in 2017, 2018 and 2020 most of the catches are between 55 and 75 cm. The mean lengths in the years 2010-2016 was between 47 and 59 cm, whereas in 2017, 2018 and 2020 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, 2018 and 2020 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 (Table 1D and Figure 2C).

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. An ALK was available for 2009-2011 only from the Portuguese fishery and was applied to the total commercial length distribution to derive the total age distribution of the commercial catches. 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. Since 2018 only the survey ALK has been available, and it has been used for both commercial and survey indices.

Catch-at-age

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. Catch proportions at age over time (Figure 3) indicate that overall the bulk of the catch is comprised of 3-5 years age cod. However, between years 2006 and 2014 the catches contained mostly age 3 and 4 individuals; in the period 2015-2020, ages 5 to 8 were the most dominant.

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 and age 7 in 2020, that corresponds to the 2013 cohort, that was the first of the weak cohorts, and that had never appeared before 2019. 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. And the 2014 cohort, that was negative until age 5 in 2019 and age 6 in 2020.

Mean weight-at-age

For 2020, mean weight-at-age has been computed using length-weight relationships from the commercial sampling. For this year, there are three commercial length-weight relationships available: EU-Estonia, EU-Portugal and Faroes. All of them are presenting in Figure 4 besides the 2020 EU survey one. The EU survey relationship gives the highest weight for the higher lengths. The Estonian and Portuguese relationship give a very similar pattern. The longliner Faroese relationship is quite different from the rest, being the smaller individuals bigger than for the rest, and the higher individuals thinner than in the rest. As most of the catch went from trawlers, and Portugal had the biggest catch, the Portuguese length-weight relationship was applied to the commercial data to calculate the mean weight-at-age in the catch.

Mean weight-at-age for 1988-2020 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 in those years. In 2020, a quite high increase can be seen in the ages 4+, decreasing for ages 2 and 3.

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 in 2020.

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 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 1988-2020 are presented in González-Troncoso *et al.* (2021).

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). Between 2012 and 2019 both biomass and abundance had a decreasing trend, due mainly to the failure of the recruitment. In 2020, and increase can be observed in both indices, mainly due to an increase in the numbers of almost all the ages (except ages 1, 5 and 8+) with respect to year 2019. It is remarkable the increase in ages 3 and 4, that implies that the cohorts of 2016 and 2017 could be better than estimated in the past.

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 2014-2020 presented a high value, which indicates the strength of the 2006-2011 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. The recruitment in 2020 is estimated to be slightly lower than the 2019 one, but it is still better than the 2015-2018 recruitments. To point out that the values of the EU survey in 2020 are all positive, probably due to a year effect. Even ages 3 (from the 2017 cohort) and 5 (from the 2015 cohorts) are positive.

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. In 2020, a decrease in the mean weight of the youngest ages (1-5), and a quite high increase in the rest of the ages can be observed.

Maturity at age

Maturity ogives are available from the EU survey for years 1990-1998, 2001-2006 and 2008-2020. 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 until 2019 and decreasing for 2020 for all ages.

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 around 5 years old with ups and downs.

Assessment methodology

A Bayesian SCAA model was fitted to the data. Ages are from 1 to A+=8+ and years are from 1988 to 2020. The cohorts are modelled forward 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 2020

Catch in tonnes in all years; Years with catch-at-age: 1988-2001, 2006-2020

Tuning with EU survey for 1988 to 2020

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 2021 was calculated using the numbers estimated by the assessment at the beginning of 2021, applying the maturity ogive and mean weight at age in stock from 2020.

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 2020 the biomass is below 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 2021, 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 and 2020 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 just below F_{lim}. In 2020 the F_{bar} decrease slightly. 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 2020, the F decreased slightly in all ages with respect to 2019, with high F values at ages 5-6. 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 (2010-2020) and Figure 13B the mean of the three last years (2018-2020) PR *versus* the 2020 PR. Until 2017, all the years have a similar and increasing PR by age. Since 2018, age 6 was the most caught age. In 2018 and 2019, ages 7 and 8+ are the second most caught, being age 5 in the case of 2020. For that, the mean PRs of the last three years is slightly different to the 2020 one, mostly disagreeing in ages 5+.

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 and 2020, 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 bycatches of other fisheries. Age 4 shows a decreasing trend since 2014, reaching in 2020 the lowest value of the series. For ages 6 and 7 an increasing trend can be observed since 2006 until 2018 for age 6 and 2017 for age 7, decreasing since then. These results are quite different to those estimated in the last approved assessment (González-Troncoso *et al.*, 2020).

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 and 2020, the decrease in biomass continues, but an increase in the abundance in 2019 and 2020 (very slight in 2020) can be seen. Both total biomass and abundance are in 2020 below the mean values of the series.

Estimates of stock abundance at age for 1988-2020 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 since 2018), 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, but big positive residuals in the last year of the EU survey can be observed in ages 3 and 5. This is consequence of the year effect in the 2020 EU survey mentioned above (Figure 7). Following the bad 2015 and 2017 cohorts, the standardized values of the survey must be negative for those ages in 2020, but they are both positive. 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 2004 and 2016 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 15 408 tons, and an 80% confidence interval between 13 847 and 17 745 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 2018-2020 data as 0.196. 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 2018-2020 as well as the value of F_{lim} and $F_{statusquo}$ (defining the latter as the mean fishing mortality over 2018-2020).

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, and in year 2019. This year the 2019 recruitment has been revised to a lowest value. But no patterns are evident in recent years. The downwards revision of the 2011-2012 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, although the 2019 one was revised to a lowest value.

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 and 2020 values are quite similar and they are 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 for two years, from 2021 to the start of 2024, were conducted. Only two years are presented due to the high uncertainty in the parameters of the stock. 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 2021: estimated from the assessment.

Recruitments for 2021-2024: Recruits per spawner were drawn randomly from 2017-2019 (corresponding to the recruitment of 2017-2019 and number of matures of 2016-2018). The 2020 value of recruits per spawner was omitted due to uncertainty in estimating the recruitment.

Maturity ogive for 2021-2024: Mean of the last three years (2018-2020) maturity ogive.

Natural mortality for 2021-2024: Natural mortality from the 2020 assessment results.

Weight-at-age in stock and weight-at-age in catch for 2021-2024: Mean of the last three years (2018-2020) weight-at-age.

PR at age for 2021-2024: Mean of the last three years (2018-2020) PRs.

F_{bar}(ages 3-5): Four scenarios were considered:

(Scenario 1) Fbar=Fsq (median value = 0.131).

(Scenario 2) Fbar=0 (no catch).

(*Scenario 3*) F_{bar}=3/4F_{lim} (median value = 0.147).

(*Scenario 4*) F_{bar}=1/2F_{lim} (median value = 0.098).

(*Scenario 5*) Catch in 2022-2023=1 500 tons.

(*Scenario 6*) Catch in 2022-2023=1 875 tons.

(*Scenario 7*) Catch in 2021-2022=2 250 tons.

(*Scenario 8*) Catch in 2021-2022=3 000 tons.

All scenarios assumed that the Yield for 2021 is the established TAC (1 500 t).

Results for the four options are presented in Tables 11-26 and Figure 28. They indicate that under all scenarios with F_{bar}>0, total biomass during the projected years will decrease, whereas the SSB is projected to increase slightly in 2024. The probability of SSB being below B_{lim} in 2023 is high (≥13%) in the scenarios with F_{bar}=F_{sq} and F_{bar}=3/4F_{lim}, while being very low (≤10%) in the rest of the cases. The probability of SSB in 2024 being above that in 2021 ranges between <1% and 90%, depending on the scenario.

Under all scenarios, the probability of F_{bar} exceeding F_{lim} is less than or equal to 2% in 2022 and 2023.

To note that projections of risk, in particular more than one year ahead (even Tables between 11 and 26), will inherently include more uncertainty than projected median stock sizes (odd Tables between 11 and 26). The risks are typically derived from the tails of a probability distribution which are less precisely estimated compared to the median (centre) of the same distribution.

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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 2020 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	4371			1643			1607	17381
2020	8458	4234	545	477		2263			786			204	8509

[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	2020
Total catch	9192	9794	9003	13985	14290	13785	14023	13928	6447	17520	8458
Total trawler	9192	9794	9003	10095	12034	10125	10208	10762	4210	12968	5416
Total longliner	0	0	0	3889	2256	3659	3814	3166	3166	4552	3042
% longliner	0	0	0	28	16	27	27	23	49	26	36

Table 1C. Summary of the length distributions in 2020 of each country with samples, the total commercial and the survey.

Country	EU-Estonia	EU-Portugal	Faroes	Norway	Total commercial	Survey
Number of sampled individuals	330	5083	2987	2457	10857	5029
Gear	Trawl	Trawl	Longline	Longline		Trawl
Range (cm)	47-83	36-120	26-130	35-128	26-130	12-128
Mean (cm)	65	62	69	78	64	42
Mode (cm)	64	63	70	79	63	63

Table 1D. Mean and mode length of the total commercial and the survey length distribution for 2010-2020.

	Year	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Mean	Commercial	57	58	59	47	52	53	56	64	64	61	64
	Survey	30	21	31	34	44	46	49	52	55	43	41
Mode	Commercial	54	54	54	42	51	54	39	63	63	60	63
	Survey	18	15	18	24	33	42	36	42	54	21	33

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
2020	0	0	41	541	440	734	616	687

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
2020	0.078	0.266	0.735	1.346	1.843	2.551	2.991	4.636

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
2020	7137	4733	25203	13495	5678	4109	3336	687	631	938	566	126	54	14	29	0	0	8	0	66744	67442

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
2020	0.054	0.209	0.364	1.015	1.667	2.47	2.982	4.703

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	0.021	0.050	0.114	0.247	0.461	0.666	0.819	0.935	5.186
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	0.900	0.999	1.000	1.000	1.000	3.452
2000	0.000	0.001	0.153	0.973	1.000	1.000	1.000	1.000	3.369
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	0.266	0.920	0.997	1.000	1.000	1.000	3.308
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
2020	0.000	0.000	0.003	0.041	0.402	0.908	0.993	1.000	5.149

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	84735	80471	89532	23079	19519	27539	62668	48653	83774	0.525	0.484	0.569
1989	95755	91012	100832	29028	24838	33983	125724	96044	167237	0.628	0.582	0.681
1990	88205	83809	92917	32372	28565	36447	112197	87243	150377	0.740	0.687	0.792
1991	74875	69080	82708	24950	21889	28304	382676	298457	499770	0.441	0.405	0.482
1992	88210	81517	95961	25719	23061	28463	310084	244082	415078	1.427	1.332	1.523
1993	61493	57746	65972	10352	9256	11747	20920	16186	27741	0.973	0.906	1.046
1994	54274	50730	57880	21090	18638	23826	38590	29747	50523	1.377	1.297	1.460
1995	19680	18503	20971	13411	12429	14516	16010	12339	21301	1.317	1.239	1.398
1996	7252	6863	7653	3576	3278	3880	1000	771	1333	0.479	0.436	0.525
1997	6194	5836	6574	4000	3678	4307	880	669	1168	0.926	0.851	1.003
1998	3081	2823	3360	2673	2443	2917	1458	1126	2004	0.323	0.286	0.365
1999	2522	2243	2819	2251	1994	2538	220	168	305	0.210	0.180	0.243
2000	2809	2471	3165	2188	1890	2481	4129	3115	5559	0.064	0.054	0.076
2001	3515	3131	3983	2150	1890	2417	9675	7381	13188	0.075	0.061	0.095
2002	3792	3422	4199	2414	2164	2684	913	689	1255	0.020	0.017	0.024
2003	5007	4504	5673	2847	2579	3143	25288	19780	33567	0.006	0.005	0.007
2004	8564	7753	9544	4328	3944	4766	766	598	1013	0.002	0.002	0.002
2005	13509	12035	15388	6594	5940	7379	55670	42786	74532	0.002	0.002	0.002
2006	29809	26561	33990	10824	9920	11897	89394	69177	118609	0.053	0.046	0.061
2007	44461	40360	49196	15408	13847	17745	119808	93417	159876	0.014	0.013	0.016
2008	59947	55091	65681	26805	24767	29209	106692	81326	141435	0.027	0.024	0.031
2009	80896	74709	88107	41784	38587	45322	152011	116848	200309	0.020	0.018	0.023
2010	108935	101160	118460	61116	56532	66072	262805	204317	348897	0.128	0.113	0.142
2011	112358	104161	121854	53433	49396	57967	418241	321082	559678	0.137	0.123	0.157
2012	152957	139993	168417	55838	51611	60994	329137	254144	439282	0.095	0.084	0.107
2013	140604	130514	151563	89117	81729	96429	48744	37334	64101	0.097	0.086	0.109
2014	138183	128752	149400	86779	79679	94648	148777	114678	198403	0.075	0.065	0.085
2015	120038	111816	129828	80773	74070	88798	56152	42331	74814	0.084	0.073	0.096
2016	124170	114984	135036	87576	80455	96111	9455	7252	12598	0.087	0.076	0.100
2017	105063	97076	114272	87836	80239	96428	77476	57525	106016	0.051	0.045	0.058
2018	97726	89946	106980	76205	69330	84640	11775	8772	16206	0.076	0.066	0.086
2019	82785	75596	91027	63141	57161	70201	81300	57764	115282	0.171	0.150	0.193
2020	57585	51748	64070	39942	35042	45635	80563	55373	116020	0.146	0.125	0.173

Table 8. F at age (posterior median).

