…intended for ToR c) Re-examine and update (if necessary) MSY and PA reference points according to ICES guidelines (see Technical document on reference points).

Surplus Production Model for North Sea cod

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Abstract

The classic Surplus Production Model (SPM) approach can be useful for understanding the basic population dynamics, even for data rich stocks, and for defining so-called Operating Models in management plan evaluations. SPMs automatically include all density dependent factors, not only that in recruitment, and are simple and transparent. When combined with information from meta-analysis on the shape of the production curve and the value of Fmsy, SPMs can be a robust way of getting SSBmsy and MSY for stocks with a short time series of observation or for stocks which have been exposed to changes in productivity due to regime shifts. The approach was applied to North Sea cod. It showed that the productivity of the stock and its stock biomass reference points have greatly varied over time.

Introduction

If a surplus production model (SPM) is to be used for defining biological reference points or as Operating Model (OM) in a Management Strategy Evaluation (MSE) the first step is to find appropriate SPMs.

The reason why SPMs are interesting in this context is that they 1) automatically include all density dependent factors, not only that in recruitment, and 2) are simple and transparent. In the way applied below they can furthermore be 3) useful if the timeseries are short.

This note discusses how this can be done with the North Sea cod stock as an example. North Sea cod is very data rich and thus offers insights to details of the population dynamics that only very few other fish stocks do.

This cod stock has experienced large fluctuations in size, fishing mortality, catch and recruitment over the years (Figure 1). It is obvious that there were overfishing in 1980-2000. However, despite reduced SSB it produced quite good recruitment for some years, but since 1997 recruitment has been low and apparently without much relationship to the SSB. F has gone down substantially from the period 1980-2000 to recent years and have been as low as in the 1960s, which resulted in a booming cod stock then. The stock has not reacted that way in recent year.

The stock was especially high in 1960-1990s compared to both before and after (Figure 2). In 1921-1940 the SSB decreased from about 250 kt to about 100 kt but R did not change much. It seems thus that Blim must have been lower than 100 kt in that period. There were 5 years of very low fishing during WW2 but SSB only increased from about 100 kt to about 200 kt, which is inconsistent with the increased expected by ICES present population model (2019, WKNSMSE Figure 3.4.2.1.) where a closure of fishing should result in an increase from about 100 kt to about 600 kt in 5 years. The reason for ICES possible overestimation will be discussed later.

As explained by ICES (2019) all stock components have decreased since 1988 and the southern stock component extremely so, since 1999.

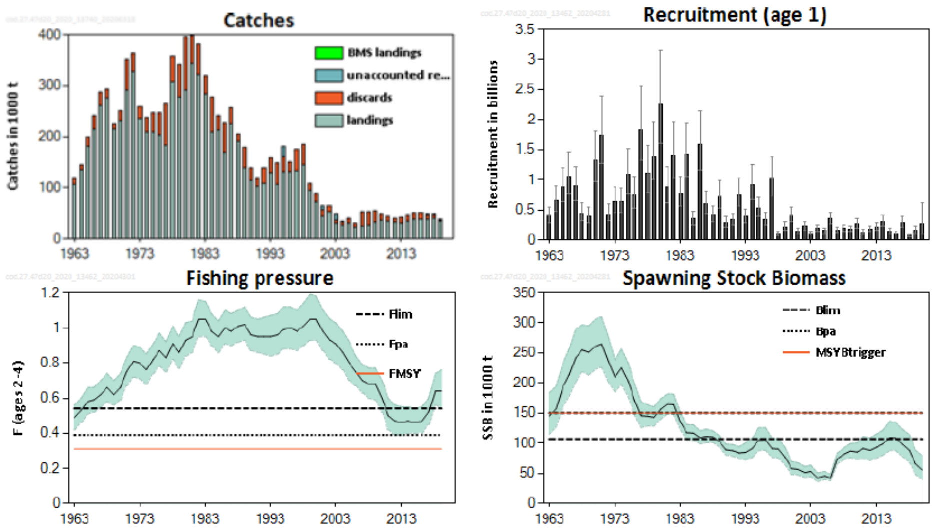


Figure 1 Cod in Subarea 4, Division 7.d, and Subdivision 20. Summary of the stock assessment. Catches are assessment estimates. Only positive unaccounted removals are plotted (see Table 5). Shaded areas (F, SSB) and error bars (R) indicate 95% confidence intervals. Landings below minimum conservation reference size (BMS) as officially reported.

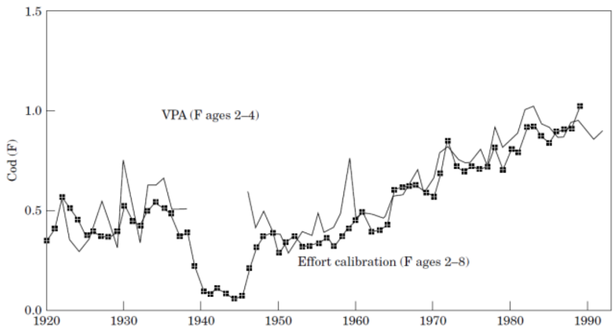


Figure 2. Fishing mortality rates for cod, as estimated by the new VPA (for 1921–1992 as averages of ages 2–4), contrasted with the results (for 1920–1989 as averages of ages 2–8) of ICES (1992).

Figure 4. Recruitment (as age 1 fish in millions) and spawning-stock biomass (in thousand tonnes) for cod 1921–1993, as estimated by VPA.

Figure 2. *North Sea cod. Fishing mortality, SSB and recruitment back to 1921, based on Pope and Macer (1996) with catch data from ICES (1969). An extract of the catch data table is given in Annex 4 .*

ICES (2020b) suggest, based on genetic studies, egg surveys, trawl surveys, tagging studies, meristic studies, and life history parameters, that the stock assessment should support advice for managing the genetically distinct Viking cod and Dogger cod populations, separately.

In the present study we still operate mainly with the concept of one stock, because we do not have long data series for the Viking cod and Dogger cod populations as separate stocks. However, we make considerations to the facts that the "one" stock probably consists of two stocks and that the Dogger stock probably is so depleted that it needs a separate management measure, like "no directed fishery for cod in the southern area".

The basic approach is to 1) explore the fit of historical data on stock size and production to SPM models and reveal indications of regime shifts just based on this, 2) explore the historical data on the stock-recruitment relationship and reveal indications of regime shifts just based on this, and 3) link 1) and 2) to come up with the best possible SPM model for this combined cod stock valid for the coming 10 years.

The observed indications of regime shifts will be linked to pressures on the cod stock from predation, food competition and climate in a separate document (WK Doc HS3 WKNSEA 2021).

Material, methods, and result

SPM models

Based on observed surplus production (SP) and total stock biomass (TB) an SPM can be established by fitting to these observations. SP is the annual catch plus the change in TB from one year to the next. Figure 3a shows the SP vs the TB based on the stock assessment from ICES (2020a) covering the years 1963-2020. We have discarded the most recent two years due to expected large uncertainties in the values, as indicated by the strong retrospective pattern in the assessment (ICES 2019). Also shown are the fitted (maximum likelihood – least squared deviation of residual SP/TB – the CV of SP assumed to be normally distributed and proportional to TB) SPM model. The shape of the SPM was taken from the meta-analysis by Thorson *et al.* (2012) who considered 141 stocks and obtained the shape of the SPM for Gadiformes stocks. The shape parameter Bmsy/K was estimated to be 0.439, i.e., quite close to 0.5 which is the classic Schaefer SPM curve. The top point of the curve was determined by the Fmsy value estimated by Sparholt *et al.* (2020) as 0.55 (expressed in biomass of catch divided by TB where TB is corrected for weight-at-age at 1st January) obtained also from a meta-analysis using an ensemble of models. SSB is obtained from TB by the relationship between the ration TB/SSB to F in the time series.

There is an issue with the weight-at-age in the stock data used by ICES (2020a). ICES use the same data as used for weight-at-age in the catch. This means the weight-at-age in the stock of age 1 and maybe also to some extent of age 2 are overestimated, due to the selectivity of the commercial fishing gear. The IBTS 1q survey gives a much more realistic estimate and this was on average a factor of 7 smaller for age 1. Furthermore, because ICES calculate TB as the product of stock numbers at 1 January and weight-at-age in the catch (which represent about the middle of the year) TB gets substantially overestimated by ICES.

In Figure 3b we have corrected the ICES TB by replacing the weight-at-age of age 1 from the catch with weight-at-age from the IBTS 1q. This will reduce the TB is general and make it less dependent on recruitment. It will of course also influence the SP as a part of the SP is the change in TB from one year to the next. K (carrying capacity), SSBmsy and MSY all reduces, compared to calculations based on ICES weight-at-ages.

In Figure 3c we have furthermore corrected weight-at-age for all ages, by for each age taking the mean of the weight-at-age of that age and of the age group one year younger (see WKNSEA HS1 2021). As both represent the middle of the year the mean of these two are regarded as a better representing of weight-at-age on 1 January. K, SSBmsy and MSY all reduces compared to calculations based on both other sets of weight-at-ages.

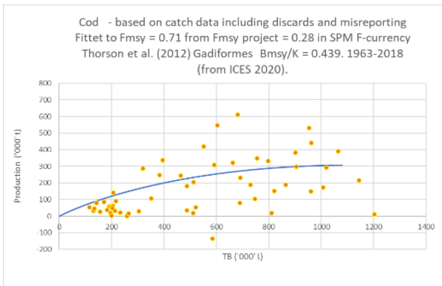
It seems quite important that realistic weight-at-age are used in the analysis.

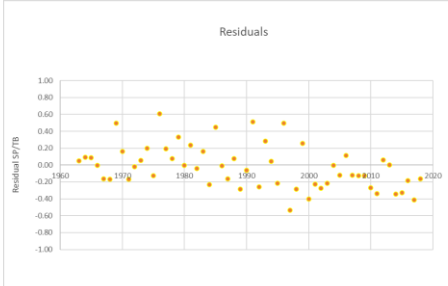
The SPM in Figure 3c is probably the best reflection of the stock dynamic. It is well within the maximum possible stock sizes for North Sea cod of 2 million t if most other fish stock are reduced to low levels, as estimated by Andersen and Ursin's (1977) iconic model of the North Sea ecosystem. However, even for this SPM model it seems obvious, that there are too many points below the curve at small TB values.

In Figure 4a we have shorten the time series to 1988-2018 because the residuals indicate a regime shift there and a regime shift have been reported in the North Sea in the period 1983-1988 by several studies, e.g., Beaugrand *et al*. (2015). However, even on this plot there are too many points below the curve at low TBs and the residuals indicate another breakpoint around 1998.

a) TB from ICES 2020

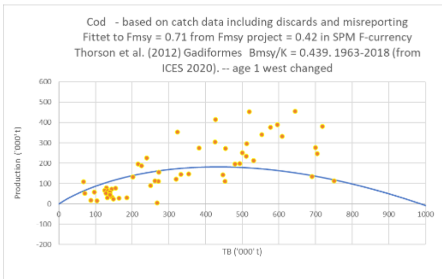
K	2546
TBmsy	1118
SSBmsy	308
SSBmsy in ICES-SSB currency	406
MSY	319
R^2	0.60

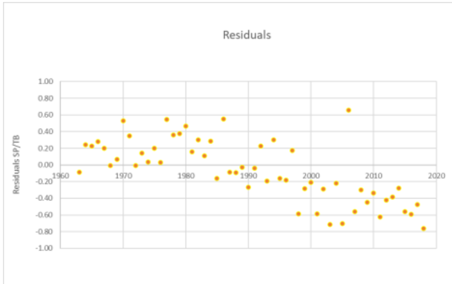




b) TB moderated by using real stock weigth-at-age for age 1

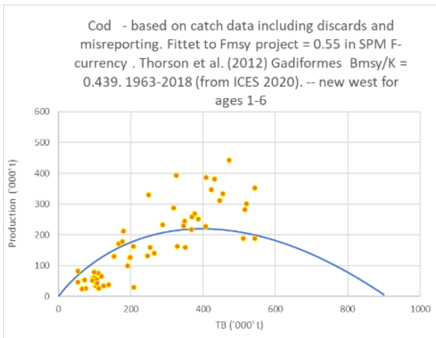
K	989
TBmsy	434
SSBmsy	181
SSBmsy in ICES-SSB currency	230
MSY	183
R^2	0.50





c) TB moderated by using real stock weigth-at-age for all ages

K	755
TBmsy	332
SSBmsy	144
SSBmsy in ICES-SSB currency	183
MSY	183
R^2	0.53



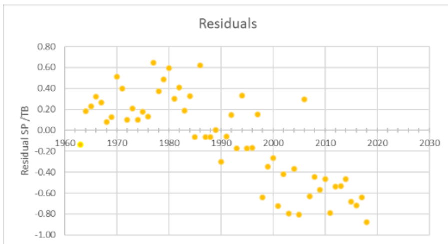
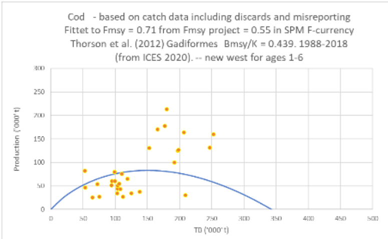
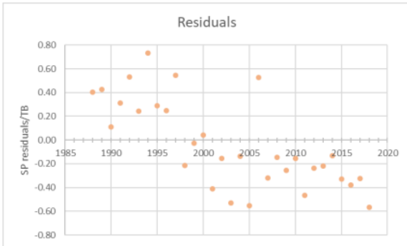


Figure 3. *Cod North Sea. Surplus Production Models fitted to historic observations of Surplus Production vs total stock biomass (TB). Surplus Production is catch plus change in TB from one year to the next. In a) the TB value from ICES (2020a) is used. In b) this TB was replaced with TB corrected regarding weight-at-age for age 1 based on IBTS data. In c) TB was replaced with TB corrected regarding the weight-at-age for the rest of the age groups so that they reflect the situation at 1st January each year. "Old SSB currency" is ICES (2020) current way of calculating SSB (multiplying stock numbers at 1st January with weight-at-age in the middle of the year). Biomass in '000' t.*

a) 1988-2018

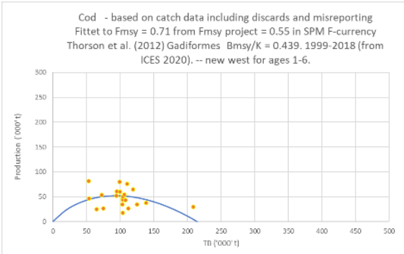
K	343
TBmsy	151
SSBmsy	65
SSBmsy in ICES-currency	83
MSY	83

