INTER-BENCHMARK PROCESS ON WESTERN BALTIC COD (IBPWEB)

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International Council for the Exploration of the Sea
Conseil International pour l'Exploration de la Mer

H.C. Andersens Boulevard 44-46

DK-1553 Copenhagen V

Denmark

Telephone (+45) 33 38 67 00

Telefax (+45) 33 93 42 15

www.ices.dk

info@ices.dk

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Editor

Alexandros Kokkalis

Authors

Michael Wall Andersen • Casper Willestofte Berg • Massimiliano Cardinale • Margit Eero
Steffen Funk • Kristiina Hommik • Uwe Krumme • Anders Nielsen • Mikaela Bergenius Nord
Marie Storr-Paulsen • Thomas Theodorsen

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i Executive summary

The assessment of Western Baltic cod had serious issues, with very large retrospective pattern observed during the assessment of WGBFAS in 2021. This led the group to not accept the assessment and triggered an inter-benchmark process. Therefore, the overall objective of the Western Baltic cod Inter-benchmark process (IBPWEB) was to resolve the issues with the assessment of the stock. Online meetings were held in June 2021 and had two external reviewers.

Three different avenues were investigated during the process that aimed to resolve the assessment issues: i) natural mortality and maturity, ii) survey indices, iii) assessment model options.

The natural mortality was updated based on a meta-analysis method and contemporary mark-recapture data from SD22. The maturity ogives that showed large changes in recent years were deemed not trustworthy by the group who decided to use a constant maturity ogive equal to the 1998-2021 average. The survey index model was updated: a Delta-Lognormal GAM with time-invariant spatial effect, no ship effects and last age group 4+. Most important changes in the assessment model, was the use of independent F processes between age groups instead of the previously used dependent ones, and the downscaling of the last data-year's catch estimate to 1/10, as there were indications of age group sampling issues potentially due to Covid disruptions.

Finally, the reference points for the stock were updated and accepted. The external reviewers agreed and accepted all proposed changes.

ii Expert group information

Expert group name	Inter-Benchmark Process on Western Baltic cod (IBPWEB)
Expert group cycle	Annual
Year cycle started	2021
Reporting year in cycle	1/1
Chair(s)	Alexandros Kokkalis, Denmark
Meeting venue(s) and dates	16, 21, and 28 June 2021 (15 participants)

1 Introduction

This report contains the main topics that were considered and the outcomes of the Inter-Benchmark process for western Baltic cod (IBPWeb). The process was triggered by WGBFAS after finding the assessment of the stock in 2021 not acceptable, especially considering the strong retrospective patterns that were observed.

The most important avenues that were discussed during this IBP were:

- Updating the natural mortality to fit with stock specific life history parameters;
- Update the survey model;
- Change age structure in survey to 4+ group;
- Change from an annual maturity to a fixed value for all years;
- Change model setting for F to be an independent random walk for all age groups;
- Down weight catch in last data year; and
- Update reference points.

All the above points are described in the following sections. Each section contains a summary of the decisions taken.

1.1 Description of the inter-benchmark process

The IBPWeb took place online on 16, 21 and 28 June 2021. The process was reviewed by two external reviewers, Helen Dobby (Marine Scotland Science, UK) and Verena Trenkel (IFREMER, France). Both experts about the stock and the methods used attended the process and participated in the discussions and the decisions. Finally, two representatives of the fishing industry partly participated in the meeting.

The time between plenary meetings was used by the stock responsible and other assisting experts to deal with comments and requests from the reviewers and to finalise the different parts of the work. The final accepted assessment and reference points were based on the consensus of all participants in the topics that were addressed. All the points are presented in this document, along with a report from the two reviewers.

2 Stock Western Baltic cod

2.1 Stock ID and substock structure

Cod in the Baltic Sea is assessed and managed as two separate stocks, i.e. eastern and western Baltic cod, located in ICES subdivisions (SD) 24–32 and 22–24, respectively. There is clear evidence that eastern Baltic cod regularly occur in SD 24 (Hemmer-Hansen *et al.*, 2019). Given the apparent difference in biological parameters between the two stocks, eastern cod needs to be separated from the western stock, for stock assessment purpose (Eero *et al.*, 2014). Since the benchmark in 2013, assessments have been conducted by stock, i.e. separating between eastern and western Baltic cod in the mixing area in SD 24. In the current assessment, the time-series starts in 1985 since stock splitting data have not been available for the earlier part of the time-series.

It has been speculated if SD 23 (the Sound), is a different stock or stock component and in this inter-benchmark a model run with Stock Synthesis model (SS3; Methot and Wetzel, 2013) was conducted to investigate the difference in substock development and is briefly described and discussed below.

The ICES stock assessment of western Baltic cod is carried out at the stock unit level without spatial considerations. Here we developed an integrated spatial model considering western Baltic cod as one stock but constituted by two subpopulations (morphs), one in the Sound (SD 23) and one in the Western Baltic (SD22 and 24). Diagnostic of the models was based on the work of Kell *et al.*, 2021 and Carvalho *et al.*, 2021. Assessment of cod in the Western Baltic (ICES SD 22-24) was conducted using SS3. The model of cod in the Western Baltic is a two areas, two morphs, one sex, yearly age based model where the population is comprised of 12+ age-classes. The reference model starts in 1946, has four fleets, one bycatch fleet (seals) and five surveys, the first starting in 1995. Weight-at-age of the commercial and recreational catches was estimated separately for SD 23 and SD 22 & 24 and derived from data available at WGBFAS combining landings and discard and weighted by the corresponding numbers. For the historical part of the time-series (i.e. 1903–1976), the average of the weight-at-age as estimated using all available years was used for both commercial and recreational fisheries. For the surveys, the weight-at-age as estimated by all available years was used. Missing or unrealistic values were substituted by the average of adjacent weight. Maturity-at-age was estimated separately for SD 23 and SD22&24. Maturity was estimated separately for SD 23 and SD22&24. Stock weights were assumed equal to survey weight and inputted separately for SD 23 and SD22&24. Missing or unrealistic values were substituted by the average of adjacent weight.

Historic data have not been separated between western and eastern Baltic stock in SD 24. Therefore, these are not used in the present stock assessment. However, mixing ratios are available since 1977 and a future benchmark should explore their quality and the possibility of including historical catches in the assessment.

The results showed that cod in the different areas showed a different biology and dynamic, which should be accounted for in an area/morph model. The results showed that there is no" best model" according to diagnostics so that an ensemble would more appropriate for this stock. Cutting the time-series deteriorates the model estimation so the model should be extended at least from 1946. M used in SAM might be mis-specified (i.e. too low) and does not match the stock dynamic as described by the data. Also, models that uses M derived from the growth model has more convergence issues than using T_{max} or the average of the two methods. The model retrospective is unstable after three years. Runs test and hindcasting are moderately fine. Hindcasting of the age structure is exceptionally good, which implies that the stock biology and dynamic is well described by the model. Retrospective pattern after three years is partially linked to the large 2016-year class and it is likely an exceptional event. The largest conflict when it comes to the 2016-year class is given by the Pondnet survey, down weighting it alleviate the retrospective issue and model stability. Mortality seems to increase in last years but mostly for old fish, which might support the seal hypothesis contra the discard hypothesis.

A model with an additional fleet (bycatch fleet of the seals) and with discards modelled (with or without seals) separately were also tested. The discard separated model showed the best performances in terms of diagnostics and might be worth to pursue in future benchmarks. To improve the model, the SWE SD23 survey would be beneficial. Adding sample size of the commercial and recreational samples and CV of the Pondnet survey would be beneficial.

2.2 Issue list

The main issue with the assessment of cod in SD 22-24 was to investigate reasons for the very large retrospective pattern in both SSB and F that triggered WGBFAS to not accept the assessment in 2021. This inter-benchmark aimed;

i. To evaluate survey indices and assess the inclusion of older age groups in tuning indices;
ii. To investigate if we have model assumptions that are not valid anymore, to solve the problem with the retrospective pattern in F and SSB;
iii. Any evidence for increased natural mortality.

2.3 Scorecard on data quality

Sampling of the commercial fishery has in 2020 been influenced by the Covid situation. Although both Germany and Denmark have managed to conduct sampling with observer trips as well as on the landing sites and self-samples on a quarterly basis, the sampling was not conducted in all months. In Denmark the observer programs were stopped on 15 March until mid-June 2020 and again in November until end December 2020. Further, the randomly selected draw list was sat on hold from March and the rest of 2020 and an individual more selected draw list was created to minimise the contact between people. Especially in SD 24 the numbers of observer trips have in 2020 decreased compared to former years. This could have an influence on the discard estimate especially as the directed cod fishery has been prohibited (see section 3.4). In Germany, the sampling could basically be continued as in previous years and reduced sampling reflected reduced catches, both in the commercial and recreational fisheries.

2.4 Multispecies and mixed fisheries issues

In later years several regulations have been introduced with the aim to protect the Eastern Baltic cod stock component in SD 24 and to protect the spawning stock component of Western Baltic cod in the spawning season in SD 22 and SD 23. These regulations have changed the fishing pattern with a total stop for all fisheries in the main spawning season in SD 22 and in the last two years (2020, 2021) no direct fishing on cod in SD 24 (Table 2.1, figures 2.1 and 2.2).

Table 2.1. Management regulation on closed areas and season and on bag limits in the commercial and recreational fisheries.

Year	Area (SD)	Time period	restricted distance from coast	Regulation	Bag limits (recreational fishery)	restricted depth
2016	22-24	15.02.-31.03. 1.5 months		2015/2072 17. Nov. 2015	No bag limit	
2017	22-24	01.02.-31.03. 2 months		2016/1903 28. Oct. 2016	5 cod/day 3 cod/day (1/2-31/3)	
2018	22-24	01.02.-31.03. 2 months		2017/1970 27. Oct. 2017	5 cod/day 3 cod/day (1/2-31/3)	
2019	22-24	No closure		2018/1628 30. Oct. 2018	7 cod/day	
2020	22-23	01.02.-31.03. 2 months		2019/1838 30. Oct. 2019	5 cod / day in time period 01.02-31.03 2 cod / day	not deeper 20 m
	24	entire year 12 months	not further than 6 nm		5 cod / day in time period 01.02-31.03 2 cod / day	not deeper 20 m
2021	22-23	01.02.-31.03. 2 months		2020/1579 29. Oct. 2020	5 cod / day in time period 01.02-31.03 2 cod / day	
	24	entire year 12 months	not further than 6 nm			not deeper 20 m

However, the same gear is used in the flatfish (mainly plaice) fishery and the cod fishery. As the plaice stocks in both SD 21-23 and SD 24-32 are in a very good shape and the advice as well as quota have been increasing in later years this could lead to an increased incentive to discard cod caught as unwanted bycatch in the flatfish fishery in SD 24 where the directed cod fishery is now prohibited (Table 2.1).

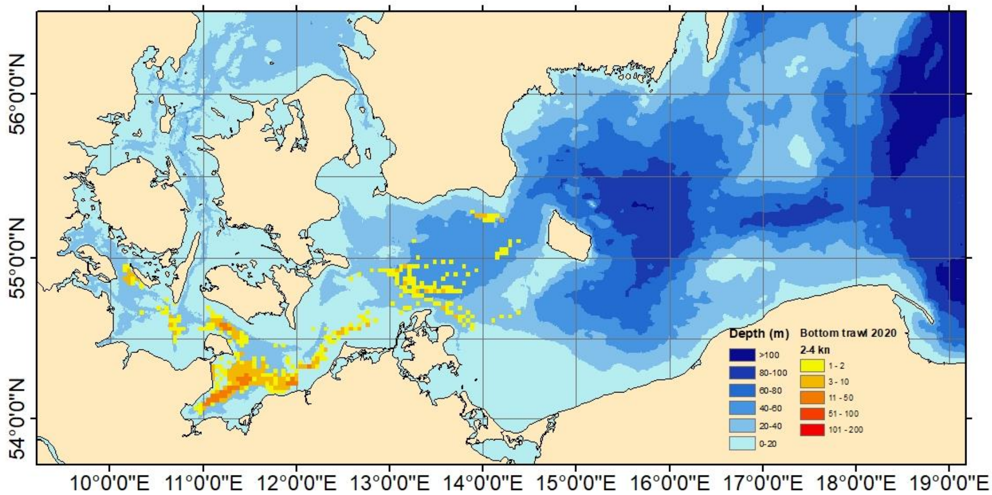

Figure 2.1. VMS data from 2020 in the Danish trawl fishery (OTB) fishing at 2-4 kn. and with a minimum of 50% cod in the catch (directed cod fishery).

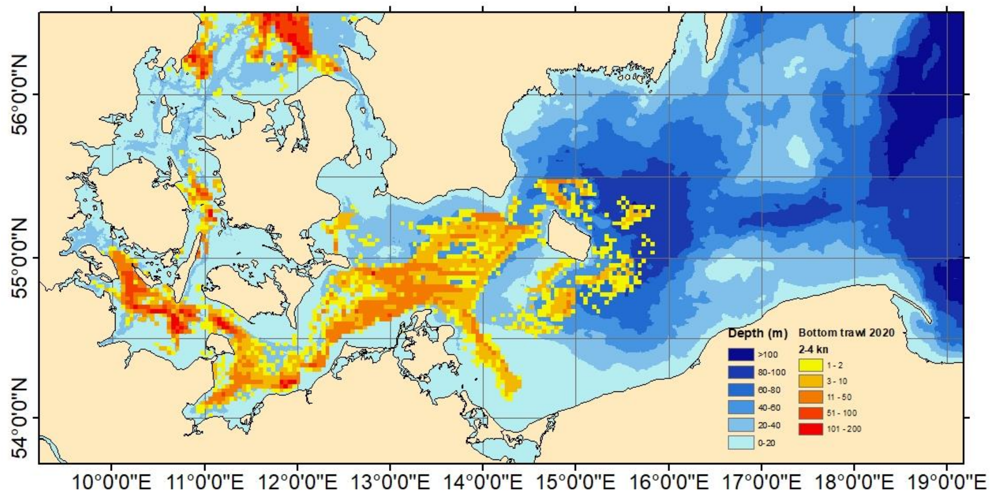

Figure 2.2. VMS data from 2020 in the Danish trawl fishery (OTB) fishing at 2-4 kn. and including all fisheries (mainly plaice, cod and flounders).

2.5 Ecosystem drivers and natural mortality

Natural mortality has for this stock not been based on any analysis. Instead, a value of 0.2 has been used for ages 2-7. For age 1 a multi species SMS was conducted in 1997 and a constant value at 0.242 has been applied since for this age group. In the Eastern Baltic cod stock, the natural mortality has been increasing and was updated in the latest benchmark. An increased concern was raised in the western Baltic cod stock as well, as condition factors have decreased as well as information on an increase in the populations of predators, e.g. grey seals and cormorants. Therefore, the natural mortality was investigated during the inter-benchmark.

2.5.1 Life history analysis

Analyses were carried out to estimate the natural mortality by age for Western Baltic cod, using information on life history parameters such as longevity and growth. These analyses suggest a different shape of M at age compared to the approach used in the assessment at present, and higher M values for younger ages (Eero and Cardinale, 2021 WD Estimation of natural mortality for Western Baltic cod).

Different methods were applied to provide alternative estimates of natural mortality for Western Baltic cod. The Hoenig method (1983) was applied to derive M for Western Baltic cod and it is based only on maximum age for teleosts. The maximum observed age (tmax) for Western Baltic cod recorded during BITS surveys since 1991 is 11 years and 13 years in Danish commercial catch data. However, as throughout this period the fishing mortality on the stock has been high, the maximum observed age probably is not representing longevity. For comparison, for a neighbouring slower-growing stock, eastern Baltic cod, for which longer and more comprehensive time-series of data are available, fish up to 20 years of age have been recorded (ICES WKBALTCOD2 2019). Given a lack of good stock specific information, in the present analyses, 25 years was applied as longevity of Western Baltic cod, representing cod fish in general. This resulted in M at 0.17, based on the Hoenig method (1983). For sensitivity, M value at 0.21 is obtained with longevity of 20 years, and 0.28 with longevity of 15 years.

A more recent paper by Then *et al.*, (2015) analysed data from 226 studies (including Hoenig 1983) to evaluate the robustness of life-history based M inferences. Based on updating and testing indirect estimators of natural mortality using information on 201 fish species, Then *et al.*, (2015) recommend the use of their updated maximum age-based estimator when possible and an updated von Bertalanffy K-based method otherwise.

Comprehensive analyses estimating M from different methods were carried out for the neighbouring Eastern Baltic cod stock at last benchmark (ICES 2019, WD by Cardinale, M). As a result, the two approaches suggested by Then *et al*., were selected for the final assessment for E Baltic cod. For this reason, and for consistency with the neighbouring stock, the present analyses for Western Baltic cod are also focusing on the approaches by Then *et al.* (2015).

The life history parameters (Table 2

.2) used included von Bertalanffy growth parameters estimated from contemporary tagging data for Western Baltic cod from SD 22 (McQueen *et al.*, 2019), and a and b parameters of length-weight relationship estimated from BITS surveys (1996-2021), used to derive age specific values of M.

Table 2.2. Life history parameters used in M calculations

Life history parameters	Value	Source
k (combined sex)	0.11	McQueen *et al*., 2019
Linf (combined sex)	154.56	McQueen *et al.*, 2019
to (combined sex)	-0.13	McQueen *et al.*, 2019
Max age (combined sex, tmax)	25	based on cod in general
a	0.00000792	BITS Q1 & Q4
b	3.0563	BITS Q1 & Q4

Natural mortality can be expected to be higher in young fish and decline with age. Proxy methods to infer age-dependent M in younger fish are given by Lorenzen (1996) and Gislason *et al.* (2010). The Gislason method generally gives lower M estimates for adult fish. Brodziak *et al.*

(2011) suggested that methods such as Lorenzen (1996) can be used to derive the relative age-dependent patterns for younger fish, but can be re-scaled to give M at older ages that are more similar to those from methods using (e.g.) tmax. Therefore, the Lorenzen (1996) method was used to estimate age-dependent M values for Eastern Baltic cod.

The Then *et al.* (2015) tmax based method (i.e. $M = 4.899\ tmax^{-0.916}$) gives an M value of 0.257.

The Then *et al.*, (2015) von Bertalanffy K-based method, which uses the parameters of the von Bertalanffy growth curve, ($M = 4.118\ K^{0.73}\ Linf^{-0.33}$), predicts M = 0.156.

Both methods were calculated as suggested by Then *et al.* (2015), which are based on maximum age (tmax) and parameters of the Bertalanffy growth curve.

The Lorenzen (1996) method was used to estimate age-dependent M values for Western Baltic cod and the results are given in Figure 2.3 and Table 2.3. Lorenzen M values were rescaled to give mean M at ages 10-15, which are equivalent to the Then *et al.* (2015) prediction of 0.257 and 0.156 for tmax 25 years old and growth-based method, respectively. Therefore, the following M options could be explored:

1. Lorenzen M (age specific) rescaled to M = 0.156 from Then’s growth-based method
2. Lorenzen M (age specific) rescaled to M = 0.257 from Then’s tmax method
3. Average of the two methods 1 and 2
4. Continue with the M values that have been used in stock assessments for Western Baltic cod previously (SPALY).