	F at age							
Year	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8+**
1988	0.000	0.018	0.343	0.591	0.633	0.640	0.772	0.772
1989	0.000	0.011	0.366	0.799	0.720	0.770	0.847	0.847
1990	0.000	0.018	0.389	0.922	0.906	1.200	1.032	1.032
1991	0.000	0.023	0.302	0.481	0.540	0.553	0.658	0.658
1992	0.000	0.143	0.999	1.502	1.768	1.414	1.958	1.958
1993	0.000	0.085	0.687	1.153	1.074	1.504	0.851	0.851
1994	0.000	0.190	1.004	1.750	1.374	1.327	0.979	0.979
1995	0.000	0.188	0.556	1.515	1.874	2.296	2.154	2.154
1996	0.000	0.047	0.248	0.494	0.691	0.894	0.810	0.810
1997	0.000	0.113	0.574	0.848	1.347	1.985	1.792	1.792
1998	0.000	0.044	0.198	0.319	0.451	0.527	0.387	0.387
1999	0.000	0.024	0.230	0.178	0.217	0.217	0.079	0.079
2000	0.000	0.005	0.126	0.026	0.040	0.031	0.010	0.010
2001	0.000	0.008	0.137	0.035	0.052	0.039	0.013	0.013
2002	0.000	0.002	0.035	0.010	0.015	0.011	0.004	0.004
2003	0.000	0.000	0.010	0.003	0.005	0.003	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	0.038	0.045	0.031	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	0.038	0.035	0.029	0.029
2009	0.000	0.001	0.008	0.025	0.029	0.028	0.032	0.032
2010	0.000	0.011	0.070	0.129	0.183	0.187	0.206	0.206
2011	0.000	0.011	0.088	0.109	0.214	0.268	0.365	0.365
2012	0.000	0.006	0.060	0.076	0.148	0.194	0.282	0.282
2013	0.000	0.006	0.065	0.076	0.150	0.205	0.275	0.275
2014	0.000	0.003	0.034	0.085	0.104	0.164	0.224	0.224
2015	0.000	0.003	0.048	0.084	0.119	0.193	0.226	0.226
2016	0.000	0.003	0.039	0.099	0.121	0.144	0.219	0.219
2017	0.000	0.002	0.018	0.045	0.090	0.149	0.192	0.192
2018	0.000	0.002	0.028	0.057	0.141	0.247	0.197	0.197
2019	0.000	0.002	0.059	0.139	0.313	0.496	0.328	0.328
2020	0.000	0.002	0.041	0.106	0.292	0.435	0.233	0.233

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	62668	141851	95558	30056	4363	977	715	284	338970	45557
1989	125724	15734	76063	47606	13024	1779	346	323	280120	42303
1990	112197	31236	8506	37154	16741	4898	555	198	211887	32214
1991	382676	28193	16788	4053	11528	5236	993	188	449788	21663
1992	310084	95793	15086	8750	1948	5212	2024	431	439162	11829
1993	20920	78262	45001	3879	1530	257	855	245	151244	6267
1994	38590	5237	39103	15908	959	402	39	331	100652	14368
1995	16010	9618	2348	10071	2151	187	72	92	40843	10623
1996	1000	4034	4348	943	1725	257	13	13	12389	2776
1997	880	251	2089	2395	448	673	70	8	6836	3027
1998	1458	219	123	833	796	90	62	9	3608	1697
1999	220	366	115	71	471	392	36	35	1717	1027
2000	4129	56	195	64	46	292	214	45	5037	706
2001	9675	1031	30	121	49	34	193	181	11296	591
2002	913	2413	558	19	92	36	22	254	4325	808
2003	25288	228	1314	380	14	70	24	183	27539	1389
2004	766	6349	124	920	297	11	47	139	8672	1402
2005	55670	193	3470	88	719	229	7	125	60553	5068
2006	89394	13942	105	2437	68	556	156	88	106964	3474
2007	119808	22435	7587	68	1833	50	365	166	153157	4908
2008	106692	30197	12236	5303	53	1396	34	362	155654	9798
2009	152011	26668	16379	8500	4020	39	913	256	209357	15615
2010	262805	37841	14469	11473	6476	3018	26	796	337299	22575
2011	418241	66074	20441	9514	7913	4174	1692	444	528575	19594
2012	329137	105327	35618	13204	6680	4917	2158	1044	498305	23112
2013	48744	83040	56910	23659	9579	4446	2733	1676	231330	56789
2014	148777	12157	44768	37524	17121	6380	2445	2334	271718	43576
2015	56152	37210	6613	30593	27031	11965	3664	2639	176500	43014
2016	9455	13969	20219	4448	22074	18546	6627	3471	99410	35460
2017	77476	2373	7626	13698	3140	15097	10828	5644	136103	34587
2018	11775	19327	1294	5271	10225	2222	8810	9483	69242	24912
2019	81300	2951	10566	888	3900	6880	1174	10283	118141	20768
2020	80563	20306	1614	7023	602	2195	2822	5495	120844	10893

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	0.60	0.35	0.24	0.26	0.39	0.33	0.41

Table 11. N-at-age in prediction years (medians) with $F_{bar}=F_{sq}=0.131$ including total number and number of matures.

Year/Age	1	2	3	4	5	6	7	8+	Total	Matures
2021	23447	20224	11061	1082	4933	350	959	4511	65390	8328
2022	17859	5902	10955	7744	832	3611	216	3466	49551	8068
2023	16934	4553	3239	7345	5451	503	1629	1878	40392	7148
2024	14629	4328	2530	2183	5185	3300	226	1844	32941	7777

Table 12. Projections results (median and 80% CI) with $F_{bar}=F_{sq}=0.131$.

Year	Total Biomass		SSB		P(SSB<B_{lim})	P(SSB_{24} >SSB_{21})	Yield	P(F>F_{lim})
2021	45787	(40635 - 51559)	27058	(23458 - 31446)	<1%	1%	1500	<1%
2022	42969	(37884 - 48389)	24420	(21335 - 27970)	<1%		6525	<1%
2023	34733	(29703 - 40345)	18598	(15605 - 21773)	13%		5291	<1%
2024	29999	(24718 - 36318)	19822	(16344 - 23723)	8%			

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
2021	23447	20224	11061	1082	4933	350	959	4511	65390	8328
2022	17859	5902	10955	7744	832	3611	216	3466	49551	8068
2023	16934	4553	3246	7671	6043	644	2444	2460	42899	8971
2024	18355	4328	2536	2296	6009	4680	436	3382	40734	11212

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

Year	Total Biomass		SSB		P(SSB<B_{lim})	P(SSB_{24} >SSB_{21})	Yield	P(F>F_{lim})
2021	45787	(40635 - 51559)	27058	(23458 - 31446)	<1%	90%	1500	<1%
2022	42969	(37884 - 48389)	24420	(21335 - 27970)	<1%		0	<1%
2023	41143	(36076 - 46765)	24071	(21037 - 27322)	<1%		0	<1%
2024	42102	(36620 - 48376)	30514	(27027 - 34628)	<1%			

Table 15. N-at-age in prediction years (medians) with $F_{bar}=3/4F_{lim}=0.147$ including total number and number of matures.

Year/Age	1	2	3	4	5	6	7	8+	Total	Matures
2021	23447	20224	11061	1082	4933	350	959	4511	65390	8328
2022	17859	5902	10955	7744	832	3611	216	3466	49551	8068
2023	16934	4553	3238	7311	5388	489	1557	1822	40154	6970
2024	14268	4328	2529	2170	5111	3167	210	1722	32072	7488

Table 16. Projections results (median and 80% CI) with $F_{bar}=3/4F_{lim}=0.147$.

Year	Total Biomass		SSB		P(SSB<B_{lim})	P(SSB_{24} >SSB_{21})	Yield	P(F>F_{lim})
2021	45787	(40635 - 51559)	27058	(23458 - 31446)	<1%	<1%	1500	<1%
2022	42969	(37884 - 48389)	24420	(21335 - 27970)	<1%		7160	1%
2023	34111	(29091 - 39726)	18092	(15086 - 21246)	17%		5694	2%
2024	28966	(23642 - 35277)	18923	(15516 - 22770)	13%			

Table 17. N-at-age in prediction years (medians) with $F_{bar}=1/2F_{lim}=0.098$ including total number and number of matures.

Year/Age	1	2	3	4	5	6	7	8+	Total	Matures
2021	23447	20224	11061	1082	4933	350	959	4511	65390	8328
2022	17859	5902	10955	7744	832	3611	216	3466	49551	8068
2023	16934	4553	3240	7424	5594	537	1809	2013	40967	7572
2024	15454	4328	2531	2213	5391	3613	269	2160	34666	8512

Table 18. Projections results (median and 80% CI) with $F_{bar}=1/2F_{lim}=0.098$.

Year	Total Biomass		SSB		P(SSB<B$_{lim}$)	P(SSB$_{24}$ >SSB$_{21}$)	Yield	P(F>F$_{lim}$)
2021	45787	(40635 - 51559)	27058	(23458 - 31446)	<1%	4%	1500	<1%
2022	42969	(37884 - 48389)	24420	(21335 - 27970)	<1%		5000	<1%
2023	36238	(31192 - 41834)	19854	(16887 - 23067)	5%		4254	<1%
2024	32578	(27213 - 38900)	22092	(18612 - 25996)	1%			

Table 19. N-at-age in prediction years (medians) with Catch=1500 tons including total number and number of matures.

Year/Age	1	2	3	4	5	6	7	8+	Total	Matures
2021	23832	20224	11061	1082	4933	350	959	4511	66187	8322
2022	17266	6166	10955	7744	832	3611	216	3466	48444	8071
2023	16859	4506	3382	7598	5913	612	2248	2324	42239	8553
2024	17691	4319	2457	2338	5824	4338	379	2972	38254	10311

Table 20. Projections results (median and 80% CI) with Catch=1500 tons.

Year	Total Biomass		SSB		P(SSB<B$_{lim}$)	P(SSB$_{24}$ >SSB$_{21}$)	Yield	P(F>F$_{lim}$)
2021	45787	(40635 - 51559)	27058	(23458 - 31446)	<1%	58%	1500	<1%
2022	42969	(37884 - 48389)	24420	(21335 - 27970)	<1%		1500	<1%
2023	39661	(34603 - 45288)	22807	(19826 - 26087)	1%		1500	<1%
2024	38994	(33591 - 45246)	27691	(24211 - 31752)	<1%			

Table 21. N-at-age in prediction years (medians) with Catch=1875 tons including total number and number of matures.

Year/Age	1	2	3	4	5	6	7	8+	Total	Matures
2021	23832	20224	11061	1082	4933	350	959	4511	66187	8322
2022	17266	6166	10955	7744	832	3611	216	3466	48444	8071
2023	16859	4506	3381	7581	5879	604	2201	2293	42099	8430
2024	17463	4319	2457	2332	5778	4253	365	2874	37720	10122

Table 22. Projections results (median and 80% CI) with Catch=1875 tons.

Year	Total Biomass		SSB		P(SSB<B$_{lim}$)	P(SSB$_{24}$ >SSB$_{21}$)	Yield	P(F>F$_{lim}$)
2021	45787	(40635 - 51559)	27058	(23458 - 31446)	<1%	48%	1500	<1%
2022	42969	(37884 - 48389)	24420	(21335 - 27970)	<1%		1875	<1%
2023	39291	(34238 - 44913)	22482	(19454 - 25735)	1%		1875	<1%
2024	38216	(32795 - 44488)	27028	(23511 - 31085)	<1%			

Table 23. N-at-age in prediction years (medians) with Catch=2250 tons including total number and number of matures.

Year/Age	1	2	3	4	5	6	7	8+	Total	Matures
2021	23832	20224	11061	1082	4933	350	959	4511	66187	8322
2022	17266	6166	10955	7744	832	3611	216	3466	48444	8071
2023	16859	4506	3381	7561	5844	596	2153	2259	41956	8327
2024	17177	4319	2457	2326	5731	4168	351	2776	37314	9882

Table 24. Projections results (median and 80% CI) with Catch=2250 tons.

Year	**Total Biomass**		**SSB**		**P(SSB<B_{lim})**	**P(SSB_{24} >SSB_{21})**	**Yield**	**P(F>F_{lim})**
2021	45787	(40635 - 51559)	27058	(23458 - 31446)	<1%	36%	1500	<1%
2022	42969	(37884 - 48389)	24420	(21335 - 27970)	<1%		2250	<1%
2023	38923	(33871 - 44544)	22151	(19150 - 25412)	1%		2250	<1%
2024	37438	(32028 - 43736)	26354	(22862 - 30373)	<1%			

Table 25. 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
2021	23832	20224	11061	1082	4933	350	959	4511	66187	8322
2022	17266	6166	10955	7744	832	3611	216	3466	48444	8071
2023	16859	4506	3380	7524	5775	580	2058	2194	41668	8142
2024	16819	4319	2456	2313	5616	3989	324	2579	36337	9464

Table 26. Projections results (median and 80% CI) with Catch=3000 tons.

Year	**Total Biomass**		**SSB**		**P(SSB<B_{lim})**	**P(SSB_{24} >SSB_{21})**	**Yield**	**P(F>F_{lim})**
2021	45787	(40635 - 51559)	27058	(23458 - 31446)	<1%	20%	1500	<1%
2022	42969	(37884 - 48389)	24420	(21335 - 27970)	<1%		3000	<1%
2023	38196	(33139 - 43808)	21520	(18528 - 24739)	2%		3000	<1%
2024	35865	(30453 - 42155)	24986	(21477 - 28888)	<1%			

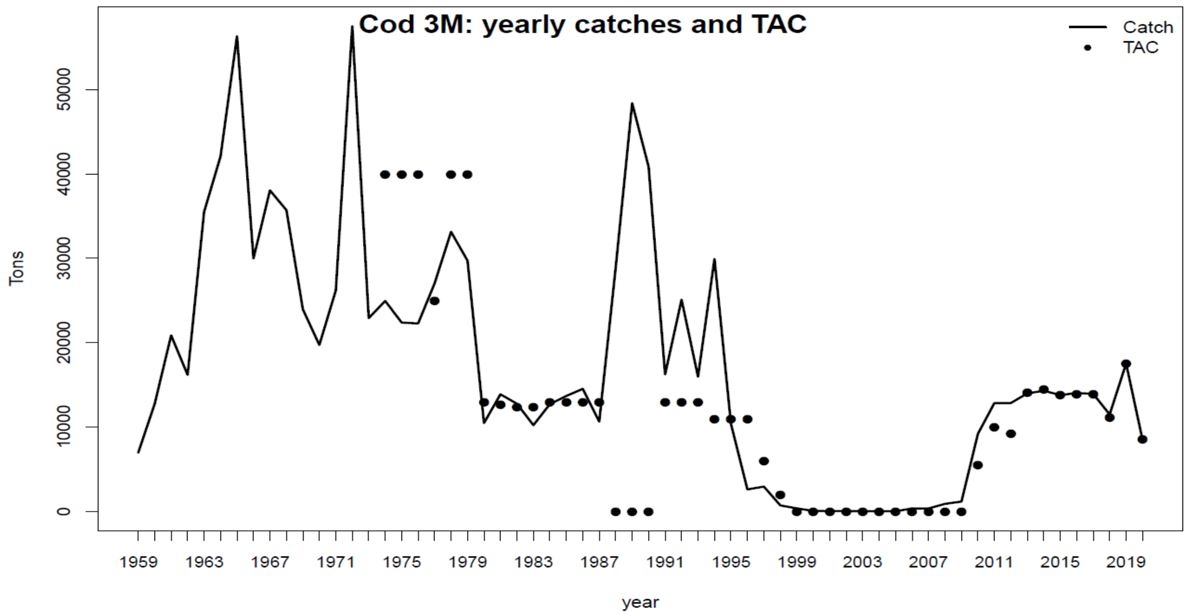


Figure 1. Catch and TAC of the 3M cod for the period 1959-2020.