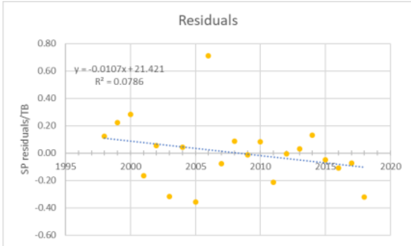




b) 1998-2018

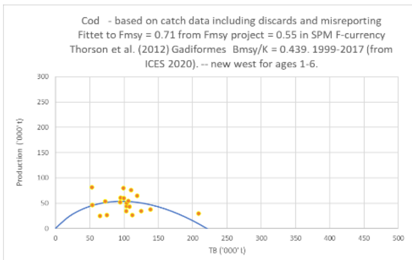
K	221
TBmsy	97
SSBmsy	42
SSBmsy in ICES- currency	54
MSY	54

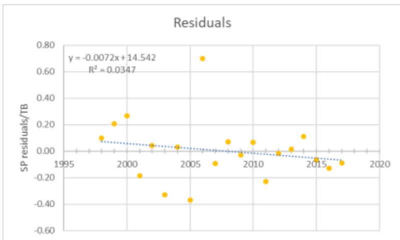




c) 1998-2017

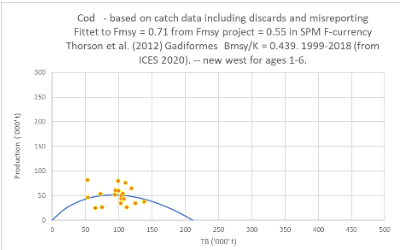
K	221
TBmsy	97
SSBmsy	42
SSBmsy in ICES- currency	54
MSY	54

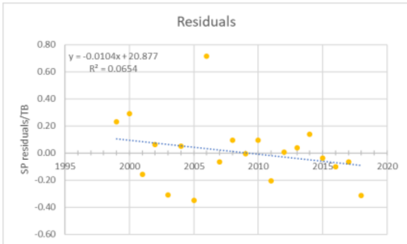




d) 1999-2018

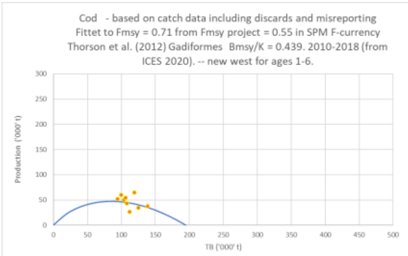
K	211
TBmsy	93
SSBmsy	40
SSBmsy in ICES- currency	51
MSY	51





e) 2010-2018

K	195
TBmsy	86
SSBmsy	37
SSBmsy in ICES- currency	47
MSY	47



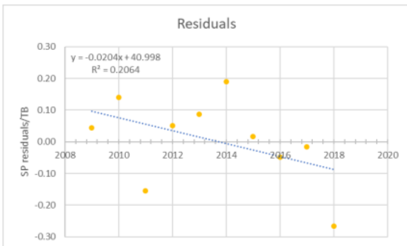
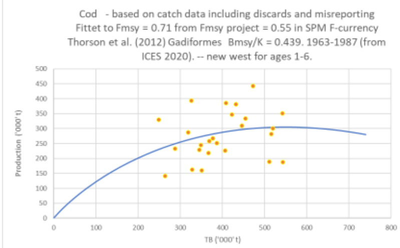
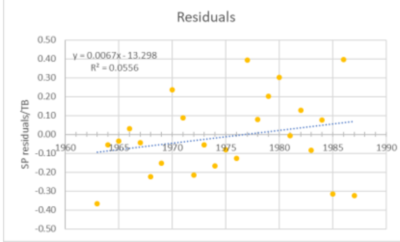


Figure 4. *Cod North Sea. Surplus Production Models fitted to historic observations of Surplus Production vs total stock biomass (TB). Surplus Production is catch plus change in TB from one year to the next. Compared to Figure 3 c) the time series was shortened in various ways. Biomass in '000' t.*

a) 1963-1987

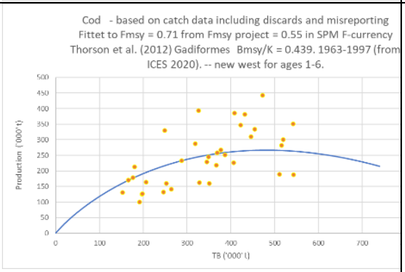
K	1256
TBmsy	551
SSBmsy	240
SSBmsy in ICES-currency	305
MSY	305

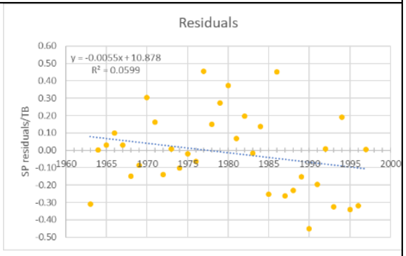




b) 1963-1997

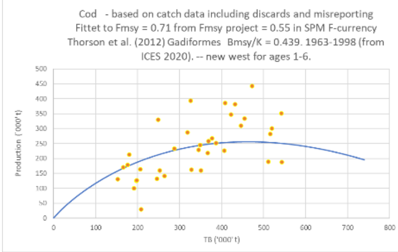
K	1097
TBmsy	482
SSBmsy	209
SSBmsy in ICES-currency	266
MSY	266

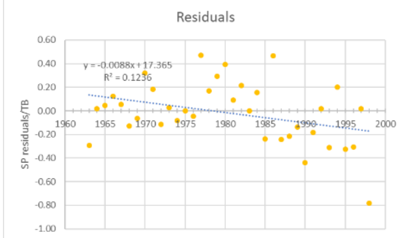




c) 1963-1998

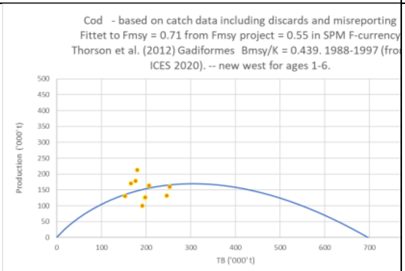
K	1051
TBmsy	464
SSBmsy	202
SSBmsy in ICES- currency	257
MSY	257

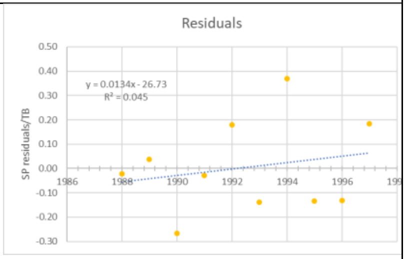




d) 1988-1997

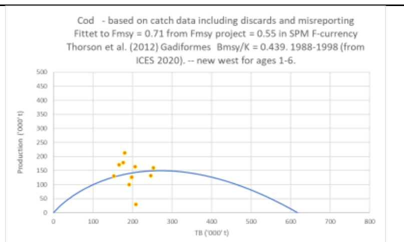
K	697
TBmsy	306
SSBmsy	133
SSBmsy in ICES- currency	169
MSY	169

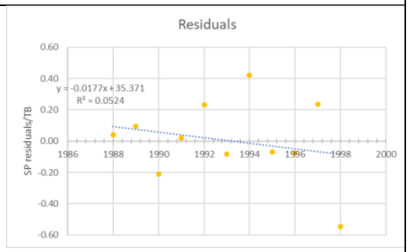




e) 1988-1998

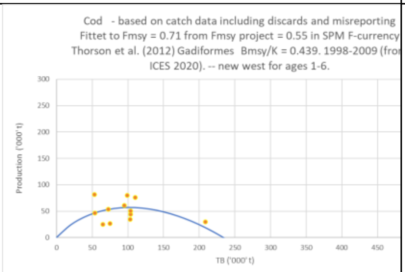
K	618
TBmsy	271
SSBmsy	118
SSBmsy in ICES- currency	150
MSY	150

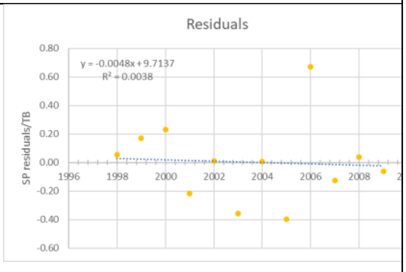




f) 1998-2009

K	234
TBmsy	103
SSBmsy	45
SSBmsy in ICES- currency	57
MSY	57





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g) 1999-2009

K	231
TBmsy	101
SSBmsy	44
SSBmsy in ICES- currency	56
MSY	56

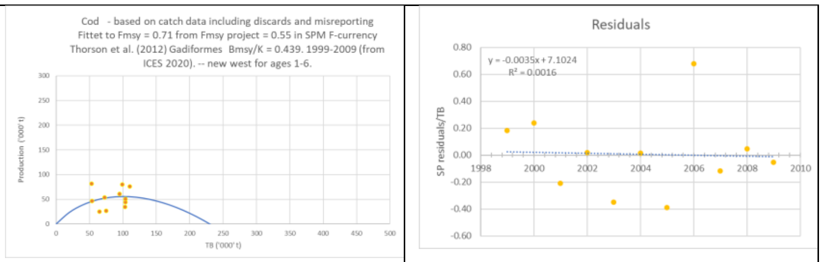


Figure 5. *Cod North Sea. Surplus Production Models fitted to historic observations of Surplus Production vs total stock biomass (TB). Surplus Production is catch plus change in TB from one year to the next. Compared to Figure 3 c) the time series was shortened to in various ways. Biomass in '000' t.*

In Figure 4b we shortened the time series further to 1998-2018. Residuals seems to be evenly distributed around the curve, although there is a slight, non-significant downward trend.

The 2018 point is low and might be responsible for the trend. In Figure 4c we deleted 2018 but the trend did not go away.

In Figure 4d we looked at deleting the 1998 point because its TB was much higher than for the rest of the years, but it did not change much compared to Figure 4b.

An even shorter period, 2010-2018, was tested to see if the trend in residuals could be eliminated. It could not be eliminated (Figure 4e) and we still have a downward trend in residuals indicating a low productivity in recent years.

We than looked at each regime. In 1963-1987 the SPM model seems to reflect the stock productivity well, and the residuals are evenly distributed with only a weak, non-significant time trend (Figure 5a). Expanding the period to 1963-1997 works also quite well although the points since 1986 are a bit lower (Figure 5b). Including one year more 1963-1998 did not change the fit much, but the point for 1998 has the lowest residual and probably belongs to the next regime (Figure 5c). The periods 1988-1997 and 1988-1998 also both fit the SPMs well although the 1998 point seems to be an outlier (Figure 5d and e). For 1998-2009 and 1999-2009 the fits are also good, and it does not matter much whether 1998 is included or not. This, together with the fact that 1998 was an outlier in the previous period, indicated that 1998 belongs to the regime 1998-2009.

This leaves us with three regimes for North Sea cod based on this SPM approach: 1963-1987, 1988-1997, and 1998-2018. The K, SSBmsy and MSY varied substantially (Table 1) between these regimes, for instance MSY is reduced from over 300,000 t per year in the first period to only 52,000 t per year in the most recent period.

A Pseudo-Blim can be calculated based on the production curve. In the USA 25% of the virgin stock is used to define Blim (Grabiel and Mace, 1999). According to ICES (2019) the current Blim of 90,000 t is 7% of SSB at F=0, when R is assumed to be at the level of the period 1988-onwards. The ICES values of 7% is likely an underestimate because the estimated SSB at F=0 is likely an overestimate due to density dependence in growth, maturity and natural mortality not being accounted for. We suggest 15% of SSB at F=0 as used by NAFO (2004). The resulting values are shown in Table 1 for each regime.

Table 1. *North Sea cod. K, SSBmsy, and MSY based on surplus production models for different time periods. Pseudo-B_{lim} is taken as 15% SSB at F=0 (as used by NAFO (2004)) - in ICES SSB-currency. Biomass in '000' t.*

Time period	K carrying capacity. Total stock biomass	Bmsy Total stock biomass	SSBmsy	SSBmsy in ICES SSB-currency	Pseudo-Blim	MSY
1963-1987	1256	551	240	305	92	305
1988-1997	697	306	133	169	51	169
1998-2018	214	94	41	52	16	52

Recruitment

There is a clear correlation between recruitment and SSB when considering the entire time series (Figure 6, top panels). When fitting a traditional hockey-stick model to the data however, it becomes clear that there is a strong trend over time with values below the curve in the most recent decade or two.

When the periods 1963-1996 and 1997-2019 are considered, no trend in residuals within each period is apparent. Alternative periods were considered in Annex 2, but they all gave worse fits to the data. A possible regime shift in the late-1980s is not obvious from the data. Thus, the recruitment data looked upon in this way indicate that there only is a regime shift in 1996-1997.

The productivity in terms of recruitment of the stock decreased from the first to the period, from 6.13 to 4.05 age-1 cod per kg of SSB at SSBs below the breakpoint (Table 3). The maximum recruitment varied more, from 878 million age-1 cod in the first period to 185 million in the second period. The break point (Blim) was at an SSB of 143 kt in the first period at 46 kt in the second period.

