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Total number of authors:
17

Publication date:
2021

Document Version
Publisher's PDF, also known as Version of record

DTU

DTU Aqua
National Institute of Aquatic Resources

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DTU Aqua Report no. 393-2021

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European Union
European Maritime and Fisheries Fund

HAV & FISK

Colophon

Title:	Improving knowledge base for management of cod stocks in the Baltic Sea and in the Kattegat
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DTU Aqua Report no.:	393-2021
Year:	Scientific work finalized October 2021. Report published December 2021
Reference:	Eero, M. et al. 2021). Improving knowledge base for management of cod stocks in the Baltic Sea and in the Kattegat. DTU Aqua Report no. 393-2021. National Institute of Aquatic Resources, Technical University of Denmark, 87 pp. + app.
Cover photo:	Cod. Photo: Colourbox.dk/Jørgen Flemming
Published by:	National Institute of Aquatic Resources, Kemitorvet, 2800 Kgs. Lyngby, Denmark
Download:	www.aqua.dtu.dk/publikationer
ISSN:	1395-8216
ISBN:	978-87-7481-317-0

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Project summary

The project ”Improving knowledge base for management of cod stocks in the Baltic Sea and in the Kattegat” focused on the key challenges for assessment and management of the Eastern and Western Baltic cod and cod in the Kattegat. The project was funded by European Maritime and Fisheries Fund and the Danish Fisheries Agency. The activities in the project involved providing new biological knowledge, advancing methods, and conducting data analyses and modelling.

For the eastern Baltic cod, a new method for estimating age and growth based on otolith microchemistry was validated, which can in future replace the traditional age readings that are known to be problematic for the stock. A new approach for determining cod fecundity was also developed. This improves information of cod reproductive potential as well as alternative spawning stock biomass estimates from egg production methods, also applied in this project. The work of the present project as well as earlier related projects was synthesized to contribute to ICES benchmark in 2019 where analytical stock assessment for the eastern Baltic cod was re-established. Furthermore, the project demonstrated that future possible recovery of the eastern Baltic cod depends on ecosystem drivers affecting stock productivity, and communicates new challenges for management associated with ecosystem changes and the complexity of factors affecting cod.

For the western Baltic cod, the project investigated ways to deal with stock mixing in survey data, and provided a currently optimal solution to this that is used in ICES stock assessment today. The impact of assumed historical recreational catch values on stock assessment was also investigated. The results demonstrated that it is beneficial for assessment quality to include recreational catch information in the assessment even when good quality data are available only for a few latest years. Impact of uncertainties in different data inputs (amount and age structure of discards and recreational catch, mean weight and maturity, stock mixing) on stock assessment and advice was also explored, based on the example of western Baltic cod. These analyses increased our understanding of the relative impacts of possible inaccuracies in different data inputs and their annual updates on stock assessment and associated management advice.

For cod in the Kattegat, the project provided new genetic information on mixing of North Sea and Kattegat stocks that improves our understanding of spatio-temporal variations in stock mixing. These data on stock mixing are utilized in developing a stock assessment model within this project, which is a modification of the present SAM model. The stock assessment model was modified to take into account inflow of juvenile cod from the North Sea and estimate their return migration when the fish become mature. This facilitates evaluating status of different stock components.

The project additionally provided new knowledge on the impacts of supporting fisheries management measures such as spawning closures and regulations of fisheries selectivity. We concluded that if spawning closures are applied, these should cover most of the stock distribution area during most of the spawning season, to avoid possible counterproductive effects. For western Baltic cod, understanding of recruitment processes was enhanced, for example, the recent stronger 2016 year-class was found to be likely related to high abundance of favourable food for

larvae. Spawning closures do not appear to be among the dominant factors affecting year-class strength in Western Baltic cod.

The project also investigated fisheries selectivity effects on reduction in abundance of larger Eastern Baltic cod in later decades. The results showed that fisheries likely contributed to this development in some years, however other factors must be more influential as the larger individuals disappeared simultaneously from fisheries and survey catches.

Background and outline of the project

The present project addressed stock assessment and management related issues that concern three cod stocks in the Danish waters, i.e. eastern Baltic cod, western Baltic cod and cod in the Kattegat. The aim of the project was to improve the quality of stock assessments and scientific advice for management by focusing on selected key issues for those stocks, involving improved data inputs and biological understanding as well as stock assessment and management analyses and modelling.