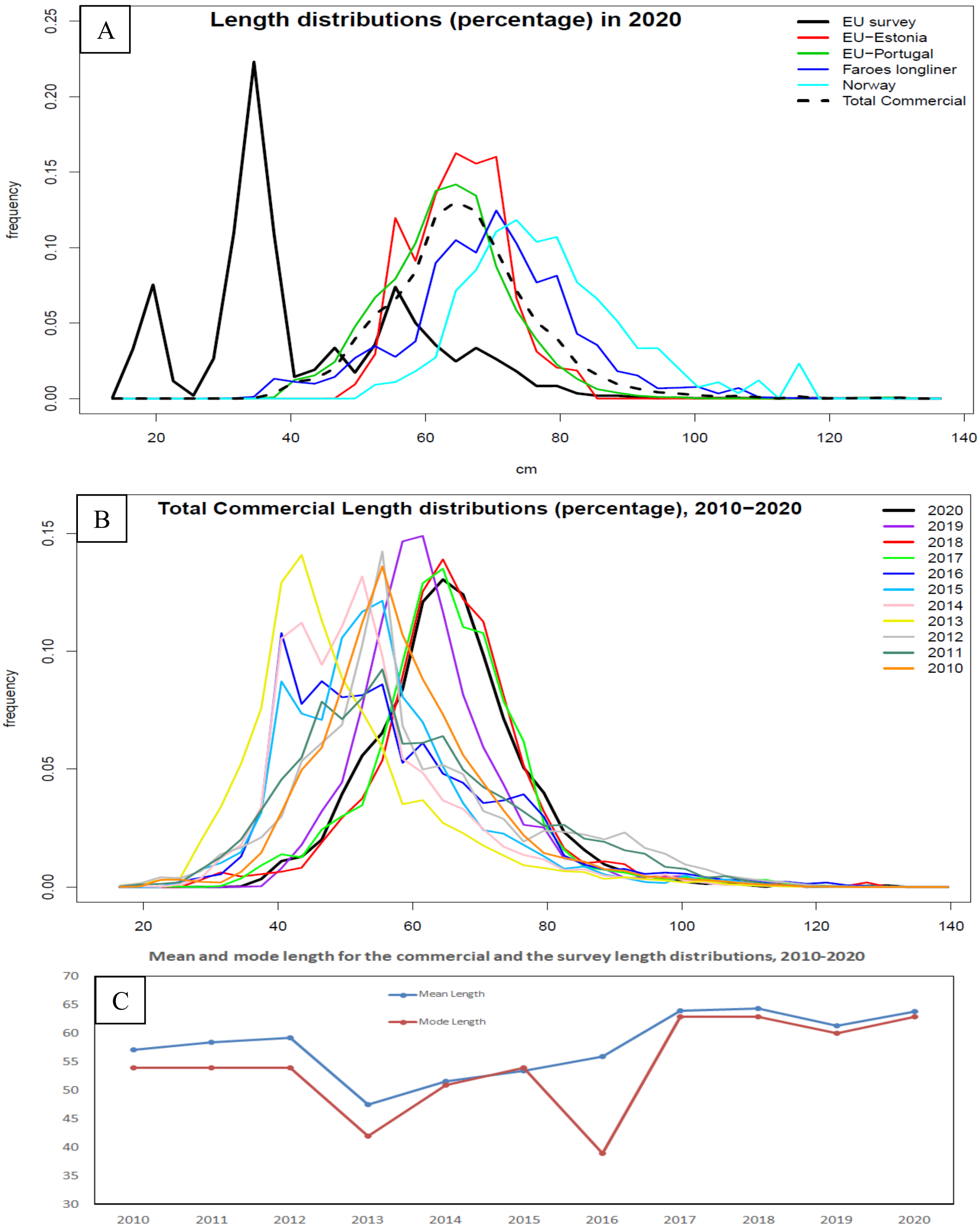


Figure 2. Length frequencies in commercial catches and EU survey in 2020 (A), and the total commercial for the last fishery period (2010-2020) (B). In (C), the mean and the mode length of the commercial length distribution is shown (2010-2020).

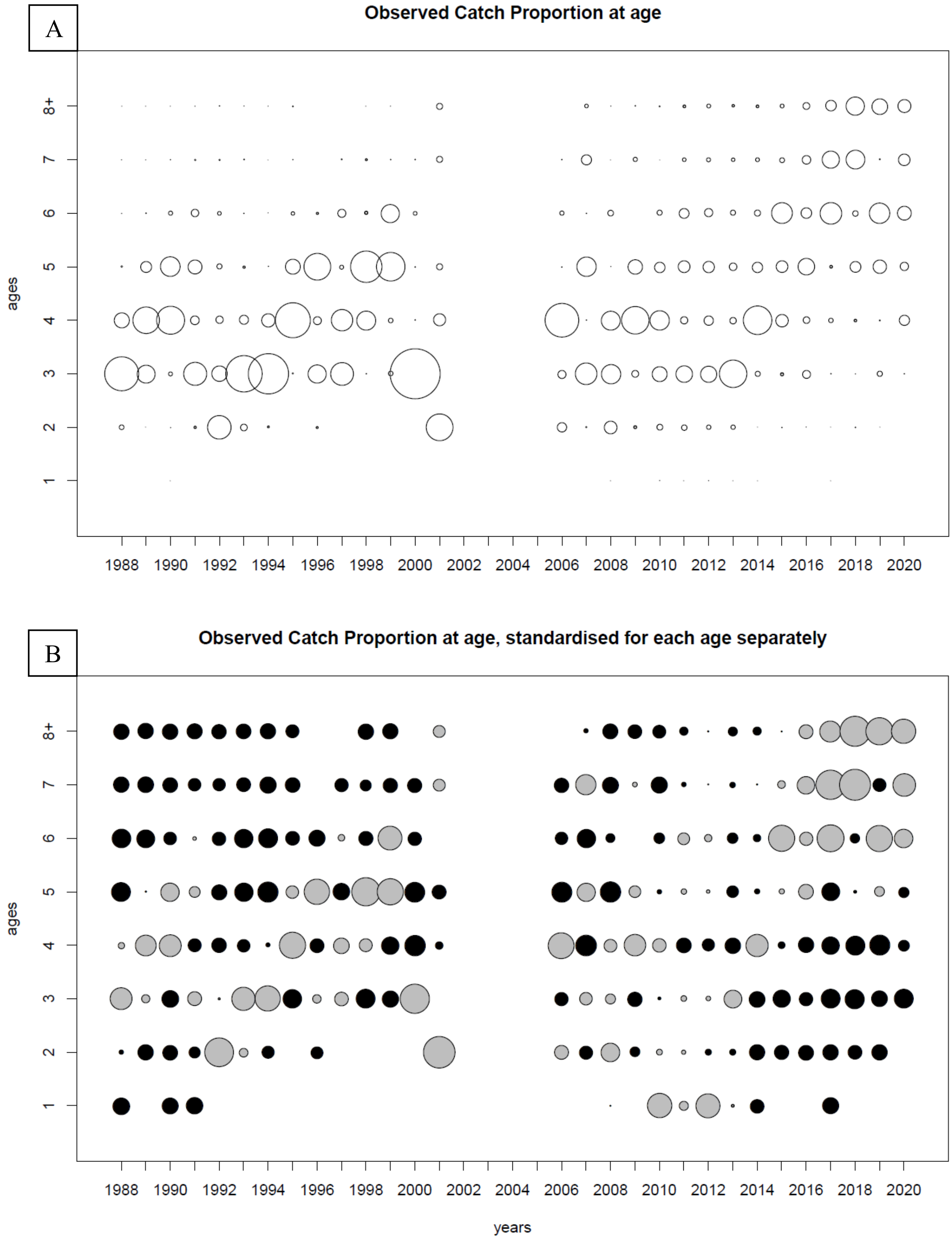


Figure 3. Commercial catch proportions at age (A) and standardised proportions at age (B). In B, grey and black values indicate values above and below the average. The larger the bubble size the larger the magnitude of the value.

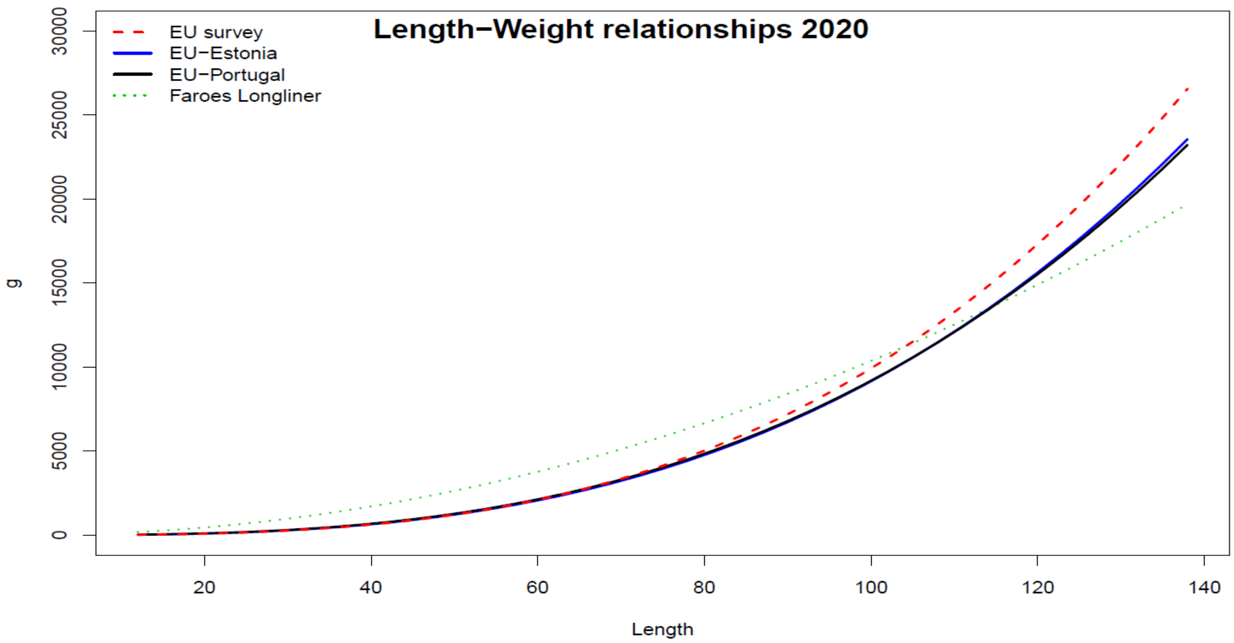


Figure 4. Length-weight relationships for commercial catches and EU survey in 2020.

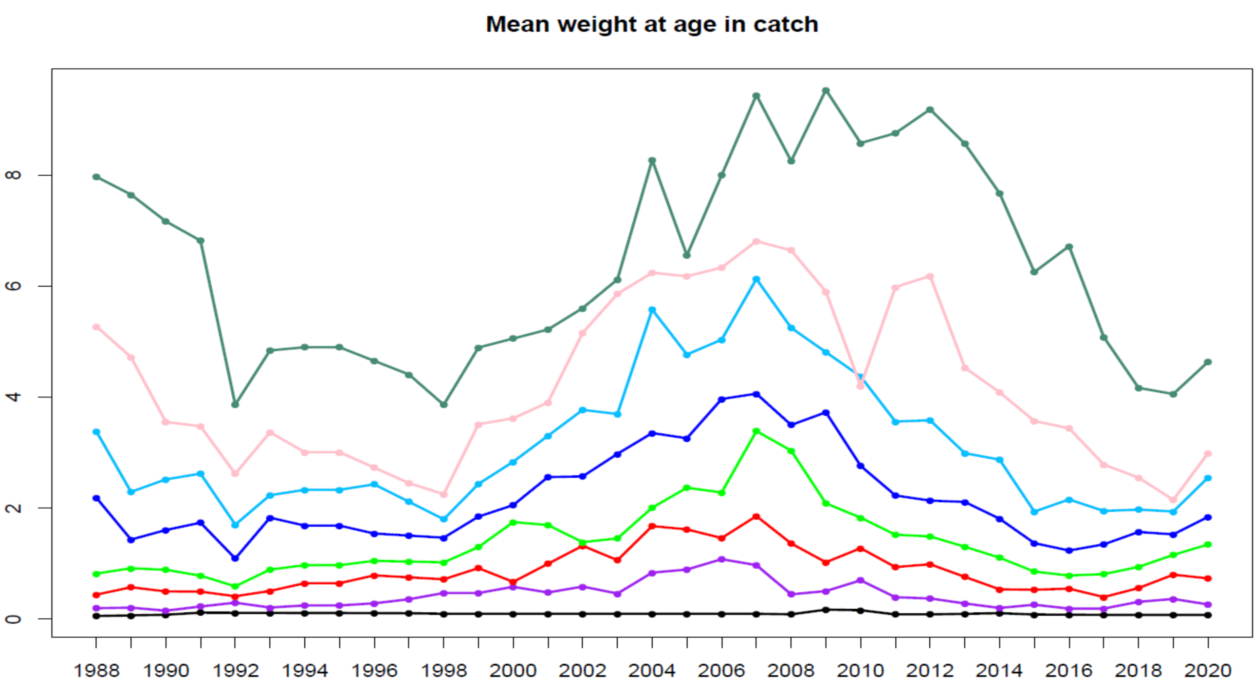


Figure 5. Catch mean weight at age.

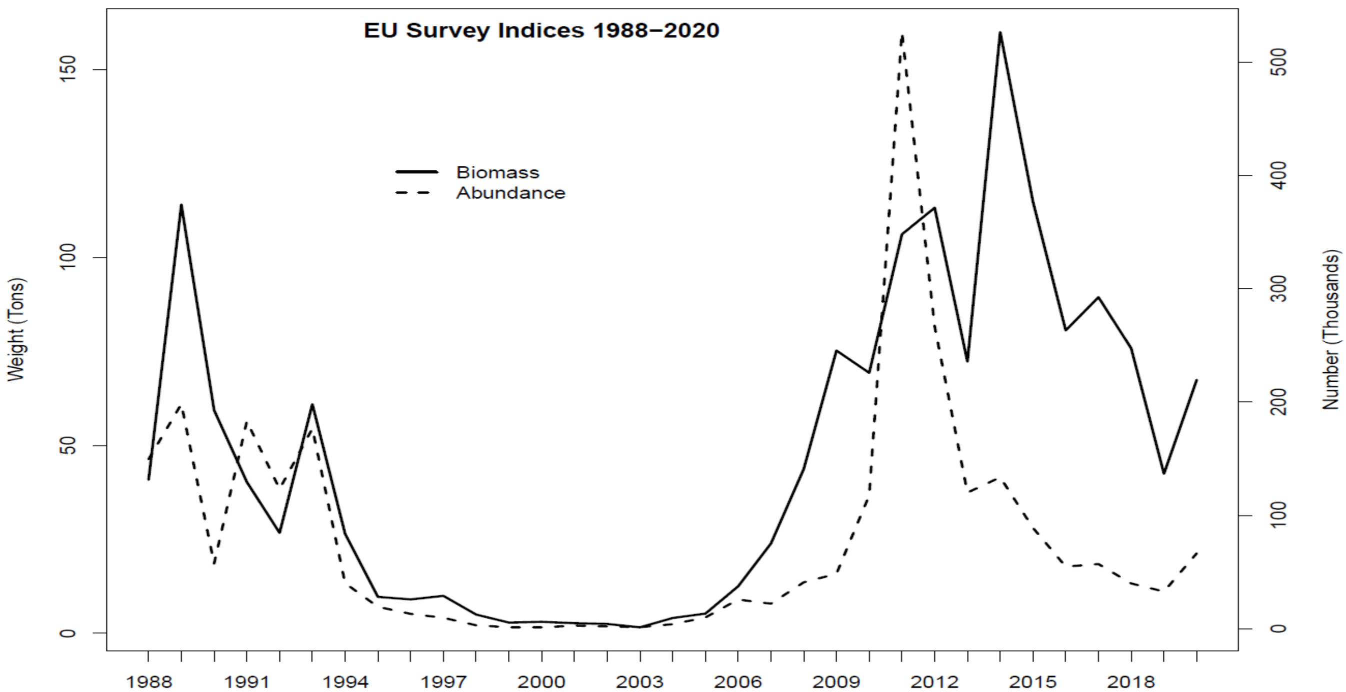


Figure 6. Biomass and abundance from EU surveys.