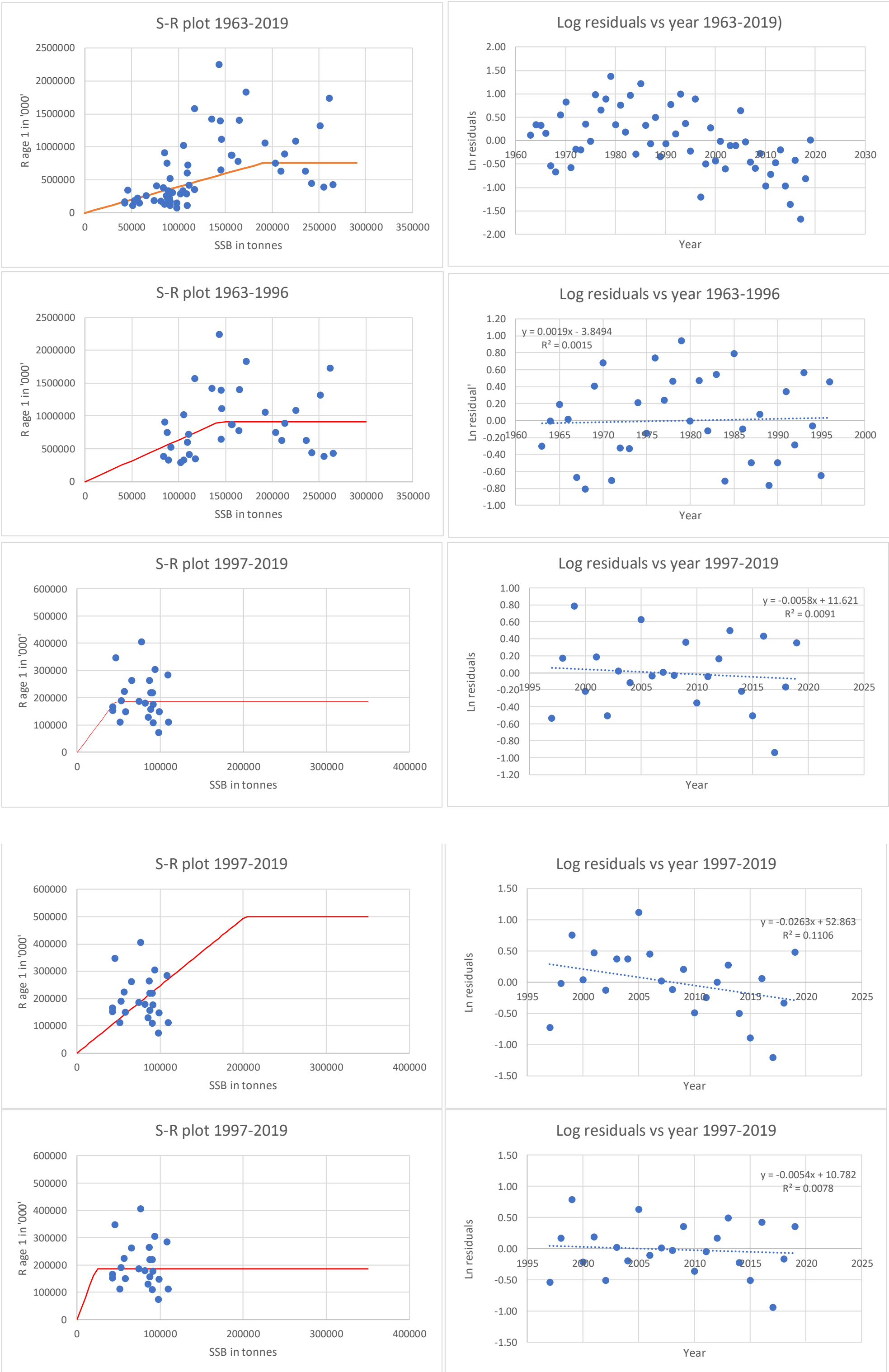


Figure 6. *North Sea cod. Recruitment vs SSB (left panels) and ln residuals vs year (right panels) for the entire time series 1963-2019 and by period – 1963-1997 and 1998-2019. Trendlines for the residuals shown as well as their parameters. For the residual plots the year represent the year class. The two bottom rows of panels are alternative S-R models to 1997-2019 plots (with SSQ=3.73), the last but second row panels where the breakpoint is forced to be above the range of the observations and has a SSQ=6.34, and bottom panels*

where the breakpoint is forced to be below the range of observations and has a SSQ=3.76. Based on data from ICES 2020.

Table 2. *North Sea cod. Parameter estimates of the hockey-stick S-R model by time period. Based on minimum sum of square deviations in the log scale.*

	Slope, r , in No/kg SSB	**Maximum recruitment, b, in millions**	**Blim in '000't**
1963-1996	**6.13**	**878**	**143**
1997-2019	**4.05**	**185**	**46***

* This breakpoint could be much lower, as the data fits almost as well models with lower values all the way down to almost zero (see the Discussion section).

Comparing the SPM and the recruitment analysis

When comparing regime shifts based on SPM with that based on recruitment, one should take account of a time delay of about 1-2 years before recruitment materialised into stock biomass. A regime-shift in recruitment in 1997 would indicate a regime-shift in SPM in 1998 or 1999. Only the 1997/1999 regime shift point is apparent in both data sets. Based on the SPM the decrease in productivity is about a factor of 6 from the 1963-1987 period to the 1999-2018 period, while it decreased by a factor of 5 (878/185) at SSB above Blim based on the recruitment data. However, when SSB is low (<Blim), recruitment only decreased by a factor of 1.5 (6.13/4.05).

The regime-shift in 1987-1988 apparent in the SPM analysis was not seen in the recruitment analysis. Thus, this must be caused by some changes in the population dynamic of the stock at the post-recruitment stage.

The Pseudo-Blim (15% of the virgin SSB in the ICES "SSB-currency") value of 92 kt from the SPM analysis for the period 1963-1987 is lower than the Blim of 143 kt from the recruitment analysis for 1963-1996. For 1988-1997 the Pseudo-Blim values from the SPM is only 51 kt. It must mean that while recruitment is still increasing with SSB above these values (as the estimated break point in the S-R model is at 143 kt), it is counter-acted by some other mechanisms at the post-recruit stage that reduces the production of the stock, and more so in the 1988-1997 period than in the 1963-1987 period. Likely mechanisms are density dependent growth, maturity and natural mortality at the post-recruit stage.

The Pseudo-Blim from the SPM analysis for 1998-2018 is only 16 kt while it is 46 kt from the recruitment analysis. As for the 1988-1997 period this indicates that the mechanism at the post-recruit stage counter-acting increased recruitment at SSB above 16 kt (but below 46 kt) is still acting in this period. What this extra strength in the counter-acting mechanism on the post-recruit stage is due to, is a mystery (see WK Doc HS3 WKNSEA 2021).

Biological reference points for the most recent period 1998-2018 are SSBmsy = 52 kt (in the ICES "SSB-currency") and MSY = 52 kt. The Pseudo-Blim might be set at 30% SSBmsy equal to 16 kt. A reasonable Bpa would be 35 kt (the CV of the IBTS biomass indices is 0.12, therefore the assessment using more data should have a smaller CV, maybe around 0.10) and this could be the MSYBrigger value as well, because this is consistent with the 5% lower percentile of SSBmsy (an expert judgement based on the above analysis).

Discussion

To make a model where "observations" are output from other models as done here, is not ideal. However, the "best" is often the worst enemy of the "good" and the modelling quickly becomes complex and in-transparent if everything is done within one model. It was therefore concluded by the global initiative of fish stock assessment SISAM and of the ICES Theme session in 2017 to split the modelling into separate units that are simpler and more transparent. Furthermore, in fisheries science there is a long tradition to use model output from sequential population analysis as "observations" in stock-recruitment modelling.

The IBTS stock biomass value suddenly dropped from a relatively high level until and including the 1q 2017 to 3q 2017 by almost 200 kt, and stayed at that lower level for one and a half years (Figure 7). The assessment has a strong retrospective pattern in recent years (see Annex 1). What the reason for this strong retrospective pattern remains unclear but might be due to this drop in the IBTS series which the SAM assessment model could not manage to mimic. The reason for this sudden drop in stock size is unknown. One can speculate that there have been more discards than accounted for, that there was an influx of marine mammals eating cod, or that some disease or parasite infection hit the stock.

A sensitivity analysis was performed that used research vessels data from the IBTS 1q and 3 q data trawl survey instead of TB from the assessment. These IBTS indices are very well correlated with the assessment data as can be seen in Figure 7 (top panel). The IBTS 1q is well correlated with the IBTS 3q indices indicating good quality in the survey data for this stock. SPMs based on the IBTS indices together with the catch data gave almost similar SPMs curves as those above based on TB from the assessment for the period prior to 1998 (Annex 1). The IBTS data and the catch data are independent data series, while the assessment TB is not completely independent of the catch data as these are used to estimate TB. However, the TB is normally regarded as more a precise estimate of the stock than the IBTS data because it uses in addition to the catch in weight, both the IBTS data and data from age composition of the catch and is therefore preferred in the present study over the IBTS data. As can be seen from Figure 7 the IBTS 1q and 3 q data are deviating from the assessment TB in some of the recent years, most notably in 2016 and 2017. Because the IBTS surveys both in q1 and q3 have a high precision and they agree with each other, it cannot be ruled out that they probably are more correct than the assessment in those years and that the assessment did not reflect well, the sudden change in stock size in these years. We tried separate SPMs based only on the IBTS 1q and IBTS 3q surveys (and commercial catches) and the two SPMs were very consistent with each other (Figure 8), again illustrating the high quality of these surveys. Compared to the SPM based on the TB from the assessment, the biological reference point SSBmsy increased from 52 kt to 54 kt for IBTS 1q and 56 kt for IBTS 3q (in the ICES "SSB-currency"), MSY from 52 kt to 54 kt for IBTS 1q and 56 kt for IBTS 3 q, and the Pseudo-Blim from 16 kt to 17 kt for both IBTS SPMs, i.e., almost the same values. Thus, this sensitivity analysis showed that using TB from the assessment is fine and that the retrospective pattern in the assessment in recent years did not matter much.

The SPM models used in the present analysis was tested against SPMs determined by the software SPiCT (Pedersen and Berg 2017), which cast surplus production models as state-space models that separate random variability of stock dynamics from error in observed indices of biomass. This was regarded as an unnecessary complexity in the present analysis and sensitivity runs showed that the two methods gave almost identical results when based on the same data (see Annex 2).

The fixation of the shape of the SPM curve and of the Fmsy value are of course important for the robustness of the SPM approach used here. Often there is too little information in the data in the time series to determine these two aspects well, even for data rich stocks. For this stock Sparholt *et al.* (2020) used three different production curve shapes and found Fmsy to be 0.57, 0.32, and 0.53 for the Schaefer curve, the Thorson *et al.* (2012) "all taxa" and Thorson *et al*. (2012) "Gadiformes" shape SPMs, respectively. Froese *et al.* (2016) used the Schaefer curve and found Fmsy to be 0.55. Sparholt *et al.* (2019) used an age-based model with density dependent recruitment, growth, and cannibalism to find Fmsy as 0.55. The ICES multispecies model Collie *et al.* (2006) found Fmsy to be 0.68. Sparholt *et al.* (2020) also used a GLM type model based on life history parameters to find Fmsy as 0.55 for this stock. It therefore seems that Fmsy equal to 0.55 as used in the present analysis is justified. Values of 0.50 or 0.60 would also be justified, but probably not values either much lower or much higher than these.

The shape of the SPM curve could be different. This was tested. The shape of the curve is determined by the "n" parameter, which might change if the juvenile cod (0-group cod) survival is impaired, for instance due to extra high predation from e.g., grey gurnards, extra food competition with the large pelagic stocks, and extra predation by the mackerel. All this would indicate a shift to the right of the top point because it will be beneficial for the stock to have a large adult stock to boost the number of cod larvae produced and this way counter-act the impaired survival of recruits. Of course, the stock of adults should not be too large, so that food competition and cannibalism more than counter-act the improved recruitment. In Figure 9 we have forced the shape of the curve to shift the peak to the right by forcing n=3. We have also fixed K to 600 kt – about half the value pre-1999 - due to the collapse of the southern cod stock. However, the residuals show a much stronger trend over time than in the SPM for the same period above (Figure 4d) and therefor can be said not to fit the observations since 1999 as well.

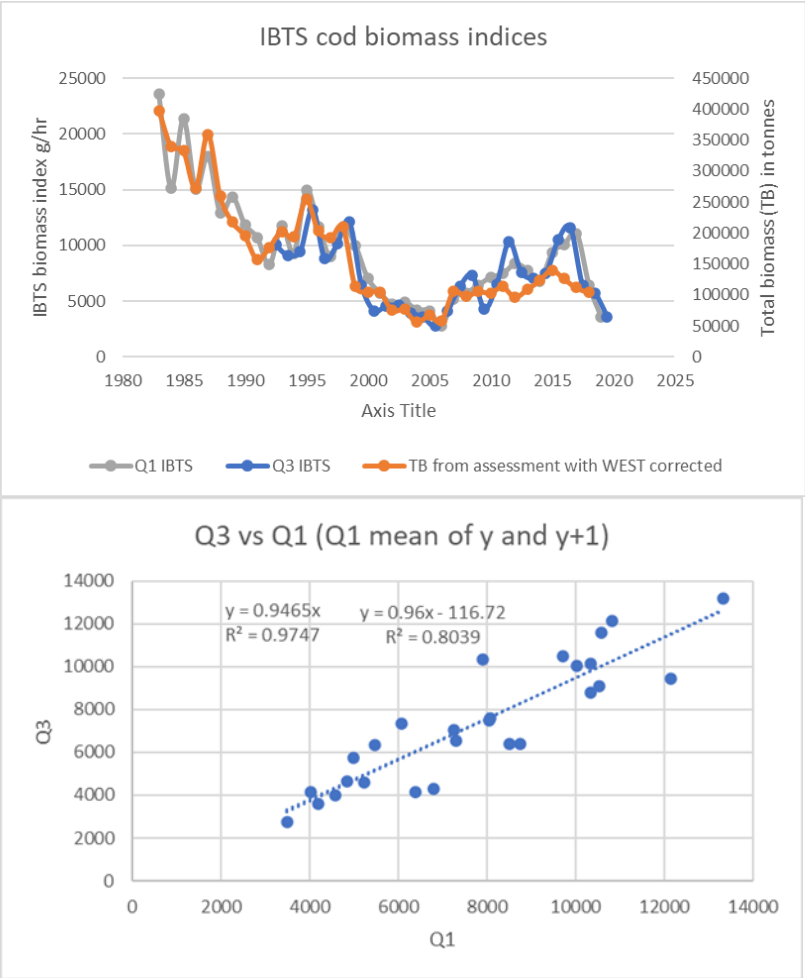
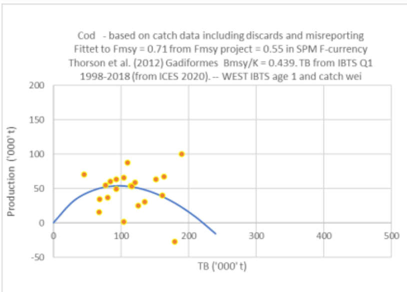
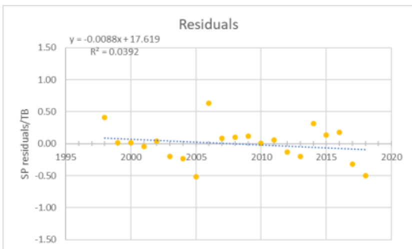


Figure 7. *North Sea cod. Top panel: IBTS biomass indices of quarter 1, quarter 3 and the total stock biomass from the assessment (ICES 2020). Note the unusual drop in IBTS indices from 3q 2017 to 1q 2018 of about 100,000 t stock biomass - the total commercial catch in 2017 was 48,000 t. Bottom panel: IBTS quarter3 against that of quarter 1. For quarter 1 the mean of the index in year y and y+1 is used.*

OM3.1: 1998-2018, TB based on IBTS q1

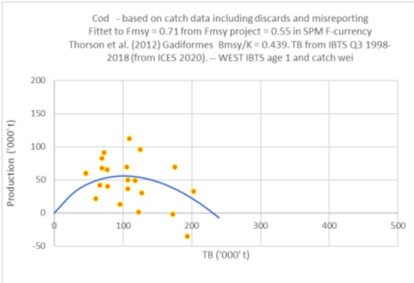
K	221
TBmsy	97
SSBmsy	42
SSBmsy in ICES-currency	54
MSY	54
SSQ	1.51





OM3.2: 1998-2018, TB based on IBTS q3

K	232
TBmsy	102
SSBmsy	44
SSBmsy in ICES-currency	56
MSY	56
SSQ	2.01



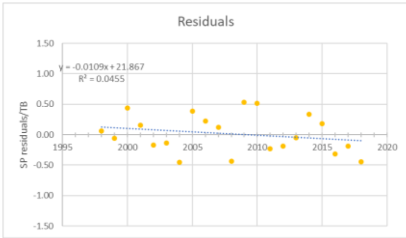
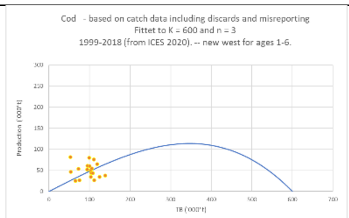


Figure 8. *Cod North Sea. Surplus Production Models fitted to historic observations of Surplus Production vs total stock biomass indices from IBTS trawl survey in quarter 1 and 3 respectively. Biomass in '000' t.*

1999-2018, K forced to be 600 kt and n=3.0.