For eastern Baltic cod, the key issues for stock assessment addressed in this project included a pronounced decline in productivity and how to properly account for this in stock assessment analyses. The present project contributed new biological knowledge by developing and applying new advanced methodologies for estimating and validating changes in growth, as well as reproductive capacity of the stock. In terms of stock assessment, the work in this project contributed to re-establishing quantitative stock assessment in ICES, taking into account changes in growth and natural mortality. Further, alternative supplementary method for determining spawning stock size was developed and applied for the Eastern Baltic cod that is based on egg production method, and is using information on reproductive capacity of the stock.

For western Baltic cod, key issues for stock assessment included mixing with the eastern Baltic cod in the management area of the western stock, as well as recreational catch. The present project investigated how to best account for stock mixing in survey indices as input to stock assessment. Further, we explored the impact of recreational catch on stock assessment results, particularly addressing the robustness of stock assessment to assumptions on historical recreational catch values where actual data are not available.

For cod in the Kattegat, a main issue for stock assessment is stock mixing. The present project contributed new knowledge on the magnitude and interannual variability in mixing of Kattegat and North Sea cod populations within Kattegat, using genetic technics. This new knowledge is then utilized in modifying a stock assessment model to be able to account for stock mixing when assessing the status of Kattegat cod stock.

The present project addressed also issues related to management reference points, focusing on i) challenges in estimating the reference points under changing stock productivity (based on the example on Eastern Baltic cod) and ii) sensitivity of the reference points to uncertainties in some data inputs to stock assessment (based on the example of the western Baltic cod).

Among supplementary management measures, spawning closures have been in focus for management of the Baltic cod in later years. In this project, we conducted a review of their potential effects on the Eastern Baltic cod recruitment. For Western Baltic cod, considerably less information on recruitment processes is available, compared to the eastern stock. Thus, in this project we investigated the recruitment dynamics of the western Baltic cod including identifying its drivers, This information allow evaluating also the potential role of spawning closures in determining recruitment success in later years. Other relevant management measures focus on regulations on fishing gear selectivity, for eastern Baltic cod in particular. In this project, we investigated to what extent selective fisheries removal of larger individuals could have contributed to the pronounced truncation of size structure of the eastern Baltic cod observed during the latest decade.

In this project, we also investigated robustness of stock assessment and management advice to uncertainties in different data inputs. This was based on the example of western Baltic cod, where stock assessment includes several data inputs not considered in many other assessments, e.g. stock mixing rates and recreational catch. The aim of these analyses were to explore whether the stock assessment and advice are relatively more robust to uncertainties in some type of data compared to other, to possibly help prioritize data collection under increasing complexity of assessments and corresponding data needs.

The project prioritized communication and dissemination of the project results and the issues and challenges faced for stock assessment and management regarding the cod stocks. This includes both communication within international scientific community through publications and ICES workshops, as well as communication with relevant stakeholders and managers via relevant meetings.

1. Improving selected input data & assumptions for stock assessments

1.1 Eastern Baltic cod

1.1.1 A new approach to age and growth estimation using otolith microchemistry

Background

Information on fish age and growth is essential for more data demanding and advanced stock assessment methods. At present, the age of Baltic cod is determined by the traditional method of annual ring interpretation of their otoliths. It is well known that for the eastern Baltic cod, there are inconsistencies in age readings between readers and institutes around the Baltic Sea because no clear annual rings are deposited in the otoliths. The present stock assessment for Eastern Baltic cod uses information from traditional age readings to convert length to age within the assessment model. This is one of the main uncertainties in the present stock assessment and affects the exact estimates for growth as well as natural mortality (ICES 2020). Therefore, an improved method to obtain updates for growth changes is important to ensure a high quality assessment of this stock.

The otoliths of fish consist primarily of calcium carbonate and protein and grow as a function of environmental conditions and the fish's metabolic rate. However, additionally some trace elements and isotopes are incorporated in response to physiology, and thus have potential to "record" a fish's growth from hatch to capture. For example, in western Baltic cod, minima in the element phosphorus clearly identifies annual rings (Hüssy et al. 2021). A first comprehensive study by Heimbrand et al. (2020) and Limburg et al. (2018) indicated that in particular phosphorus and magnesium are candidates for this method. However, before using such an approach to obtain growth and age estimates for stock assessment purposes, an in-depth validation of the methodology is necessary.