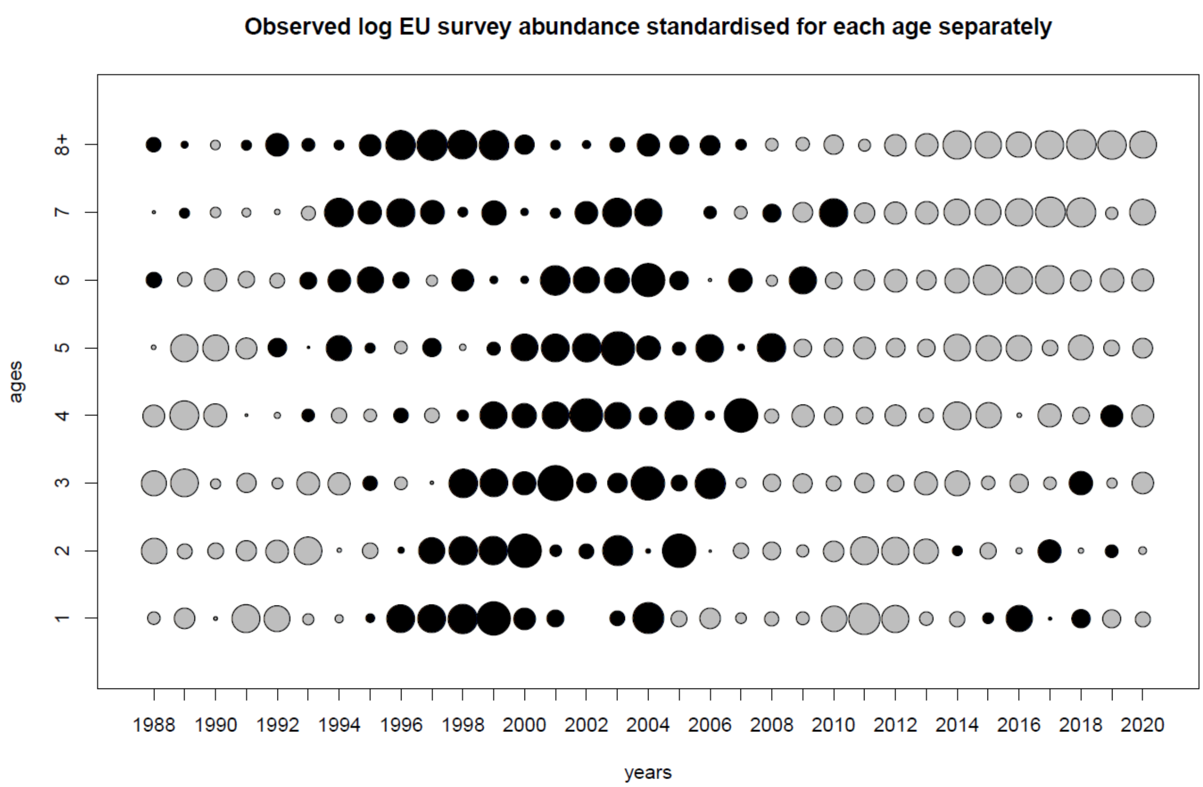


Figure 7. Standardised log(Abundance at age) indices from EU survey. Grey and black values indicate values above and below the average. The larger the bubble size the larger the magnitude of the value.

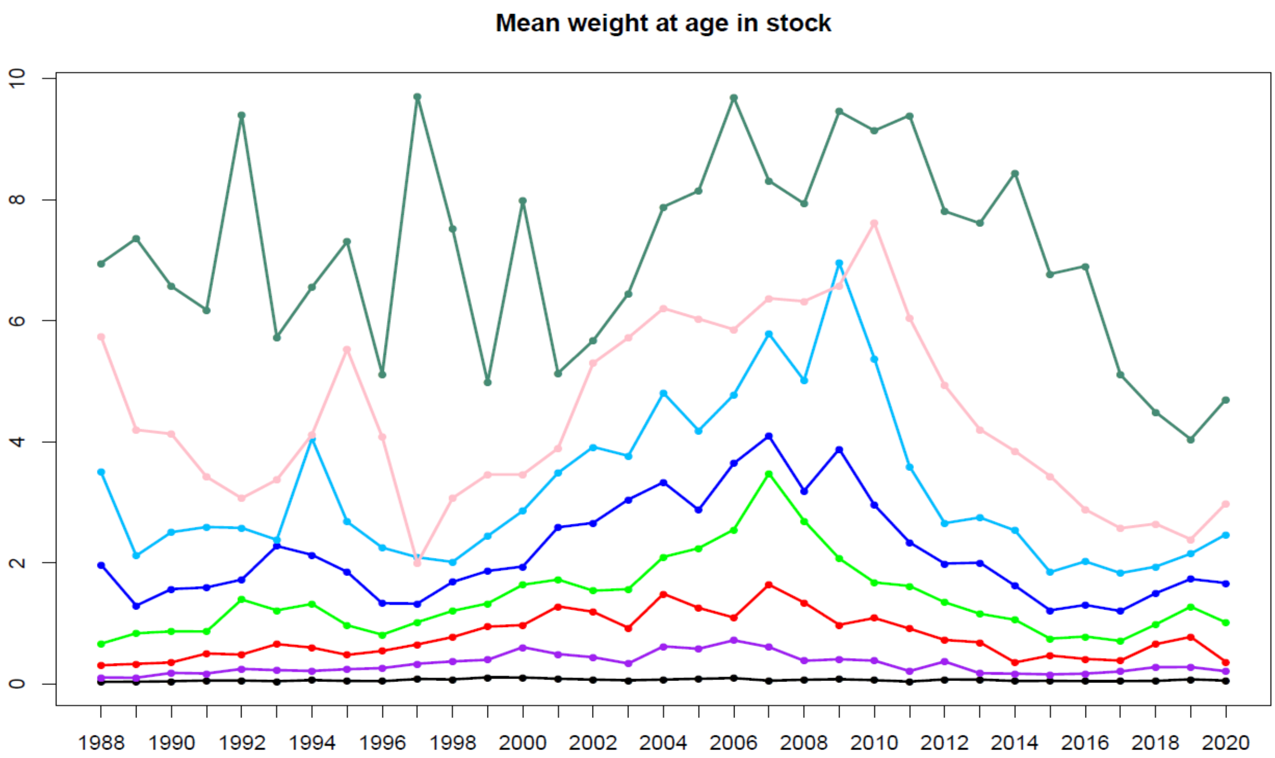


Figure 8. Stock mean weight at age.

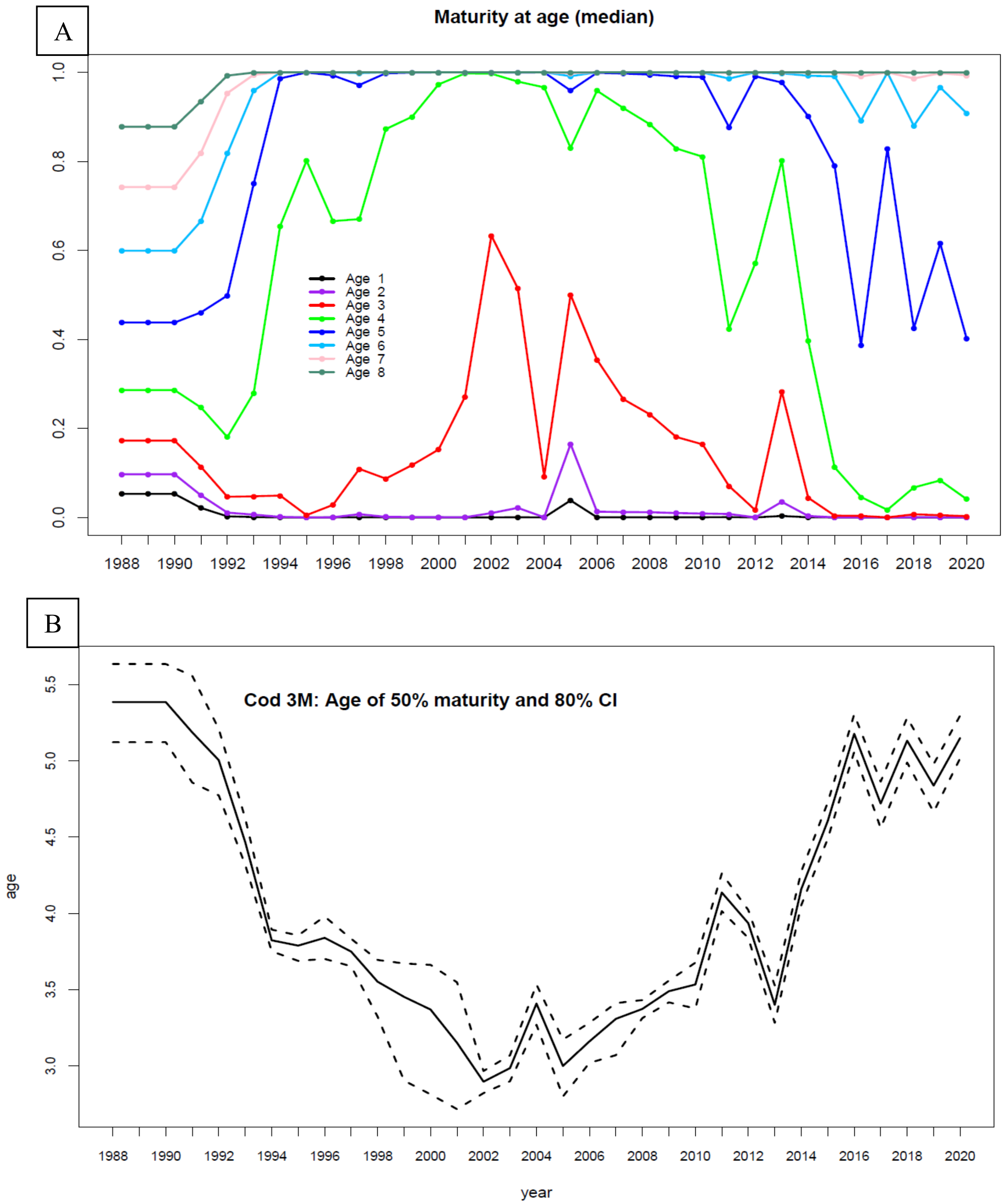


Figure 9. Maturity ogive by age (A) and age at which 50% of fish are mature (B).

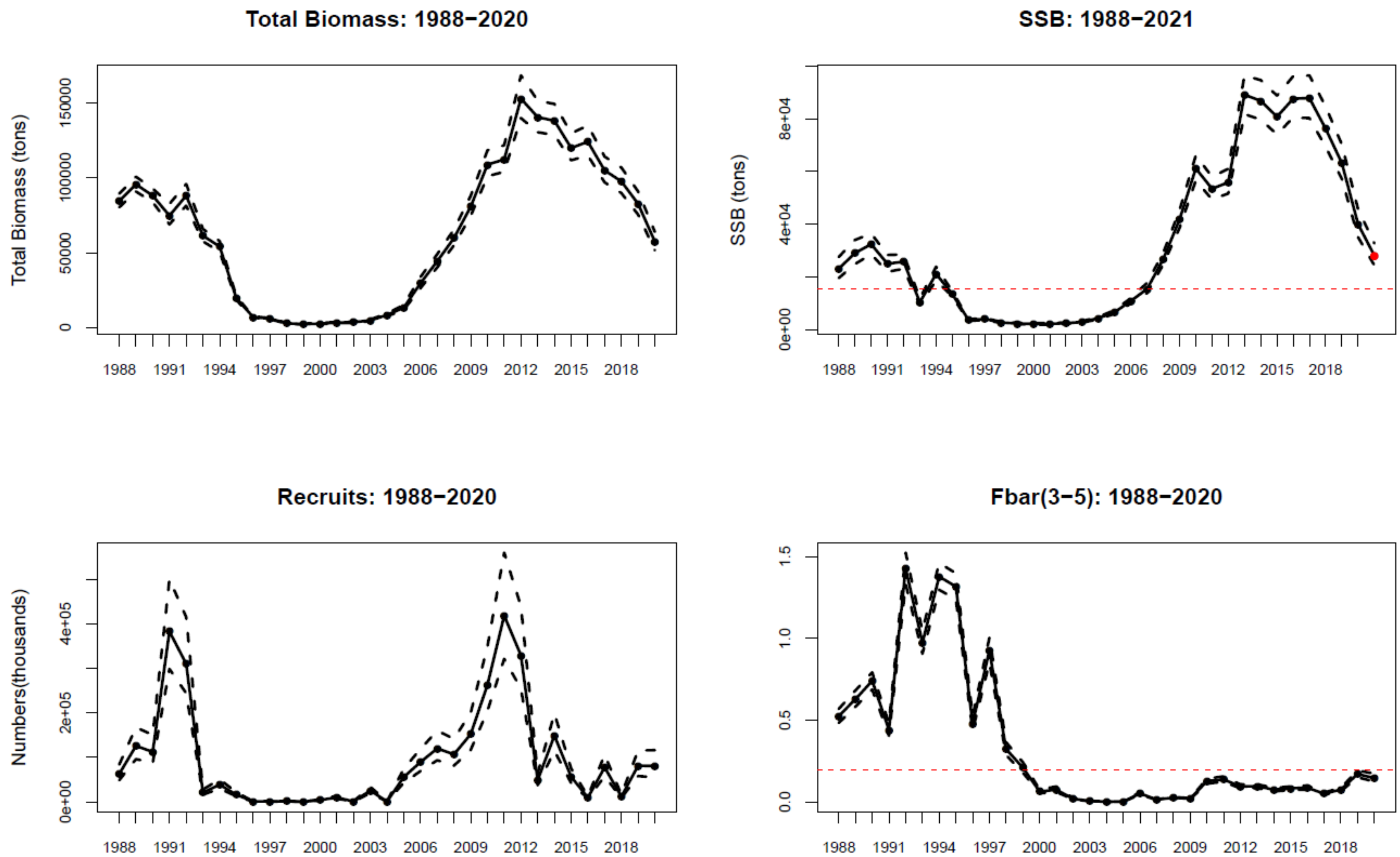


Figure 10. Estimated trends in biomass, SSB, recruitment and F_{bar}. The solid lines are the posterior medians and the dashed lines show the limits of 80% posterior credible intervals. Red point in the SSB plot indicates the SSB in 2020. Red horizontal line in the SSB graph represents median B_{lim} = medianSSB_{2007} = 15 408 tons. Red horizontal line in the F_{bar} graph represents median F_{lim} = 0.196 (with the last three years parameters).