K	600
TBmsy	334
SSBmsy	145
SSBmsy in ICES-currency	185
MSY	114



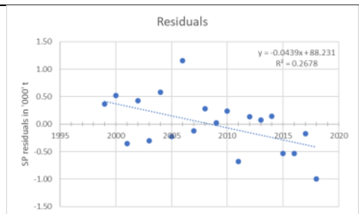


Figure 9. *Cod North Sea. Surplus Production Models fitted to historic observations of Surplus Production vs total stock biomass (TB). K was forced to be 600 kt to take account of the loss of the southern stock and the shape parameter to n=3 to take account of reduced R/SSB due to grey gurnard predation and food competition with the increased pelagic stocks on the pre-recruit level. Biomass in '000' t.*

Conclusion.

The productivity of the North Sea cod has decreased in the past decades. There seems to be a regime shift in the late-1980s, not in recruitment but in production of post-recruits. There is a clear regime shift in the late-1990s in recruitment and the reduced productivity in the post-recruits from the previous period seem to continue.

Biological reference points for the most recent period 1998-2018 are SSBmsy = 52 kt (in the ICES "SSB-currency") and MSY = 52 kt. The Pseudo-Blim might be set at 30% SSBmsy equal to 16 kt. A reasonable Bpa would be 35 kt (the CV of the IBTS biomass indices is 0.12, therefore the assessment using more data should have a smaller CV, maybe around 0.10) and this could be the MSYBrigger as well, because this is consistent with an expert judgement based on sensitivity analysis, of the 5% lower percentile of SSBmsy.

For use as OM in MSEs this SPMs should probably be explored as the core model. The SPM in Figure 9 with "n" = 3 could be explored as an alternative, but less likely.

If management continue with the current approach ignoring the new stock productivity situation and the split in stock structure it is likely to result in a quick collapse of the southern stock and a foregone sustainable yield of the northern stock. It seems better to base the management on the "best available science" and to 1) accept the split into two stocks, 2) close the directed fishery on the southern stock component to slow down the collapse and increase the probability to save the stock, 3) manage the northern stock according to revised biological reference points, and 4) follow the situation closely the coming years with a view of revising the new reference points in 10 years' time unless there are clear indications on changed productivity.

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Annex 1. **Various SPMs Sensitivity analysis.**

To test the sensitivity of the results to uncertainties in the assessment by ICES similar analysis were conducted but instead of using the assessment TB, IBTS estimates were used. The average ratio between the assessment TB and the IBTS index was used to scale the IBTS indices to absolute stock biomass. As shown in Figure 7 the trends over time in the assessment TB and in the indices were quite similar so this is in reality mainly checking the effect of the smoothing of TB implicit in the assessment due to linking the cohorts from one year to the next in the calculations, which smoothing the IBTS indices are without.

Based on the IBTS indices of number-at-age and weight-at-age from ICES 2020 WGNSSK, biomass indices have been calculated. For age 1 in quarter 1 the weight was obtained from the length distribution in the IBTS 1q survey assuming the Fulton condition factor to be one. For the other ages it was taken from the mean of weight-at-age from the catches. These were averaged over two age groups to represent the start of the year. For IBTS quarter 3 the weight of age 1 was also obtained as above from the length distribution in the IBTS 3q survey assuming the Fulton condition factor to be one. The IBTS stock biomass indices are shown in Figure 7. The R^2 between theme was very high, 0.97. The results in terms of SPM is shown in Figure 8.

Table A1 shows the extracted key parameters. For the period 1988-1999 the IBTS 1q and assessment based SPMs gives rather similar carrying capacity K values of 645 kt and 590 kt respectively, and for MSY 157 kt and 143 kt. For the period 1999-2018 the IBTS 1q, IBTS 3q, and the assessment-based analysis gives K equal to 325 kt, 327 kt, and 209 kt. The corresponding MSY are 79 kt, 79 kt and 51 kt. A quite good agreement between the estimates, at least compared to the very different values when other periods are considered, but actually the IBTS based estimates are about 50% higher.

Table A1. Overview of results. "Assessment" means SPM based on TB from the ICES routine annual assessment of the stock (ICES 2020). For the SPMs "assessment", "ass log" and "ass SPiCT" was based on assessment TB with the weight-at-age corrected to weights at 1st January. SPiCT was run with very informative (cv = 0.001) priors on n, q, and r. Biomass in '000't. SPiCT assumes a log normal distribution while if SPiCT is not specified it is because a normal distribution with CV proportional to TB is used except for "Ass log err" where a log normal distribution was used. Biomass in '000' t.

SPM basis	Time period	K carrying capacity In total stock biomass	Bmsy In total stock biomass	SSBmsy	SSBmsy in ICES currency SSB	MSY
	Time series shorten by discarding various numbers of the start years					
Assessment	1963-2018	755	332	144	183	183
Ass log err	1963-2018	908	399	173	221	221
Ass SPiCT	1963-2018	823	360	156	198	198
IBTS 1q	1983-2018	694	305	133	169	169
Assessment	1988-2018	343	151	65	83	83
	By regime – a shift assumed in 1988 and again in 1999					
Assessment	1963-1987	1256	551	240	305	305
Ass log err	1963-1987	1165	511	222	283	283
Ass SPiCT	1963-1987	1257	550	238	303	303
Assessment	1988-1998	618	271	118	150	150
Ass log err	1988-1998	530	233	101	129	129
Ass SPiCT	1988-1998	666	292	125	160	160
IBTS 1q	1988-1998	645	283	123	157	157
Assessment	1999-2018	211	93	40	51	51
Ass log err	1999-2018	197	86	38	48	48
Ass SPiCT	1999-2018	216	95	41	52	52
IBTS 1q	1999-2018	307	135	59	74	74
IBTS 1q SPiCT	1999-2018	317	139	60	76	76
IBTS 3q	1999-2018	314	138	60	76	76
IBTS 3q SPiCT	1999-2018	299	131	57	72	72

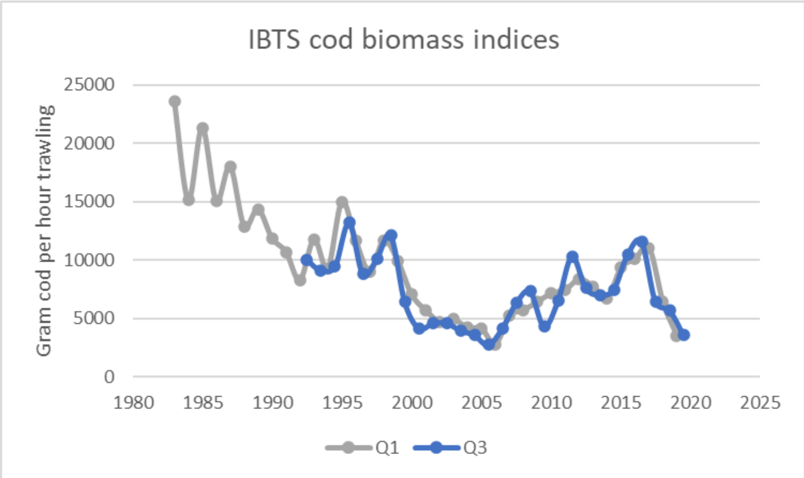


Figure A1. *North Sea cod. IBTS biomass indices of quarter 3 vs that of quarter 1. For quarter 1 the mean of the index in year y and y+1 is used.*

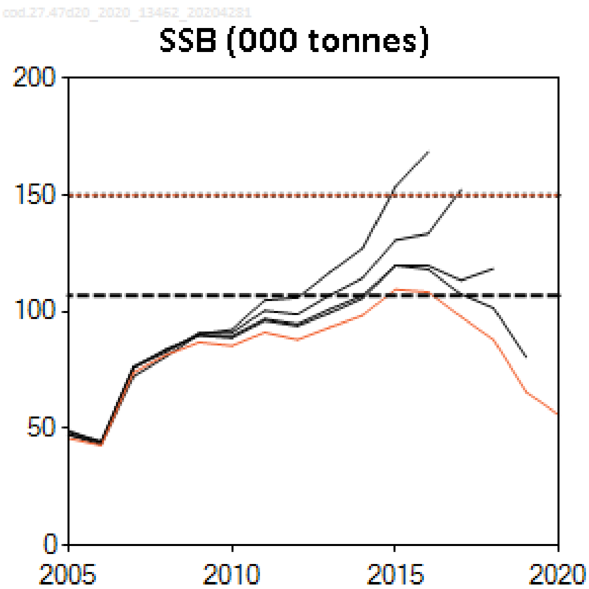
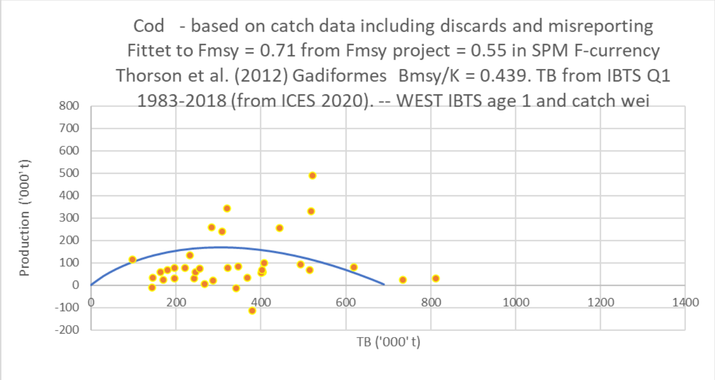
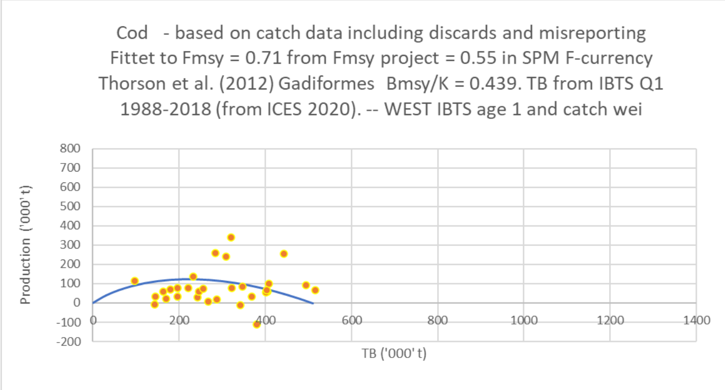


Figure A2. *North Sea cod. Retrospective pattern from the ICES assessment (ICES 2020a).*

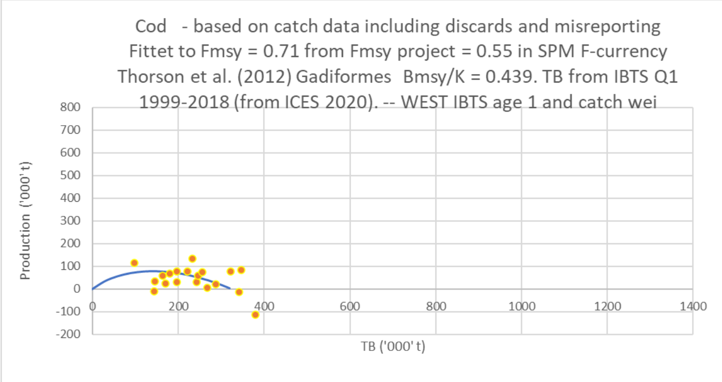
K	694
TBmsy	305
SSBmsy	133
SSBmsy in ICES-SSB currency	169
MSY	169



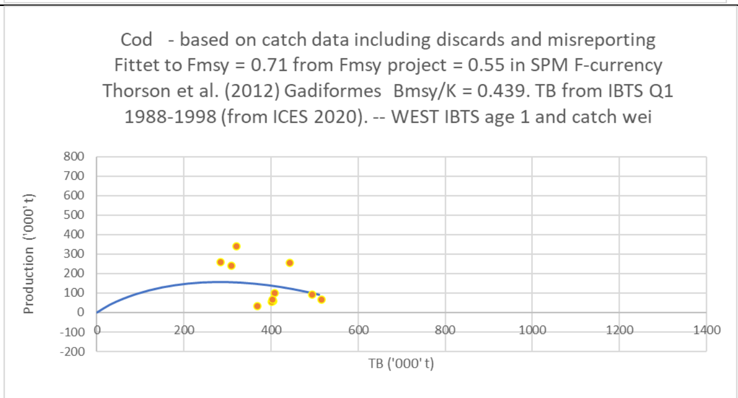
K	507
TBmsy	223
SSBmsy	97
SSBmsy in ICES-SSB currency	123
MSY	123



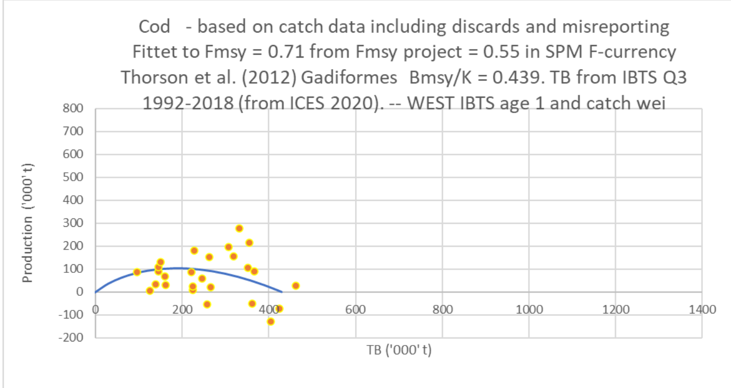
K	325
TBmsy	143
SSBmsy	62
SSBmsy in ICES-SSB currency	79
MSY	79



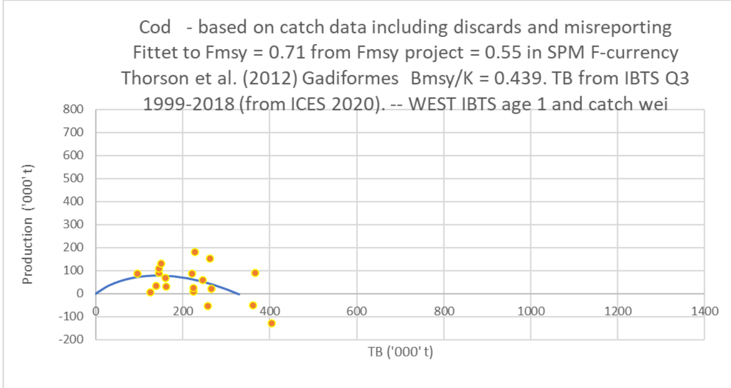
K	645
TBmsy	283
SSBmsy	123
SSBmsy in ICES-SSB currency	157
MSY	157