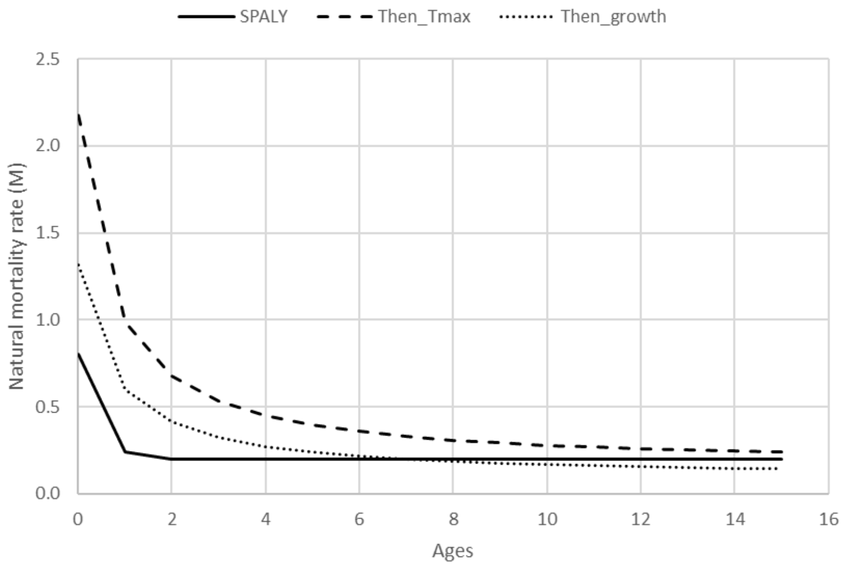

Figure 2.3. Natural mortality by age values inferred from Lorenzen (1996) rescaled to a mean M of 0.257 at ages 10-15 (based on Then *et al.*, 2015 maximum age method, for a maximum age of 25 years) and mean M of 0.156 at ages 10-15 (based on Then *et al.*, 2015 growth method). The results are compared with the M at age values presently used in stock assessment of Western Baltic cod (SPALY).

Table 2.3. Western Baltic cod natural mortality by age values estimated using: Lorenzen (1996) age specific) rescaled to M=0.257 at ages 10-15 (Then *et al.*, 2015 maximum age method (tmax); Lorenzen (1996) age specific) rescaled to M=0.156 at ages 10-15 (Then *et al*., 2015 growth method)

age class	Length (cm)	Weight (kg)	M Lorenzen	Scaled to Then tmax	Scaled to Then growth
0.5	10.3	0.010	1.545	2.172	1.318
1.5	25.4	0.155	0.702	0.987	0.598
2.5	38.8	0.570	0.482	0.678	0.411
3.5	50.9	1.302	0.380	0.535	0.324
4.5	61.7	2.345	0.321	0.451	0.274
5.5	71.4	3.660	0.282	0.397	0.241
6.5	80.0	5.195	0.255	0.359	0.218
7.5	87.8	6.895	0.235	0.331	0.201
8.5	94.7	8.704	0.220	0.309	0.188
9.5	101.0	10.575	0.208	0.292	0.177
10.5	106.6	12.465	0.198	0.279	0.169
11.5	111.6	14.340	0.191	0.268	0.163
12.5	116.0	16.174	0.184	0.259	0.157
13.5	120.0	17.945	0.179	0.251	0.152
14.5	123.6	19.638	0.174	0.245	0.148
15.5	126.9	21.244	0.170	0.239	0.145
16.5	129.7	22.755	0.167	0.235	0.142
17.5	132.3	24.169	0.164	0.231	0.140
18.5	134.6	25.485	0.161	0.227	0.138
19.5	136.7	26.704	0.159	0.224	0.136
20.5	138.6	27.828	0.157	0.221	0.134
21.5	140.2	28.863	0.156	0.219	0.133
22.5	141.7	29.811	0.154	0.217	0.132
23.5	143.1	30.678	0.153	0.215	0.131
24.5	144.3	31.469	0.152	0.214	0.130
25	144.8	31.837	0.151	0.213	0.129
	mean 10-15	16.968	0.183	0.257	0.156

Decision taken by IBPWEB

It was decided at the IBPWEB to use the Then growth method as it was based on stock specific data derived from contemporary mark-recapture study in SD 22 (McQueen *et al.*, 2019). Further, the estimates were similar to other cod stocks (e.g. cod in Division 6.a (west of Scotland)), although lower than the natural mortality used in the North Sea cod assessment.

2.5.2 Predation by seals

The grey seal (*Halichoerus grypus*) occurrence in the Western Baltic increased over the past years and was in 2019 counted on land during the moulting season to be just below 1000 individuals. A new still unpublished study from DTU Aqua investigated the two main grey seal areas in the Western Baltic to assess the seals´ feeding pattern. Based on these data, an average annual consumption of cod has been estimated. In 2019, this amount is estimated to be just below 600 t cod. A time-series of grey seal consumption rate on cod from 2001 to 2019 based on a 5-year interval has been populated.

The increasing grey seal occurrence in the Baltic has caused debates among the fishing community in the recent years. In the beginning of the 19^{th} century, the grey seal occurrence in the Baltic was much larger, estimated to be around 90 000 animals but hunting and pollution decreased the population size to below 10 000 animals, until 15 years ago when protection measures resulted in increasing stock levels. In 2000, HELCOM estimated the Baltic grey seal occurrence to be close to 10 000 animals, in 2006 this increased to 20 000 and in 2019 the estimated number of grey seals was 38 000. As large numbers of grey seals require a considerable food supply like fish and as there has been theories that seals have been part in the eastern Baltic cod stock's decrease, fishers are concerned of the increasing seal stock abundance. The present section provides an attempt to quantify the amount of cod eaten by the Baltic grey seals in the Western Baltic Sea based on newly published and unpublished data.

A study by Galatius *et al.* (2020) concluded that the grey seal occurrence in Kattegat, the southern and western Baltic has steadily increased since 2003 from 146 individuals, close to 1% of the total population in the Baltic to 2537 individuals in 2019 close to 7% of the total grey seal population in the Baltic

After personal communication with the author, it was possible to get the data at a finer scale and only covering the Western Baltic area, for the four locations: Rødsand, Rügen, Måkläppen, and Bosserne. The data were provided as an average by year in 5-year periods (Table 2.4).

Table 2.4. Grey seal abundance in the western Baltic by year interval and area.

Year interval	Rødsand	Bosserne	Total grey seal abundance in the Western Baltic area
2001-2005	3	0	112
2006-2010	54	1	248
2011-2015	95	2	648
2016-2019	99	19	977
Year interval	**Rügen**	**Måkläppen**	
2001-2005	0	109	
2006-2010	3	191	
2011-2015	4	546	
2016-2019	17	843	

The amount of cod in a seal's diet varies widely between locations, seasons, age, sex and individuals. If the seal feeds for example on sandeel, only an average of 4 kg is required per day owing to the high energy content of the fish compared to an average of 7 kg when feeding on cod (SCOS, 2009). However, as an average, an adult seal is estimated to consume approximately 4.5 kg of fish per day (Eero *et al.*, 2011).

A still unpublished study from DTU Aqua estimated and compared consumption data from the two main grey seal locations in the western Baltic Sea Måkläppen (SD 24) and Rødsand (at the edge between SD22 and SD 24), based on faeces collected at the seals´ haulout sites. The data were collected in the period 2014–2017 at Måkläppen in all four quarters but in Rødsand only in 3 quarters (quarter 1 is missing) (Table 2.5). The data indicated large fluctuations in prey species composition by season and area, but with a clear pattern of higher amount of cod in the diet further towards the eastern areas.

Table 2.5. Proportion of cod (N) in the seal diet depending on area and quarter.

Area	Q1	Q2	Q3	Q4	average
Måkläppen	0.63	0.18	0.27	0.51	0.40
Rødsand	N/A	0.33	0.02	0.02	0.12

As grey seal abundance was only available in 5-year average periods, some simplified assumptions were made using an annual average per area. Further, the smaller area Rügen was added together with Måkläppen in the diet composition and the other smaller area Bosserne was added together with Rødsand. Based on the annual cod consumption rate for the two areas (Måkläppen: 0.40; Rødsand: 0.12) and the assumption of an average diet of 4.5 kg fish a day, an area specific cod consumption was estimated (Table 2.6).

Table 2.6. Grey seal abundance in Rødsand +Bosserne (top) and Måkläppen+ Rügen (bottom) along with estimates of annual consumption of all fish and cod.

Rødsand +Bosserne			
year interval	grey seal abundance	tonnes fish/year	tonnes cod/year
2001-2005	3	5	1
2006-2010	54	89	11
2011-2015	97	159	20
2016-2019	117	192	24

Måkläppen+ Rügen			
year interval	grey seal abundance	tonnes fish/year	tonnes cod/year
2001-2005	109	179	71
2006-2010	193	318	126
2011-2015	551	904	360
2016-2019	860	1412	562

Decision taken at the IBWEB

Although acknowledged that the grey seal abundance has been increasing in later years and that this potentially has an influence on the natural mortality, it was decided by the group that the calculations were still premature to be included in the stock assessment. An annual estimate would be preferable as well as more analysis on the diet by sites. Furthermore, the impact of other predators such as cormorants, harbor porpoises or common seals could also be included to provide a more holistic estimate of predation-induced natural mortality. It was therefore decided that these estimates should not be included in the final assessment runs. Sensitivity runs were conducted with the increased natural mortality estimates.

2.6 Stock Assessment

2.6.1 Surveys

Prior to this inter-benchmark the survey indices for WB cod were derived using a Delta-LognormalGAM model for the ages 1 to 4 in Q1 and 0 to 4 in Q4: The model fitted data from the BITS survey starting in 1992, although indices were only used in the assessment from 1996 and 1999 in quarters 1 and 4 respectively. Two different survey gears were used historically, TVS and H20, but only the TVS in later years. An externally estimated length-based conversion factor between two Danish vessels (new and old "Havfisken") was applied prior to running the survey index model.

The model contains a time-invariant spatial effect as well as gear, ship and time-of-day effects.

A number of alternative indices were tested prior to the benchmark.

In order to simplify the model and avoid potential problems due to scarcity of age samples in the early years, the alternative indices were estimated based on a reduced dataset.

The reduction was to only consider the years actually used in the assessment, and to only use hauls taken with the TVS gear. Seven different model formulations were tested, see table below:

	Name	Distribution	Spatial_effect	Ship_effect
1	LN	Delta-Lognormal	Fixed	Yes
2	Gamma	Delta-Gamma	Fixed	Yes
3	Tweedie	Tweedie	Fixed	Yes
4	TV.LN	Delta-Lognormal	Time-varying	No
5	TV.Tweedie	Tweedie	Time-varying	No
6	Tweedie.noS	Tweedie	Fixed	No
7	LN.noS	Delta-Lognormal	Fixed	No

The different indices were evaluated based on the AIC and Mohn's rho of the SAM model (see table below) as well as the Mohn's rho of the survey indices themselves.

name	AIC	mohn.SSB	mohn.F	mohn.R
LN	1072.831	0.228	-0.160	0.299
Gamma	1123.305	0.204	-0.140	0.278
Tweedie	1142.011	0.276	-0.174	0.276
TV.LN	1078.621	0.244	-0.155	0.027
TV.Tweedie	1150.598	0.362	-0.227	-0.001
Tweedie.noS	1120.245	0.244	-0.171	-0.020
LN.noS	1061.227	0.197	-0.153	0.022

The results indicated that the Delta-Lognormal distribution with a fixed (time-invariant) spatial effect and without random ship effects gave the best results. Removing the ship effect reduced the Mohn's rho for the survey indices themselves as well as in the assessment model and also improved the AIC.

As an extra test, the ship effect was also removed from the original model using the usual data setup (i.e. the full dataset from 1992 and including the H20 gear), and a similar improvement in AIC and Mohn's rho was found.

Finally, the plus-group setting for the surveys was investigated. Prior to the benchmark the indices included up to age 4, but it was suggested to see if more ages could be included. It was concluded that the last age could be changed from 4 to 4+.

Using a 5+ group was also investigated, but particularly for the Q4 indices, these were considered too uncertain to include in the assessment due to small sample sizes and a large Mohn's rho for the index of this age group.

Decision taken at the IBPWEB

The final selected survey index was therefore the Delta-Lognormal GAM model with time-invariant spatial effect, no ship effects (except for the externally estimated conversion for

"Havfisken"), last age group 4+, and only using data collected with the TVS gear in years actually used in the assessment.

2.6.2 Weights, maturities, growth

Weights: Weight-at-age had decreased recently, both in the commercial and recreational dataset. This affected particularly the 2016-year class. No further analysis specifically focusing on weight data was not conducted for the inter-benchmark.

Maturity: Critical to the final estimates of SSB and subsequently R in fish stock assessments is information on age-dependent maturation schemes of the stock. In the WBC assessment, the BITS Q1 monitoring, which is used to define the maturity ogive, has recorded a strong change in the maturity ogives since the year 2000. While in 2000 the relative proportion of mature individuals in age class 2 was still at 30%, it has increased over time, with maximum values of more than 70% recorded in recent times. Funk *et al*. (Funk S, Floeter J, Krumme U, Möllmann C 2021 WD Alternative explorative stock assessment changes the perception of the state of Western Baltic cod) used ecological knowledge and data of seasonal changes in depth use of WBC in SD 22 from Funk *et al.* (2020) and argued that the increase in maturity is an artefact of the BITS concentrated on soft-bottom areas mostly below 20 m water depth. Thus, the proportion on non- (or skip) spawners, which mostly use shallower waters during the spawning season, is systematically biased when stock size decrease. Therefore, Funk *et al.* (WD) tested a revised maturation scheme, namely a constant maturity using the data from the beginning of the time series.

Growth: McQueen *et al.*, 2019 provides the most reliable and contemporary estimate of growth of WBC. Presently, there are no data that suggest a recent decrease in growth of WBC but the analysis of recaptures in McQueen *et al*. 2019 ended in 2015. The dominance of the 2016-year class in the stock (while the 2015- and 2017-2020-year classes were poor) and the Rosa Lee effect may have led to a decrease in growth in the most recent years when only the slower-growing survivors of the 2016 cohort are left. However, no data have been analysed on this issue.

Decision taken at the IBWEB

The group did not trust the increase in maturity in recent years and decided to use a constant maturity by age, estimated as an average from 1998-2021.

2.6.3 Assessment model

Several model settings were tested in sensitivity runs and compared for improved AIC, Log likelihood and Retro. The two main changes in the settings were 1) to change F random walk from being dependent on neighbouring age groups to become independent of neighbouring age groups and 2) to down weight the influence of the commercial caches in the last data year.

1. F independent of neighbouring ages.

In the SPALY assessment, F (random walk) was dependent on the development of the neighbouring ages. This assumption seems to be true for the most part of the time series (Figure 2.5). However, in later years this assumption seems not to hold true for 5+ ages anymore. Large changes in the management system in later years can be a reason for this (spatial and temporal closure, bag-limits etc.

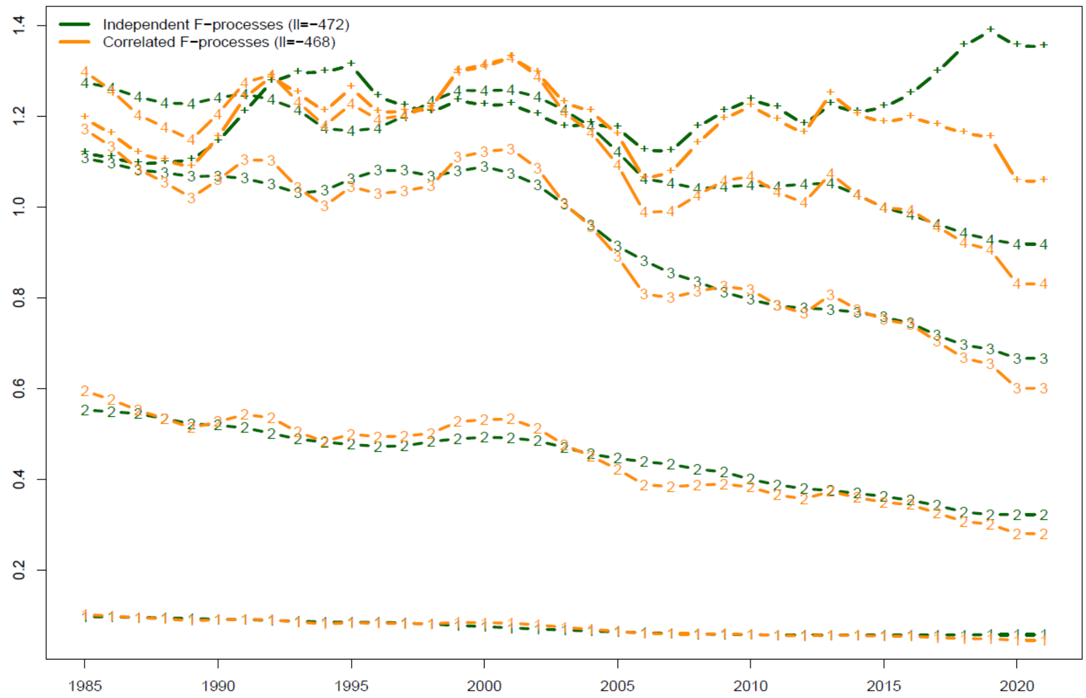

Figure 2.5. F independent (green) and dependent (orange) of neighbouring ages.

The change in F settings did improve the retrospective pattern from a Mohn's Rho at -0.49 in the SPALY to -0.16 in the version with the changed settings, the Mohn's Rho for SSB improved from 0.6 to 0.22 (Table 2.7). The AIC and Log (L) did worsen slightly by the changes, however as the parameters changed these numbers are not comparable.

Table 2.7. Mohn's Rho, AIC and Log (L) for 2 runs with independent F by age and dependent F by age.

name	SSB	F	R	Retro SSB	RETRO F	Retro R	AIC	Log (L)	Par
SPALY	8335	0.927	16763	0.6	-0.49	0.27	1001.15	-476.58	24
F_RW	7558	1.072	15877	0.22	-0.16	0.17	1006.59	-480.29	23

2. Down weight the influence of the commercial caches in the last data year

Although the Mohn's Rho improved by the change to F independent by age, the F pattern was still outside the confidence intervals in the retro (Figure 2.6). For this reason, several different settings were investigated to analyse if it was possible to obtain a more robust estimate (Table 2.8). Options with catch scaling in 12 years, 4 years, and 2 years was investigated. Further, it was investigated if the catch scaling was used on 2 different size groups (smaller and larger fish). Additional tests were performed, allowing the selectivity to change between years and fixing the selectivity across all years. Removal of catch the last year or downscaling the catch the last year and only removal of age 6 and 7 the last year. From all the sensitivity runs it was evident that the catches of older age groups in the last data year was causing the retrospective pattern. A reason for this could be the decreased sampling effort in 2020 due to Covid or changes in the fishing patterns.

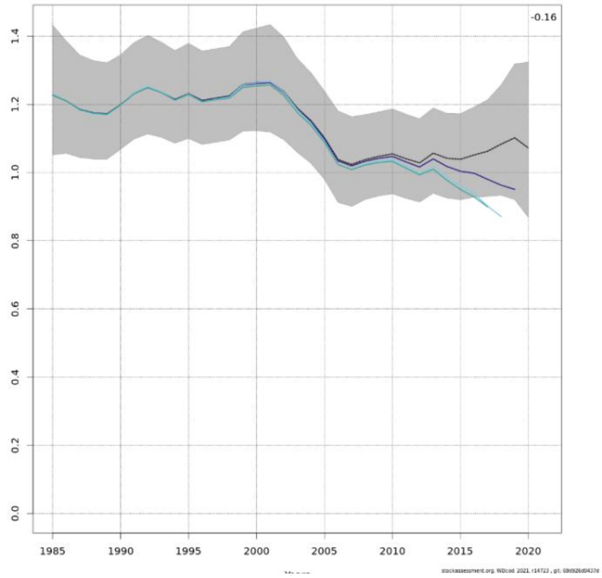

Figure 2.6. Retrospective pattern in F after the introduction of F independent of neighbouring age groups. Mohn's Rho is -0.16.