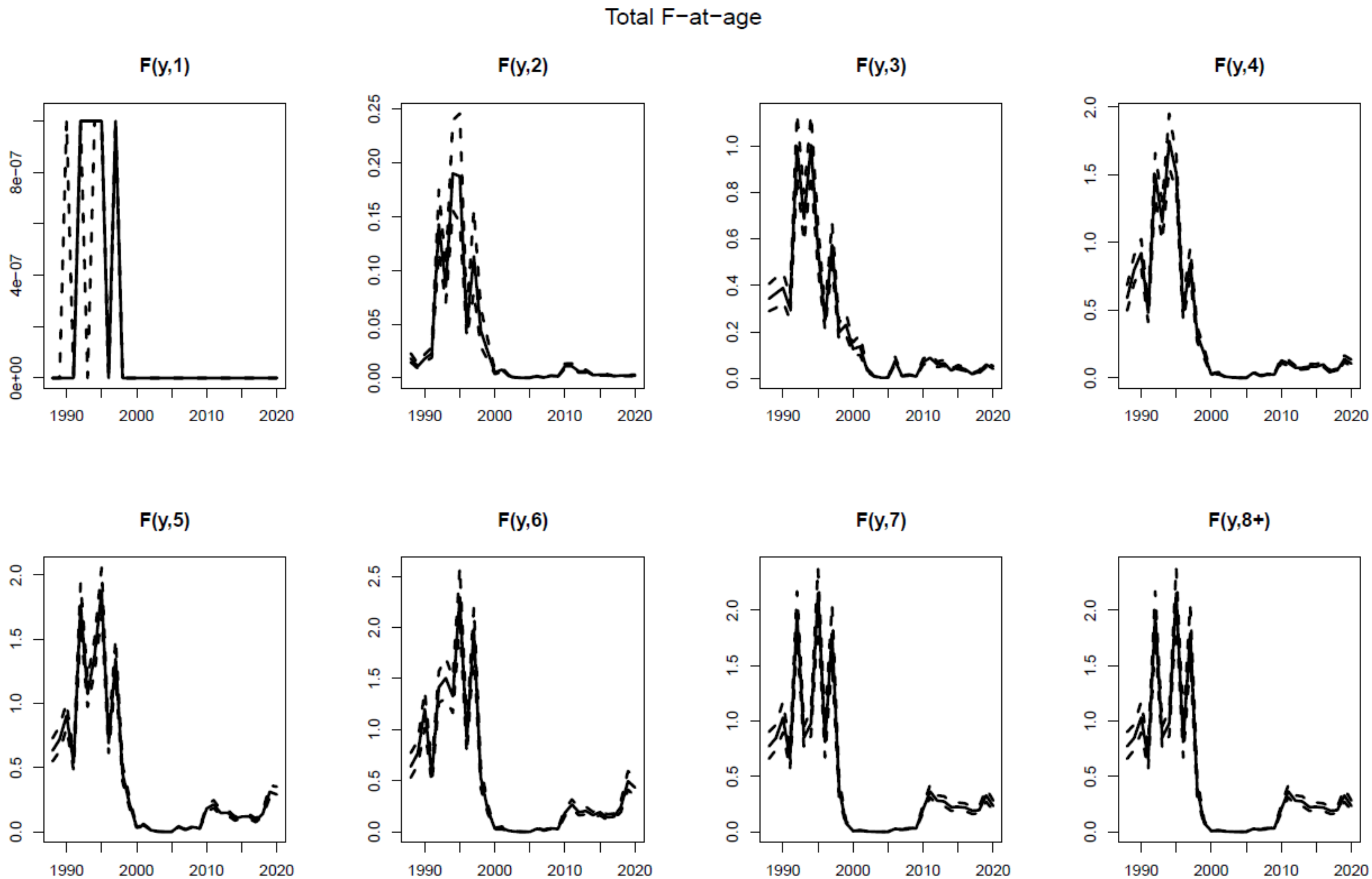


Figure 11. Estimated fishing mortality at age. The y-axis scale is different in all the graphs.

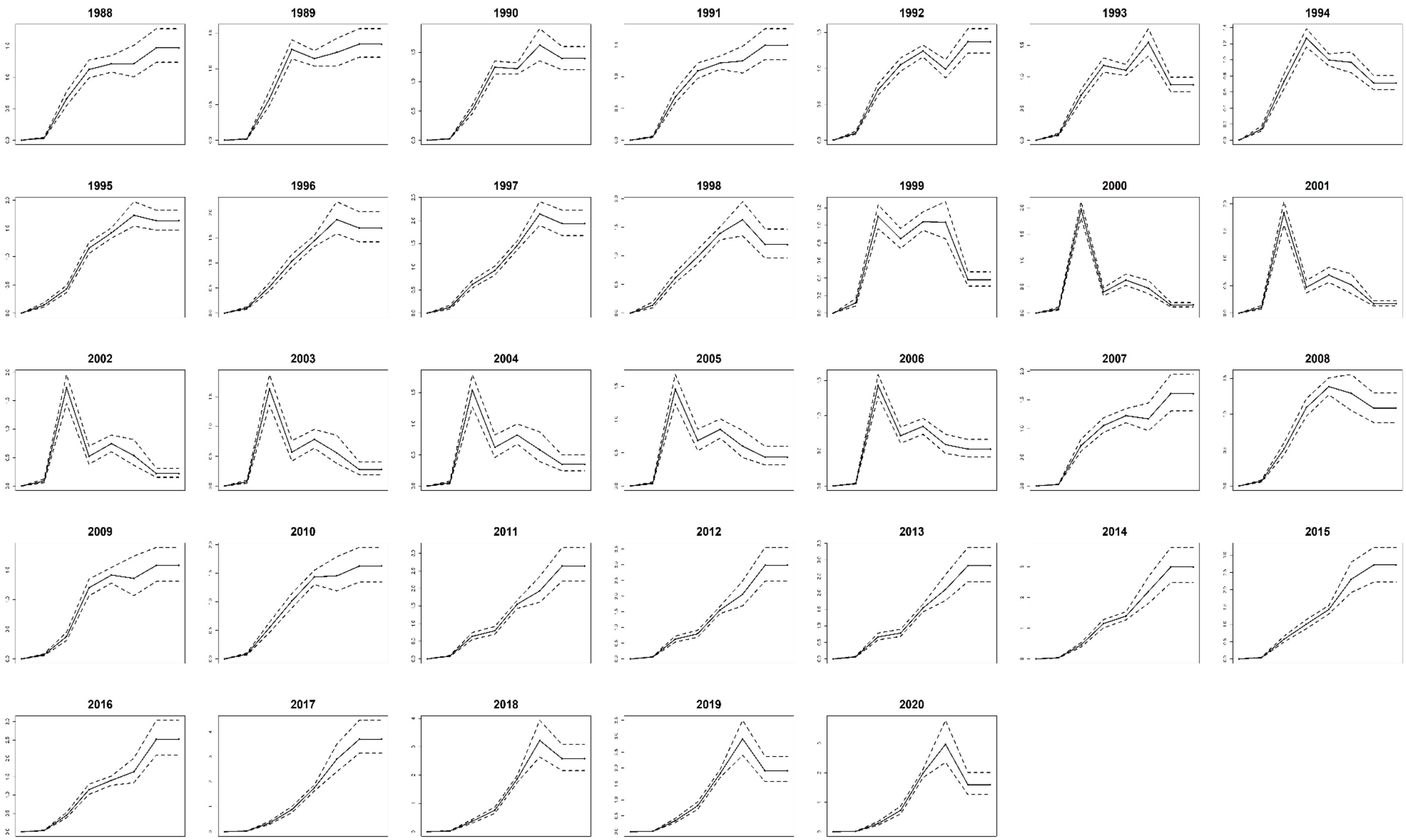


Figure 12. Estimated PR (F/F_{bar}) per age and year. The y-axis scale is different in all the graphs.

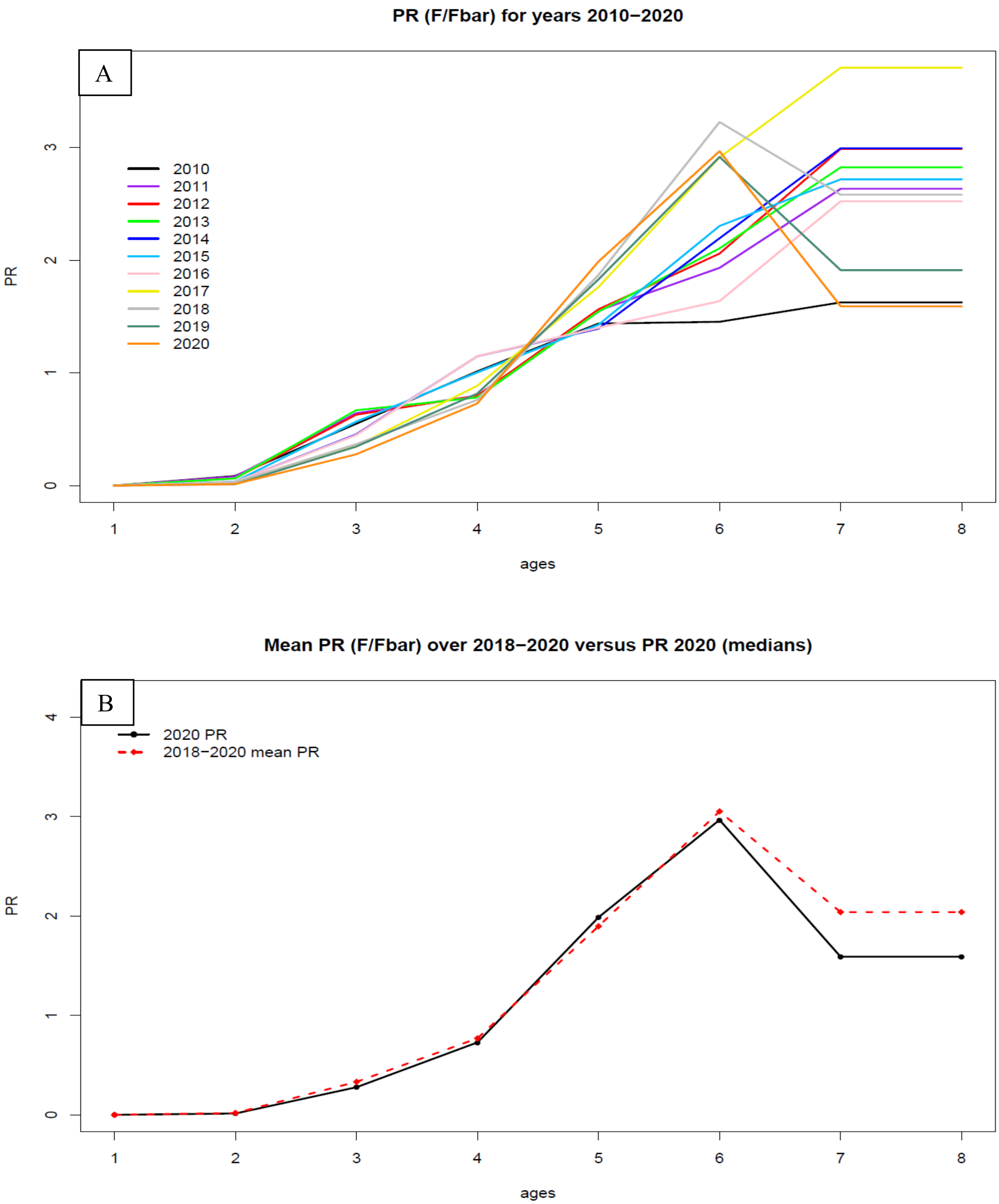


Figure 13. A) Estimated PR (F/F_{bar}) per age for the last ten years and (B) mean of 2018-2020 PR versus 2020 PR (posterior medians).

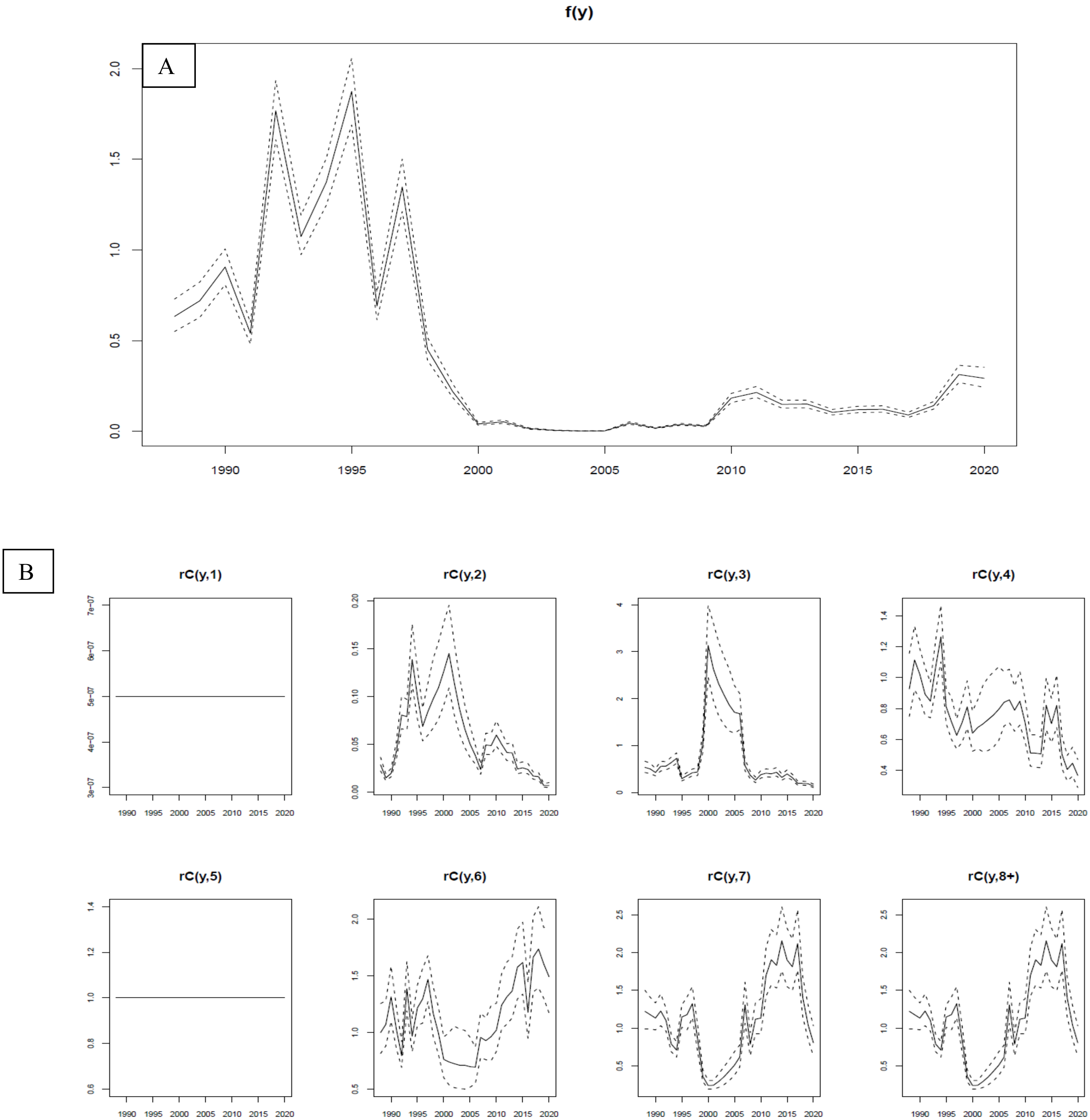


Figure 14. Components of the semi-separable model for Fishing Mortality: F[y,a]=*f*[y]**rC*[y,a].

