…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).

Biological reference points for North Sea cod

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Based on analysis in WK Doc HS1-4 WKNSEA 2021, this document concludes on which S-R model that best represent the current situation for cod in the North Sea and what Blim might be.

It was concluded in the above mentioned WG Docs, that it is appropriate to consider the period 1997-present as a relative stable period for the S-R relationship. At the same time, the knowledge about the stock dynamics and the environmental pressures on cod from before this period also contains information, and this is included in various ways below.

The following is under the assumption that the management should only allow directed fishing on the northern stock and unavoidable by-catch of cod in the southern North Sea. It seems to be almost a fact that the southern cod stock is depleted, and it is likely that this is mainly due to climate changes. This southern stock needs a high degree of protection, 1) not to extirpate it completely and 2) to keep the hope alive that it might miraculously recover – maybe due to genetic adaptation.

Recruitment per SSB decreased in the late 1990s (Figure 1 top panel). According to WK_Doc_HS3 a reasonable split into two periods 1963-1996 and 1997-present can be argued. Figure 1 middle and lower panels present the S-R data and hockey-stock models for each period. The residuals are without a time trend. The resultant breakpoint and slope are presented in Table 1. The break point decreased from first period of 143 kt to 46 kt in the second period. This is a larger decrease than can be expected from the disappearance of the southern stock. The southern stock accounted for 57% of the total stock pre-1997, and a corresponding decrease in the breakpoint would be to 61 kt. The slope should not decrease if the only change between the two periods is the disappearance of the southern stock. However, the slope decreased from 6.13 to 4.05. The maximum recruitment would also be expected to be reduced to 43% from the first to the second period just due to the southern component disappearing. However, the observed decrease was from 878 million age-1 cod to only 185 million, i.e., a decrease to only 21%. Thus, other factors than the disappearance of the southern stock must be impairing cod recruitment in recent years.

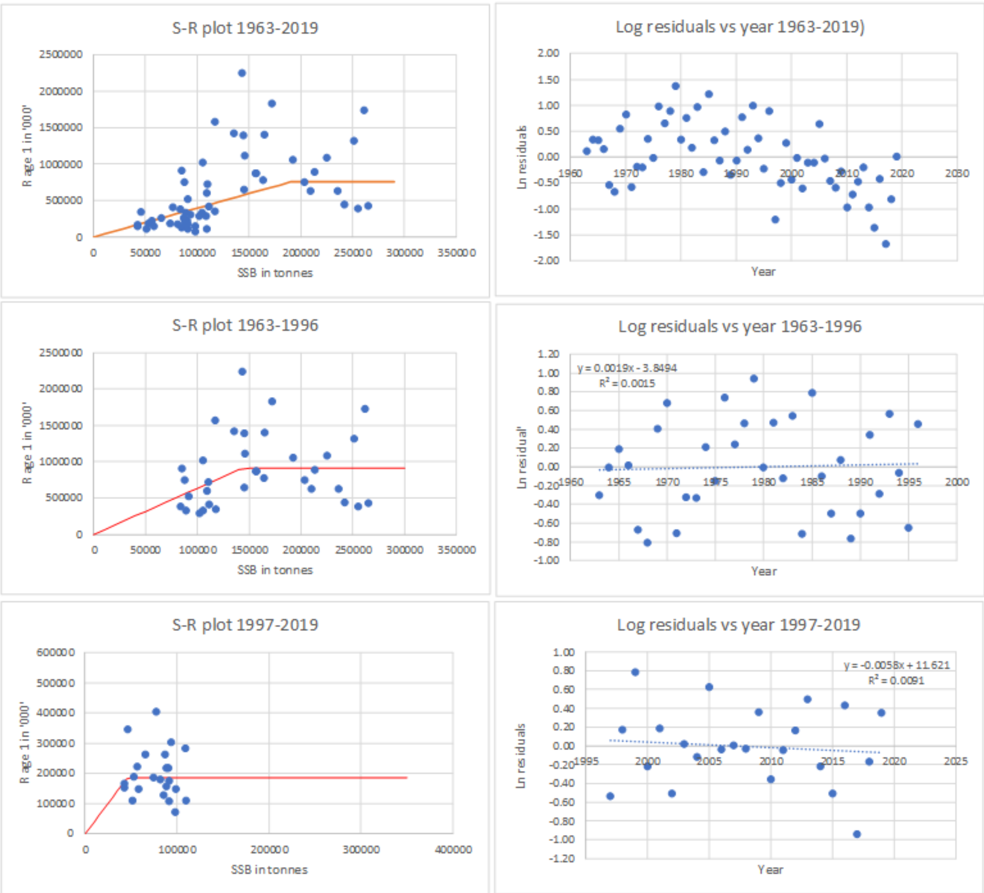

Figure 1. *North Sea cod. Recruitment vs SSB (left panels) and log residuals vs year (right panels) for various time periods. Red line is the maximum likelihood estimated hockey stock model. Trendlines for the residuals shown as well as their parameters. Based on data from ICES 2020.*