Table 2.8. Mohn's Rho (R, SSB and F), Delta AIC and Log (L) for different runs.

	logLik	DeltaAIC	R(age 0)	SSB	Fbar(3-5)	Catch
baseNewIdx4p	-472.0	29.7	13	18	-11	14
catchscaling12	-471.5	32.8	-1	1	-11	-3
catchscaling4	-459.6	9.0	-11	2	-9	0
catchscaling2	-467.4	24.6	-1	6	-7	6
fitflexSel	-492.7	69.1	16	56	-49	6
fitmulti	-471.3	28.5	13	34	-26	6
fitDWlastC	-469.4	24.7	5	11	-4	11
fitRMlastC	-459.4	4.6	3	8	-1	10
fitRMLast67	-464.5	14.8	11	11	0	13
catchscaling4DW	-458.3	6.3	-11	0	-2	0
catchscalingTime12	-421.1	0.0	-17	-1	-3	-3
catchscalingTime4	-447.0	3.8	-13	0	1	1
catchscalingTime2	-459.5	16.8	0	4	3	7

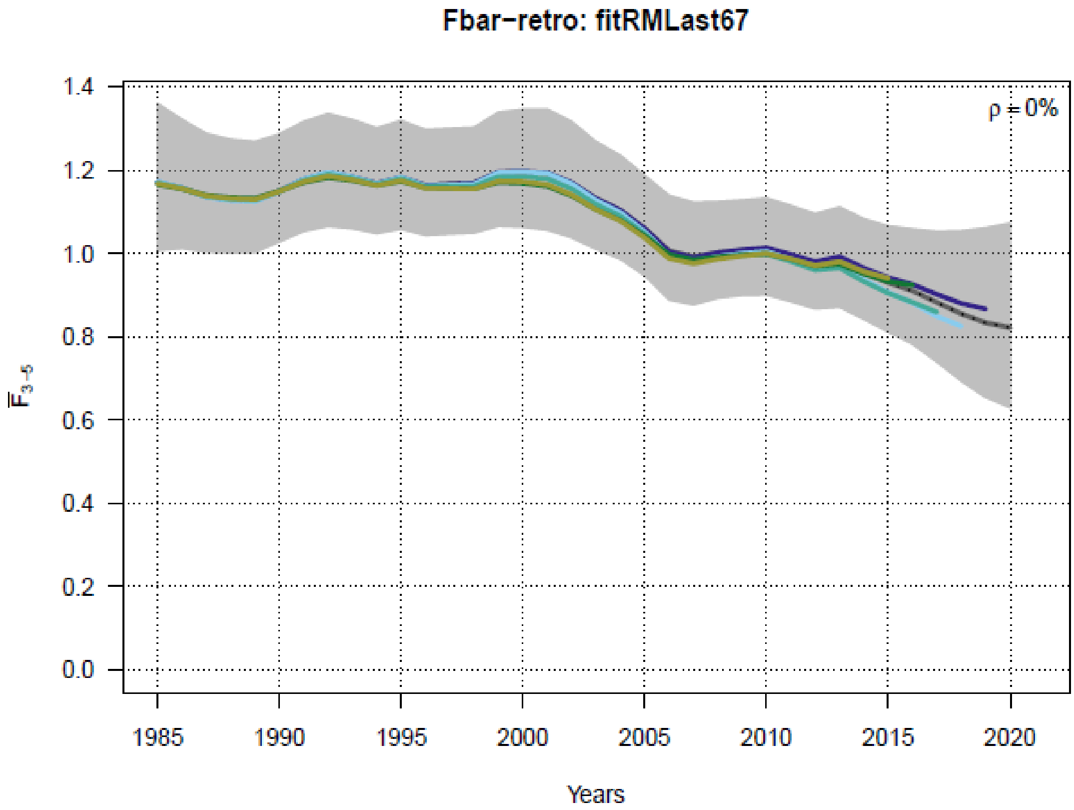

Figure 2.6. Retrospective pattern in F with exclusion of age 6 and 7 in catch matrix 2020.

Decision taken at the IBPWEB

It was decided to change the setting from F dependent of other age groups to F independent of other age groups. In SAM these options can presently not be done by year and it was therefore introduced for the whole time period. Further, it was the decision by the group to downscale the last data year's catch estimate to 1/10, as there seemed to be a problem with the older age groups sampled in 2020, maybe due to the Covid sampling program not given a good coverage over the year or changes in the fishing pattern. All settings can be found in Annex 1.

2.6.4 Short-term forecast

The following procedure was decided during the IBPWEB for the short-term projections.

The start year used in the short-term forecast is set to start one year prior to the last assessment year but then still use the last assessment year's recruitment estimate. In the last year of the assessment the estimates and their estimated uncertainties are used (including for recruitment), but for the following forecast years recruitment is sampled from the most recent 10 recruitment estimates (1000 times with replacement).

Selection pattern and stock weight is used in the short-term forecast and it is decided to use the latest three years' average.

For the intermediate year the same procedure as in former times has been used, where the TAC for the management area is multiplied with the Western Baltic cod stock proportion from the area (based on genetics and otolith shape) and the discard rate is taken into account. Further the assumed recreational catches are added. This method has in the last five years been a relatively good estimate of the intermediate years catch.

Assumptions about Catch in intermediate	2016	2017	2018	2019	2020	2021
TAC	12720	5597	5597	9515	3806	4000
WBC prop	0.58	0.58	0.66	0.59	0.753	0.864
Disc Ratio	0.05	0.02	0.05	0.042	0.097	0.050
Comm Catch	7769	3336	3858	5848	3173	3638
Recreat Catch	2558	1754	1754	2140	1315	1315
Total Catch WBC	10327	5090	5612	7988	4488	4953
Comm Landings	7373	3255	3673	5600	2865	3457
Comm Discards	396	82	185	248	308	181
Acctual catch value in the given year	9770	5347	5303	9317	4361	
* split and discard ratio is last year's value						
% difference between estimated catch and observed catch	5.4	-5.0	5.5	-16.6	2.8	

2.7 Appropriate Reference Points (MSY)

The stock recruitment relationship used included data from the whole time-series 1985-2020. The IBPWEB considered six different stock characteristic types documented by ICES in "ICES fisheries management reference point for category 1 and 2" (ICES, 2021). The stock recruitment plot did not indicate a clear S-R relationship, there is however evidence of recruitment being impaired at very low spawning stock levels, though it was not possible to estimate a breakpoint. As no breakpoint in S-R could be defined, IBPWEB decided by to use an average of the lowest SSBs (the lowest 50% median) were the recruitments were above average. The same approach was used at the last benchmark in 2019 where this corresponded to 4-year classes which gave an average SSB at 14 535 t. Following the same approach at this IBP the year classes 1990, 1991, 1993, and 2016 gave an above average recruitment and was in the lower 50% median of SSB (Figure 2.7). An average of these four SSB estimates producing the above average recruits was 15 067 t, similar to the value obtained at the previous benchmark. Using the ICES standard procedure this corresponds to a Bpa at 23 492 t (Bpa = 14067* exp(1.645*0.27). Sigma was derived from last year's SSB (2021). Fishing mortality reference points F_{MSY} were calculated using ICES standard software EqSim. Stock–recruitment relationship was defined using a hockey-stick function, setting the breakpoint at B_{lim} (15 067 t) (Figure 2.8). The entire time-series was used for S-R. For the biology and selectivity, average values from the last three years (2018-2020) were used. F_{MSY} is relatively well defined for this stock (Figure 2.9), and was estimated at 0.26 (ranges F_{MSY} low = 0.17, F_{MSY} high = 0.44). Precautionary fishing morality reference points were estimated to be at $F_{pa} = F_{p0.5} = 0.689$ (with advice rule) and $F_{lim} = 1.23$, equilibrium scenarios with stochastic recruitment: F value corresponding to 50% probability of (SSB < B_{lim}).

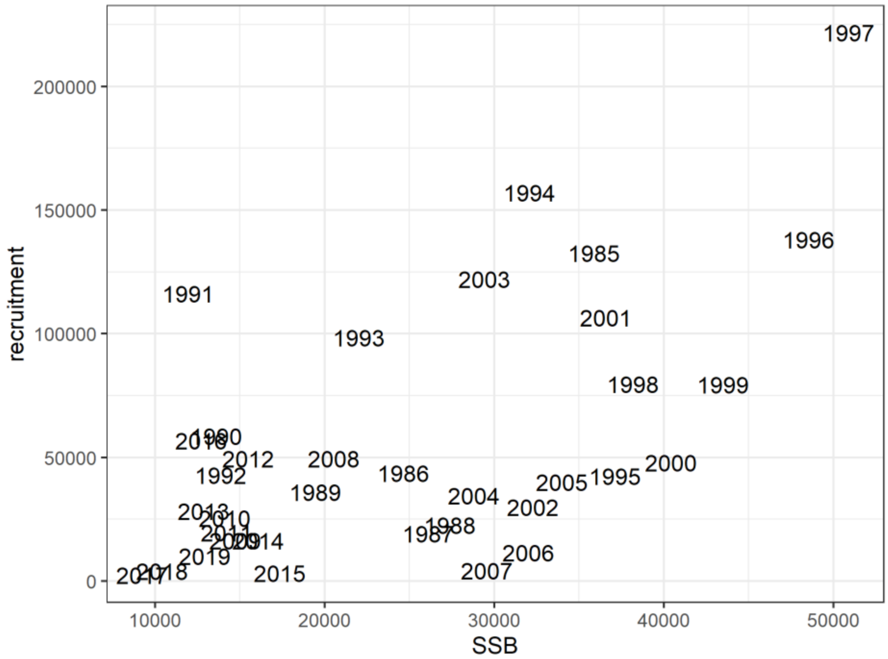

Figure 2.7. Stock recruitment relationship with the updated assessment.

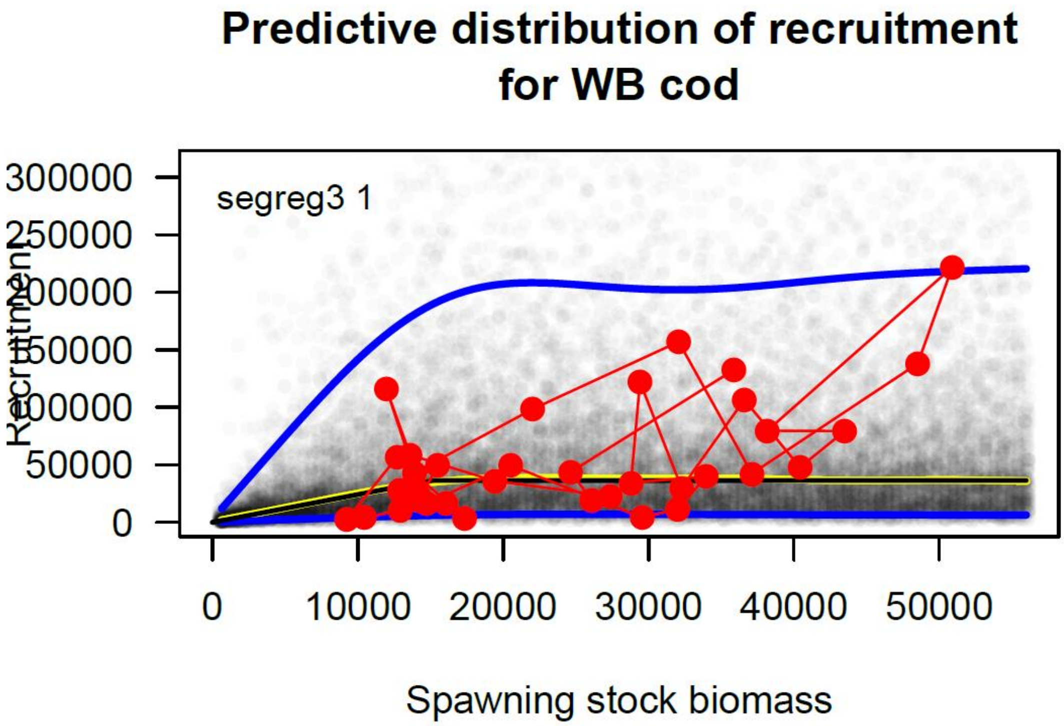

Figure 2.8. Segmented regression using EqSim with a forced breakpoint at B_{lim} (15 067).

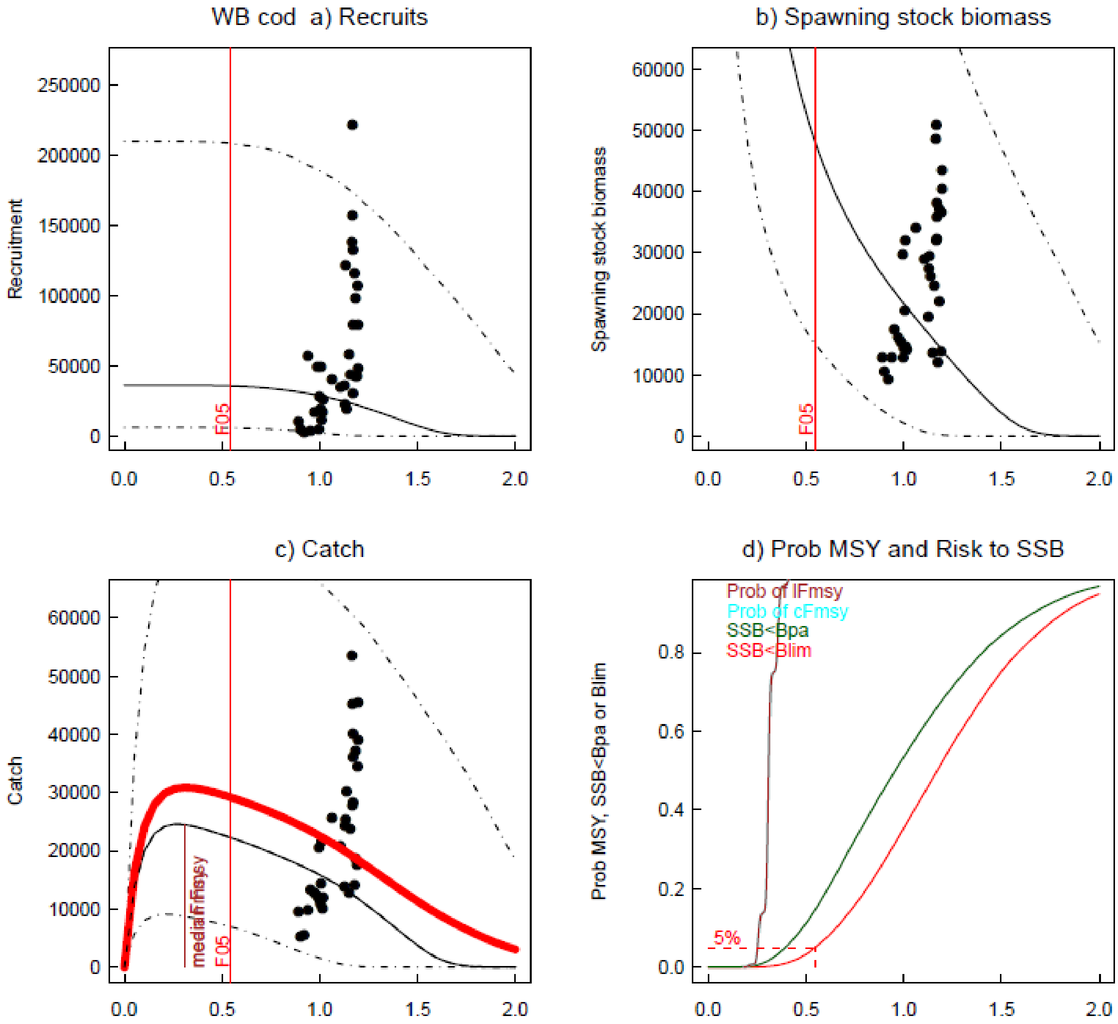

Figure 2.9. EqSim results without advice rule (Btrigger).

Table 2.9. Output from EqSim without advice rule.

FmsyMedianC	0.261
FmsylowerMedianC	0.171
FmsyupperMedianC	0.442
FmsyMedianL	0.261
FmsylowerMedianL	0.171
FmsyupperMedianL	0.442
F5percRiskBlim	0.546

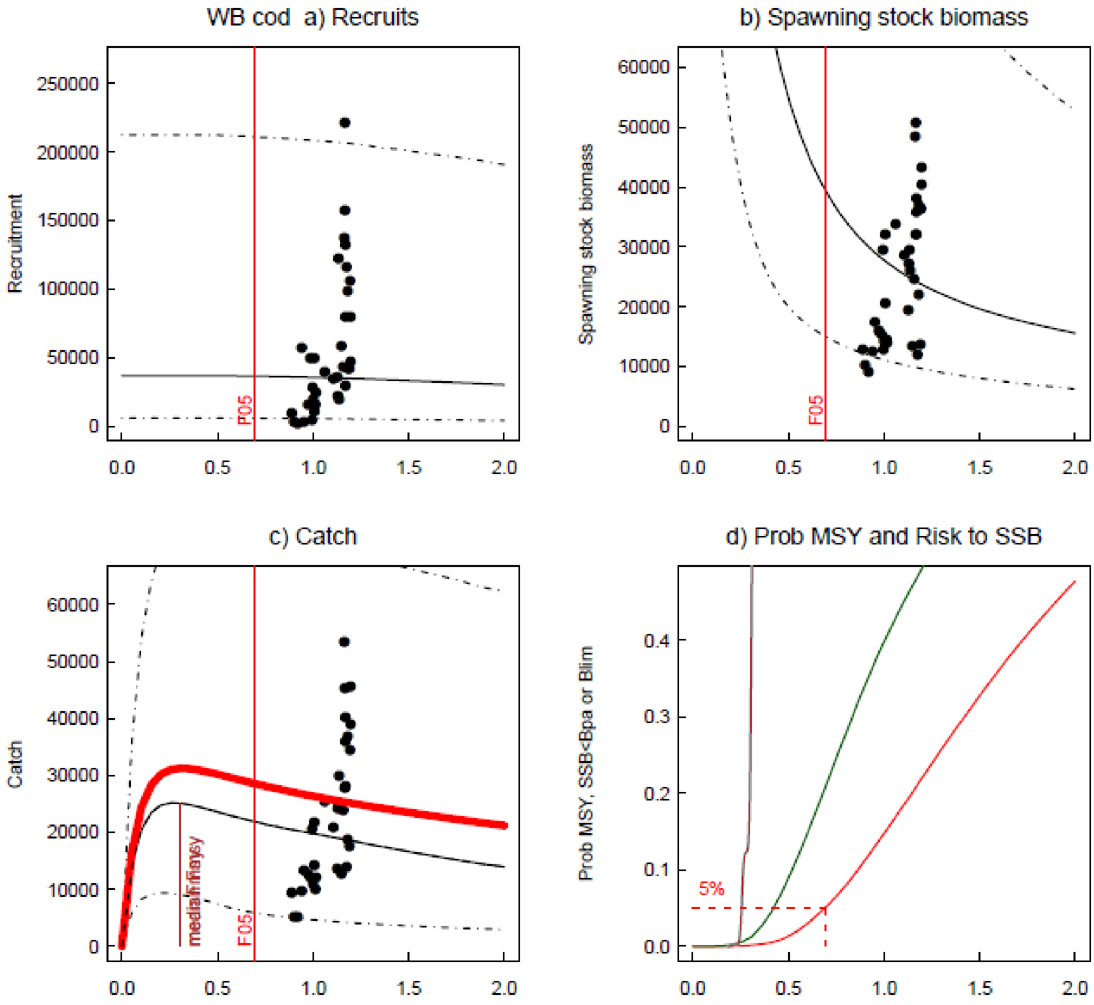

Figure 2.10. EqSim results with advice rule (Btrigger).

Table 2.10. Output from EqSim with advice rule.