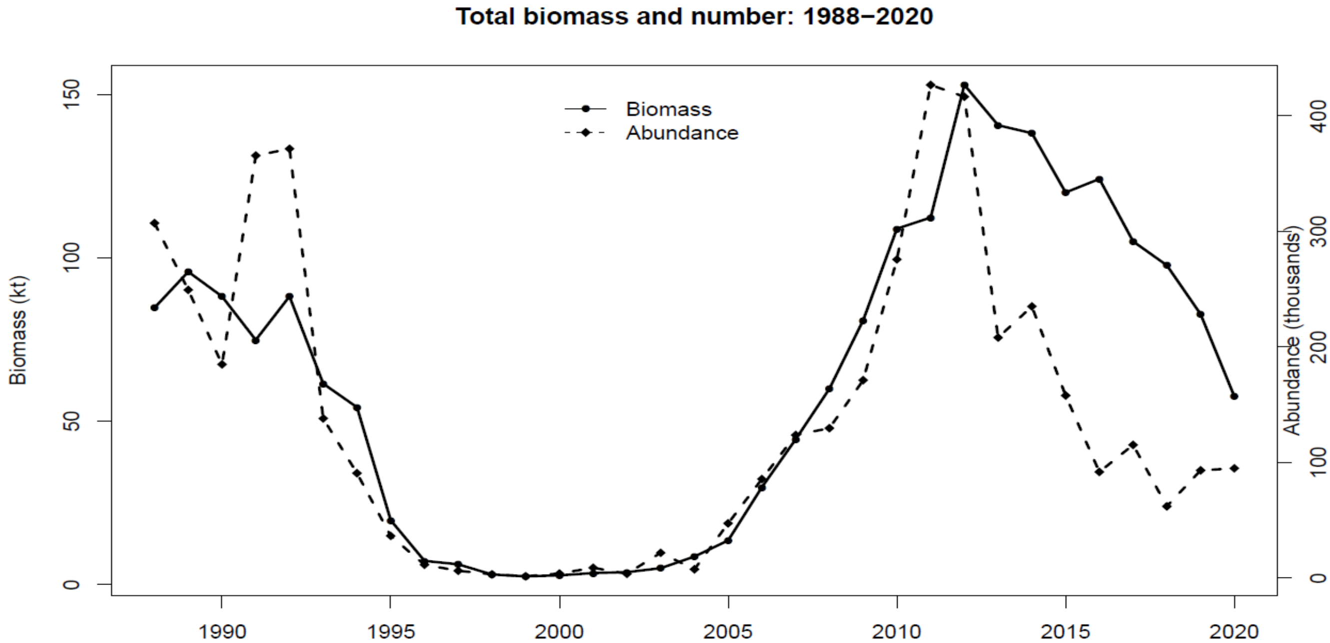


Figure 15. Estimated trends in biomass and abundance.

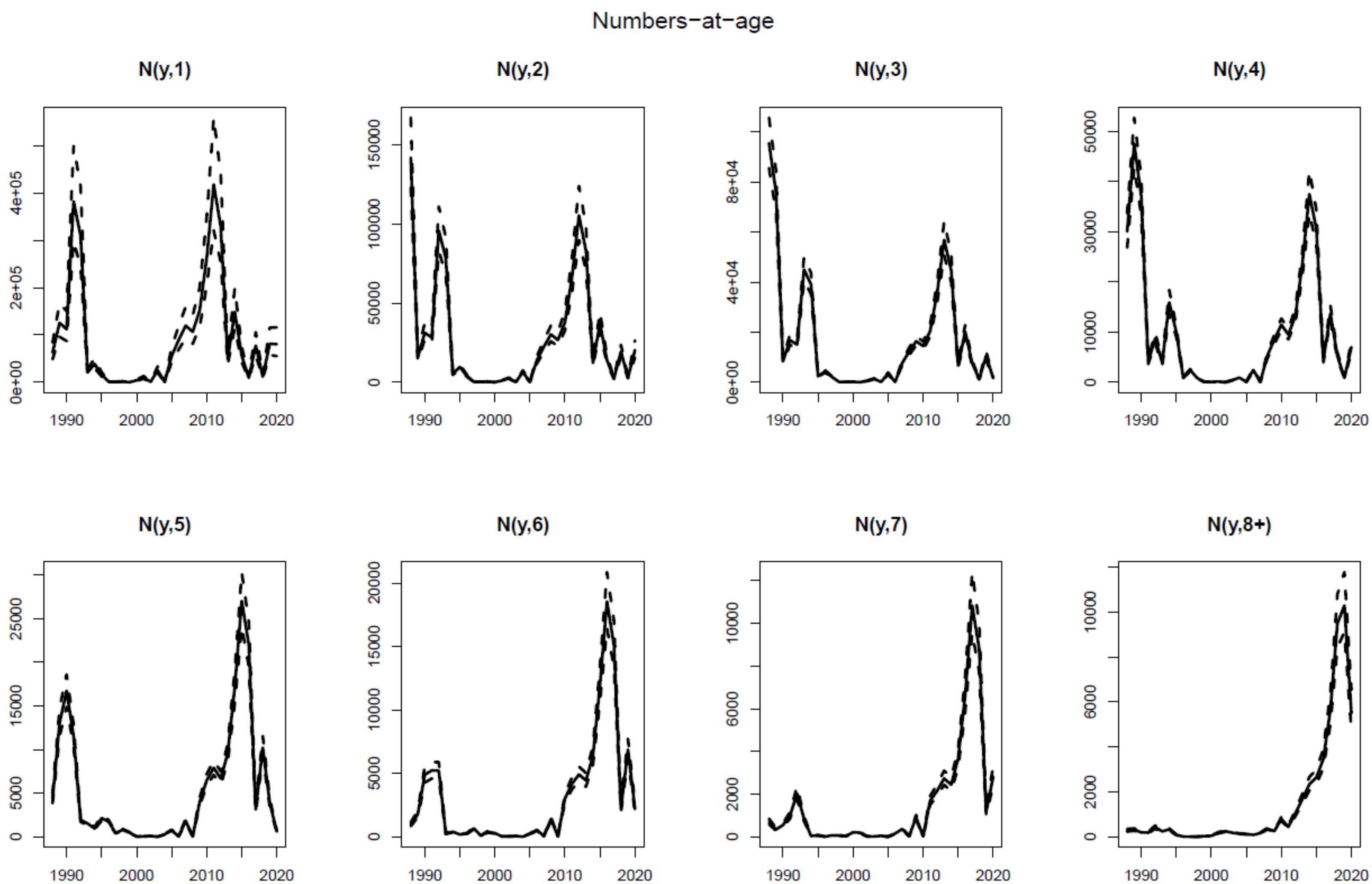


Figure 16. Estimated numbers at age. The y-axis scale is different in all the graphs.

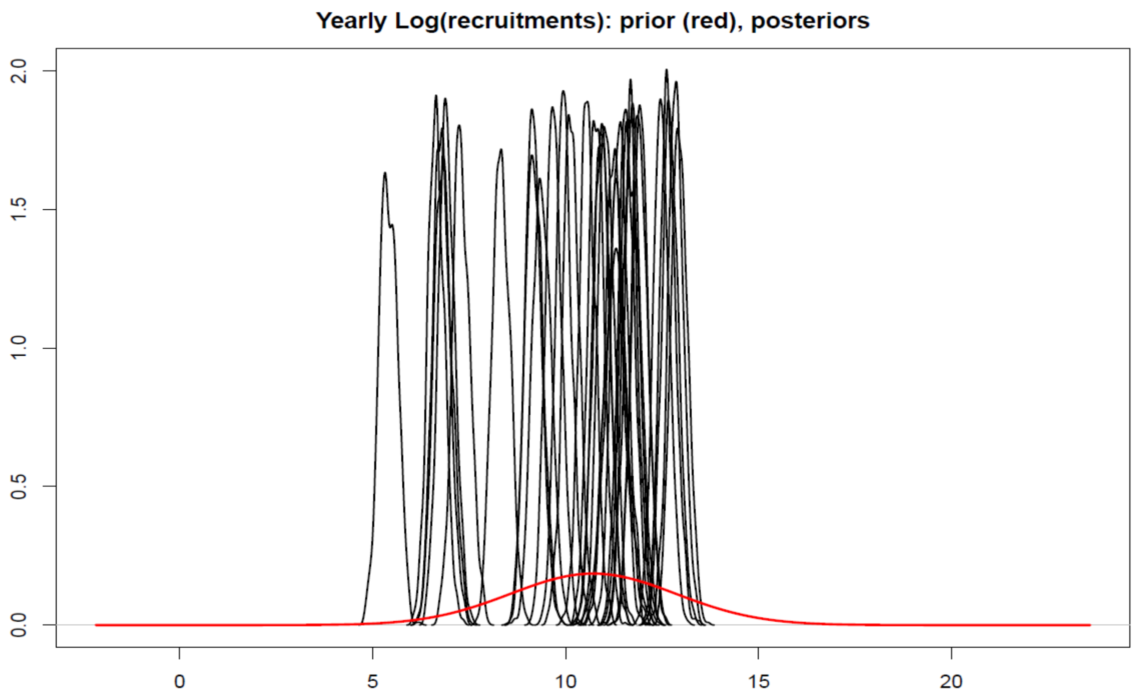


Figure 17. Prior and posterior of recruitment by year.

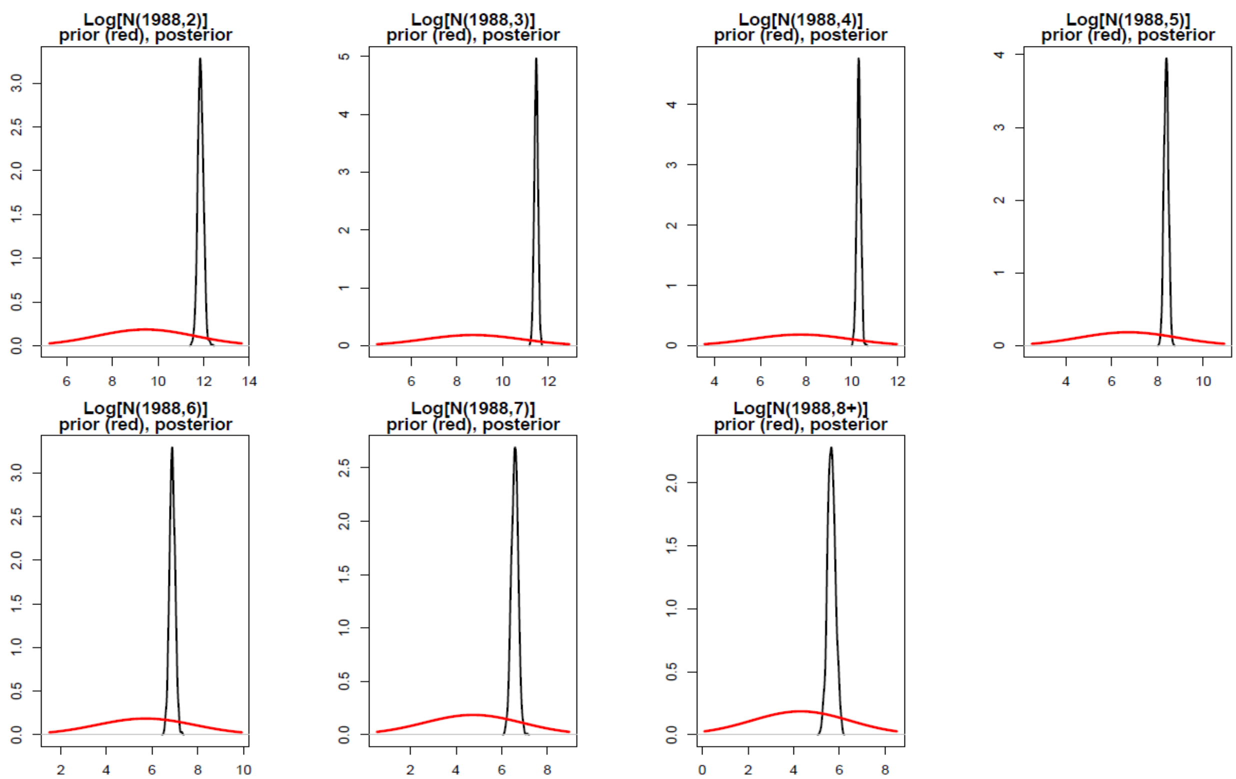


Figure 18. Prior and posterior of the numbers in the first year (1988) from age 2 to 8+.The x- and y-axis scales are different in all the graphs.

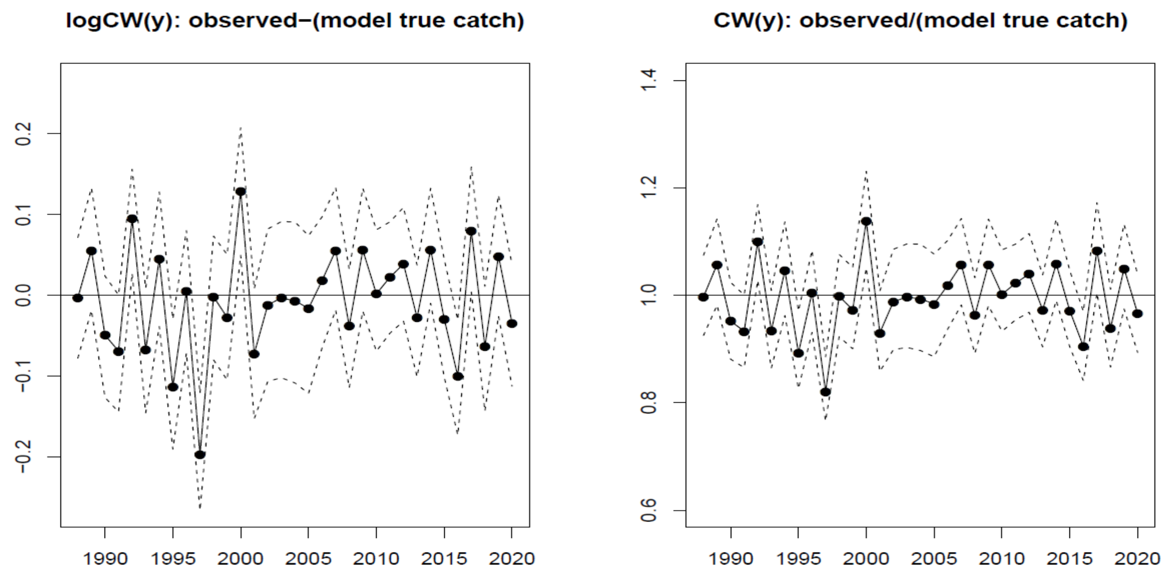


Figure 19. Observed versus estimated total catches by year.

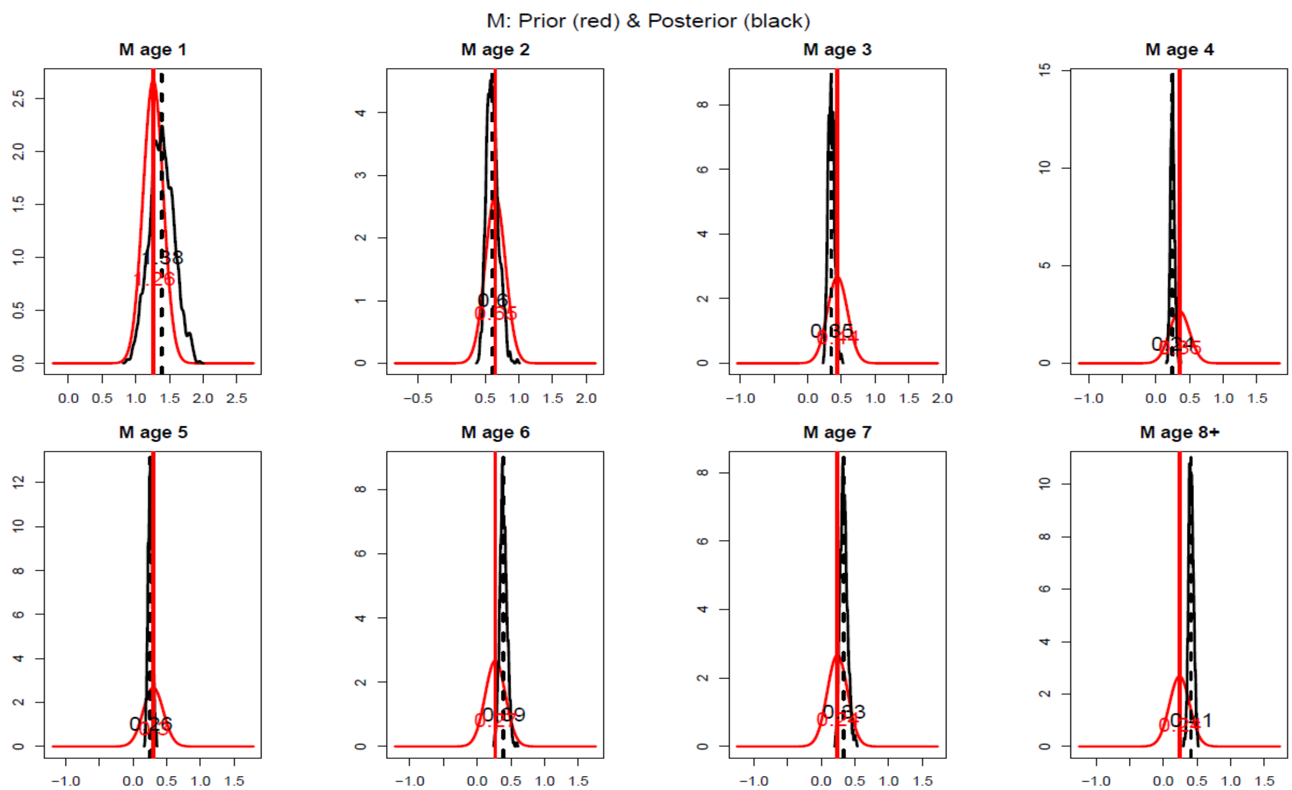


Figure 20. Estimated natural mortality by age in 2020.