The BalticSea2020 funded project "Tagging Baltic Cod" (TABACOD) provided validation that annually recurring seasonal signals do indeed occur in phosphorus and magnesium using samples of Eastern Baltic cod from an international tag-recapture experiment (Hüssy et al. 2020). However, that study was based on larger individuals older than 3-4 years, since small cod are not suitable for tagging. In FORTORSK, our objective was to provide validation for this new method based on otolith chemical composition for the estimation of age and growth of younger (<4 years of age) eastern Baltic cod.

Materials and methods

Samples

We used 53 otoliths from Baltic cod in the size range 150–350 mm captured in the Bornholm Basin (ICES SD 25) in February of 2001 and 2004. These otoliths had previously been analysed for width of daily increments to estimate the age of the fish (DECODE 2009). This method was previously used to identify problems with traditional age estimation (Hüssy 2010) as well as to estimate changes in growth patterns (Hüssy et al. 2018). The width of daily growth increments is linked to the annual cycle in environmental temperature experienced by the cod (Hüssy et al. 2010). Counting the winter zones without increments thus provides an estimate of the fish's age. These samples thus provide the means to validate both seasonality in chemical element pattern formation as well as absolute age of the fish.

In addition to the DECODE samples, we had access to eastern Baltic cod samples caught in SD 25 from 1930's to present time. Data from these samples originate from the Swedish FORMAS project "Losing track of time" [grant No. 2015-865] and were kindly made available to FORTORSK by Professor Karin Limburg (SUNY-ESF) and Yvette Heimbrand (SLU Aqua).

Chemical and statistical analysis
Trace element analyses of the DECODE samples were carried out by Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS) at the Geological Survey of Denmark and Greenland (GEUS), employing a NWR213 frequency-quintupled Nd:YAG solid state laser system from Elemental Scientific Lasers (ESI) that was coupled to an ELEMENT 2 double-focusing, single-collector magnetic sector field ICP-MS from Thermo-Fisher Scientific. The otoliths were analysed along a transect from the nucleus to the dorsal edge of the otolith following the axis of maximum growth. The data thus represent elemental signatures spanning from hatch to death of each individual.

An objective method for identifying extrema values in the elemental profiles was designed by first smoothing the profiles with local polynomial regression "loess" (R Development Core Team, 2018) in "R". Local extrema, maxima and minima were then identified with the "peaks" function, where a peak/valley is defined as the measurement in a sequence which is greater/smaller than all other measurements within a window of width span centred at that element. The minima are hypothesized to represent winter growth zones. The distance from the otolith core to these minima, were then regressed on the distance to the known distance of the respective winter growth zone derived from the daily increment analysis.

Results

Validation
Analysis of correspondence between daily increment patterns and element signals in individual cod shows that the distance of elemental minima is linearly related with the corresponding winter zones derived from daily increment analysis (Fig. 1.1.1). Lowest correlation coefficients occur for the environmentally regulated elements Sr and Ba (both $r^2 \leq 0.60$), with Pb as a notable exception ($r^2 = 0.73$). Elements under physiological control – notably P and Zn - show the highest correlation coefficients (both ≥ 0.73). The two elements under environmental and physiological control differ in their correlation with a high correlation in Mg ($r^2 = 0.73$) but considerably lower in Mn ($r^2 = 0.62$). The strongest correlation between element minima and winter zones is found in P ($r^2 = 0.79$). A strong correlation means, that minima in P and Mg correctly identify winter, and the number of minima correspond to the fish's age.

These results show that in the youngest age classes of eastern Baltic cod, in particular P is providing accurate age estimates, followed by Mg. Examples of P profiles for four different eastern Baltic cod (Fig. 1.1.2) show the correspondence of minima in P compared to winter zones in two fish from the DECODE sample. Fig. 1.1.2 also shows examples of two cod that are considerable older, and demonstrate that the seasonality in P profiles persists throughout at least the first 7 years of eastern Baltic cod's life.