In WK_Doc_HS3 it was concluded that the increased grey gurnards predation, food competition with herring and mackerel and possibly herring and mackerel predation on pre-recruit cod can fully explain the decrease in slope. The magnitude of the impairment is at least as much as indicated by the decrease in slopes mentioned above – grey gurnard increased predation mortality from 2.0 to 3.0 should give an even larger decrease in slope (decrease by a factor of exp(-1.0) = 0.37) from 6.13 to 2.26. The predation estimates by grey gurnards is based on many stomachs sampled but only in a few years and these could be extraordinary years, so it is probably prudent to accept a somewhat lower value of the extra predation mortality from grey gurnards.

No factor was found to be clearly linked to the decreased maximum recruitment. If the SSB is big enough the reduced recruitment per SSB should be compensated by more cod eggs spawned. This would point towards a higher breakpoint. This was forced to the S-R hockey stick model in Figure 2 middle panel. Maximum recruitment was fixed to about half of the 1963-1996 level. Of obvious reasons, there are no information in the SSB and R observation set to indicated how far above the maximum SSB in the period 1997-present the breakpoint should be. All fixed breakpoint values above the maximum SSB will give the same fit to the observation. However, judged from the trend in the residuals a model with a high SSB breakpoint is not supported by the observations of SSB and R in the period 1997-present.

Any low SSB breakpoint will be almost as well supported as the 46 kt value from the maximum likelihood estimation because 46 kt is close to the lowest observed SSB and thus any breakpoint below will give almost as good a fit to the observations (Figure 2 lower panel).

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. The numbers in bracket are from S-R models with no breakpoint and 600 million recruits assumed to be the maximum number*. *From WK Doc HS3 WKNSEA 2021.*

	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).

Figure 2. *North Sea cod. Recruitment vs SSB (left panels) and log residuals vs year (right panels) for the entire time series 1997-2019. Top panel is the least SSQ deviation of log values with an SSQ=3.73, the middle plot where the breakpoint is forced to be above the range of the observations SSQ=6.34, and bottom panels where the breakpoint is forced to be below the range of observations SSQ=3.76. Trendlines for the residuals shown as well as their parameters. Based on data from ICES 2020.*

Discussion

All compromise between the indications by the data and analysis above points towards a slope of about 3 and maximum recruitment of about 250 million for the recent decades. Figure 3 show the resultant S-R model. This implies at Blim of 80 kt. However, the SSQ is high and Blim inconsistent with the SPM results of WKNSEA HS2-4 where Bmsy is estimated to 54 kt (see Annex 1).

Even a breakpoint at 46 kt is probably too close to Bmsy of 54 kt, and this points towards a lower breakpoint, which as stated above is almost as consistent with the observation of S-R in the period 1997-present. Thus, a model with a higher slope but still below 6.14 is needed. A slope of 5 might be a reasonable value because it is between 4.05 and 6.14 and has a low SSQ of 3.76 (Figure 4). It gives a breakpoint of 37 kt.

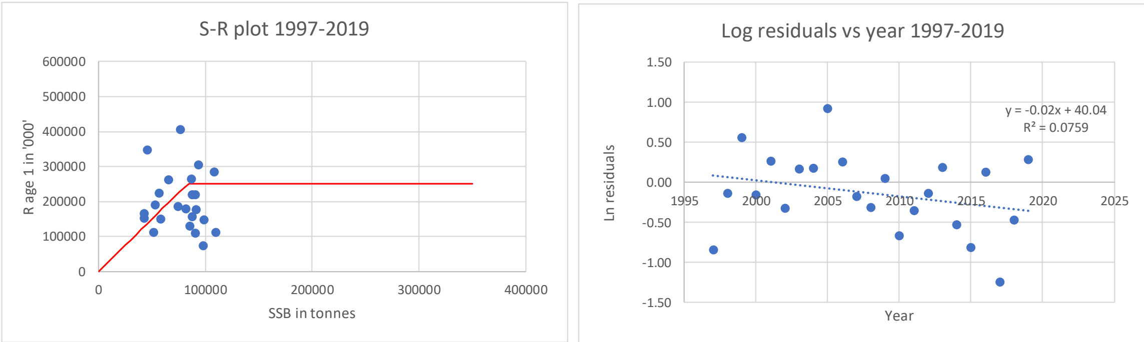

Figure 3. *North Sea cod. S-R model with a slope 3.0 and maximum R of 250 million. Blim then becomes around 80 kt. SSQ=5.74*.