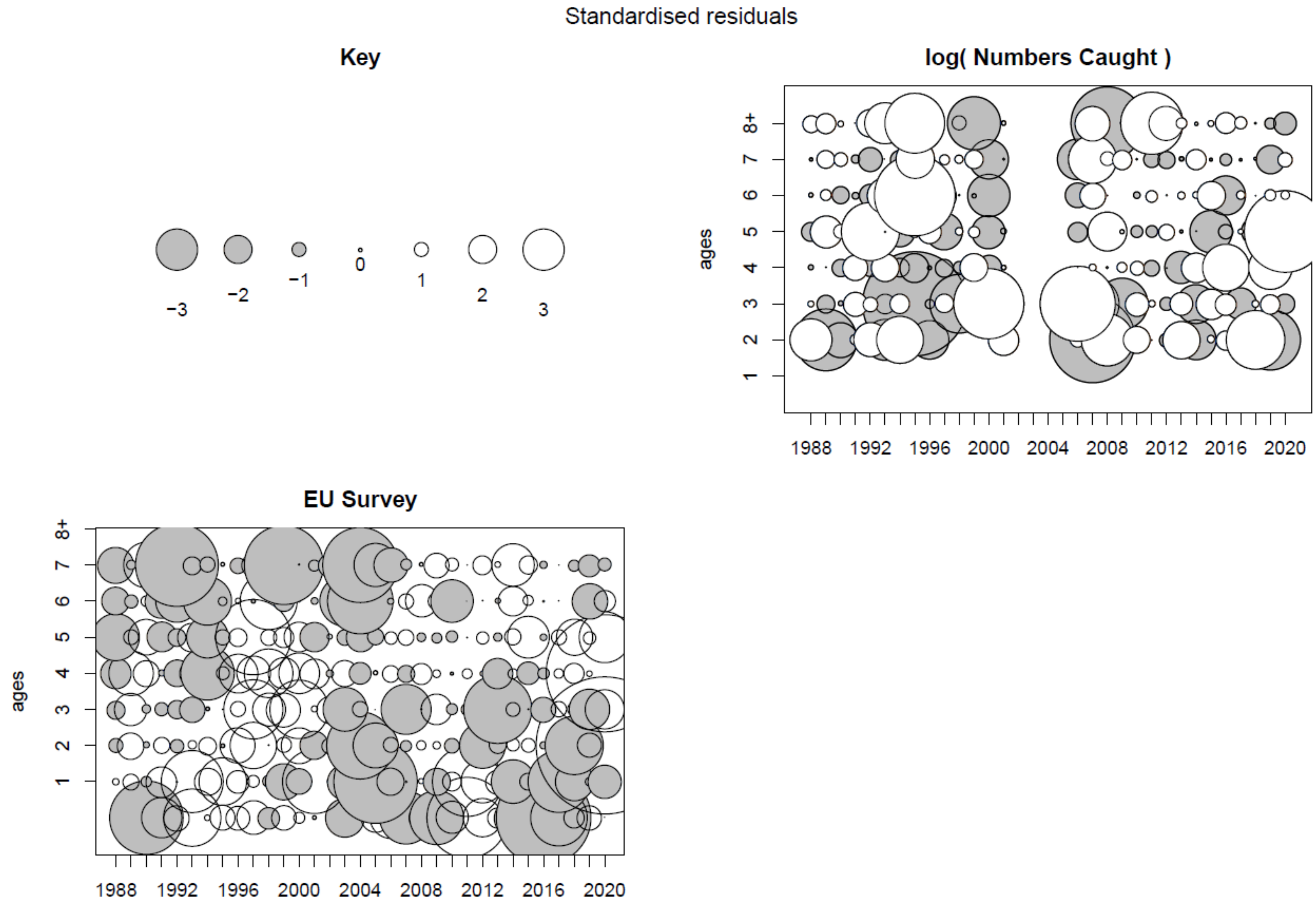


Figure 21. Standardised residuals (observed minus fitted value) in logarithmic scale of catch numbers at age and EU survey abundance indices at age. Grey and black values indicate values above and below the average. The larger the bubble size the larger the magnitude of the value.

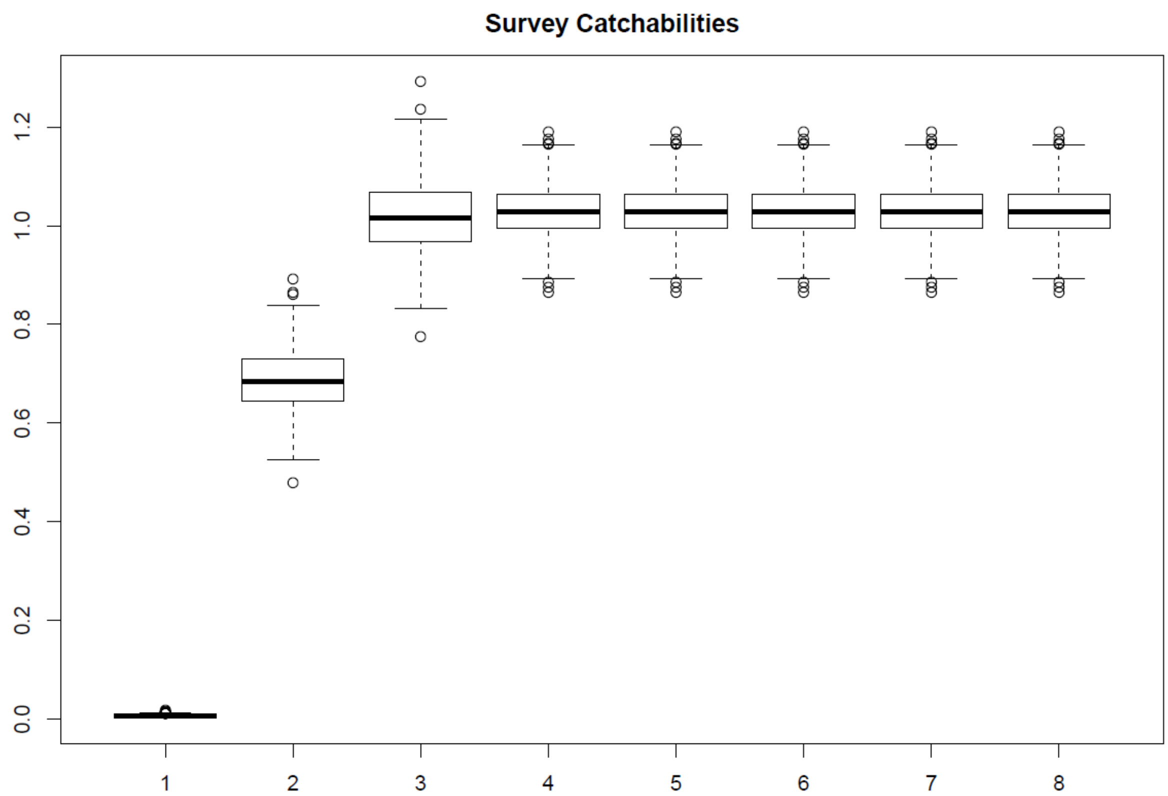


Figure 22. EU survey catchabilities distribution

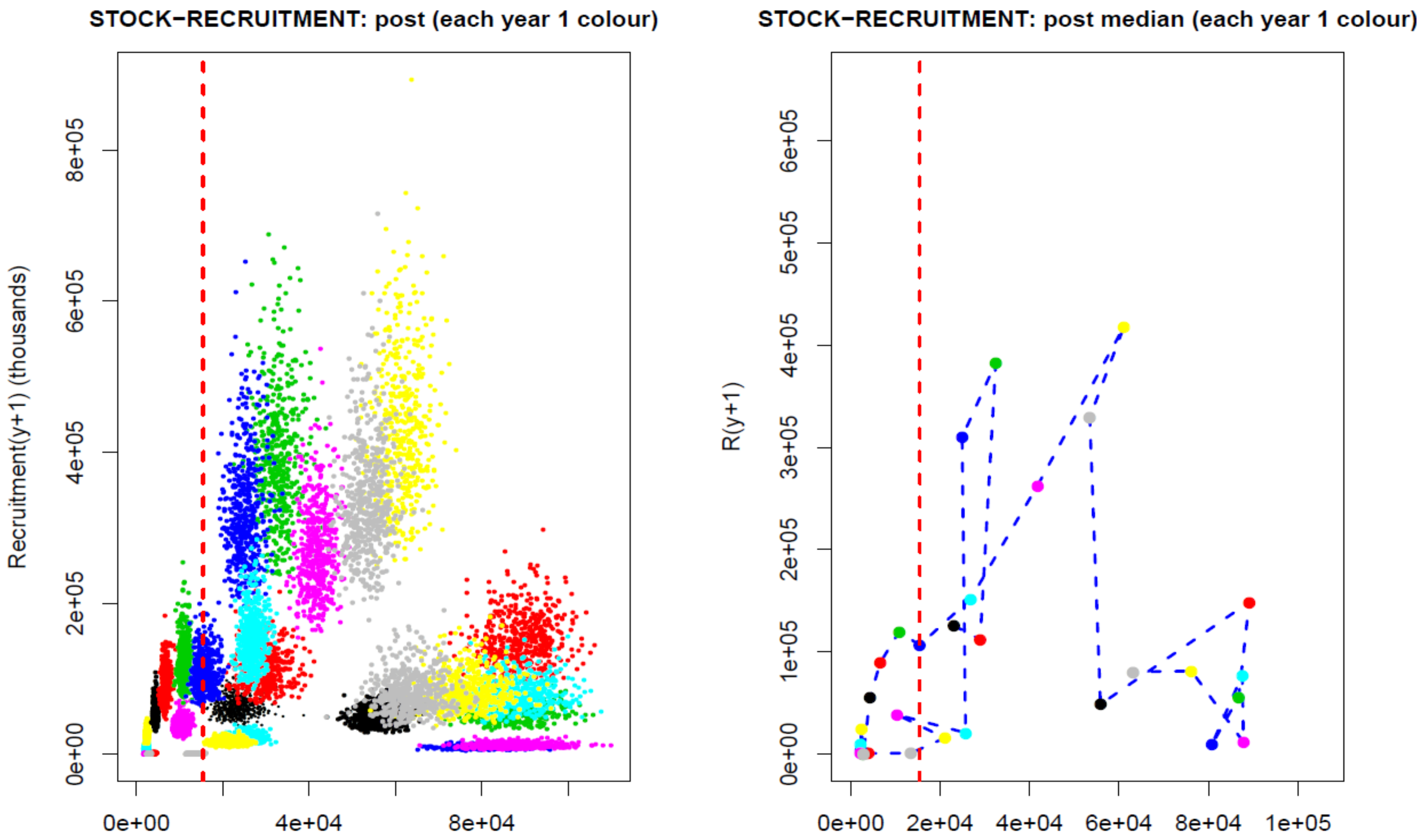
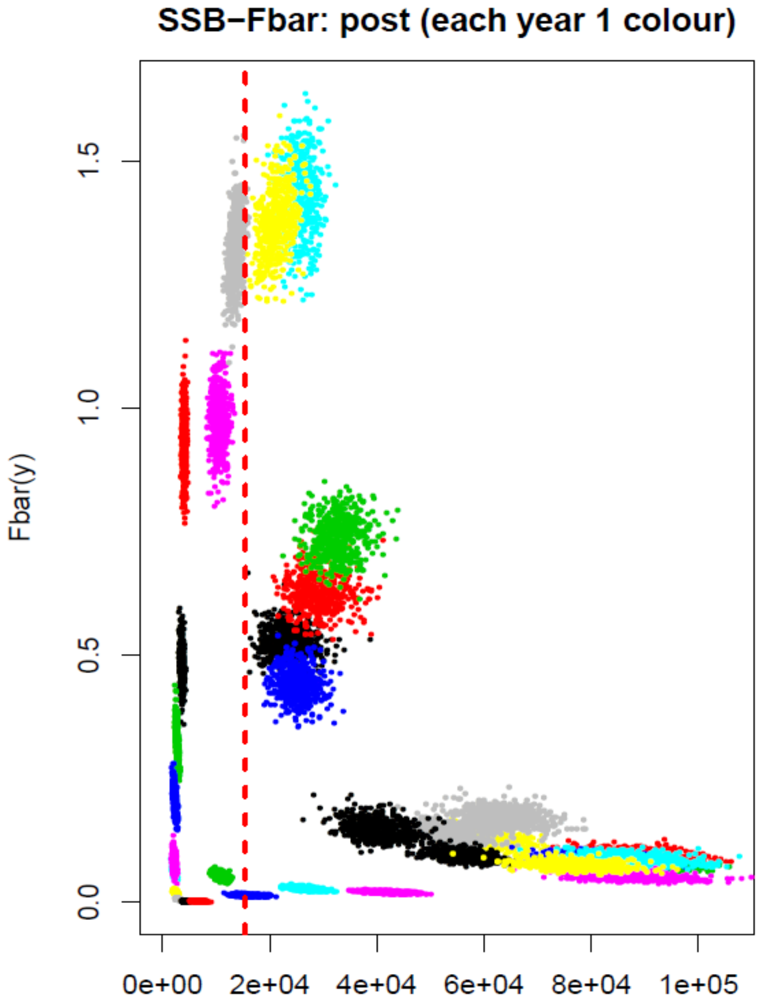


Figure 23. Stock-Recruitment plots. The value of median B_{lim}=medianSSB_{2007}=15 408 tons is shown as the red vertical line.