K	432
TBmsy	190
SSBmsy	82
SSBmsy in ICES-SSB currency	105
MSY	105

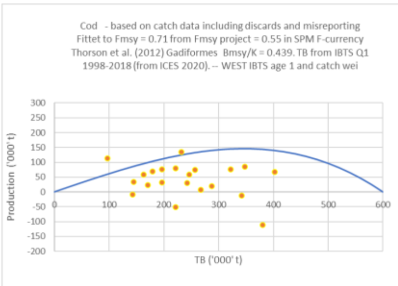


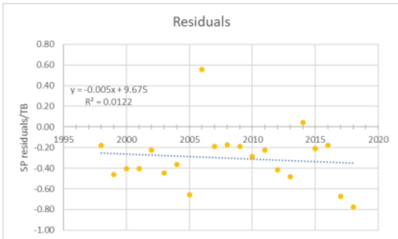
K	327
TBmsy	144
SSBmsy	62
SSBmsy in ICES-SSB currency	79
MSY	79
R^2	



a) 1998-2018 IBTS q1, K=600, n=3.0

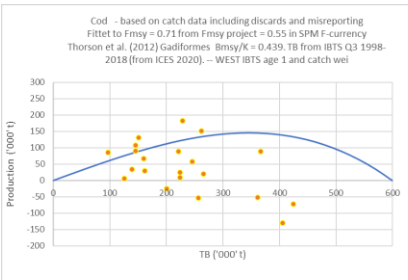
K	600
TBmsy	263
SSBmsy	115
SSBmsy in ICES-currency	146
MSY	146

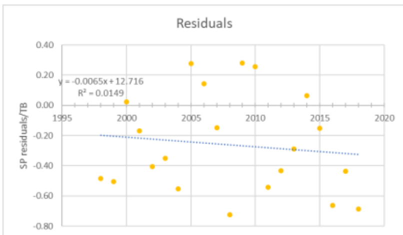




b) 1998-2018 IBTS q3, K=600, n=3.0

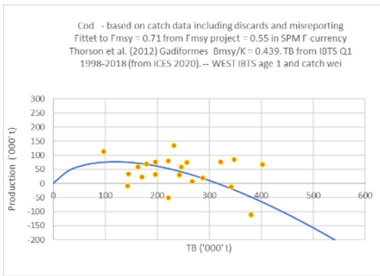
K	600
TBmsy	263
SSBmsy	115
SSBmsy in ICES- currency	146
MSY	146

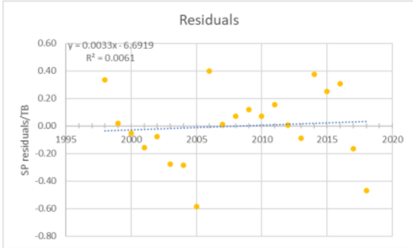




a) 1998-2018 IBTS q1, variable K and n

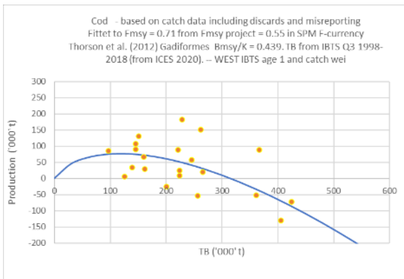
K	315
TBmsy	138
SSBmsy	60
SSBmsy in ICES-currency	77
MSY	77
n	1.05

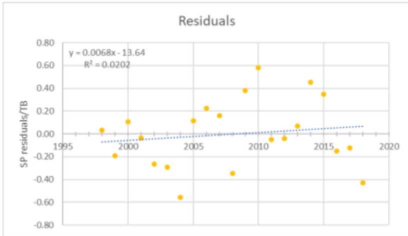




b) 1998-2018 IBTS q3, variable K and n

K	315
TBmsy	138
SSBmsy	60
SSBmsy in ICES- currency	77
MSY	77
n	1.05



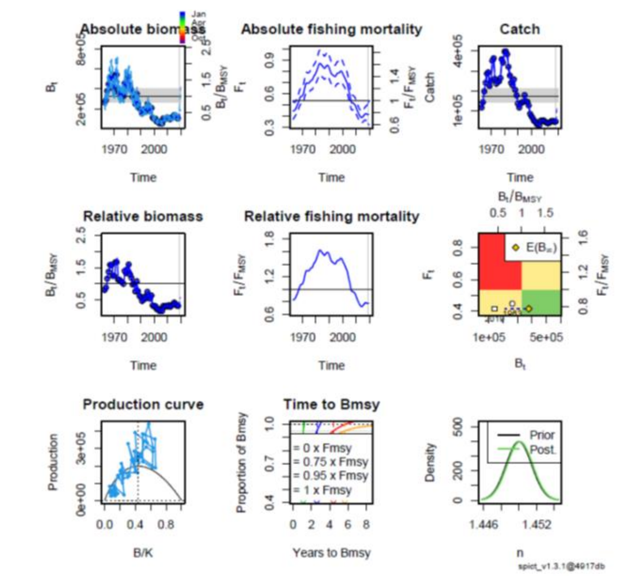


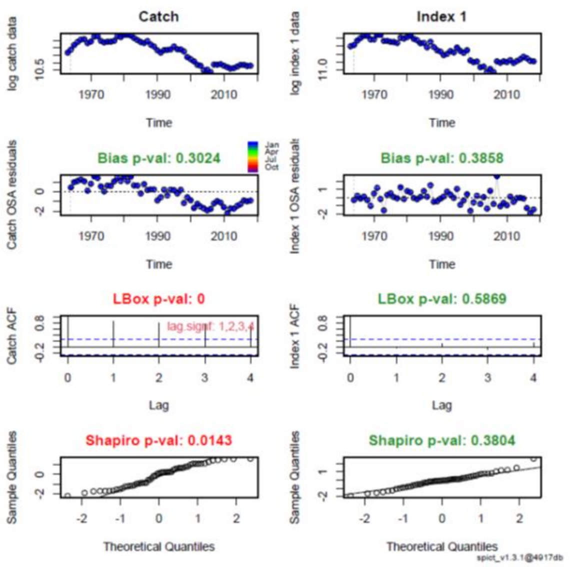
Annex 2. SPiCT runs.

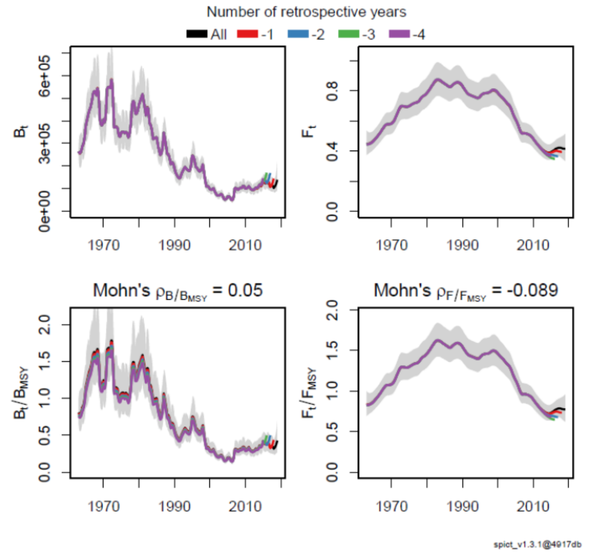
Various SPiCT runs (Pedersen and Berg 2017) were run based on the Total stock biomass (TB) from the assessment but with weight-at-age corrected to 1 January each year. SSBmsy was obtained from TBmsy by the same relationship as for the other SPMs. SSBmsy in the ICES SSB-currency (i.e. with weight-at-age as in the catch rather than in the stock at 1. January) was obtained also with the same relationship to the for the other SPMs.

1963-2018:

Convergence: 0 MSG: relative convergence (4)						
Objective function at optimum: -22.7164151						
Euler time step (years): 1/16 or 0.0625						
Nobs C: 56, Nobs I1: 56						
Priors						
	logn	~	dnorm[log(1.45),	0.001^2]	(fixed)	
	logalpha	~	dnorm[log(1),	2^2]		
	logbeta	~	dnorm[log(1),	2^2]		
	logr	~	dnorm[log(0.797),	0.001^2]	(fixed)	
	logq1	~	dnorm[log(1),	0.001^2]	(fixed)	
Model	paramete	estimates	w	95%	CI	
	estimate	cilow	ciupp	log.est		
	alpha	6.95E-02	1.46E-02	3.31E-01	-2.66681	
	beta	2.00E-01	2.88E-02	1.39E+00	-1.6104	
	r	7.97E-01	7.96E-01	7.99E-01	-0.22633	
	rc	1.10E+00	1.10E+00	1.10E+00	0.095164	
	rold	1.77E+00	1.76E+00	1.78E+00	0.57189	
	m	1.98E+05	1.62E+05	2.43E+05	12.1968	
	K	8.23E+05	6.71E+05	1.01E+06	13.62044	
	q	1.00E+00	9.98E-01	1.00E+00	9.1E-06	
	n	1.45E+00	1.45E+00	1.45E+00	0.371653	
	sdb	3.57E-01	3.10E-01	4.13E-01	-1.02901	
	sdf	7.45E-02	5.10E-02	1.09E-01	-2.59697	
	sdi	2.48E-02	5.22E-03	1.18E-01	-3.69582	
	sdc	1.49E-02	2.20E-03	1.01E-01	-4.20736	
Determini	reference	points	(Drp)			
	estimate	cilow	ciupp	log.est		
	Bmsyd	3.60E+05	2.94E+05	4.42E+05	12.79479	
	Fmsyd	5.50E-01	5.48E-01	5.51E-01	-0.59798	
	MSYd	1.98E+05	1.62E+05	2.43E+05	12.1968	
Stochastic	reference	points	(Srp)			
	estimate	cilow	ciupp	log.est	rel.diff.Drp	
	Bmsys	3.27E+05	2.67E+05	399922.9	12.69635	-0.10344
	Fmsys	5.38E-01	5.34E-01	0.54148	-0.62061	-0.02289
	MSYs	1.75E+05	1.43E+05	214581.6	12.07337	-0.13137

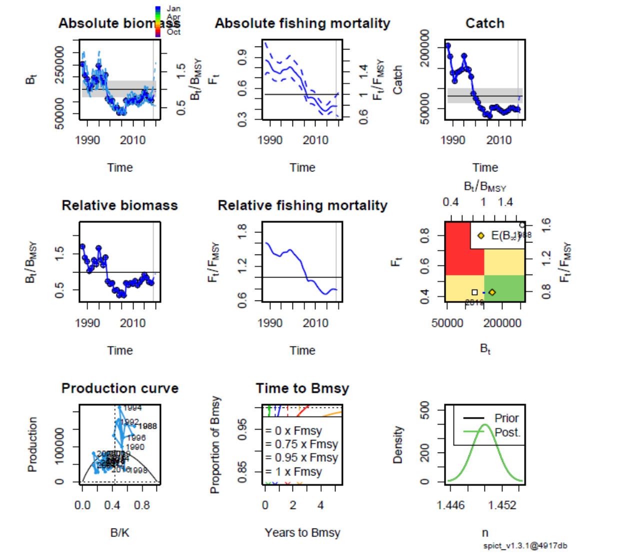


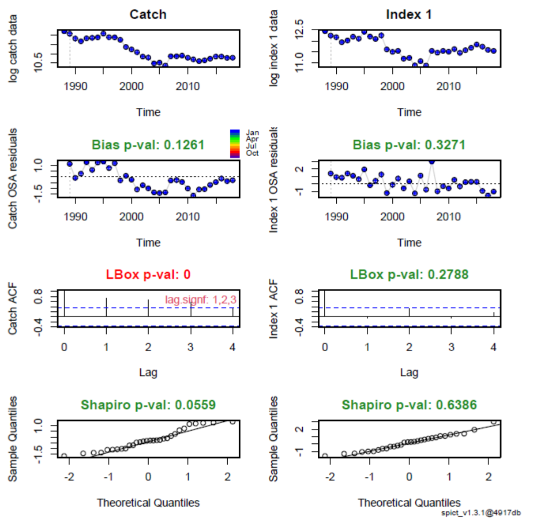


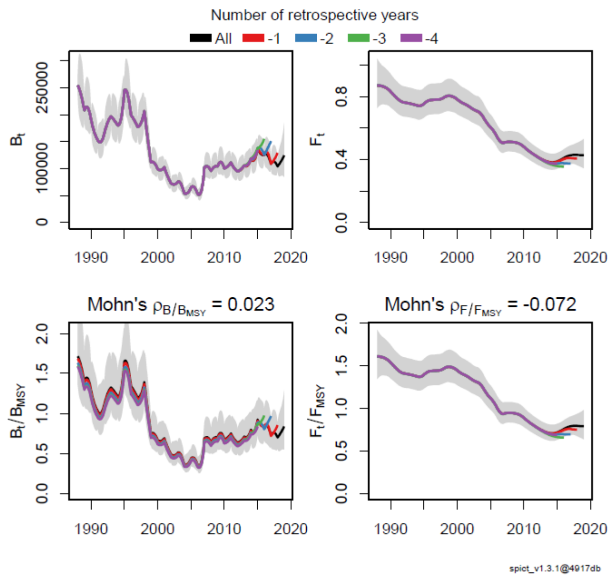


1988-2018:

Convergence: 0 MSG: relative convergence (4)						
Objective function at optimum: -20.4048838						
Euler time step (years): 1/16 or 0.0625						
Nobs C: 31, Nobs I1: 31						
Priors						
	logn	~	dnorm[log(1.45),	0.001^2]	(fixed)	
	logalpha	~	dnorm[log(1),	2^2]		
	logbeta	~	dnorm[log(1),	2^2]		
	logr	~	dnorm[log(0.797),	0.001^2]	(fixed)	
	logq1	~	dnorm[log(1),	0.001^2]	(fixed)	
Model	parametei	estimates	w	95%	CI	
	estimate	cilow	ciupp	log.est		
	alpha	1.09E-01	2.04E-02	5.79E-01	-2.21989	
	beta	2.36E-01	3.11E-02	1.80E+00	-1.44286	
	r	7.97E-01	7.96E-01	7.99E-01	-0.22629	
	rc	1.10E+00	1.10E+00	1.10E+00	0.095276	
	rold	1.77E+00	1.76E+00	1.78E+00	0.57216	
	m	8.78E+04	7.05E+04	1.09E+05	11.38292	
	K	3.65E+05	2.93E+05	4.54E+05	12.80648	
	q	1.00E+00	9.98E-01	1.00E+00	-5E-06	
	n	1.45E+00	1.45E+00	1.45E+00	0.371582	
	sdb	3.08E-01	2.51E-01	3.76E-01	-1.17911	
	sdf	8.17E-02	5.03E-02	1.32E-01	-2.5053	
	sdi	3.34E-02	6.36E-03	1.75E-01	-3.399	
	sdc	1.93E-02	2.65E-03	1.40E-01	-3.94816	
Determini	reference	points	(Drp)			
	estimate	cilow	ciupp	log.est		
	Bmsyd	1.60E+05	1.28E+05	1.99E+05	11.98079	
	Fmsyd	5.50E-01	5.48E-01	5.52E-01	-0.59787	
	MSYd	8.78E+04	7.05E+04	1.09E+05	11.38292	
Stochastic	reference	points	(Srp)			
	estimate	cilow	ciupp	log.est	rel.diff.Drp	
	Bmsys	1.49E+05	1.19E+05	1.85E+05	11.90883	-0.07461
	Fmsys	5.41E-01	5.37E-01	5.45E-01	-0.61458	-0.01684
	MSYs	8.03E+04	6.45E+04	9.98E+04	11.293	-0.09408

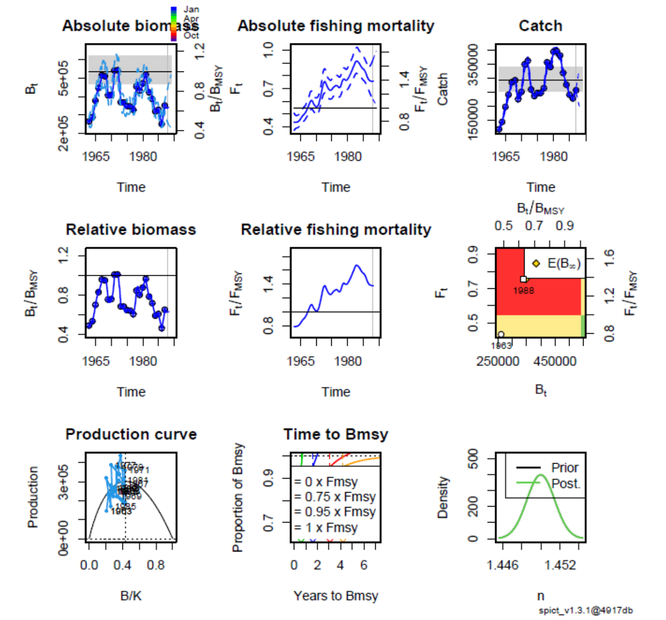


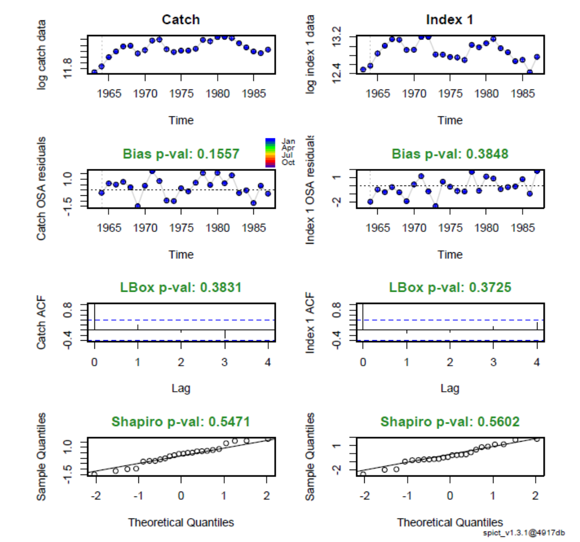


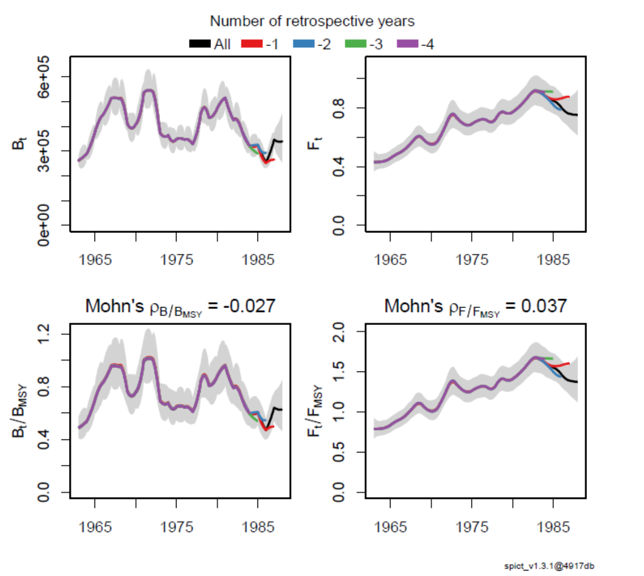


1963-1987:

Convergence: 0 MSG: relative convergence (4)						
Objective function at optimum: -36.2069245						
Euler time step (years): 1/16 or 0.0625						
Nobs C: 25, Nobs I1: 25						
Priors						
	logn	~	dnorm[log(1.45),	0.001^2]	(fixed)	
	logalpha	~	dnorm[log(1),	2^2]		
	logbeta	~	dnorm[log(1),	2^2]		
	logr	~	dnorm[log(0.797),	0.001^2]	(fixed)	
	logq1	~	dnorm[log(1),	0.001^2]	(fixed)	
Model	paramete	estimates	w	95%	CI	
	estimate	cilow	ciupp	log.est		
	alpha	1.82E-01	3.23E-02	1.03E+00	-1.70311	
	beta	1.96E-01	2.66E-02	1.45E+00	-1.62823	
	r	7.97E-01	7.96E-01	7.99E-01	-0.22627	
	rc	1.10E+00	1.10E+00	1.10E+00	0.095309	
	rold	1.77E+00	1.76E+00	1.78E+00	0.572232	
	m	3.03E+05	2.63E+05	3.49E+05	12.62063	
	K	1.26E+06	1.09E+06	1.45E+06	14.04417	
	q	1.00E+00	9.98E-01	1.00E+00	-6.3E-06	
	n	1.45E+00	1.45E+00	1.45E+00	0.371564	
	sdb	1.71E-01	1.29E-01	2.26E-01	-1.76879	
	sdf	9.42E-02	5.69E-02	1.56E-01	-2.36252	
	sdi	3.11E-02	5.88E-03	1.64E-01	-3.4719	
	sdc	1.85E-02	2.82E-03	1.21E-01	-3.99075	
Determini	reference	points	(Drp)			
	estimate	cilow	ciupp	log.est		
	Bmsyd	5.50E+05	4.77E+05	6.35E+05	13.21847	
	Fmsyd	5.50E-01	5.48E-01	5.52E-01	-0.59784	
	MSYd	3.03E+05	2.63E+05	3.49E+05	12.62063	
Stochastic	reference	points	(Srp)			
	estimate	cilow	ciupp	log.est	rel.diff.Drp	
	Bmsys	5.39E+05	4.67E+05	6.21E+05	13.19689	-0.02181
	Fmsys	5.47E-01	5.45E-01	5.49E-01	-0.60294	-0.00512
	MSYs	2.95E+05	2.56E+05	3.40E+05	12.59384	-0.02716

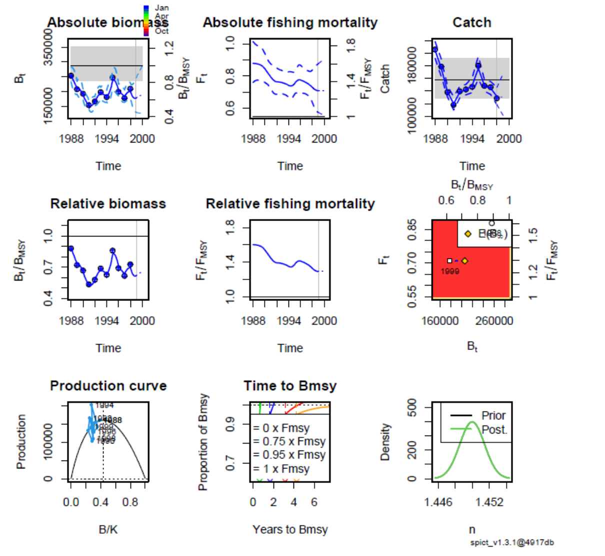


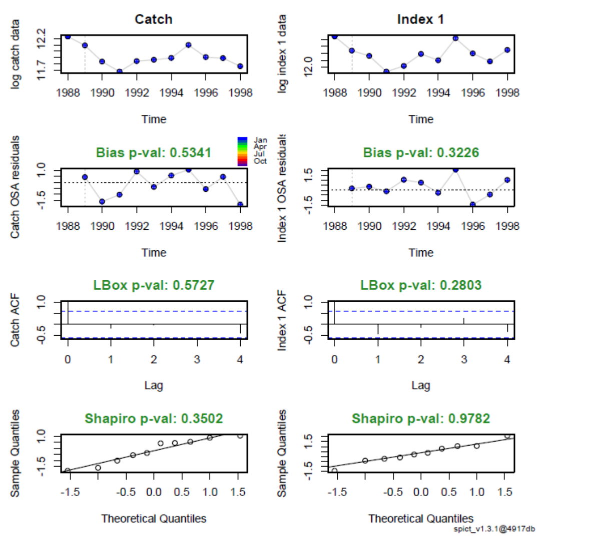


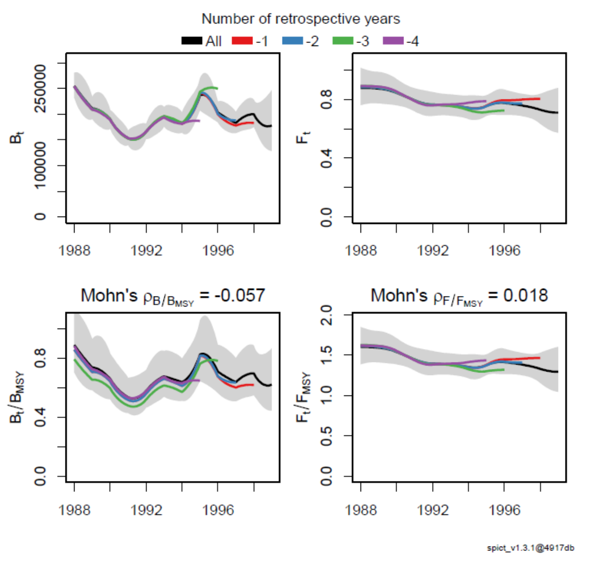


1988-1998:

Convergence: 0 MSG: relative convergence (4)						
Objective function at optimum: -20.4482343						
Euler time step (years): 1/16 or 0.0625						
Nobs C: 11, Nobs I1: 11						
Priors						
	logn	~	dnorm[log(1.45),	0.001^2]	(fixed)	
	logalpha	~	dnorm[log(1),	2^2]		
	logbeta	~	dnorm[log(1),	2^2]		
	logr	~	dnorm[log(0.797),	0.001^2]	(fixed)	
	logq1	~	dnorm[log(1),	0.001^2]	(fixed)	
Model	parametei	estimates	w	95%	CI	
	estimate	cilow	ciupp	log.est		
	alpha	3.47E-01	5.45E-02	2.22E+00	-1.05731	
	beta	5.43E-01	4.59E-02	6.42E+00	-0.61047	
	r	7.98E-01	7.96E-01	7.99E-01	-0.22627	
	rc	1.10E+00	1.10E+00	1.10E+00	0.095315	
	rold	1.77E+00	1.76E+00	1.78E+00	0.572244	
	m	1.60E+05	1.31E+05	1.96E+05	11.98529	
	K	6.66E+05	5.46E+05	8.13E+05	13.40882	
	q	1.00E+00	9.98E-01	1.00E+00	-8E-07	
	n	1.45E+00	1.45E+00	1.45E+00	0.371561	
	sdb	1.45E-01	7.42E-02	2.84E-01	-1.93025	
	sdf	6.08E-02	1.67E-02	2.21E-01	-2.80049	
	sdi	5.04E-02	1.17E-02	2.17E-01	-2.98756	
	sdc	3.30E-02	4.22E-03	2.58E-01	-3.41096	
Determini	reference	points	(Drp)			
	estimate	cilow	ciupp	log.est		
	Bmsyd	2.92E+05	238926.3198	3.56E+05	12.58312	
	Fmsyd	5.50E-01	0.54848	5.52E-01	-0.59783	
	MSYd	1.60E+05	131416.0689	1.96E+05	11.98529	
Stochastic	reference	points	(Srp)			
	estimate	cilow	ciupp	log.est	rel.diff.Drp	
	Bmsys	2.87E+05	2.35E+05	3.51E+05	12.56755	-0.0157
	Fmsys	5.48E-01	5.45E-01	5.51E-01	-0.60153	-0.0037
	MSYs	1.57E+05	1.29E+05	1.93E+05	11.96596	-0.01952

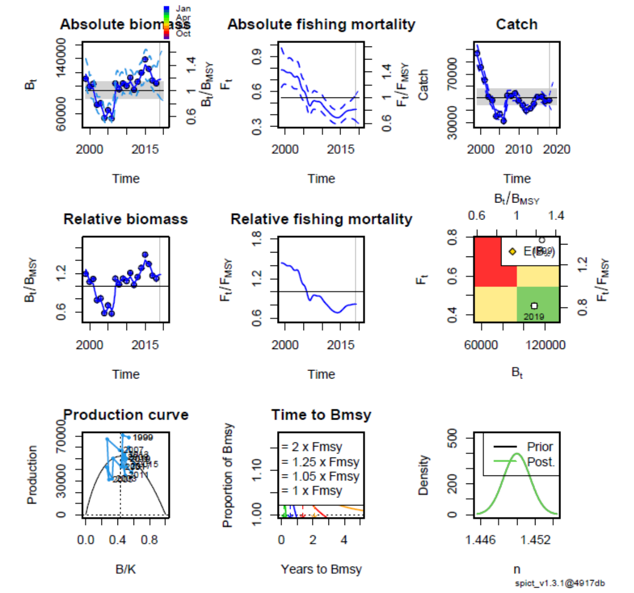


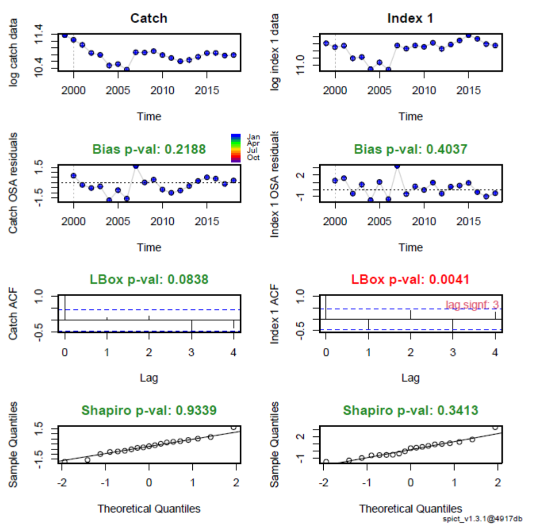


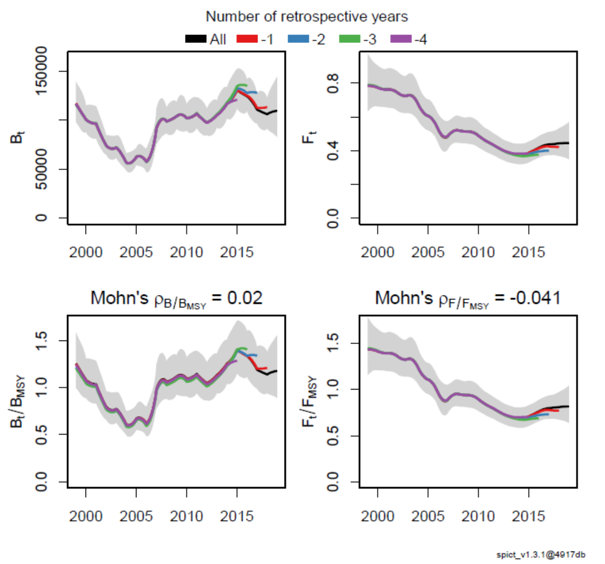


1999-2018:

Convergence: 0 MSG: relative convergence (4)						
Objective function at optimum: -24.1829156						
Euler time step (years): 1/16 or 0.0625						
Nobs C: 20, Nobs I1: 20						
Priors						
	logn	~	dnorm[log(1.45),	0.001^2]	(fixed)	
	logalpha	~	dnorm[log(1),	2^2]		
	logbeta	~	dnorm[log(1),	2^2]		
	logr	~	dnorm[log(0.797),	0.001^2]	(fixed)	
	logq1	~	dnorm[log(1),	0.001^2]	(fixed)	
Model	paramete	estimates	w	95%	CI	
	estimate	cilow	ciupp	log.est		
	alpha	5.10E-01	1.19E-01	2.18E+00	-0.67351	
	beta	4.38E-01	1.04E-01	1.84E+00	-0.82623	
	r	7.98E-01	7.96E-01	7.99E-01	-0.22627	
	rc	1.10E+00	1.10E+00	1.10E+00	0.095309	
	rold	1.77E+00	1.76E+00	1.78E+00	0.572231	
	m	5.21E+04	4.55E+04	5.96E+04	10.86064	
	K	2.16E+05	1.89E+05	2.48E+05	12.28417	
	q	1.00E+00	9.98E-01	1.00E+00	-5E-07	
	n	1.45E+00	1.45E+00	1.45E+00	0.371565	
	sdb	1.60E-01	8.69E-02	2.95E-01	-1.83208	
	sdf	1.11E-01	5.99E-02	2.06E-01	-2.1966	
	sdi	8.16E-02	3.07E-02	2.17E-01	-2.50559	
	sdc	4.87E-02	1.49E-02	1.59E-01	-3.02284	
Determini	reference	points	(Drp)			
	estimate	cilow	ciupp	log.est		
	Bmsyd	9.47E+04	82696.71708	1.08E+05	11.45847	
	Fmsyd	5.50E-01	0.548477	5.52E-01	-0.59784	
	MSYd	5.21E+04	45484.2731	5.96E+04	10.86064	
Stochastic	reference	points	(Srp)			
	estimate	cilow	ciupp	log.est	rel.diff.Drp	
	Bmsys	9.29E+04	8.13E+04	1.06E+05	11.43949	-0.01917
	Fmsys	5.48E-01	5.44E-01	5.51E-01	-0.60234	-0.00451
	MSYs	5.09E+04	4.45E+04	5.81E+04	10.83706	-0.02385

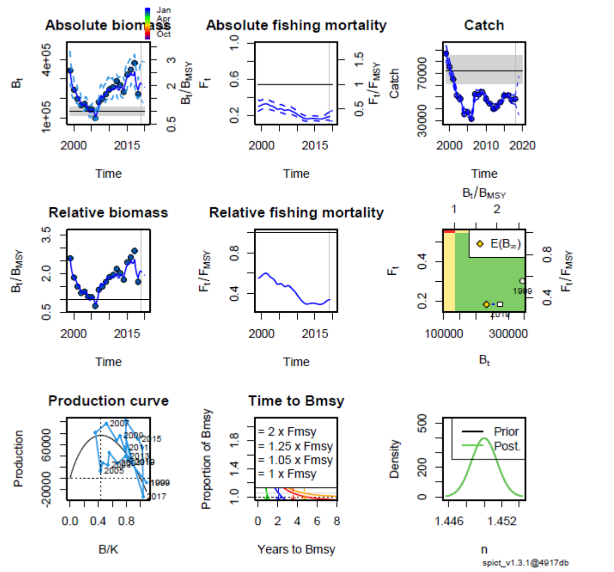


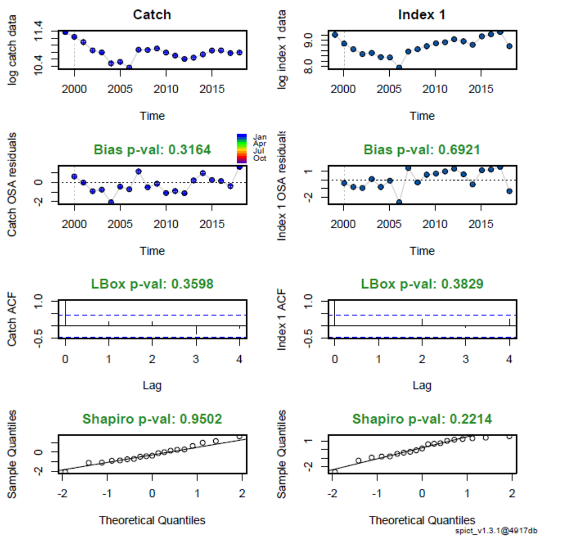


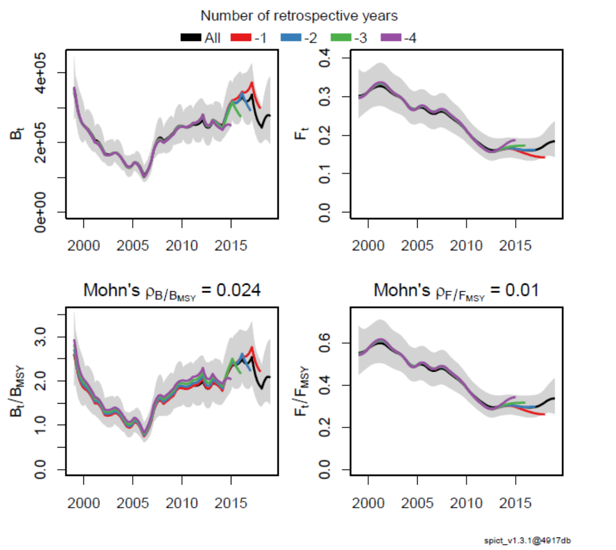


IBTS 1q 1999-2018:

Convergence: 0 MSG: relative convergence (4)						
Objective function at optimum: -17.4109799						
Euler time step (years): 1/16 or 0.0625						
Nobs C: 20, Nobs I1: 20						
Priors						
	logn	~	dnorm[log(1.45),	0.001^2]	(fixed)	
	logalpha	~	dnorm[log(1),	2^2]		
	logbeta	~	dnorm[log(1),	2^2]		
	logr	~	dnorm[log(0.797),	0.001^2]	(fixed)	
	logq1	~	dnorm[log(0.029),	0.001^2]	(fixed)	
Model	parametei	estimates	w	95%	CI	
	estimate	cilow	ciupp	log.est		
	alpha	3.78E-01	1.13E-01	1.27E+00	-0.97157	
	beta	3.32E-01	4.49E-02	2.46E+00	-1.10278	
	r	7.97E-01	7.96E-01	7.99E-01	-0.22628	
	rc	1.10E+00	1.10E+00	1.10E+00	0.095304	
	rold	1.77E+00	1.76E+00	1.78E+00	0.572221	
	m	7.64E+04	6.45E+04	9.05E+04	11.24325	
	K	3.17E+05	2.68E+05	3.76E+05	12.66679	
	q	2.90E-02	2.89E-02	2.91E-02	-3.54046	
	n	1.45E+00	1.45E+00	1.45E+00	0.371567	
	sdb	2.45E-01	1.70E-01	3.53E-01	-1.40585	
	sdf	1.05E-01	5.66E-02	1.96E-01	-2.25042	
	sdi	9.28E-02	3.36E-02	2.56E-01	-2.37742	
	sdc	3.50E-02	5.50E-03	2.22E-01	-3.35321	
Determini	reference	points	(Drp)			
	estimate	cilow	ciupp	log.est		
	Bmsyd	1.39E+05	1.17E+05	1.64E+05	11.84109	
	Fmsyd	5.50E-01	5.48E-01	5.52E-01	-0.59784	
	MSYd	7.64E+04	6.45E+04	9.05E+04	11.24325	
Stochastic	reference	points	(Srp)			
	estimate	cilow	ciupp	log.est	rel.diff.Drp	
	Bmsys	1.33E+05	1.12E+05	1.57E+05	11.79598	-0.04615
	Fmsys	5.44E-01	5.40E-01	5.49E-01	-0.60842	-0.01064
	MSYs	7.22E+04	6.11E+04	8.53E+04	11.18706	-0.0578

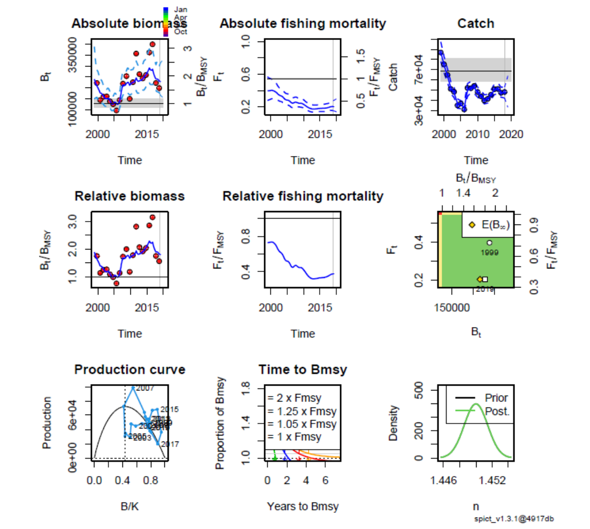


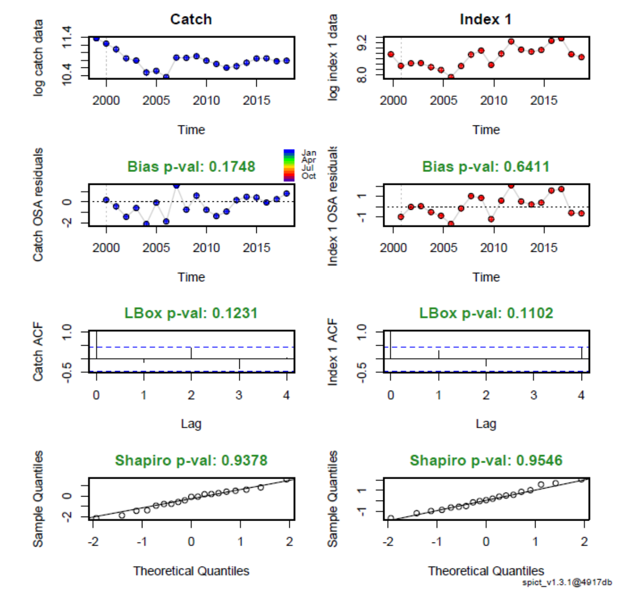


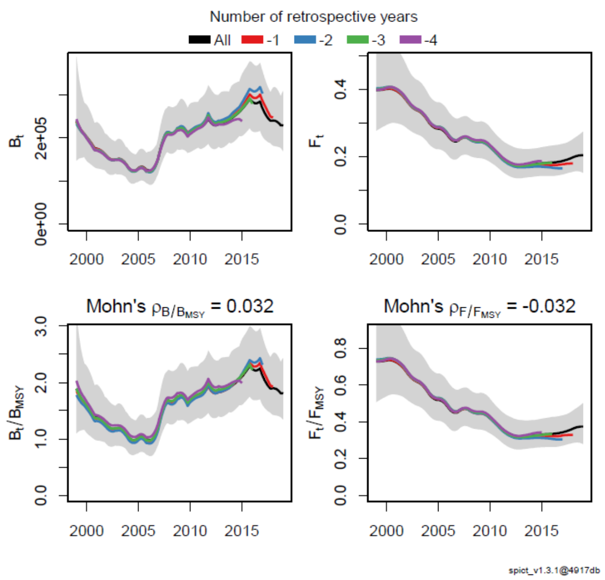


IBTS 3q 1999-2018:

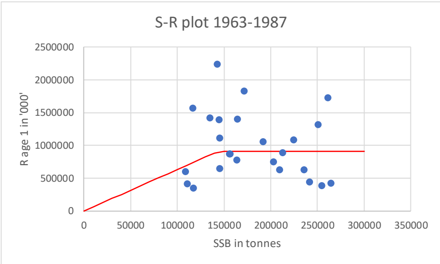
Convergence: 0 MSG: relative convergence (4)						
Objective function at optimum: -9.7356176						
Euler time step (years): 1/16 or 0.0625						
Nobs C: 20, Nobs I1: 20						
Priors						
	logn	~	dnorm[log(1.45),	0.001^2]	(fixed)	
	logalpha	~	dnorm[log(1),	2^2]		
	logbeta	~	dnorm[log(1),	2^2]		
	logr	~	dnorm[log(0.797)	0.001^2]	(fixed)	
	logq1	~	dnorm[log(0.029)	0.001^2]	(fixed)	
Model	paramete	estimates	w	95%	CI	
	estimate	cilow	ciupp	log.est		
	alpha	1.01E+00	4.85E-01	2.08E+00	0.005895	
	beta	4.81E-01	1.24E-01	1.86E+00	-0.7321	
	r	7.97E-01	7.96E-01	7.99E-01	-0.22628	
	rc	1.10E+00	1.10E+00	1.10E+00	0.095302	
	rold	1.77E+00	1.76E+00	1.78E+00	0.572218	
	m	7.20E+04	6.10E+04	8.50E+04	11.18472	
	K	2.99E+05	2.53E+05	3.53E+05	12.60826	
	q	2.90E-02	2.89E-02	2.91E-02	-3.54046	
	n	1.45E+00	1.45E+00	1.45E+00	0.371567	
	sdb	2.11E-01	1.34E-01	3.31E-01	-1.55764	
	sdf	1.20E-01	6.24E-02	2.32E-01	-2.11736	
	sdi	2.12E-01	1.32E-01	3.40E-01	-1.55174	
	sdc	5.79E-02	1.94E-02	1.73E-01	-2.84946	
Determini	reference	points	(Drp)			
	estimate	cilow	ciupp	log.est		
	Bmsyd	1.31E+05	1.11E+05	1.55E+05	11.78256	
	Fmsyd	5.50E-01	5.48E-01	5.52E-01	-0.59785	
	MSYd	7.20E+04	6.10E+04	8.50E+04	11.18472	
Stochastic	reference	points	(Srp)			
	estimate	cilow	ciupp	log.est	rel.diff.Drp	
	Bmsys	1.27E+05	1.08E+05	1.49E+05	11.74946	-0.03366
	Fmsys	5.46E-01	5.42E-01	5.50E-01	-0.60565	-0.00783
	MSYs	6.91E+04	5.89E+04	8.12E+04	11.14355	-0.04203