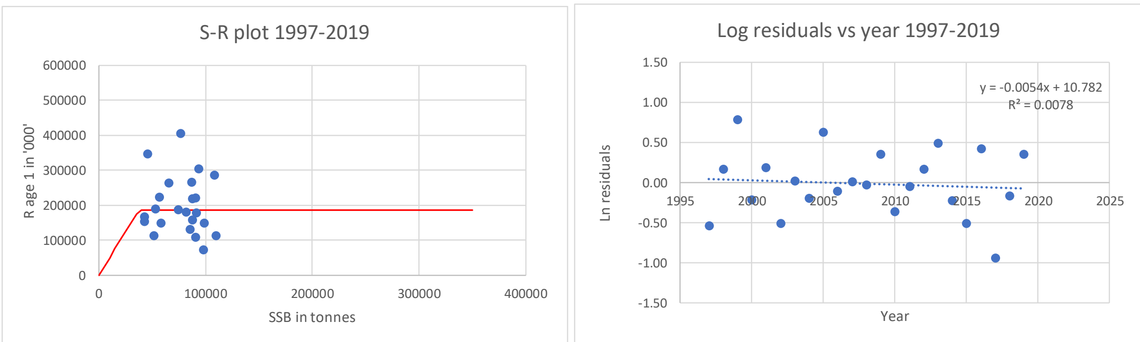

Figure 4. *North Sea cod. S-R model with a slope 5.0 and maximum R of 185 million. Blim then becomes 37 kt. SSQ=3.76*.

Conclusion

The S-R model in Figure 4 with a breakpoint at 37 kt and a maximum recruitment of 185 million age-1 cod seems to be fitting the high amount of data on this stock, the current knowledge and S-R observation for the period 1997-present best.

References.

WK Doc HS1 WKNSEA 2021.

WK Doc HS2 WKNSEA 2021,

WK Doc HS3 WKNSEA 2021.

WK Doc HS4 WKNSEA 2021.

Annex 1. OMs based IBTS data instead of assessment data.

The following OMs can be regarded as plausible population dynamics for the North Sea cod stock for the coming decades:

1. OM1: The fact that we only have one of the two cod now in the Northern area and that this stock historically (1963-1996) has been 43% of the total stock (measured as fraction of age-1 cod in the northern area compared to total North Sea, based on IBTS quarter1 data), mean that K, MSY and Bmsy should only be 43% of the values in 1963-1996, i.e., K = 549 kt, MSY = 133 kt, Bmsy = 241 kt, and SSBmsy = 133 kt. SSQ = 5.14.
2. OM2: OM1 is clearly not fitting well with observations since 1998. In OM2 the curve is fitted to the observation in 1998-2018 by letting MSY vary (which is the same as Fmsy varies). K = 549 kt, MSY = 75 kt, (Fmsy= 0.40), Bmsy = 241 kt, and SSBmsy = 133 kt. SSQ = 1.48.
3. OM3: Here K is fitted instead of MSY. K = 221 kt, MSY = 54 kt, Bmsy = 97 kt, and SSBmsy = 54 kt. The fit is a little better than for OM3 as SSQ = 1.12.

OM3 was also ran with IBTS 1q data and IBTDS 3q data, instead of assessment data on stock biomass. All three runs gave very similar parameters values and therefore there is no need to consider the IBTS based ones in separate MSEs.

The reduced productivity of the Northern stock in 1998-present compared to pre 1998 as indicated by OM2 and OM3 compared with OM3 is justified by to the increased predation on pre-recruit cod by grey gurnards, the increased food competition from mackerel and herring and a likely increased predation on pre-recruit cod by mackerel and herring (see WK HS2 and WK HS3). In other words we see this reduced productivity in the cod data and we see the reasons in the environmental data.

The weighing of OM1- OM3 is a challenge. OM1 is not fitting the observation of production well in the period and should have a low weight. OM2 a median weight as it fits the data well but is out of line with the value of Fmsy obtained from multispecies models, life history models and cod stocks in other areas. OM3 should have the highest weight because it fit the data well, and its Fmsy value is consistent with multispecies models, life history models and cod stocks in other areas. OM3 is furthermore consistent with OMs based on the IBTS data. The set of weight could be OM1 = 0.1, OM2 = 0.3, OM3 = 0.6.