FmsyMedianC	0.261
FmsylowerMedianC	0.171
FmsyupperMedianC	0.462
FmsyMedianL	0.261
FmsylowerMedianL	0.171
FmsyupperMedianL	0.462
F5percRiskBlim	0.689
Btrigger	23492

3 External Reviewers Comments

The motivation for the Inter-benchmark meeting was to address a serious degradation in the retrospective pattern which became evident at the 2021 assessment WG. While there had been a moderately poor retrospective pattern at previous assessment WGs, the use of updated survey data (some ages corrected in DATRAS) at the 2021 WG led to a substantial revision in the assessment results, unacceptable Mohn's rho on both F and SSB and a subsequent rejection of the SPALY assessment by the WG. A number of possible causes/solutions for the poor retrospective pattern were identified for exploration ahead of the IBP including potential changes in natural mortality, extending the survey age range, modifying the calculation of the survey index, fixing maturity ogives and invalid model assumptions associated with changing fishery selectivity.

Evidence was presented to suggest that natural mortality is likely to have increased on this stock over time – possibly due to decreased stock condition and increased seal abundance (and consequently increased predation). There was a proposal by the assessor to make use of seal abundance and diet data (mostly unpublished) to estimate natural mortality within the stock assessment model. However, the reviewers expressed reservations with this approach due to the reliability of these data (limited sampling and lack of annual estimates) and considered their use in the assessment model to be premature. Furthermore, such a major change would seem beyond the scope of an IBP and more appropriate for consideration during a full benchmark process. This approach was therefore not pursued further. Natural mortality estimates were, however, revised to provide age dependent values on the basis of mean weights-at-age and stock dependent growth parameters. The resulting values appeared reasonable when compared to other cod stocks.

Up to now annual estimates of maturity ogives were derived from BITS survey data which showed increasing proportions mature over time. Convincing evidence was presented for biased estimates due to the survey missing parts of the population, in particular immature individuals which are found in shallower unsampled waters. The decision to calculate an average constant maturity ogive seems a reasonable approach to deal with the issue and facilitates short-term projections.

Major changes in the management of this stock including a spawning closure in place since 2016 are believed likely to have impacted fishery selectivity. Therefore, it was considered appropriate to free up the estimation of F at age and allow the F-at-age to be modelled as independent random walks rather than with correlation between ages. There was a substantial improvement in the retrospective pattern following this change, although still not completely acceptable, with some of the retrospective peels remaining outside the confidence intervals.

During the process of exploring the use of an extended survey age range, some simplifications were made to the modelled indices including only the years used in the assessment in the index calculation (due to few age samples in early years) and removing the vessel effect due to substantial uncertainty in the estimate. This resulted in improved survey index Mohn's rho and also improvements to the assessment retrospective and therefore seemed to be a reasonably well justified adjustment. Assessment model runs were compared (Mohn's rho, AIC) for different survey age ranges. Extending both the Q1 and Q4 BITS survey indices to age 5+ gave an improved Mohn's rho on F, but this option was not pursued as the 5+ index was considered too uncertain with large survey index Mohn's rho for this age group. The latter appeared to relate only to the Q4 index and the justification for excluding age 5+ from the Q1 survey was less clear, particularly given that a substantial number of individuals at age 5 appear to be caught by this survey (comparable numbers to age in the Q4 survey). Given this, the inclusion of age 5+ in the Q1 survey is perhaps something that could be revisited at a future benchmark.

Further assessment model sensitivity analysis was presented which explored the use of a catch scaling factor (over different year and age ranges) to account for 'missing catch' or other unaccounted mortality i.e. potential additional natural mortality. While improvements occurred in the Mohn's rho (for both SSB and F) in these model runs, the catch scaling factor did not appear to be the 'solution' given the F retro peels all diverged from the final assessment results and catch-at-age residuals remained poor in the final year. Focus then switched to the catch data in the final year and it was found that the patterns in the residuals and retrospective analysis could be almost entirely eliminated by removing or down-weighting the 2020 catch data at ages 6 and 7. As described in Section 3.3, catch sampling of this stock has been significantly impacted by the Covid-19 pandemic (limited seasonal coverage and vessel pool). It is entirely plausible that this has had an impact on the reliability of the catch-at-age estimates for 2020 and the reviewers agree with the approach to down-weight the catch-at-age data for 2020. It is also worth noting that there have been similar issues in other stocks and ad hoc solutions have also been implemented in those cases (e.g whg-6a, had.27.7b-k).

As in many stocks, the main difficulty in calculating reference points was the derivation of Blim. This stock has a wide dynamic range of SSB and there is evidence of recruitment impairment at low SSB (the description for a 'Type 2' stock), yet no segmented-regression breakpoint could be defined within the range of SSB values. Similar difficulties in deriving a value for Blim arose at the previous benchmark (ICES, 2019) of this stock and the assessors argued that it would be pragmatic to follow the same ad hoc approach to estimating Blim as agreed at that meeting. The justification being that the approach had previously been deemed acceptable and was also expected to be relatively temporary given likely new ICES guidance on reference points (following WKREF) and the likelihood of a further benchmark in the near future. At the 2019 benchmark, Blim was defined as 'the average of the lowest SSB in years with above average recruitment' (with average SSB over 1991, 1993, 2003 and 2016 used as the estimate). While the reviewers were happy with this general approach they felt that the justification for the choice of specific S-R pairs required some further clarity, in particular exactly how many SSB values to include in the averaging. The solution was to tighten the definition such that Blim is defined as the average of the SSBs below the median SSB which have above average recruitment. The subsequent estimation of MSY reference points was relatively straightforward and followed the ICES Technical Guidelines.

A significant amount of time and effort had been put into preparation for the IBP by a large team of people. Although the amount of work presented was commendable, there was perhaps an over-expectation as to what could be changed and achieved during a short IBP, although much of the supporting work will be useful for the next full benchmark. The presentations and WDs provided through the process provided a thorough investigation of issues relevant to the Terms of Reference and beyond (e.g. presentation of spatial variation in growth indicating potentially different subpopulation dynamics). Some exploratory analysis of the catch-at-age data (as usually presented at assessment WGs) may have enabled quicker identification of problems with the 2020 catch data, although this is easy to say in hindsight. The discussions focused on relevant issues, which have been addressed, and the retrospective pattern (the main issue) has been resolved, at least for the time being. The solutions were incorporated in the stock assessment methodology and Stock annex. Comments and questions from the external reviewers and other members of the IBP have also been addressed and justification for the decisions made are in general, adequately documented in this report.

Reviewers find the quality of the assessment appropriate to be used as basis for advice.

4 Conclusions

The IBP for western Baltic cod was successful in dealing with its main objective: to identify and solve potential issues with the assessment, specifically reducing the large retrospective pattern that led WBGFAS to not accept the assessment in 2021.

Main decisions made during the IBP:

- Use of higher natural mortality based on meta-analysis methods comparable to neighbouring stocks;
- Use of constant maturity ogive averaged between 1998 and 2021, as the increase observed during the last years was not trusted;
- Update of the survey index that has last group the age 4+ and has no spatial or ship effects;
- Update of the assessment method to one that used independent F processes and downweighing the last catch data-point as the sampling was potentially impaired.

The work from the assessors was discussed during the three online meeting days and all comments and issues raised by the external reviewers were addressed. Issues for work in preparation of a future benchmark were identified and outlined in this report.

The main conclusion of IBPWEB is that the quality of the presented assessment is appropriate to be used as basis for the advice.

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Annex 1: Setting in the final assessment run

```
# Configuration saved: Wed Jun 16 15:49:38 2021
#
# Where a matrix is specified rows corresponds to fleets and columns to ages.
# Same number indicates same parameter used
# Numbers (integers) starts from zero and must be consecutive
# Negative numbers indicate that the parameter is not included in the model
#
$minAge
# The minimium age class in the assessment
 0

$maxAge
# The maximum age class in the assessment
 7

$maxAgePlusGroup
# Is last age group considered a plus group for each fleet (1 yes, or 0 no).
 1 1 1 0

$keyLogFsta
# Coupling of the fishing mortality states processes for each age (normally only
# the first row (= fleet) is used).
# Sequential numbers indicate that the fishing mortality is estimated individually
# for those ages; if the same number is used for two or more ages, F is bound for
# those ages (assumed to be the same). Binding fully selected ages will result in a
# flat selection pattern for those ages.
  -1  0  1  2  3  4  4  4
  -1 -1 -1 -1 -1 -1 -1 -1
  -1 -1 -1 -1 -1 -1 -1 -1
  -1 -1 -1 -1 -1 -1 -1 -1

$corFlag
```

```
# Correlation of fishing mortality across ages (0 independent, 1 compound symmetry,
# 2 AR(1), 3 separable AR(1).
# 0: independent means there is no correlation between F across age
# 1: compound symmetry means that all ages are equally correlated;
# 2: AR(1) first order autoregressive - similar ages are more highly correlated than
# ages that are further apart, so similar ages have similar F patterns over time.
# if the estimated correlation is high, then the F pattern over time for each age
# varies in a similar way. E.g if almost one, then they are parallel (like a
# separable model) and if almost zero then they are independent.
# 3: Separable AR - Included for historic reasons . . .  more later
 0

$keyLogFpar
# Coupling of the survey catchability parameters (nomally first row is
# not used, as that is covered by fishing mortality).
 -1 -1 -1 -1 -1 -1 -1 -1
  0  1  2  3  4 -1 -1 -1
 -1  5  6  7  8 -1 -1 -1
  9 -1 -1 -1 -1 -1 -1 -1

$keyQpow
# Density dependent catchability power parameters (if any).
 -1 -1 -1 -1 -1 -1 -1 -1
 -1 -1 -1 -1 -1 -1 -1 -1
 -1 -1 -1 -1 -1 -1 -1 -1
 -1 -1 -1 -1 -1 -1 -1 -1

$keyVarF
# Coupling of process variance parameters for log(F)-process (Fishing mortality
# normally applies to the first (fishing) fleet; therefore only first row is used)
 -1  0  0  0  0  0  0  0
 -1 -1 -1 -1 -1 -1 -1 -1
 -1 -1 -1 -1 -1 -1 -1 -1
 -1 -1 -1 -1 -1 -1 -1 -1
```

```
$keyVarLogN
# Coupling of the recruitment and survival process variance parameters for the
# log(N)-process at the different ages. It is advisable to have at least the first age
# class (recruitment) separate, because recruitment is a different process than
# survival.
 0 1 1 1 1 1 1 1

$keyVarObs
# Coupling of the variance parameters for the observations.
# First row refers to the coupling of the variance parameters for the catch data
# observations by age
# Second and further rows refers to coupling of the variance parameters for the
# index data observations by age
 -1  0  1  1  1  1  1  1
  2  3  4  4  4 -1 -1 -1
 -1  5  6  6  6 -1 -1 -1
  7 -1 -1 -1 -1 -1 -1 -1

$obsCorStruct
# Covariance structure for each fleet ("ID" independent, "AR" AR(1), or "US" for unstructured). | Possible values are: "ID" "AR" "US"
 "ID" "ID" "AR" "ID"

$keyCorObs
# Coupling of correlation parameters can only be specified if the AR(1) structure is chosen above.
# NA's indicate where correlation parameters can be specified (-1 where they cannot).
#V1 V2 V3 V4 V5 V6 V7 V8
 NA  NA  NA  NA  NA  NA  NA  NA
 NA  NA  NA  NA  NA  NA  NA  NA
 -1  0  1  1  1  1  1 -1
 -1 -1 -1 -1 -1 -1 -1 -1

$stockRecruitmentModelCode
# Stock recruitment code (0 for plain random walk, 1 for Ricker, 2 for Beverton-Holt, and 3 piece-wise constant).
 0
```

$noScaledYears

Number of years where catch scaling is applied.

0

$keyScaledYears

A vector of the years where catch scaling is applied.

$keyParScaledYA

A matrix specifying the couplings of scale parameters (nrow = no scaled years, ncols = no ages).

$fbarRange

lowest and higest age included in Fbar

3 5

$keyBiomassTreat

To be defined only if a biomass survey is used (0 SSB index, 1 catch index, 2 FSB index, 3 total catch, 4 total landings and 5 TSB index).

-1 -1 -1 -1

$obsLikelihoodFlag

Option for observational likelihood | Possible values are: "LN" "ALN"

"LN" "LN" "LN" "LN"

$fixVarToWeight

If weight attribute is supplied for observations this option sets the treatment (0 relative weight, 1 fix variance to weight).

0

$fracMixF

The fraction of t(3) distribution used in logF increment distribution

0

$fracMixN

The fraction of t(3) distribution used in logN increment distribution

0

$fracMixObs

A vector with same length as number of fleets, where each element is the fraction of t(3) distribution used in the distribution of that fleet

0 0 0 0

$constRecBreaks

Vector of break years between which recruitment is at constant level. The break year is included in the left interval. (This option is only used in combination with stock-recruitment code 3)

$predVarObsLink

Coupling of parameters used in a prediction-variance link for observations.

-1 -1 -1 -1 -1 -1 -1 -1

-1 -1 -1 -1 -1 NA NA NA

NA -1 -1 -1 -1 NA NA NA

NA NA NA NA NA NA NA NA

$hockeyStickCurve

#

20

$stockWeightModel

Integer code describing the treatment of stock weights in the model (0 use as known, 1 use as observations to inform stock weight process (GMRF with cohort and within year correlations))

0

$keyStockWeightMean

Coupling of stock-weight process mean parameters (not used if stockWeightModel==0)

NA NA NA NA NA NA NA NA

$keyStockWeightObsVar

Coupling of stock-weight observation variance parameters (not used if stockWeightModel==0)

NA NA NA NA NA NA NA NA

$catchWeightModel

Integer code describing the treatment of catch weights in the model (0 use as known, 1 use as observations to inform catch weight process (GMRF with cohort and within year correlations))

0

$keyCatchWeightMean

Coupling of catch-weight process mean parameters (not used if catchWeightModel==0)

NA NA NA NA NA NA NA NA

$keyCatchWeightObsVar

Coupling of catch-weight observation variance parameters (not used if catchWeightModel==0)

NA NA NA NA NA NA NA NA

$matureModel

Integer code describing the treatment of proportion mature in the model (0 use as known, 1 use as observations to inform proportion mature process (GMRF with cohort and within year correlations on logit(proportion mature)))

0

$keyMatureMean

Coupling of mature process mean parameters (not used if matureModel==0)

NA NA NA NA NA NA NA NA

$mortalityModel

Integer code describing the treatment of natural mortality in the model (0 use as known, 1 use as observations to inform natural mortality process (GMRF with cohort and within year correlations))

0

$keyMortalityMean

#

NA NA NA NA NA NA NA NA

$keyMortalityObsVar

Coupling of natural mortality observation variance parameters (not used if mortalityModel==0)

NA NA NA NA NA NA NA NA

$keyXtraSd

An integer matrix with 4 columns (fleet year age coupling), which allows additional uncertainty to be estimated for the specified observations

Annex 2: List of participants

Name	Institute	Email
Alexandros Kokkalis (Chair)	DTU Aqua, National Institute of Aquatic Resources	alko@aqua.dtu.dk
Anders Nielsen	DTU Aqua, National Institute of Aquatic Resources	an@aqua.dtu.dk
Casper Willestofte Berg	DTU Aqua, National Institute of Aquatic Resources	cbe@aqua.dtu.dk
Helen Dobby	Marine Laboratory	h.dobby@marlab.ac.uk
Kristiina Hommik	University of Tartu	kristiina.hommik@ut.ee
Margit Eero	DTU Aqua, National Institute of Aquatic Resources	mee@aqua.dtu.dk
Marie Storr-Paulsen	DTU Aqua, National Institute of Aquatic Resources	msp@aqua.dtu.dk
Massimiliano Cardinale	SLU Department of Aquatic Resources-SLU Aqua	massimiliano.cardinale@slu.se
Michael Wall Andersen	Danish Fishermen Producer Organisation_Fredericia	ma@dkfisk.dk
Mikaela Bergenius Nord	SLU Department of Aquatic Resources-SLU Aqua	mikaela.bergenius.nord@slu.se
Ruth Fernandez	International Council for the Exploration of the Sea	ruth.fernandez@ices.dk
Steffen Funk	University of Hamburg	steffen.funk@uni-hamburg.de
Thomas Theodorsen	Unaffiliated	thomas.theodorsen@mail.dk
Uwe Krumme	Thünen-Institute of Baltic Sea Fisheries	uwe.krumme@thuenen.de
Verena Trenkel	Ifremer Centre Atlantique	verena.trenkel@ifremer.fr

Annex 3: Resolution

An Inter-Benchmark Process on Western Baltic cod (IBPWEB), chaired by Alexandros Kokkalis, Denmark, and attended by two invited external experts Verena Trenkel, France, and Helen Dobby, UK, will be established and will meet by correspondence on 16, 21 and 28 of June 2021 to:

a) evaluate survey indices and assess the inclusion of older age groups in tuning indices;
b) investigate solutions to the problem with the retrospective pattern in F and SSB including model assumption settings and changes to input data;
c) agree and document the preferred method for evaluating stock status and short term forecast and update the stock annex as appropriate. If no robust analytical assessment method can be agreed, then propose alternative methods to provide advice including data-limited methods;
d) update the stock annex as appropriate;
e) if required re-examine and update MSY and PA reference points according to ICES guidelines (see Technical document on reference points).

Stocks	Stock leader
Cod (*Gadus morhua*) in subdivisions 22–24, Western Baltic stock (western Baltic Sea)	Marie Storr-Paulsen

The inter-benchmark will report by 6 August 2021 for the attention of ACOM.

Annex 4: Working Documents

- **Alternative explorative stock assessment changes the perception of the state of Western Baltic cod (draft working paper)**
  Steffen Funk, Jens Floeter, Uwe Krumme, and Christian Möllmann

- **Estimation of natural mortality of Western Baltic cod induced by grey seals**
  Marie Storr-Paulsen, Finn Larsen, Thomas Noack and Anders Galatius

- **Can reduced body condition have increased natural mortality of western Baltic cod in later years?**
  Margit Eero

- **Estimation of natural mortality for Western Baltic cod**
  Margit Eero, Massimiliano Cardinale

Draft working paper

Alternative explorative stock assessment changes the perception of the state of Western Baltic cod

Steffen Funk[1*], Jens Floeter[1], Uwe Krumme[2], and Christian Möllmann[1]

[1]Institute for Marine Ecosystem and Fishery Science, Centre for Earth System Research and Sustainability (CEN), University of Hamburg, Große Elbstraße 133, 22767 Hamburg, Germany.
[2]Thünen Institute of Baltic Sea Fisheries, Alter Hafen Süd 2, 18069 Rostock, Germany.

*Corresponding author: E-Mail: steffen.funk@uni-hamburg.de

Keywords: Cod, spatio-temporal distribution, habitat use, maturity, virtual population analysis

Abstract

In the Western Baltic Sea, cod (*Gadus morhua* L.) has traditionally been the most important commercial demersal fish species, but since the 1990s stock sizes and catches are in constant decline. Stock assessments of Western Baltic cod conducted annually by the ICES Baltic Fisheries Assessment Working Group (WGBFAS) are conducted with a state-space assessment model (SAM), but these assessments notoriously suffer from a retrospective pattern, i.e. estimates of recruitment and spawning stock biomass are constantly down-scaled with every updated assessment, while fishing mortality is upscaled. We here provide results of alternative explorative stock assessments using a simple Virtual Population Analysis (VPA) in which we test a revised maturation scheme that accounts for recent ecological knowledge. Our alternative assessments provided a different perception of the present stock status characterized by a historically low SSB and recruitment overfishing to be the likely major reason for the depleted state of cod in the Western Baltic Sea. Our result suggests a reconsideration of maturation schemes and stock-recruitment representation in the official stock assessment to achieve a more realistic perception of the status of Western Baltic cod.