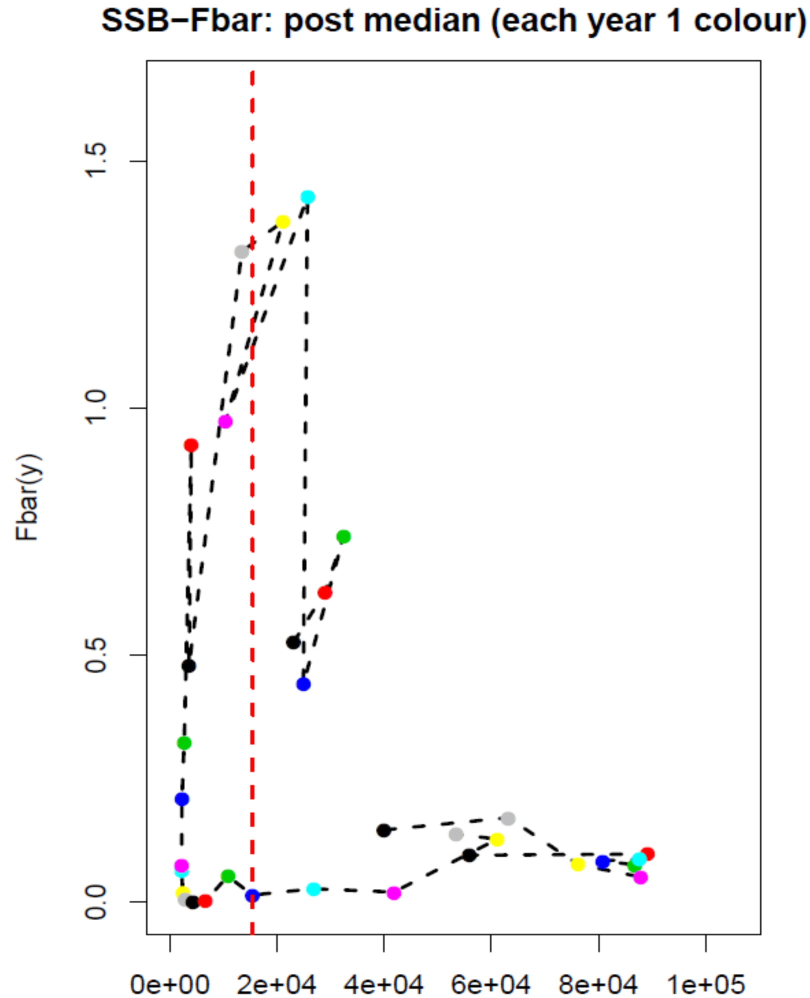


Figure 24. F_{bar} versus SSB plots. The value of median B_{lim}=medianSSB_{2007}=15 408 tons is shown as the red vertical line.

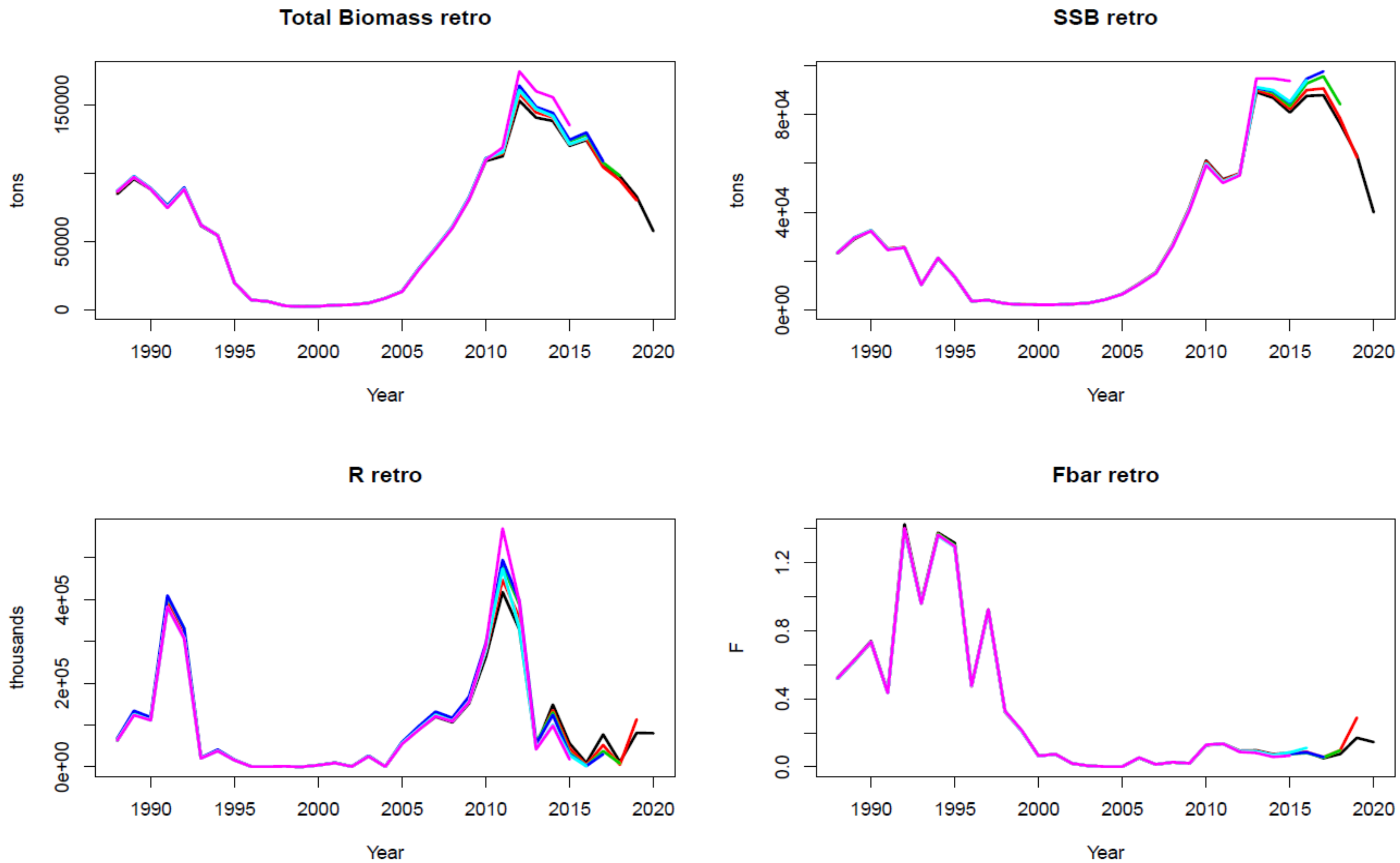


Figure 25. Retrospective patterns.

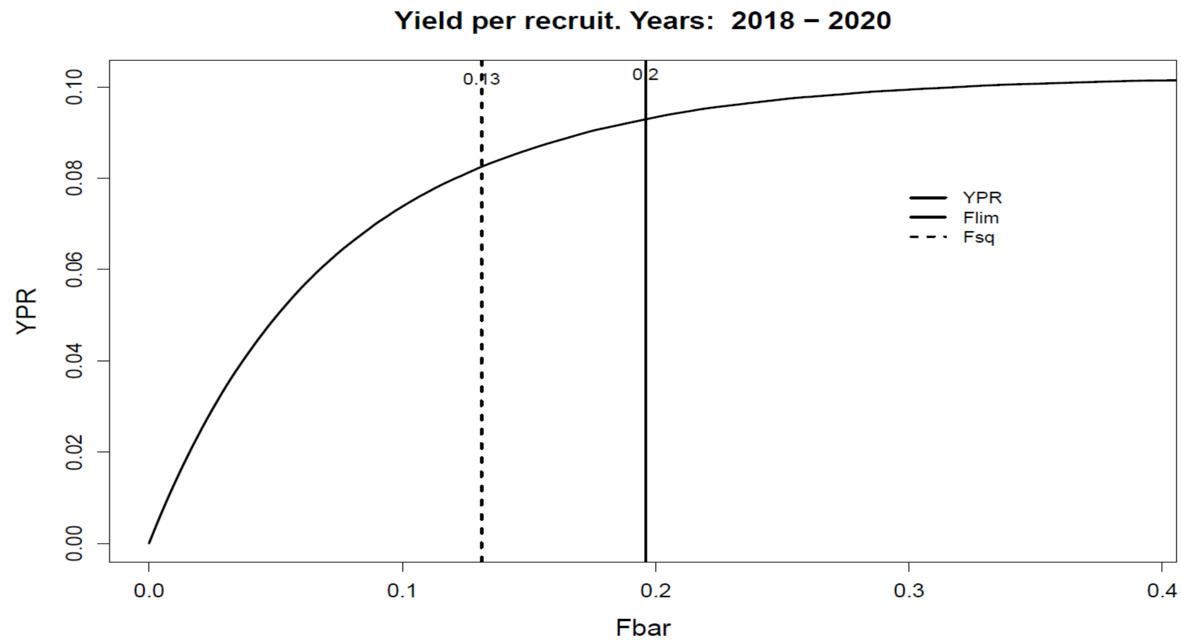


Figure 26. Yield per Recruit (2018-2020) versus F_{bar}. The values of F_{lim} ($F_{30\%SPR}$) and $F_{statusquo}$ (mean F over 2018-2020) are indicated.

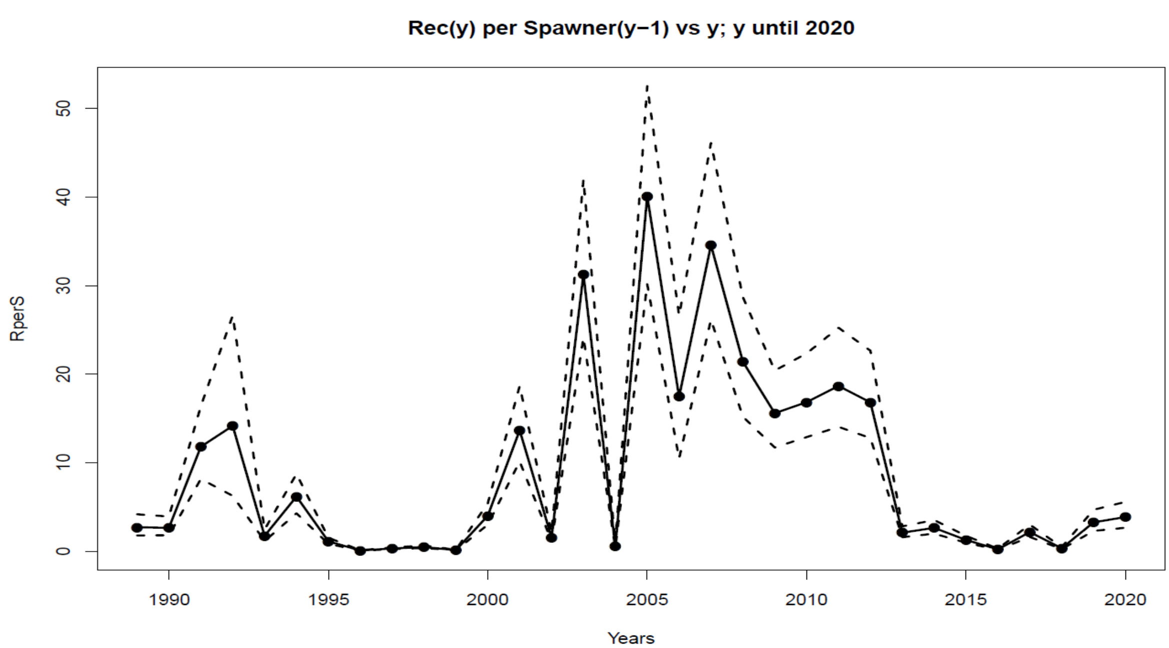
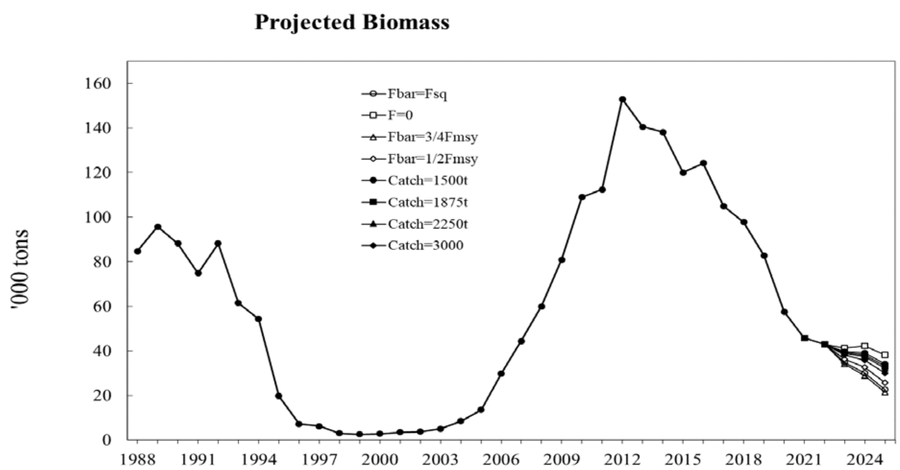
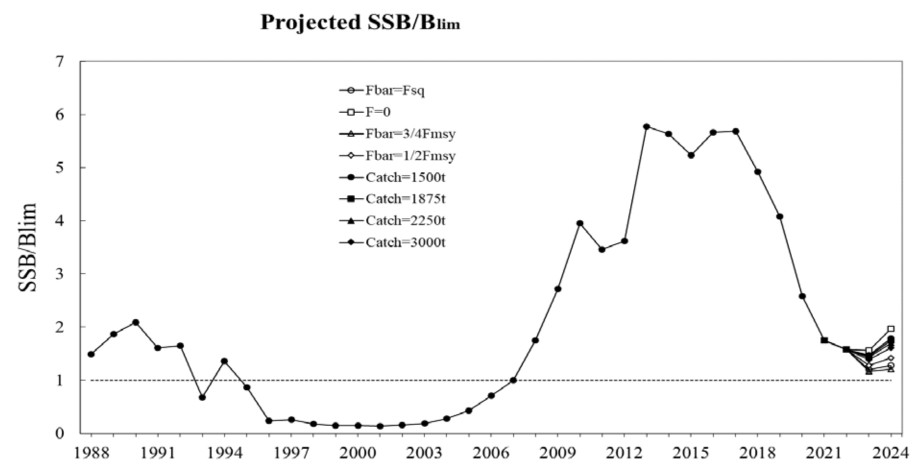


Figure 27. Estimated recruits (age 1) per spawner. First point: R_{1989}/SSB_{1988}.





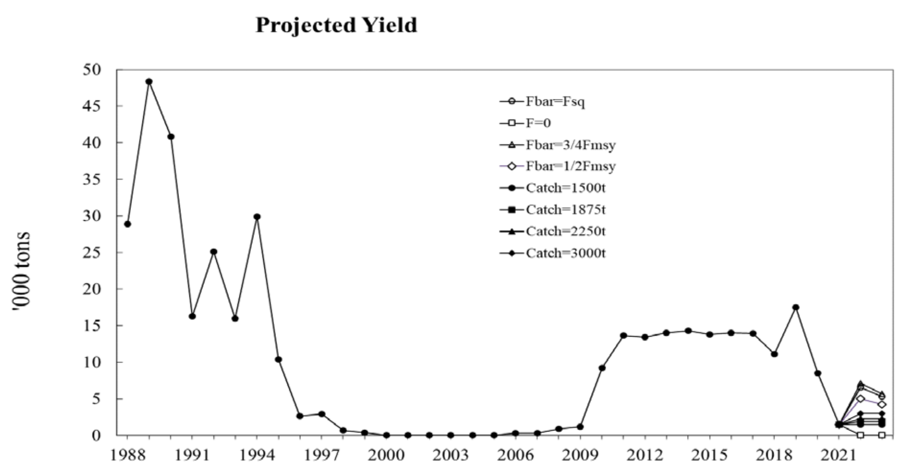


Figure 28. Projections for total Biomass, SSB/B_{lim} and Yield with different scenarios.

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. 2020) 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