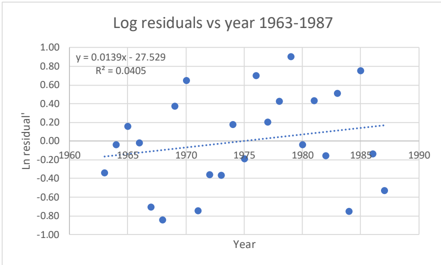


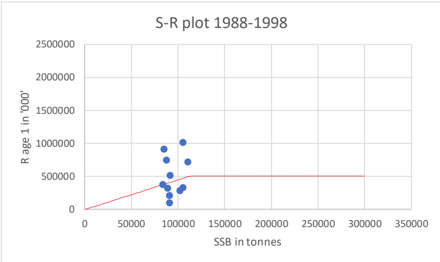


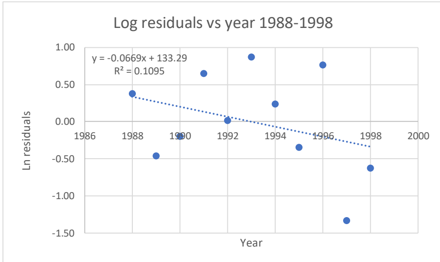


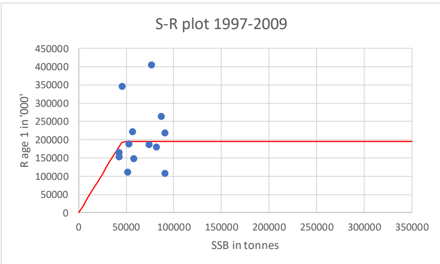
Annex 3. Alternative S-R regimes and their fit to a hockey stick model.

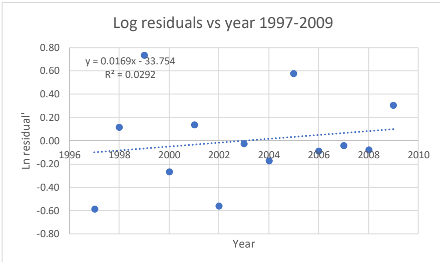


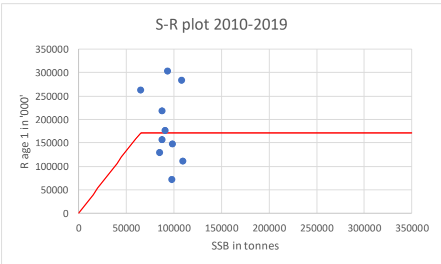


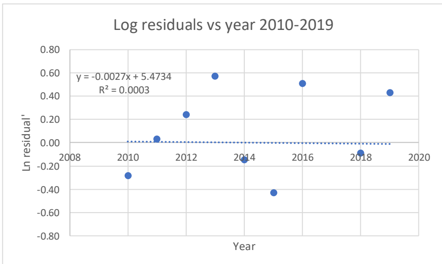


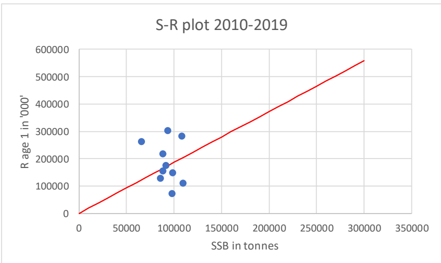


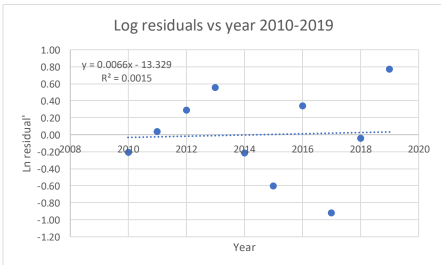


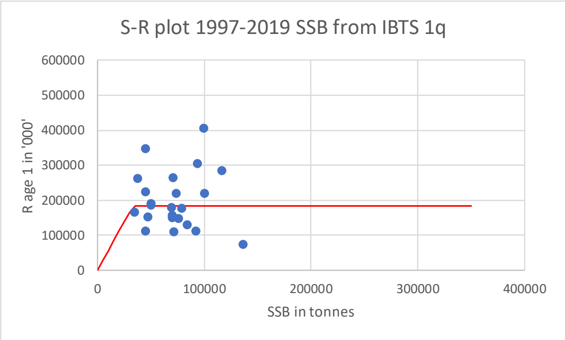


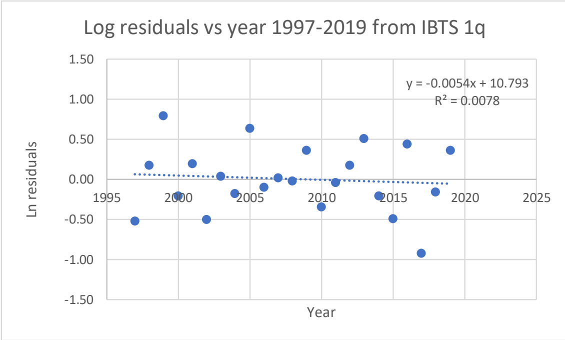









S-R plot 1997-2019 SSB from IBTS 1q
600000
500000
400000
300000
200000
100000
0
R age 1 in '000'
0
100000
200000
300000
400000
SSB in tonnes


Log residuals vs year 1997-2019 from IBTS 1q
1.50
1.00
0.50
0.00
-0.50
-1.00
-1.50
Ln residuals
1995
2000
2005
2010
2015
2020
2025
Year
y = -0.0054x + 10.793
R² = 0.0078

Annex 4. North Sea cod catch historically.

From ICES. 1969. Report of the Working Group on Assessment of Demersal Species in the North Sea. Cooperative Research Report, Series A, No. 9. 74 pp.

Table 1. Landings of cod by all vessels fishing in the North Sea (metric tons). From Bulletin Statistique - corrected to whole weight.

Year	Belgium	Denmark	England	Faroe & Iceland	France	Germany	Nether-lands	Norway [10]	Poland	Scotland	Sweden	USSR	Total
1906	365	515	48,055	-	-	2,784	2,877	4,494	-	29,674	-	-	88,764
1907	405	1,260	44,290	-	-	2,873	2,558	6,105	-	27,990	-	-	85,481
1908	988	852	43,608	-	-	4,361	2,974	8,194	-	32,988	-	-	93,965
1909	710	876	57,291	-	-	5,401	3,937	8,013 [1]	-	38,496	-	-	114,724
1910	498	989	59,125	-	-	6,368	4,126	5,805	-	38,013	-	-	114,921
1911	612	1,304	56,487	-	-	7,652	5,046	8,647	-	39,280	-	-	119,028
1912	526	1,623	53,649	-	-	9,783	7,685	17,298	-	39,031	-	-	129,595
1913	Not Av.	1,280	53,780	-	-	8,865	6,970	22,145	-	36,186	-	-	129,226
1914	"	1,740	47,560	-	-	5,568	7,538	35,041	-	63,743	181	-	161,371
1915	"	3,877	31,166	-	-	3,512	14,080	39,111	-	14,983	109	-	106,838
1916	"	3,619	18,066	-	-	221	11,344	34,445	-	13,785	160	-	81,640
1917	"	1,930	15,981	-	-	669	4,360	21,844	-	13,669	664	-	59,117
1918	"	4,636	20,812	-	-	2,917	3,070	18,362	-	14,738	677	-	65,212
1919	"	3,154	37,364	-	-	11,741	7,125	24,276	-	25,643	362	-	109,665
1920	294 [2]	1,658	63,107	-	-	11,234	4,124	36,779	-	38,220	421	-	155,837
1921	-	3,760	56,635	-	-	9,571	5,385	32,204	-	34,994	172	-	142,721
1922	-	1,444	52,237	-	-	5,882	5,494	35,401	-	30,266	575	-	131,299
1923	-	1,596	34,653	-	-	2,183	4,753	23,346	-	19,259	559	-	86,349
1924	-	2,244	33,040	-	-	3,083	3,989	19,845	-	19,236	242	-	81,679
1925	-	2,857	38,631	-	78	3,978	5,614	10,142	-	23,688	335	-	85,323
1926	-	2,973	40,526	-	198	3,673	7,114	21,998	-	22,144	428 [3]	-	99,054
1927	-	4,537	44,358	-	1,108	3,664	7,547	10,325	-	24,827	409	-	96,775
1928	30	3,902	34,469	-	163	4,010	6,769	6,537	-	22,255	372	-	78,507
1929	565	3,184	35,096	-	216	2,257	7,371	5,784	-	19,875	242	-	74,590
1930	415	4,003	39,706	-	165	3,253	9,583	6,900	-	19,431	894 [5]	-	84,350
1931	271	5,012	31,866 [4]	-	312	3,274	8,447	6,204	-	17,775	708	-	73,869
1932	454	5,865	34,870	-	198	2,878	5,818	6,191	-	20,923	1,120	-	78,317
1933	887	8,069	47,000	2	233	3,234	3,974	6,217	-	22,353	727	-	92,696
1934	639	5,923	40,599	9	244	3,547	5,846	6,722	-	21,454	2,012	-	86,995
1935	863	4,297	30,088	-	227	2,501	4,695	6,448	-	22,043	2,368	-	73,530
1936	1,143	3,687	24,696	35	215	1,993	4,824	6,571	-	19,704	1,137	-	64,005
1937	985	4,181	26,309	1	179	2,366	4,825	6,085	14	21,562	917	-	67,424
1938	1,337	4,243	25,713	24	170	3,165	6,096	6,449	(14)	22,897	975	-	71,083
1939	893	6,717	Not Av.	(24)	Not Av.	3,159	4,551	7,527	+	21,545	1,080	-	45,496

The Table is continued on the next page

Table 1. Continued.

Year	Belgium	Denmark	England	Faroe & Iceland	France	Germany	Nether-lands	Norway[10)]	Poland	Scotland	Sweden	USSR	Total
1940	Not Av.	4,857	Not Av.	Not Av.	Not Av.	223	1,179	4,638	-	11,766	51	-	22,714
1941	+	9,500	"	"	"	570	71	5,153	-	10,143	-	-	25,437
1942	28	11,128	"	"	"	11,600	140	3,346	-	11,408	-	-	37,650
1943	106	16,565	"	"	"	3,196	375	4,308	-	14,699	-	-	39,249
1944	4	14,186	"	"	"	1,837	403	3,488	-	15,561	-	-	35,479
1945	814	8,058	"	"	"	Not Av.	2,838	6,522	-	19,926	703	-	38,861
1946	3,991	20,268	48,739	"	"	9,048	8,012	6,844	-	32,068	2,090	-	131,060
1947	4,192	20,950	37,128	-	1,081	4,714	11,634	5,383	-	24,882	2,396	-	112,360
1948	4,117	11,559	33,857	-	3,395	3,376	2,908	4,172	-	19,053	2,586	-	85,023
1949	4,770	9,048	32,412	-	3,490	13,875	5,108	4,597	-	20,812	2,617	-	96,729
1950	3,230	9,587	28,226	-	2,578	3,501	3,549	5,682	-	20,182	4,279	-	80,814
1951	3,158	8,794	22,456	-	1,880	2,358	3,425	3,597	-	17,322	2,450	-	65,440
1952	3,204	12,942	24,722	-	2,630	2,805	4,682	3,529	-	24,618	2,480	-	81,612
1953	3,398	15,199	25,053	-	2,718	3,571	5,601	2,258	-	27,129	1,775	-	86,702
1954	3,497	14,977	22,957	-	2,608	4,173	5,987	2,625	-	26,878	1,943	-	85,645
1955	3,890	16,742	20,881	+	3,210	4,397	5,263	4,277	1,257	24,531	2,263	463	87,174
1956	3,296	16,430	20,812	-	3,598	4,325	5,076	5,154	1,327	22,788	2,622	768	86,196
1957	2,708	18,320	25,592	5	3,882	4,679	5,983	5,547	1,889	28,533	2,621	699	100,458
1958	3,064	17,605	27,955	12	5,833	4,637	8,043	5,577	2,059	29,991	2,211	4,378	109,365
1959	4,496	18,205	31,936	2	6,974 6)	4,742	6,520	6,921	1,745	31,284	2,169	653	115,647
1960	5,101	21,448	34,204	15	1,188 7)	4,253	8,274	4,558	1,691	25,890	2,187	888	109,697
1961	6,464	18,758	31,007	-	6,592 8)	5,448	8,102	4,631	1,577	22,903	2,851	-	108,353
1962	5,523	14,787	22,621	-	767	5,636	7,680	4,954	2,094	26,227	Not Av.	250	90,589
1963	5,151	21,289	26,335	-	4,086	5,838	7,630	4,311	1,604	33,845	"	150	110,239
1964	6,082	20,472	25,505	-	8,366	5,136	9,857	5,743	2,764	29,481	11,219 9)	571	125,196
1965	12,783	29,634	36,900	-	14,784	13,313	20,588	6,144	2,918	30,214	12,686 9)	1,658	181,622
1966	15,562	37,406	49,374	-	17,317	19,002	22,419	4,360	13,356	32,832	14,489 9)	2,360	228,477

Footnotes

1) Includes Swadish fishery in North Sea.
2) Ostende only.
3) Includes herring fishery Iceland and seining Irish Sea and Clyde.
4) Includes British landings in Holland.
5) Includes west coast of Scotland.
6) Not accounted for 126,214 all areas.
7) Includes Norwegian Sea, Spitzbergen and Bear Island.
8) Not eaccounted for 5,141.
9) Includes Kattegat and Skagerak.
10) Most of Norwegian catches are from close to the Norwegian coast. These do not strictly belong to the North Sea.

Annex 5. **North Sea cod. IBTS Z values.**

It seems that Z (of ages 2-5) is much higher in the 1st half of the year than in the 2nd half; for 1992-2019 it was 0.69 compared to 0.22 (per half year). In total Z was 0.91 per year.