Introduction

In the Western Baltic Sea cod (*Gadus morhua* L.) has traditionally been the most important commercial demersal fish species. Since the 1990s stock sizes and catches of Western Baltic cod (WBC) are in constant decline as a result of overexploitation and potentially negative impacts of climate warming on recruitment (Stiasny et al., 2018; Voss et al., 2019). As a consequence, especially the existence of the German cod fishery in the Western Baltic Sea is presently in danger of extinction.

Stock assessments of WBC conducted annually by the ICES Baltic Fisheries Assessment Working Group (WGBFAS) are conducted with a state-space assessment model (SAM) (Nielsen and Berg, 2014; Berg and Nielsen, 2016). These assessments notoriously suffer from a retrospective pattern, i.e. estimates of recruitment (R) and spawning stock biomass (SSB) are constantly down-scaled with every updated assessment, while fishing mortality is upscaled (ICES, 2020). As a consequence, a recent assessment was not accepted by WGBFAS and the advice on total allowable catches (TAC) was postponed (ICES, 2021).

Ciritical to the final estimates of SSB and subsequently R in fish stock assessments are information on age-dependent maturation schemes of the stock. In WBC stock assessments, maturity ogives are derived from the first quarter (Q1) Baltic International Trawl Survey (BITS) (ICES, 2021) in ICES sub-divisions 22 (i.e., the Belt Sea) and 23 (i.e., the Sound). BITS Q1 monitoring has recorded a strong change in the maturity ogives since the year 2000. While in 2000 the relative proportion of mature individuals in age class 2 was still 30%, it has increased over time, with maximum values of up to over 70% recorded in the meantime. This strong change was justified by the potential effects of strong size-selective effects of harvesting causing fisheries-induced evolution as demonstrated e.g. for the neighbouring Eastern Baltic cod stock (Vainikka et al., 2009).

To be reliable, maturity ogives should however ideally be estimated based on surveys that cover the full distributional range of the target species. Furthermore, ideally maturity observations should be conducted outside the spawning season and outside the spawning habitats which avoids overestimations of population maturity schemes by only targeting spawning individuals. In the case of WBC such an unbiased sampling design is often impossible due to technical limitations. Maturity ogives are derived from

BITS Q1 catches, i.e. during the main spawning season of WBC violating the unbiased sampling of maturity schemes (Bleil and Oeberst, 1997; Bleil et al., 2009).

A further bias in BITS is the limited survey coverage failing to cover the full distributional range of WBC. The use of trawling gear severely limits the activity range of the research vessels to trawlable areas (sandy and muddy grounds) which can be mostly found in depths > 20 m, i.e., the deeper channels of the Belt Sea and the Sound which are also the spawning areas of WBC (see Hüssy, 2011). Shallower areas are in contrast often characterised by hard ground structures such as cobbles, boulders and rocky reefs which pose a high risk of damaging the standardized trawl gear, and trawling is usually avoided. However, a recent study from the Belt Sea using fishers' knowledge demonstrated the importance of these shallower areas in the seasonal life cycle of WBC. WBC remain most of the year in these areas shallower than 15 m, entering the deeper channels only temporally for spawning (Funk et al., 2020). Reports of cod catches in the Belt Sea from areas shallower than 20 m, and thus from outside the spawning habitats of cod, during the first quarter by local gill net fishers (Funk et al., 2020) furthermore revealed, that cod at least partly use also shallower habitats during the spawning season, pointing towards an uncomplete coverage of the full distributional range of WBC during the first quarter by the BITS.

The observation that WBC is distributed mainly outside the deeper channels biasing BITS estimates was also corroborated by comprehensive stomach content samplings (Funk et al., 2021). These diet studies revealed that deeper channels are likely unfavoured habitats for non-spawning individuals and mostly avoided. However, competition at the favoured shallow feeding grounds may drive parts of the stock to inhabit also non-favoured feeding grounds such as the channels and basins of the area. Following this hypothesis of a potential spill-over effect, the percentage of non-mature individuals per age class at the spawning grounds is likely to increase at higher numbers of individuals in the stock, while it likely decreases with decreasing stock numbers. So we hypothesize that at low stock sizes only the spawning fraction of an age class is present at the spawning ground, leading to unrepresentatively high maturity ogive estimates.

In this study we present an alternative explorative stock assessment for WBC based on a Cohort Analysis type of Virtual Population Analysis (VPA) (Pope, 1972). We test for effects of using the presently applied variable maturation scheme versus time-invariant maturity ogives that we hypothesize to better reflect the ecology of WBC. Our alternative explorative stock assessment shows that revised maturity ogives would lead to a perception of the stock characterized by significantly lower SSB and higher F values. Furthermore, we found recent SSB estimates to be significantly lower and F significantly higher compared to the 2020 stock assessment provided by ICES using SAM.

Material and methods

VPA set up

We used official catch data of WBC (including commercial landings, discards and recreational catch estimates) from the period 1895 to 2020 derived from the latest WGBFAS report (ICES, 2021) to set up a cohort analysis after Pope (1972). As terminal F estimates (i.e., F in 2020) for the year 2020 in the first trial run, F estimates for the respective age classes from the terminal year (i.e., 2019) from the latest published SAM run derived from the WGBFAS report 2020 (ICES, 2020) were used.

For the terminal F estimates of the age class 7+ the respective estimate of the age class for 2020 was applied for the entire time series (i.e., from 1985 until 2020).

Terminal N estimates (i.e., Numbers of individuals of age 1 to 6 in 2020, as well for age 7+ for the whole period between 1985 and 2020) were calculated using the formula:

$$N_{i,k} = \frac{C_{i,k} * F_{i,k}}{F_{i,k*}} \qquad (1)$$

with $N_{i,k}$ = Number of individuals of a certain age class *k* in year *i,* $C_{i,k}$ = catch in number of individuals of age class *k* in year *i*, $F_{i,k}$ = fishing mortality of age class *k* in year *i*, and $M_{i,k}$= natural mortality of age class k in year *i.*

The numbers of individuals in the stock for all remaining age classes and years were calculated using the rearranged catch equation:

$$N_{i,k} = C_{i,k} * e^{0.5 * M_{i,k}} + N_{i+1,k+1} * e^{M_{i,k}} \qquad (2)$$

with $N_{i,k}$ = Number of individuals of a certain age class *k* in year *i,* $C_{i,k}$ = catch in number of individuals of age class *k* in year *i*, $M_{i,k}$= natural mortality of age class k in year *i,* and $N_{i+1,k+1}$ = Number of individuals of age class *k+1* in year *i+1*.

Fs for the age classes 1 to 6 for the time period between 1985 to 2019 were estimated using the formula:

$$F_{i,k} = ln\left(\frac{N_{i,k}}{N_{i+1,k+1}}\right) - M_{i,k} \qquad (3)$$

with $F_{i,k}$ = fishing mortality of age class *k* in year *i*, $N_{i,k}$ = Number of individuals of a certain age class *k* in year *i*, and $N_{i+1,k+1}$ = Number of individuals of age class *k+1* in year *i+1*.

Estimates for natural mortality (M) for each year and age class were derived from the WGBFAS report 2020 (ICES, 2020).

After this first initial trial run, we calculated new terminal F estimates by calculating mean Fs for each age class for the last five years of the time series (i.e., 2016 to 2020). New terminal F estimates for age class 7+ were estimated by calculating mean Fs for the age classes 4 to 7+ for the whole time series. This new terminal F estimates served as input parameters for the next iteration, were the calculations followed the same principal. The iteration runs were manually repeated (i.e., in this case 6 times) until differences in terminal F inputs and new estimated terminal Fs were only minor. The resulting F and N estimates of the final run served as basis for all subsequent analyses.

VPA tuning

The tuning time series given in the WGBFAS report was not integrated in our VPA. We based this decision on the fact that even in the official ICES SAM runs tuning fleet effects were reported to be highly downscaled in effect size, since otherwise even the yearly catches could not be reproduced by the SAM model (ICES, 2020). This suggests that survey indices of the tuning fleet did not correspond well to the true stock numbers, potentially due to variable spatio-temporal overlap between survey effort and stock distribution.

Relationship between maturity ogives and cod stock sizes

To test for the hypothesized effect of cod density on maturity ogive estimates during the Q1 BITS, we calculated linear regressions between maturity ogive estimates in age 2 (i.e., the age class where the most pronounced changes over time have been recorded) and the number of individuals of age 2 (4), as well as with the number of individuals in the stock for age 1 to 7+ derived from our VPA runs (5) for the period 2001 to 2020 (i.e., the period with changing maturity ogive estimates).

$$OG_{i,age2} = \alpha + \beta * N_{i,age2} + \varepsilon_i \quad (4)$$

$$OG_{i,age2} = \alpha + \beta * \sum_{k=1}^{n} N_{i,k} + \varepsilon_i \quad (5)$$

with $OG_{i,age2}$ = maturity ogive estimate of age 2 in year *i*, α = Intercept, β = slope, $N_{i,age2}$ = Number of individuals age 2 in year *i*, $\sum_{k=1}^{n} N_{i,k}$ = Sum of number of individuals of age classes 1 to 7+ in year *i*, and ε_i = error term in year *i*.

SSB estimation

Two different SSB time series were calculated to visualize the differences caused by a changing maturity as implemented in the current stock assessment in contrast to a constant maturity ogive. For this purpose, we used the maturity ogive and weight at age in stock estimates given in the latest WGBFAS report (ICES, 2020). For the calculation o, we used weight at age in stock and maturity ogive estimates at age, as well as our calculated number of individuals per age and year to calculate the corresponding SSB (6). In case of time-invariant maturity, we applied the maturity ogive estimates of 2000 from 2001 onwards (7).

$$SSB_{i,k} = N_{i,k} * W_{i,k} * OG_{i,k} \quad (6)$$

$$SSB_{i,k} = N_{i,k} * W_{i,k} * OG_{,k} \quad (7)$$

with $SSB_{i,k}$ = Spawning stock biomass age *k* in year *i*, $N_{i,k}$ = Number of individuals of age class *k* in year *i*, $OG_{i,k}$ = maturity ogive estimate for age *k* in year *i*, and $OG_{,k}$ = fixed maturity ogive estimate (taken from the period 1985-2000) for age *k*.

Stock-recruitment relationships

SSB estimates for constant and changing maturity derived from the VPA runs, as well as SSB from the ICES SAM run in 2020 (ICES, 2020) were used to calculate stock-recruitment relationships. Stock recruitment relationships were tested by calculating simple linear regressions (8). Corresponding to the current stock advices we used numbers of age 1 in the stock as recruitment estimates as response variable (i.e., for the years 1986-2020) and SSB estimates from the respective previous year as explanatory variable (i.e., for the years 1985-2019). Additionally, we tested for performances of fitting the classical Beverton - Holt stock recruitment relationship to our VPA and the official SAM data for the period where changes in WBC maturity were recorded (i.e., 2001 to 2020) (see Supplementary Material S1).

$$R_{i,age1} = \alpha + \beta * SSB_{i-1} + \varepsilon_i \qquad (8)$$

with $R_{i,age1}$ = $N_{i,age1}$ = number of individuals of age 1 in year *i*, α = Intercept, β = slope, SSB_{i-1} = SSB in year *i*-1, and ε_i = error term in year *i*.

Software used

The VPA was set up in Microsoft Excel. Subsequent data analysis and graphical visualization were performed in the statistical software and programming environment

R R Development Core Team, 2017) using the packages (Wickham, 2011), *ggplot2* (Wickham, 2009), *cowplot* (Wilke, 2017).

Results

Stock numbers

Estimated numbers of individuals (age 1 to 7+) in the WBC stock derived from the final VPA run agreed largely with the ICES SAM estimates for the earlier parts of the time-series (Fig. 1). Pronounced differences were observed for period from the mid-2000s to 2020, wherein the estimated numbers of individuals from SAM exceed largely the numbers of individuals estimated from the VPA. The VPA run showed a historic minimum value for the total numbers of individuals in the WBC stock in 2020, while the SAM estimated a historic minimum number of individuals in 2016.

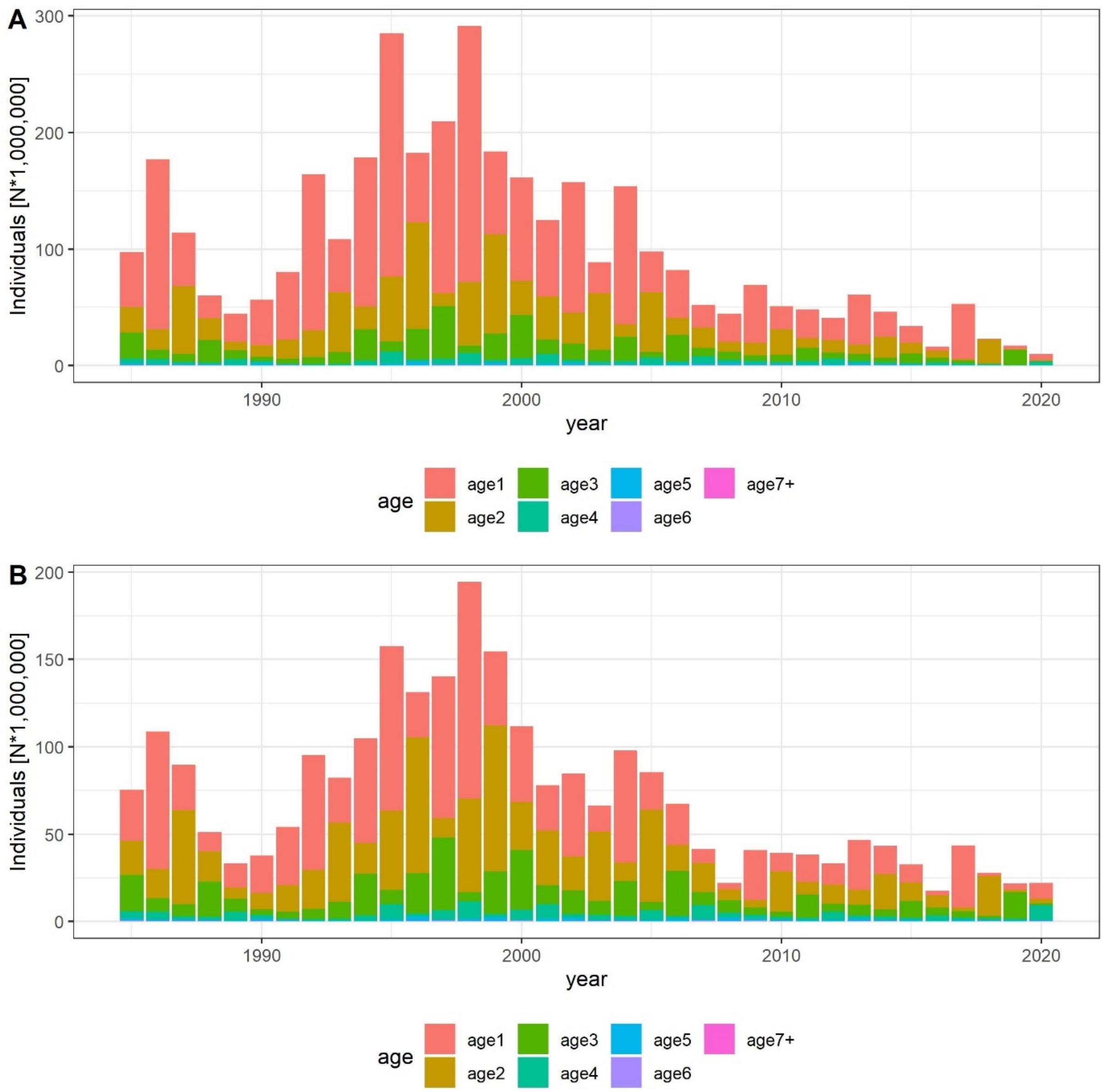

Figure 1. Number of individuals per age and year in the stock of WBC derived from VPA run (A) and derived from the ICES SAM run (ICES, 2020) (B).

Fishing mortality

Estimated fishing mortalities (ages 3 to 5) estimated by the SAM and VPA varied strongly over the investigated period (Fig. 2). From 1985 to the mid-2000s both analyses revealed F values often above 1 with maximum values exceeding 1.3. From the mid-2000s both approaches showed a decrease in F, still varying around F of 1. However, since mid 2010s ICES SAM estimated a strong decrease in F reaching a historic minimum in 2019, while our VPA lead to an in increase in F approaching an F value in 2019 only slightly lower than the historic maximum.

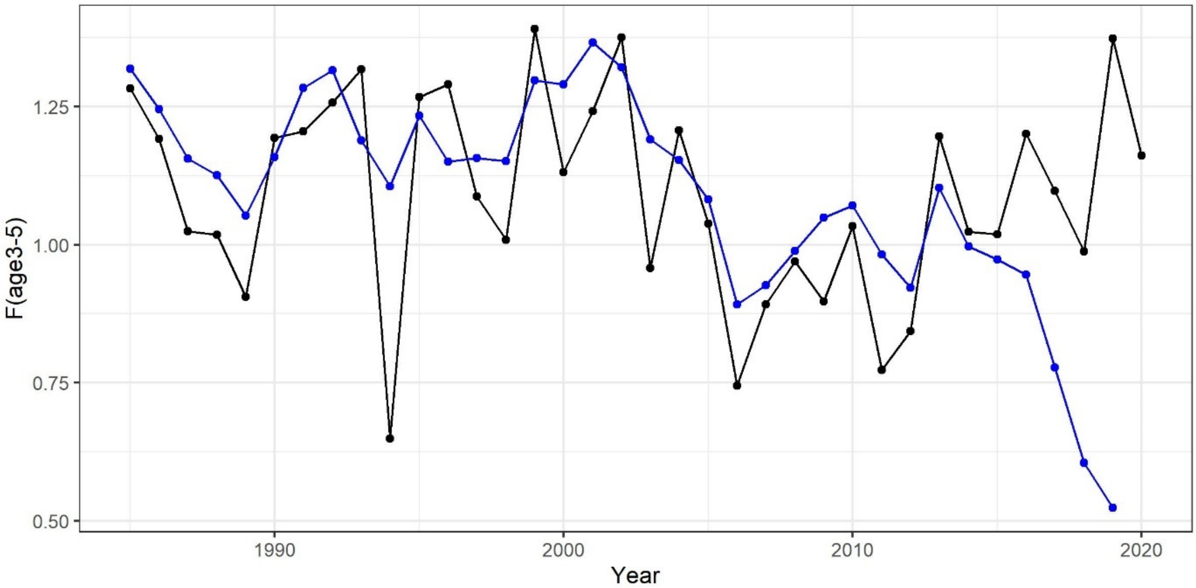

Figure 2. Fishing mortality estimates for ages 3 to 5 derived from the VPA runs (black) and ICES SAM in 2020 (ICES, 2021).

Observed changes in maturity ogive vs. stock numbers

Linear regressions revealed a significant relationship between the relative proportion mature in age 2, i.e., the age class which showed the strongest pronounced changes in maturity ogive estimates over time, and the numbers at age 2 individuals in the stock derived from our VPA (Fig. 3A). Linear regression between the proportion mature age 2 and the total number of individuals between age 1 and 7+ showed an even better fit to the data (Fig. 3B).