<table>
<tr>
<td>OM1: 1998-2018 K fixed to 549 kt and n to the standard Gadoid value
<table>
<tr><td>K</td><td>549</td></tr>
<tr><td>TBmsy</td><td>241</td></tr>
<tr><td>SSBmsy</td><td>105</td></tr>
<tr><td>SSBmsy in ICES-currency</td><td>133</td></tr>
<tr><td>MSY</td><td>133</td></tr>
<tr><td>SSQ</td><td>5.14</td></tr>
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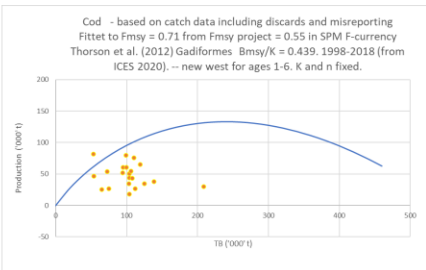
<td>
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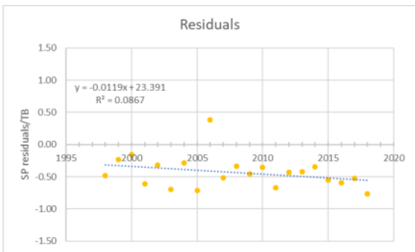
<td>
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<td>OM2: 1998-2018, Fmsy fitted to observations</td>
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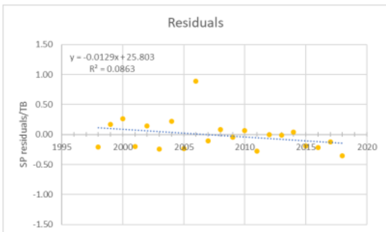
<td>
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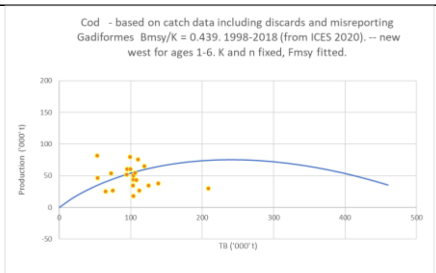
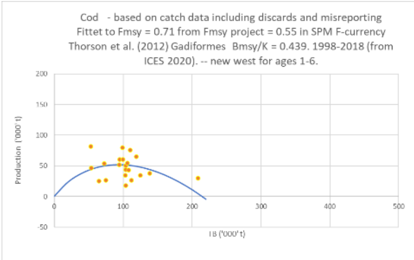
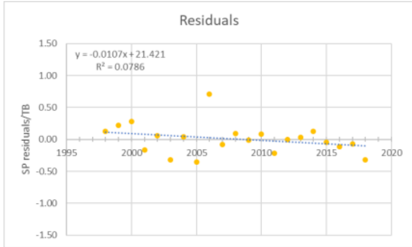
K	549
TBmsy	241
SSBmsy	105
SSBmsy in ICES-currency	133
MSY	75
SSQ	1.48



OM3: 1998-2018 K fitted to observations

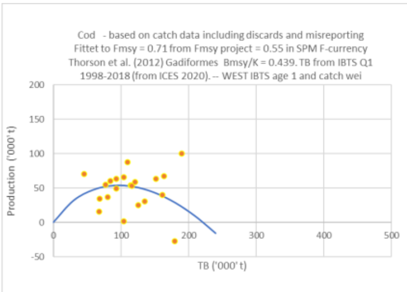
K	221
TBmsy	97
SSBmsy	42
SSBmsy in ICES-currency	54
MSY	54
SSQ	1.12

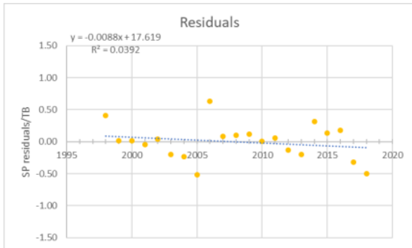




OM3.1: 1998-2018, TB based on IBTS q1

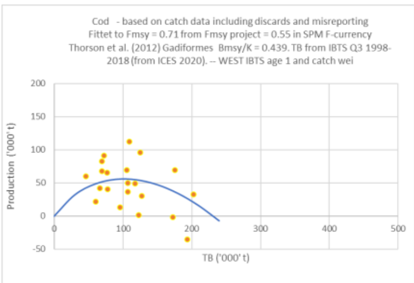
K	221
TBmsy	97
SSBmsy	42
SSBmsy in ICES-currency	54
MSY	54
SSQ	1.51





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



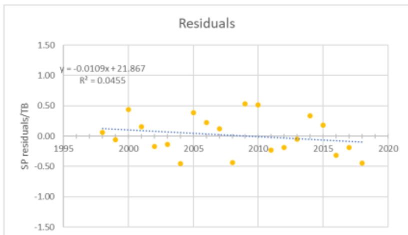


Figure A1. *North Sea cod. Alternatives OMs based on SPMs.*