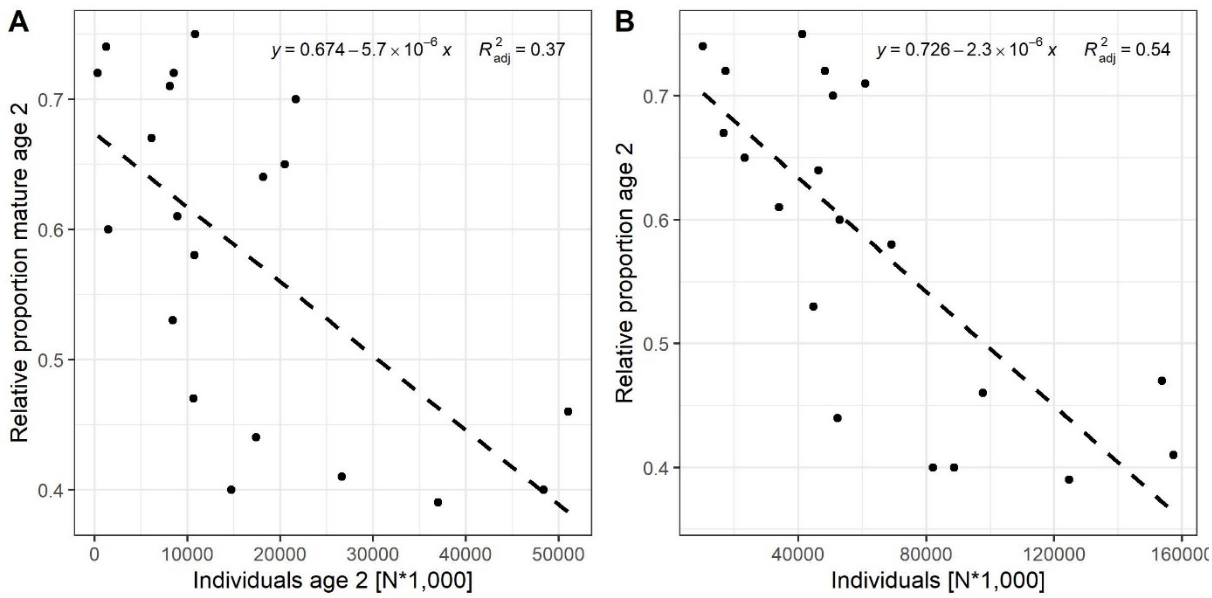

Figure 3. Relative proportion mature in age 2 (i.e., maturity ogive age 2) versus numbers of individuals at age 2 (A) and numbers of individuals at ages 1 to 7+ (B) during the period between 2001 and 2020. Dashed lines display linear regression lines. Given are furthermore the regression equations and explained variances (R^2_{adj}).

SSB estimates

SSB estimates from the VPA calculated with a changing and our fixed maturity scheme showed a distinct decline since the mid-1990s (Fig. 4), approaching historic minimum SSB values in 2020 with 4,785 t and 5,910 t, for changing and fixed maturity ogive estimates, respectively. Largest differences between SSB estimates derived from the VPA using changing and fixed maturity ogive estimates with more than 4,000 t were observed for the years 2005, 2010, and 2012. SSB estimates derived from ICES SAM, showed a similar trend until 2017. However, from 2017 to 2020 SSB estimates from ICES SAM increased, reaching a SSB of 20,799 t, a value last observed towards at end of the 2000s (Fig. 4).

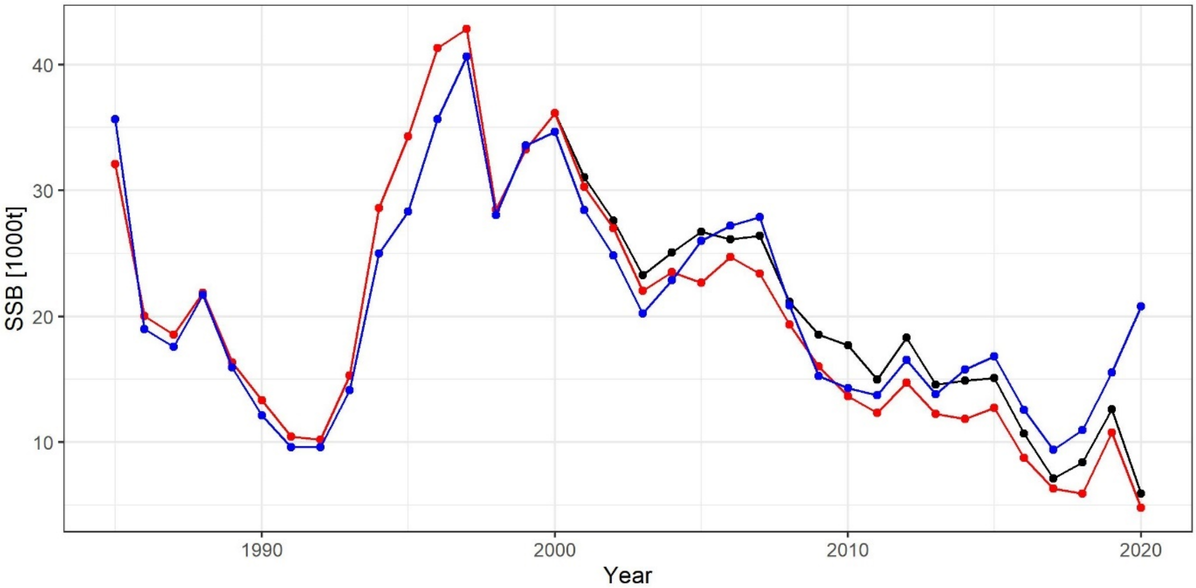

Figure 4. SSB estimates derived by VPA using changing (black) and fixed maturity ogive estimates (red), and from the ICES SAM run in 2020 (ICES, 2020) using changing maturity ogive estimates (blue).

The age composition of SSB derived from our VPA estimates using changing and fixed maturity give estimates, showed higher proportions of especially age 2 at the end of the time series. In 2018, age two cod accounted for 51.9% of the total SSB estimate calculated with changing maturity ogive estimates (Fig. 3B), while this age class accounted for only 38.4% when using the fixed maturity ogive estimates instead (Fig. 3A). Especially high proportions of age 2 in the SSB estimates from the ICES SAM, were observed 2010 and 2018 (Fig. 5C) accounting for 41.7% and 42.3%, respectively.

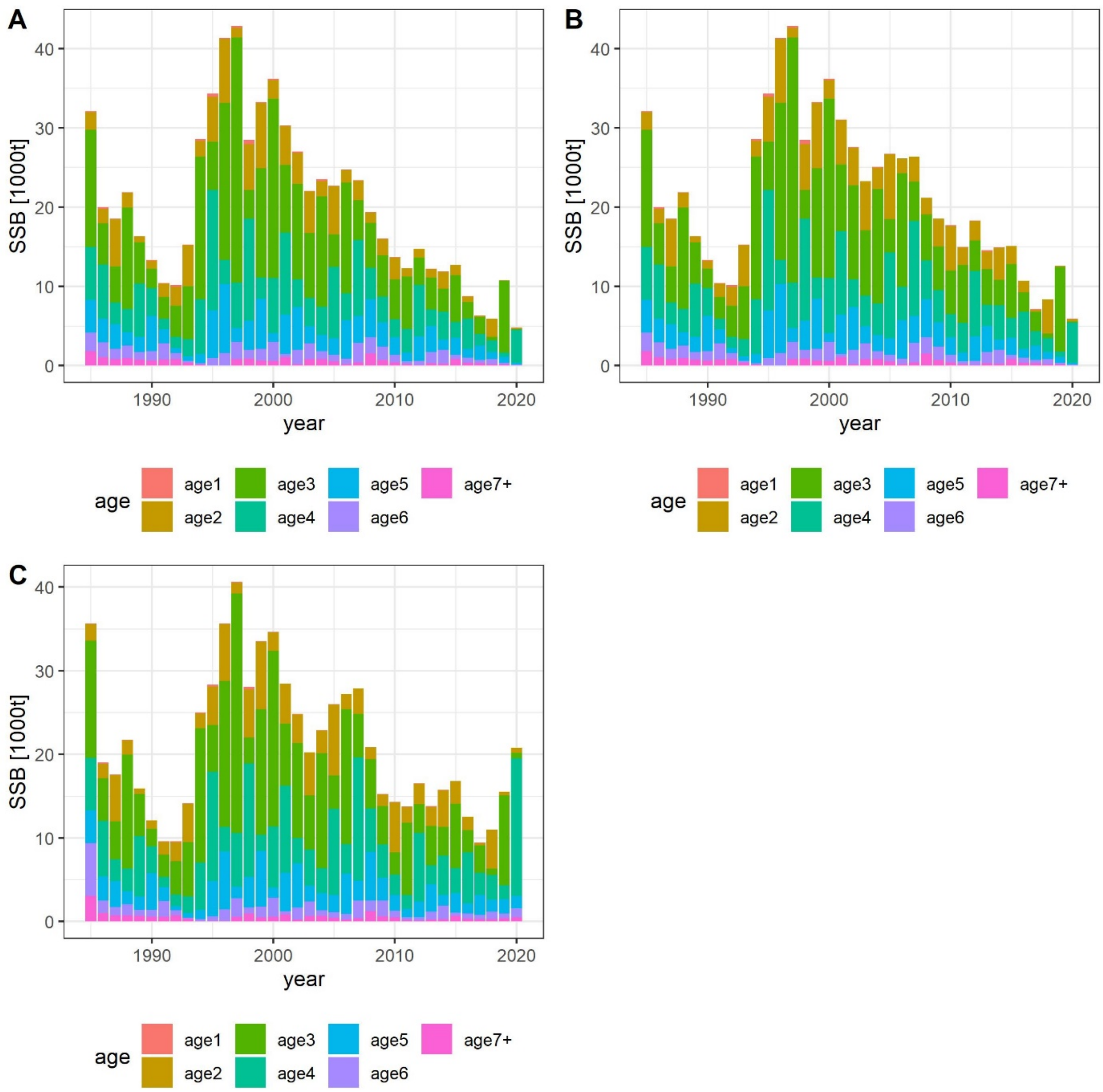

Figure 5. SSB estimates derived by VPA with fixed (A) and changing (B) maturity ogive estimates and SSB estimates from the ICES 2020 SAM run (ICES, 2020) using changing maturity ogivess.

Stock-recruitment relationships

Linear regressions between age 1 recruits and SSB showed highest explained variance for recruits estimated by the VPA using SSB based on fixed maturity ogives (Fig. 6C). Lowest explained variance was calculated for the linear regression between recruits and SSB estimated derived from the ICES SAM (Fig. 6A). Residuals of all linear regression analyses showed a pattern over time with underestimates at the beginning of the time series and overestimates of recruits at the end of the time series (Supplementary Fig. S.1.1). Alternative Beverton & Holt stock-recruitment relationships showed also a best fit for VPA estimates with fixed maturity ogives (Supplementary Table S1.2). Similar to the results of the linear regressions between SAM recruits and SSB (Fig. 6A) also the Beverton & Holt model showed only a poor fit, not well representing the dynamics of recruits over time (Supplementary Figure S.1.1).

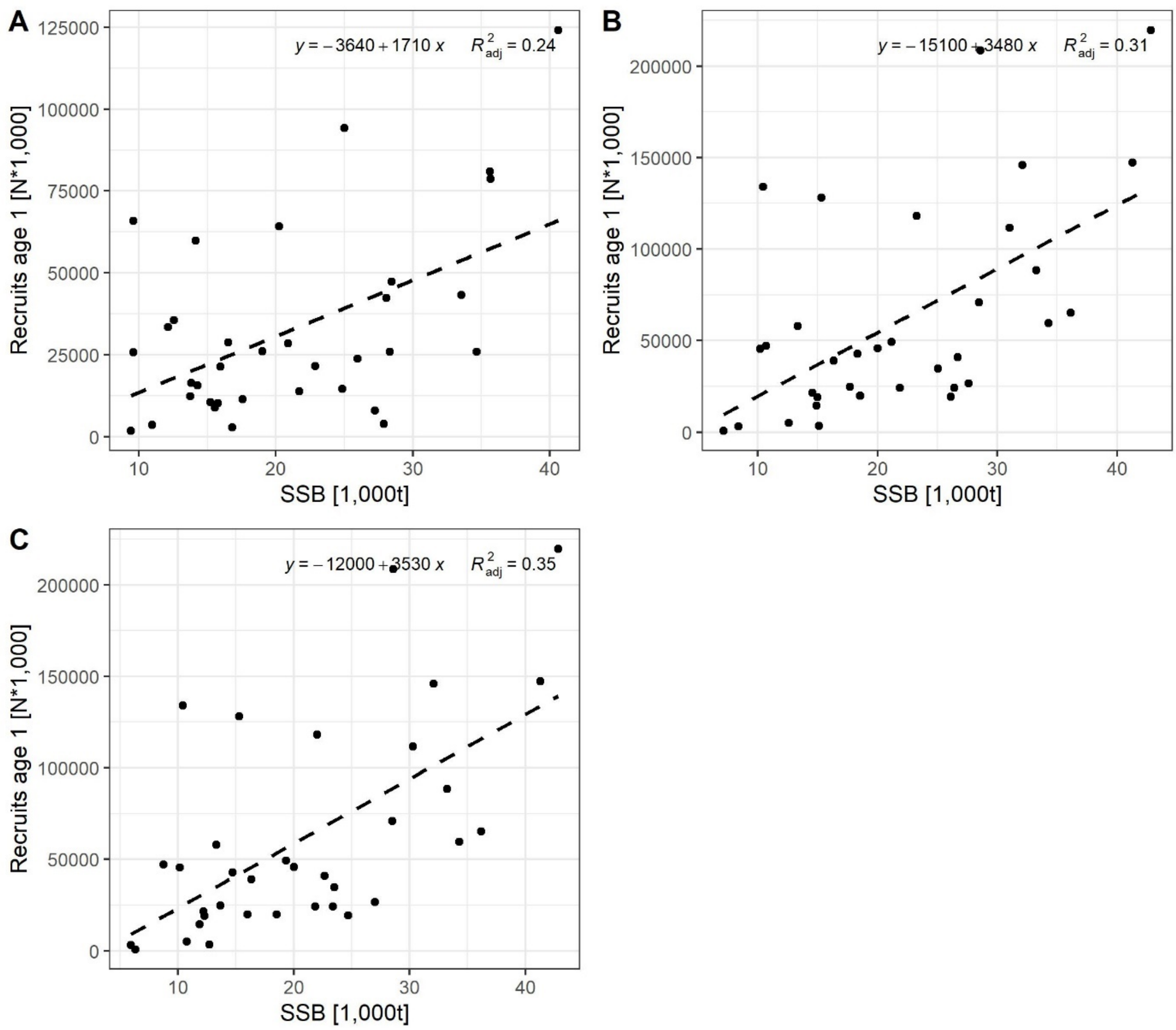

Figure 6. Recruits age 1 versus SSB with estimates derived from SAM (A), VPA with changing maturity ogives (B), and VPA with fixed maturity ogive (C). Dashed black lines display linear regression lines. Given are furthermore the regression equations and explained variances (R^2_{adj}).

Discussion

We here conducted an alternative explorative stock assessment for WBC using two different maturation schemes and provide a different perception of the present stock status of WBC. We altered the maturation scheme in our assessment model (i.e. Virtual Population Analysis) based on recent ecological knowledge of the stock which resulted in significantly lower SSB estimates. Furthermore, we found recent SSB estimates to be significantly lower and F significantly higher compared to the 2020 stock assessment provided by ICES using SAM. Our results have important implications for the TAC advice for WBC. Below we provide a detailed discussion of the main results of our study.

Reliability of maturity ogive estimates

The maturity ogives implemented in the official assessment of the WBC stock reflect and increased proportion of mature individuals in the stock at younger ages that has been related to fisheries induced evolutionary effects. It is a well-known phenomenon that size-selective fishing pressure causes individuals to mature at earlier ages and smaller sizes (Law, 2000; Heino and Godø, 2002), which has also been described for Eastern Baltic cod (Vainikka et al., 2009; Svedäng and Hornborg, 2017). However, such evolutionary effects usually come along with decreased growth rates. Earlier maturation processes and related energy investments in building up reproduction products, will result in less energy available for somatic growth and thus a general decrease in the length at age. While evolutionary effects induced by fisheries are arguably widespread, there is no evidence yet for these effects for WBC cod in the Belt Sea (i.e., the area which forms together with the Sound the distributional core area of

WBC). In case of the Sound, no sign for growth retardation in cod was observed (Svedäng and Hornborg, 2017).

Our results point clearly towards a significant relationship between the number of individuals at age 2 in the stock and their maturity ogive estimates supporting the hypothesis of density-dependent changes in spatial overlap of the survey with non-mature cod at the spawning habitats. The relationship improved additionally by using the total number of individuals in the stock. The density-dependence hypothesis is emphasized by findings of recent diet analyses showing that adult cod mainly feed on benthic invertebrates such as the common shore crab (*Carcinus maenas*) (Funk et al., 2021). Furthermore, higher occurrence of non-mature cod at the pawning habitat at higher stock numbers might be explained by a general density-dependent change in cod behaviour. For example, coastal off Newfoundland cod displayed a similar change in habitat use and aggregate at higher densities in schools leaving the shallow, coastal and structured areas to sandy unstructured habitats (Laurel et al., 2004).

We hence argue that the change in maturity ogives over the last decades (and implemented in the official stock assessment) might reflect a sampling bias, and the true proportion of mature individuals might be unchanged. Furthermore, following the problem of a sampling at the spawning habitat and a higher catchability of the BITS Q1 surveys for mature cod in general, even the conservative lower maturity ogive estimates from the period between 1985 and 2000 might be an overestimate while the real proportion of immature individuals are likely much higher. Furthermore, there could also be a considerable number of skip spawners from older age groups who are also not covered by the survey. Skip spawning is a known phenomenon in other cod stocks (e.g., see Skæraasen et al., 2012), but has not been described for the WBC stock so far.

More realistic maturity ogive estimates have further implications on the development of stock-recruitment relationships needed for stock predictions and projections. Our stock recruitment relationships revealed a better fit for VPA estimates with SSB calculated with a fixed maturity scheme than with the presently used changing maturity ogives. The poorer fit of the stock-recruitment relationships calculated using the SAM estimates may be related to a general overestimation of stock productivity in recent years, which can be directly traced back to overestimated maturity ogives, especially those of age 2 cod. Applying the SAM with constant maturity estimates in future (see also below) may in turn also enable the use of classical stock-recruitment relationships such as Ricker or Beverton and Holt instead of using a plain random walk and thus may increase the quality of recruitment predictions.

In conclusion, we hypothesize that a bias in maturity ogive determination due to an insufficient survey coverage is a more likely explaination than evolutionary effects for the observed maturity ogives. Consequently, we suggest that using time-invariant maturity ogives will result in a more realistic perception of the WBC stock.

Differences between VPA and SAM stock assessments

Our alternative explorative stock assessment using a VPA revealed recent F estimates to be much higher than estimated by SAM. Furthermore, the VPA pointed towards a stock collapse in recent years with SSB on a historic minimum value in 2020, while SAM (run in 2020; ICES 2020) pointed towards a stock recovery. We here speculate that these discrepancies in SSB and F estimates between VPA and SAM assessments could be related to the representation of the stock-recruitment-relationship in SAM where a plain random walk was implemented because classical stock recruitment relationships such as Ricker or Beverton & Holt showed a poor fit to the data (ICES, 2019). A potential decline-dampening effect of a random walk, which may occur in downward trend situations, could lead to a systematic overestimation of recruits, and subsequently stock numbers and SSB. This overestimation may manifest itself in the retrospective pattern, which is corrected downwards with every incoming catch data-year.

A further reason for the likely overestimated SSB and understimated F values in SAM might be the use of likely biased maturity ogives as described above. A SAM test run (unpublished results) with the constant maturation scheme suggested here, resulted also in higher F values since the late 2010s and SSB in 2020 to be much lower than estimated by the previous SAM run, as well as confidence intervals including a new historic minimum value (see Supplementary material S3). Underestimates of F and overestimates of SSB have been confirmed by recent assessment reports, where SSB has been scaled down annually since the late 2010s, while F has had to be revised upwards (ICES, 2020). The maturity ogive estimates may play an important part of the problem for the in general overestimated productivity of the WBC stock.

Conclusions

WBC is undoubtedly in a critical condition with important implications for local fisheries. Realible assessments of the stock state are needed for better management advice to safeguard the stock into the future. Our explorative assessments provide a less optimistic state of the stock as indicated by recent official assessments. Rather we show that changing maturity schemes based on recent ecological knowledge in our VPA (an arguably simpler stock assessment model) result in historically low SSB estimates. Furthermore, our results point towards still unsustainably high F estimates supporting the notion of recruitment overfishing of the stock. Our result suggest a reconsideration of maturation schemes and stock-recruitment representation in the official stock assessment to achieve a more realistic perception of the status of WBC. Constant maturity ogives may help to implement Ricker or Beverton & Holt SRRs in SAM, reducing the retrospective pattern which may be the consequence of the random-walk approach in combination with a time series of variable, non-representative maturity-ogives.

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Supplementary material

S1. Beverton & Holt Stock recruitment relationship

We fitted alternatively a Beverton and Holt recruitment relationship (1) to the data from the period between 2001 to 2020 (i.e., the period of recorded changes in the WBC maturity) to investigate the effect of a changing vs a fixed maturity in the SSB calculations on subsequently developed Stock recruitment relationships (Fig. S1.1). Models were fitted in R using the nls function.

$$R_i = \frac{\alpha * SSB_{i-1}}{(1+\beta * SSB_{i-1})} + \varepsilon_i \quad (1)$$

With $R_{i,age1}$ = $N_{i,age1}$ = number of individuals of age 1 in year *i*, α & β = model coefficients, SSB_{i-1} = SSB in year *i*-1, and ε_i = error term in year *i*.

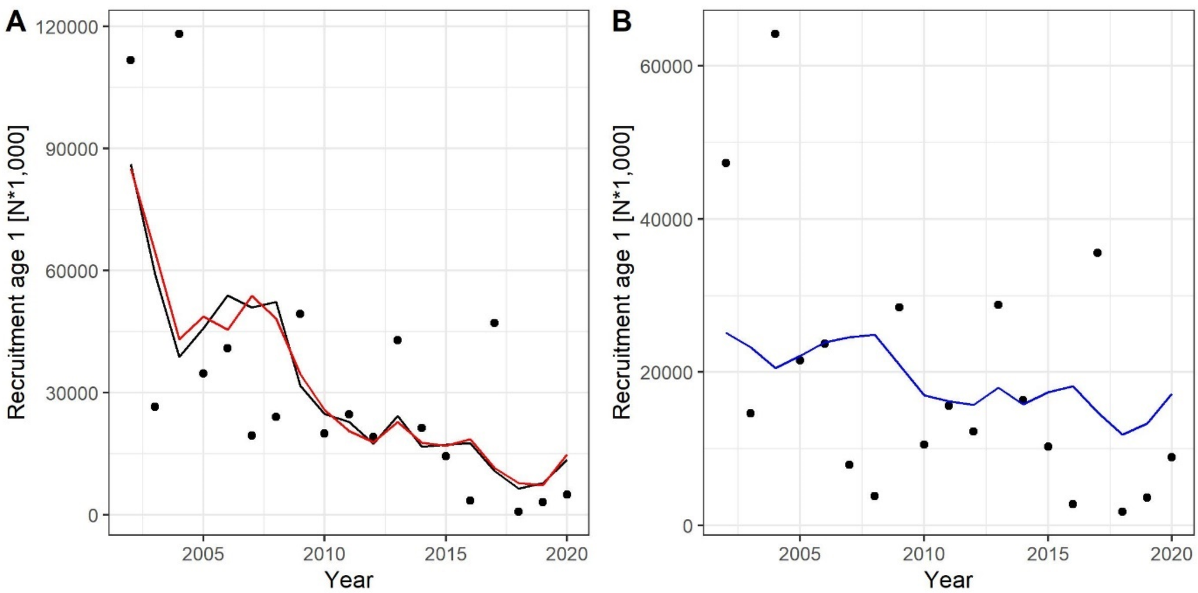


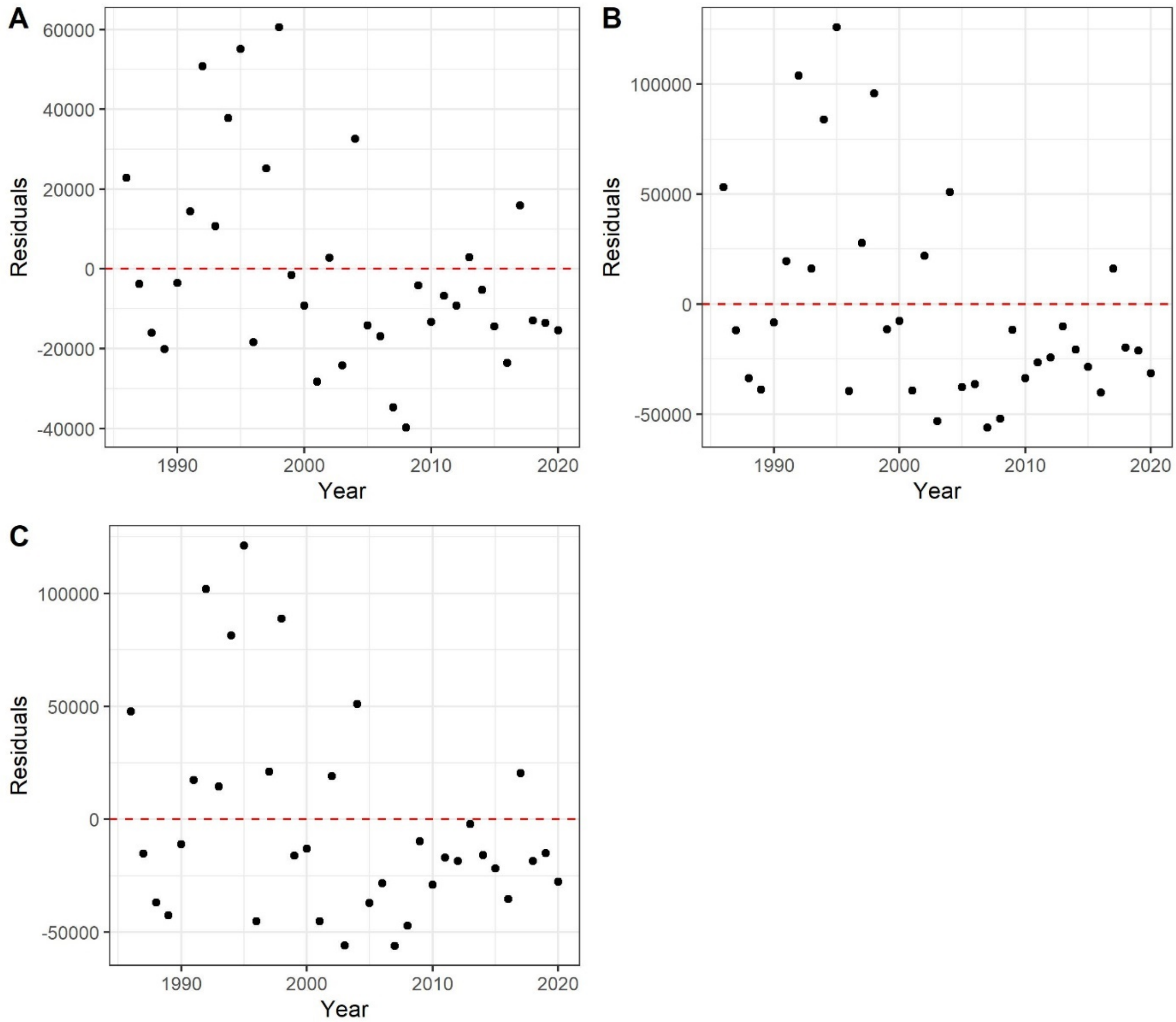
Figure S1.1. Observed Recruits age 1 from the VPA runs and the ICES SAM runs (ICES, 2020) and predicted recruitment from fitted Berverton and Holt recruitment relationships calculated using SSB values estimated with changing (blue and red) and fixed (red) maturity ogive estimates between 2001 to 2019.

To test for the goodness of fit for developed Beverton & Holt stock recruitment relationships we calculated linear regressions between observed and predicted recruits age1 (Supplementary Table S1.2).

Supplementary Table S1.2. Parameter coefficients and explained variances for linear regression between observed and predicted Recruitment age1.

Data	Intercept	Slope	$R^2_{adj.}$
VPA estimates, fixed maturity ogive	4.930e+03	8.911e-01	0.3083
VPA estimates, changing maturity ogive	3.785e+03	9.166e-01	0.3258
SAM estimates, changing maturity ogive	-3440.7629	1.1735	0.03296

S2. Residual patterns over time for developed linear stock-recruitment relationships



Supplementary Figure S2. Residuals of linear regressions between SSB estimates Recruitment. In A Recruitment and SSB estimates were taken from the ICES SAM run 2020 (ICES, 2020). In B and C Recruitment and SSB estimates were taken from the final VPA run using changing (B) and fixed maturity ogive estimates (C). Dashed red line indicates zero line.

Estimation of natural mortality of Western Baltic cod induced by grey seals

12.06. 2021

By Marie Storr-Paulsen[1], Finn Larsen[1], Thomas Noack[1] and Anders Galatius[2]

[1]Technical University of Denmark, DTU Aqua

[2]Aarhus University, Department of Bioscience

Summary

The grey seal (*Halichoerus grypus*) occurence in the Western Baltic increased over the past years and was in 2019 counted on land during the moulting season to be just below 1000 individuals. A new still unpublished study from DTU Aqua investigated the two main grey seals areas in the Western Baltic for the seals´ feeding pattern. Based on these data, an average annual consumption of cod (*Gadus morhua*) has been estimated. In 2019, this amount is estimated to be just below 600 t cod. A time series on grey seal consumption rate on cod from 2013 to 2020 based on a 5-year interval has been populated to be used in the assessment as an natural mortality rate.

Background

The increasing grey seal (*Halichoerus grypus*) occurence in the Baltic has caused debates among the fishing community in the recent years. In the beginning of the 19th century, the grey seal occurence in the Baltic was much larger, estimated to be around 90 000 animals but hunting and pollution decreased the level to below 10 000 animals, until 15 years ago where the stock level started to increase. In 2000, HELCOM estimated the Baltic grey seal occurence to be close to 10 000 animals, in 2006 this increased to 20 000 and in 2019 the estimated number of grey seals was 38 000. As large numbers of grey seals require a considerable food supply like fish and as there has been theories that seals have been part in the eastern Baltic cod stock's decrease, fishers are concerned of the increasing stock abundance. The present document provides an attempt to quantify the amount of cod eaten by the Baltic grey seals in the Western Baltic Sea based on newly published and unpublished data.

Seal abundance

A study by Galatius et al. (2020) concluded that the grey seal occurence in Kattegat, the southern and western Baltic has steadily increased since 2003 from 146 individuals, close to 1% of the total population in the Baltic to 2537 individuals in 2019 close to 7% of the total grey seal population in the Baltic (Fig. 1).

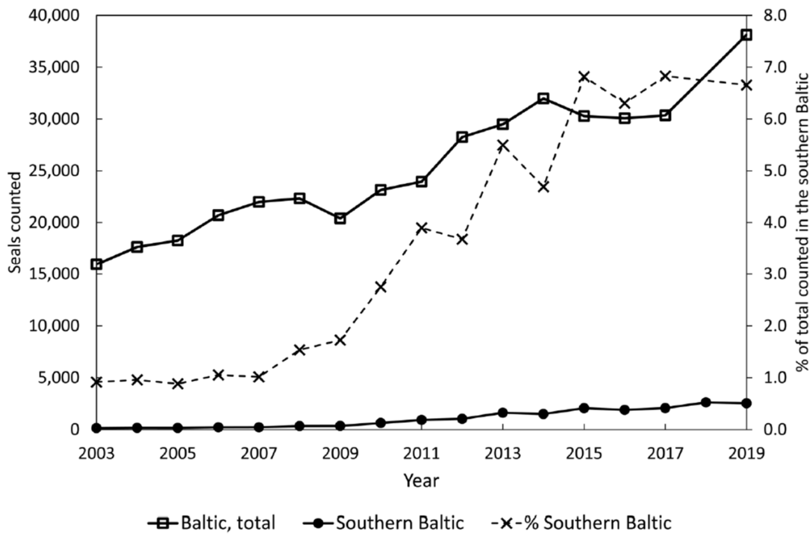


Fig. 1. Numbers of grey seals in the Baltic Sea (from Galathius et al. (2020)).

After personal communication with the author, it was possible to get the data at a finer scale and only covering the Western Baltic area, for the four locations: Rødsand, Rügen, Måkläppen and Bosserne (Fig. 2). The data were given as an average by year in 5-year periods (Table 1).

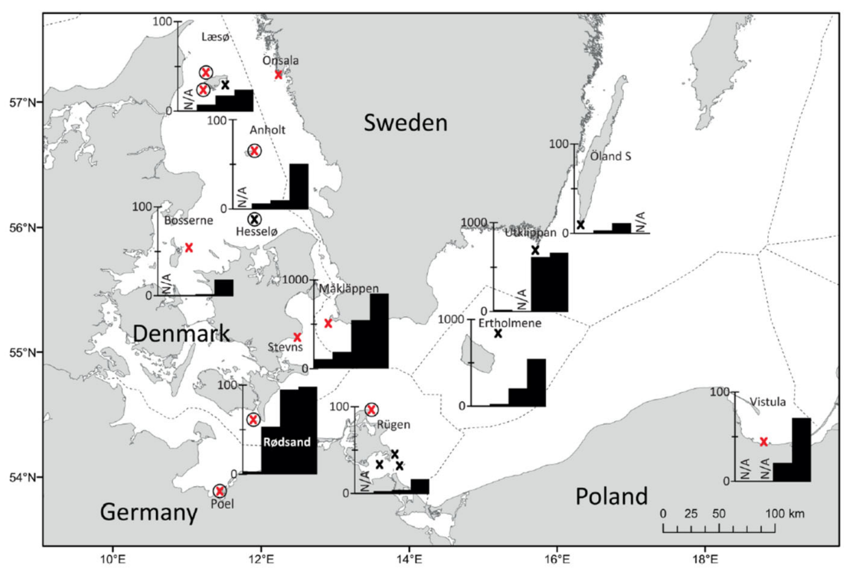


Fig. 2. Grey seal locations in Kattegat and southern Baltic Sea. Columns show abundance of grey seals with more than 10 grey seals recorded in the time steps 2001-2005, 2006-2010, 2011-2015 and 2016-2019. Notice different scales on the y-axes (from Galatius et al. (2020)).

Year interval	Rødsand	Bosserne	Grey seal abundance	Total grey seal abundance in the Western Baltic area
2001-2005	3	0	3	112
2006-2010	54	1	54	248
2011-2015	95	2	97	648
2016-2019	99	19	117	977
Year interval	**Rügen**	**Måkläppen**	**Grey seal abundance**	
2001-2005	0	109	109	
2006-2010	3	191	193	
2011-2015	4	546	551	
2016-2019	17	843	860	

Table 1. Grey seal abundance in the western Baltic by year interval and area.

Grey seal diet

The amount of cod in a seal's diet varies widely between locations, seasons, age, sex and individuals. If the seal feeds for example on sandeel, only an average of 4 kg is required per day owing to the high energy content of the fish compared to an average of 7 kg when feeding on cod (SCOS, 2009). However, as an average, an adult seal is estimated to consume approximately 4.5 kg of fish per day (Eero et al. 2011).

A still unpublished study from DTU Aqua estimated and compared consumption data from the two main grey seal locations in the western Baltic Sea Måkläppen and Rødsand based on faeces collected at the seals´ haulout sites. The data were collected in the time period 2014- 2017 at Måkläppen in all four quarters (Fig. 3) but in Rødsand only in 3 quarters (quarter 1 is missing) (Table 2). The data indicated large fluctuation in prey species composition by season and area, but with a clear pattern of higher amount of cod in the diet further towards the eastern areas.

Area	Q1	Q2	Q3	Q4	average
Måkläppen	0.63	0.18	0.27	0.51	0.40
Rødsand	N/A	0.33	0.02	0.02	0.12

Table 2. Proportion of cod in the seal diet depending on area and quarter.

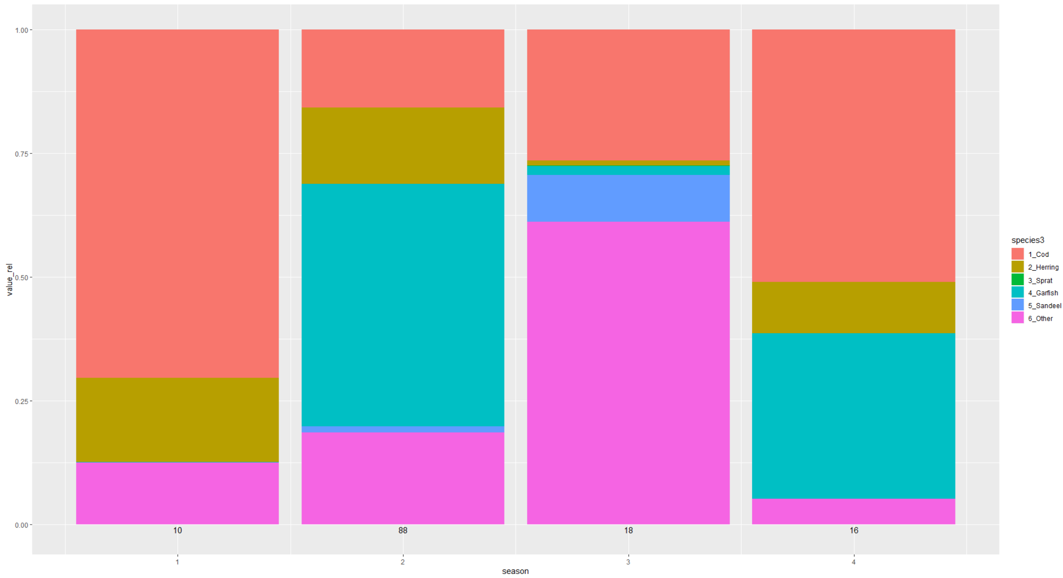


Fig. 3. Grey seal consumption by quarter and species for the area Måkläppen (DTU Aqua unpublished data)

A paper from 2019 “Diet of seals in the Baltic Sea region: a synthesis of published and new data from 1968 to 2013” synthesizes previously published and newly generated data on the diet of harbour seals, grey seals, and ringed seals in the Baltic Sea region. The study concluded that in the southwestern Baltic Sea, the species targeted by grey seal were black goby (24%), round goby (18%), cod (16%), plaice (12%), dab (6%), herring (4%), small sandeel (A. tobianus) (2%) and sand goby (2%) based on numerical numbers. As the available data did not all include information on otolith length, the paper’s results are based on numerical occurrence, and the authors concluded that this potentially underestimated the importance of larger prey species such as cod. Further, it was mentioned that the study based the prey occurrence on otoliths in seal stomach, but if the seals do not ingest the head of the fish where the otoliths are located, but only stomach (liver) or roe this will not be reflected in the study. Their conclusion was that this may particularly be true for large cod and flatfish, lumpsucker, trout, garfish and salmon that have large bony heads, are rich in easily ingested and highly nutritious eggs, liver or fat, and/or are scavenged from fishing gear. The 16% cod found in this investigation was therefore estimated as a minimum of the predated cod. The level from this paper is similar to the level found at Rødsand in the study by DTU Aqua.

Cod prey size

A prey study conducted in Norway from 2019 (Nilsson et al.) based on 182 grey seals showed that the main prey size of cod in this area were in the range 15–30 cm but occasionally up to 40 cm. However, from the study conducted by DTU Aqua there was a tendency towards larger cod being the typical prey item, even cod estimated above 80 cm were being consumed by seals. This is more in line with a study from 2015 conducted west of Scotland were the size selectivity curve for seals showed greatest selection for cod at about 50 cm (Cook et al 2015).

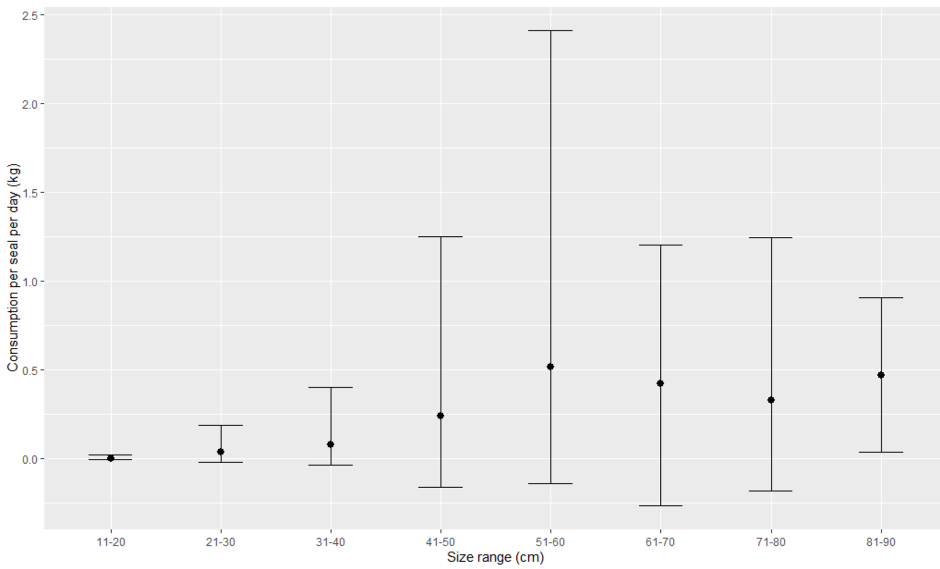


Figure 4. Estimated cod prey size as based on otoliths. Data have been merged between quarters.

Based on the data from DTU Aqua, it seems that the main target cod size are the larger fish 40-80 cm, however the confidence intervals were very wide and we therefore did not take cod size into account.

Estimated annual consumption

As grey seal abundance was only available in 5-year average periods, some simplified assumptions were made using an annual average per area. Further, the smaller area Rügen was added together with Måkläppen in the diet composition and the other smaller area Bosserne was added together with Rødsand. Based on the annual cod consumption rate for the two areas (Måkläppen: 0.40; Rødsand: 0.12) and the assumption of an average diet of 4.5 kg fish a day, an area specific cod consumption was estimated (table 2 and table 3).

Rødsand +Bosserne			
year interval	grey seal abundance	tons fish/year	tons cod/year
2001-2005	3	5	1
2006-2010	54	89	11
2011-2015	97	159	20
2016-2019	117	192	24
Måkläppen+ Rügen			
year interval	grey seal abundance	tons fish/year	tons cod/year
2001-2005	109	179	71
2006-2010	193	318	126
2011-2015	551	904	360

2016-2019	860	1412	562

Table 3.

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Can reduced body condition have increased natural mortality of western Baltic cod in later years?

By Margit Eero, DTU Aqua

Summary

Body condition of western Baltic cod has deteriorated in later years, especially in 2019-2021, based on BITS Q1 data. This has likely led to some increase in natural mortality, however the exact magnitude is sensitive to small modifications to the condition threshold below which the fish are expected to die. Based on the available information on such thresholds, the maximum additional condition-related natural mortality of age2+ western Baltic cod in 2019-2021 could be at 0.08-0.1, or possibly lower.

Background

Average Fulton's K condition factor for western Baltic cod (in SDs 22-23) caught in BITS surveys in Q1 in latest years is estimated lower compared to earlier years (Fig. 1). The condition of the western Baltic cod in 2019-2021 is comparable to the low condition of the neighboring eastern Baltic cod (Fig. 1,2). For eastern Baltic cod, natural mortality has substantially increased in later years (ICES 2020), part of which is considered to be due to poor condition (Casini et al. 2016). Therefore, it is relevant to consider whether natural mortality of the western Baltic cod may have increased as well in later years.

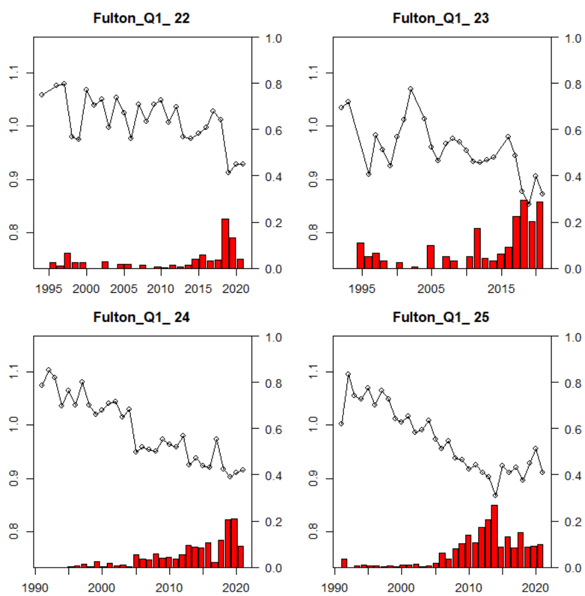

Figure 1. Average Fulton's K condition factor (the line) for cod at 40-60cm in length in Q1 BITS survey, by Subdivision. The red bars show the proportion of individuals with Fulton's K below 0.8.

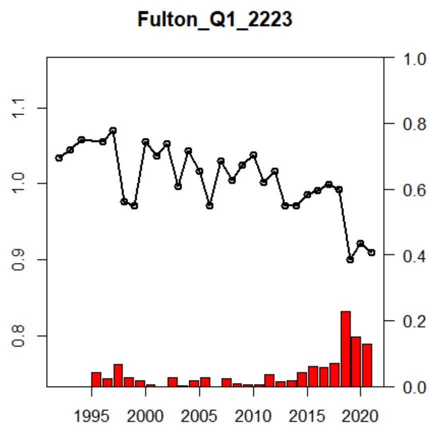

Figure 2. Average Fulton's K condition factor (the line) for western Baltic cod (SDs 22-23) at 40-60cm in length in Q1 BITS survey. The red bars show the proportion of individuals with Fulton's K below 0.8.

Material & Methods

The analyses of possible increase in natural mortality (M) of western Baltic cod due to low condition were based of similar approach as applied by Casini et al. (2016) for the eastern Baltic cod, using information from the experimental studies performed on Atlantic cod that found a negative relationship between body condition and mortality (Dutil and Lambert, 2000). Dutil and Lambert (2000) found that the fish that were not fed (starved) had K=0.42–0.67 (Fulton's K, based on fork length and gutted weight). The biological properties (e.g. liver energy and muscle energy) of some of the starved fish were similar to those of dead fish, so the authors expected them to die shortly.

We used data from BITS Q1 survey to investigate the proportion of western Baltic cod in such low condition. Dutil and Lambert (2000) used gutted weights (GW) and fork length (FL) in their condition estimates, while the BITS data available in DATRAS is for total length (TL) and whole weight (TW). Thus, first part of the analyses was focusing on finding a conversion factor between the Fulton's K calculated based on TL and TW and the Fulton's K based on FL and GW. To do this, we used individual cod data from the Danish national database for Q1 for 1995-2015, where both GW and TW data were available. To convert TL to FL, we used the same conversion factor as applied by Casini et al (2016):

$$TF = 0.99 \times TL - 0.36$$

We calculated two Fulton's condition factors for each individual cod in the Danish dataset:

$$K_T = \frac{TW}{TL^3} \times 100$$

$$K_G = \frac{GW}{FL^3} \times 100$$

For each cod, we then calculated the ratio between the two condition factors. To obtain average ratio to be used to convert K_G to K_T, we used fish between 30 and 80 cm in length. This resulted in mean ratio and standard deviation at 1.15 ± 0.08.

Thus, the condition factors reported by Dutil and Lambert (2000) as corresponding to likely mortality should be multiplied by this factor to obtain the corresponding Fulton K based on whole weight and total length. Dutil and Lambert (2000) provided a condition interval 0.42–0.67 referring to mortality. Based on this range, Casini et al (2016) in their calculations for the eastern Baltic cod used the value 0.65 as the threshold below which the fish would likely die. When applying 0.65, this would imply a condition factor 0.74 as the threshold for mortality, when calculated based on TW and TL. When applying the uppermost range from Dutil and Lambert (2000), i.e. 0.67, this corresponds to 0.77 as the threshold for mortality, when calculated based on TW and TL.

We then used the international BITS data from SDs 22-23 for Q1 in DATRAS, for length range 30-60 cm, to calculate the proportion of western Baltic cod below such condition levels.

Results

The results showed that when applying 0.74 as the border below which the fish are expected to die, up to 3% of western Baltic cod were below this critical condition in later years (Fig. 3). When applying 0.77 as the critical condition, up to 9% of cod were below that level, with a clear increase in 2019-2021 compared to earlier years (Fig. 3).

This calculation demonstrates that some increase in M in later years due to poor condition is likely, however the magnitude of this increase is influenced by relatively small modifications to the threshold condition below which the fish are expected to die. Based on the experiments by Dutil and Lambert (2000), maximum additional natural mortality due to low condition could be at 0.08-0.1 in 2019-2021, possibly lower.

This increase in M could be considered for cod at age 2+, as the condition for age1 appears to be stable in later years (Fig. 4).

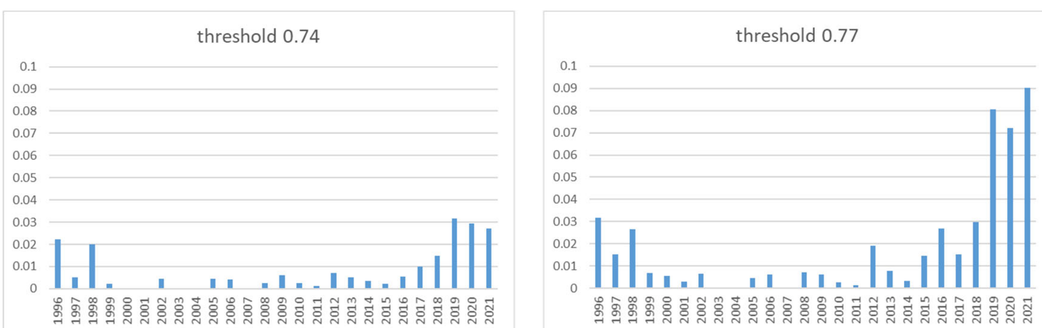

Figure 3. Proportion of western Baltic cod with Fulton K below 0.74 (left panel) and below 0.77 (right panel).

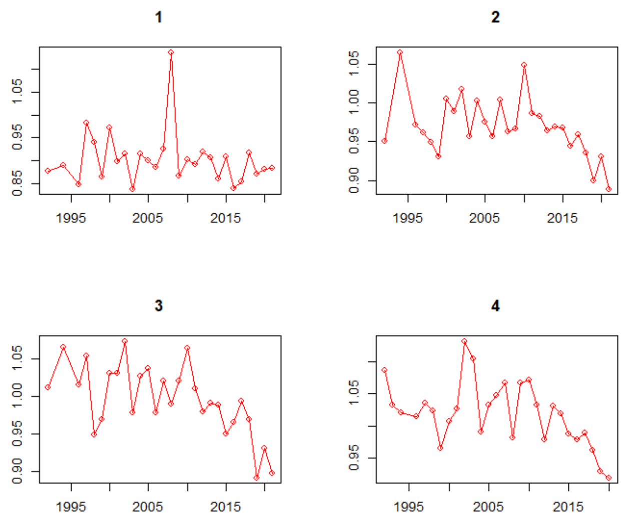

Figure 4. Fulton’s K condition factor for western Baltic cod in Q1, by age (based on BITS data).

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Estimation of natural mortality for Western Baltic cod

By Margit Eero, Massimiliano Cardinale

Technical university of Denmark, DTU Aqua; Department of Aquatic Resources (SLU Aqua), Institute of Marine Research

Summary

This working document describes the analyses carried out to estimate the natural mortality by age for Western Baltic cod, using information on life history parameters such as longevity and growth. These analyses suggest a different shape of M at age compared to the approach used in the assessment at present, and a higher M values for younger ages.

Materials and methods

Different methods were applied to estimate natural mortality for Western Baltic cod. The Hoenig method (1983) was applied to derive M for Western Baltic cod and it is based only on maximum age for teleosts. The maximum observed age (*tmax*) for Western Baltic cod recorded during BITS surveys since 1991 is 11 years and 13 years in Danish commercial catch data. However, as throughout this period the fishing mortality on the stock has been high, the maximum observed age probably is not representing longevity. For comparison, for a neighbouring stock, eastern Baltic cod, for which longer and more comprehensive time series of data are available, fish up to 20 years of age have been recorded (ICES WKBALTCOD2 2019). At lack of good stock specific information, in the present analyses, 25 years was applied as longevity of Western Baltic cod, representing cod fish in general. This resulted in M at 0.17, based on Hoenig method (1983). For sensitivity, M value at 0.21 is obtained with longevity of 20 years, and 0.28 with longevity of 15 years.

A more recent paper by Then et al., (2015) analysed data from 226 studies (including Hoenig 1983) to evaluate the robustness of life-history based M inferences. Based on updating and testing indirect estimators of natural mortality using information on 201 fish species, Then et al., (2015) recommend the use of their updated maximum age-based estimator when possible and an updated von Bertalanffy K-based method otherwise.

Comprehensive analyses estimating M from different methods were carried out for the neighboring Eastern Baltic cod stock at last benchmark (ICES 2019, WD by Cardinale, M). As a result, the two approaches by Then et al, where selected for final assessment. For this reason, and for consistency with the neighboring stock, the present analyses for Western Baltic cod are also focusing on the approaches by Then et al., (2015).

The life history parameters (Table 1) used included von Bertalanffy growth parameters estimated from tagging data for Western Baltic cod (McQueen et al. 2019), and *a* and *b* parameters of length-weight relationship estimated from BITS surveys, used to derive age specific values of M.

Table 1. Life history parameters used in M calculations

Life history parameters	Value	Source
k (combined sex)	0.11	McQueen et al.2019
L_{inf} (combined sex)	154.56	McQueen et al.2019
t_o (combined sex)	-0.13	McQueen et al.2019
Max age (combined sex, tmax)	25	based on cod in general
a	0.00000792	BITS Q1 & Q4
b	3.0563	BITS Q1 & Q4

Natural mortality can be expected to be higher in young fish and decline with age. Proxy methods to infer age-dependent M in younger fish are given by Lorenzen (1996) and Gislason et al., (2010). The Gislason method generally gives lower M for adult fish. Brodziak et al (2011) suggest that methods such as Lorenzen can be used to derive the relative age-dependent patterns for younger fish, but can be re-scaled to give M at older ages that are more similar to those from methods using (e.g.) *tmax*. Therefore, Lorenzen (1996) method was used to estimate age-dependent M values for Eastern Baltic cod.

Results

Then et al., (2015) *tmax* based method (i.e. $M = 4.899 \cdot tmax^{-0.916}$) gives an M value of 0.257.

Then et al., (2015) von Bertalanffy K-based method, which uses the parameters of the von Bertalanffy growth curve, ($M = 4.118.K^{0.73}.Linf^{-0.33}$), predicts M = 0.156.

Here we present both methods as suggested by Then et al., (2015), which are based on maximum age (*tmax*) and parameters of the Bertalanffy growth curve.

Lorenzen (1996) method was used to estimate age-dependent M values for Western Baltic cod and the results are given in Fig. 1 and Table 2. Lorenzen M values were rescaled to give mean M at ages 10-15, which are equivalent to the Then et al., (2015) prediction of 0.257 and 0.156 for *tmax* 25 years old and growth based method, respectively. Therefore, the following M options could be explored:

1. Lorenzen M (age specific) rescaled to M=0.156
2. Lorenzen M (age specific) rescaled to M=0.257

3. Average of the two methods 1 and 2
4. Continue with the M values that have been used in stock assessments for Western Baltic cod previously (SPALY).

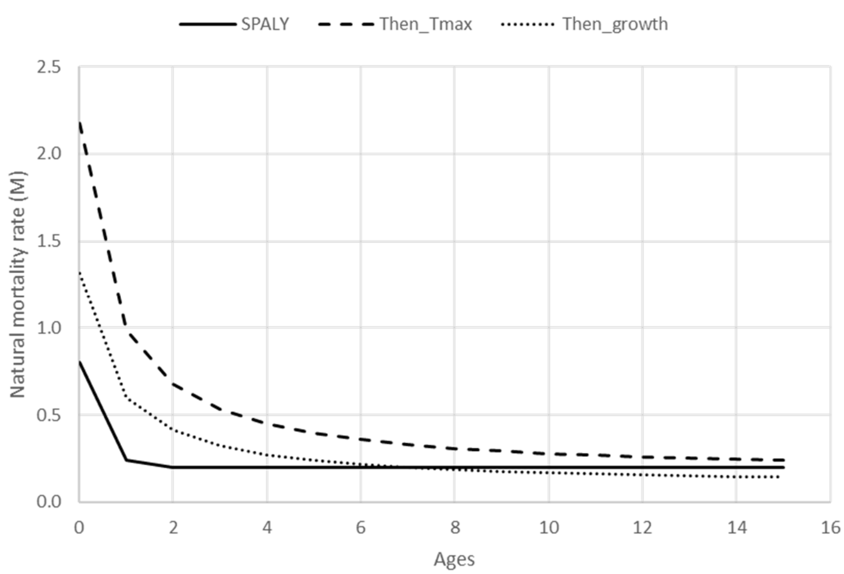

Figure 1. Natural mortality by age values inferred from Lorenzen (1996) rescaled to a mean M of 0.257 at ages 10-15 (based on Then et al 2015 maximum age method, for a maximum age of 25 years) and mean M of 0.156 at ages 10-15 (based on Then et al., 2015 growth method). The results are compared with the M at age values presently used in stock assessment of Western Baltic cod (SPALY).

Table 2. Western Baltic cod natural mortality by age values estimated using: Lorenzen (1996) (Lorenzen); Then et al., 2015 maximum age method (*tmax*) rescaled to a mean M of 0.257 at ages 10-15; Then et al., 2015 growth method rescaled to a mean M of 0.156 at ages 10-15.

age class	L	W (kg)	M Lorenzen	Scaled to Then tmax	Scaled to Then growth
0.5	10.3	0.010	1.545	2.172	1.318
1.5	25.4	0.155	0.702	0.987	0.598
2.5	38.8	0.570	0.482	0.678	0.411
3.5	50.9	1.302	0.380	0.535	0.324
4.5	61.7	2.345	0.321	0.451	0.274
5.5	71.4	3.660	0.282	0.397	0.241
6.5	80.0	5.195	0.255	0.359	0.218
7.5	87.8	6.895	0.235	0.331	0.201

8.5	94.7	8.704	0.220	0.309	0.188
9.5	101.0	10.575	0.208	0.292	0.177
10.5	106.6	12.465	0.198	0.279	0.169
11.5	111.6	14.340	0.191	0.268	0.163
12.5	116.0	16.174	0.184	0.259	0.157
13.5	120.0	17.945	0.179	0.251	0.152
14.5	123.6	19.638	0.174	0.245	0.148
15.5	126.9	21.244	0.170	0.239	0.145
16.5	129.7	22.755	0.167	0.235	0.142
17.5	132.3	24.169	0.164	0.231	0.140
18.5	134.6	25.485	0.161	0.227	0.138
19.5	136.7	26.704	0.159	0.224	0.136
20.5	138.6	27.828	0.157	0.221	0.134
21.5	140.2	28.863	0.156	0.219	0.133
22.5	141.7	29.811	0.154	0.217	0.132
23.5	143.1	30.678	0.153	0.215	0.131
24.5	144.3	31.469	0.152	0.214	0.130
25	144.8	31.837	0.151	0.213	0.129
	mean 10-15	16.968	0.183	0.257	0.156

References

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