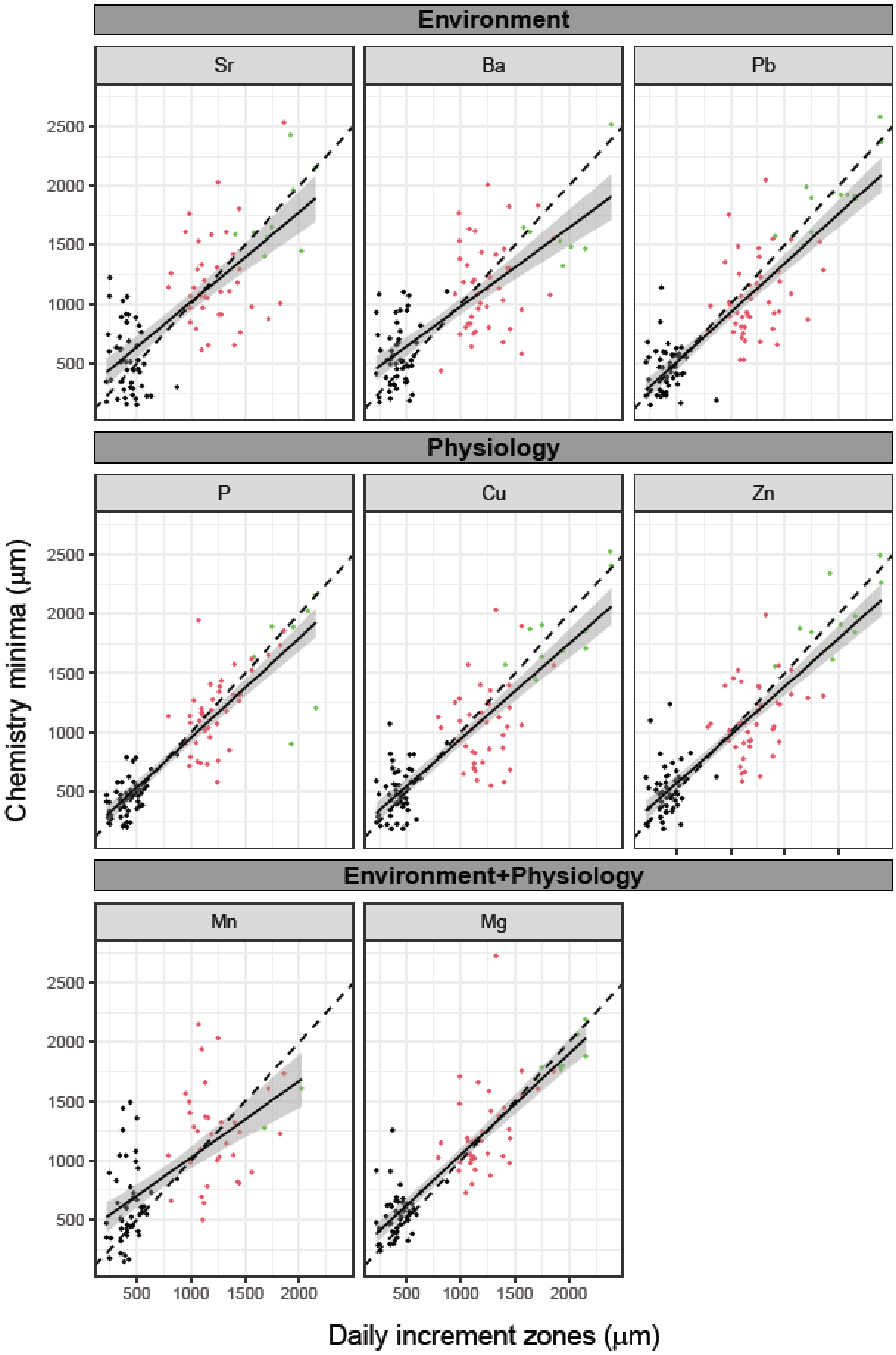


Figure 1.1.1. Relationship between minima (Min) in the chemical profiles in relation to winter zones (WZ) identified from the daily increment patterns of eastern Baltic cod < 35 cm for all elements separately. Colors indicate Min and corresponding WZ numbers, where black = 1. Min, red = 2. Min and green = 3. Min. R2 indicates Pearson correlation coefficient. Mechanisms controlling element incorporation are indicated above element name.

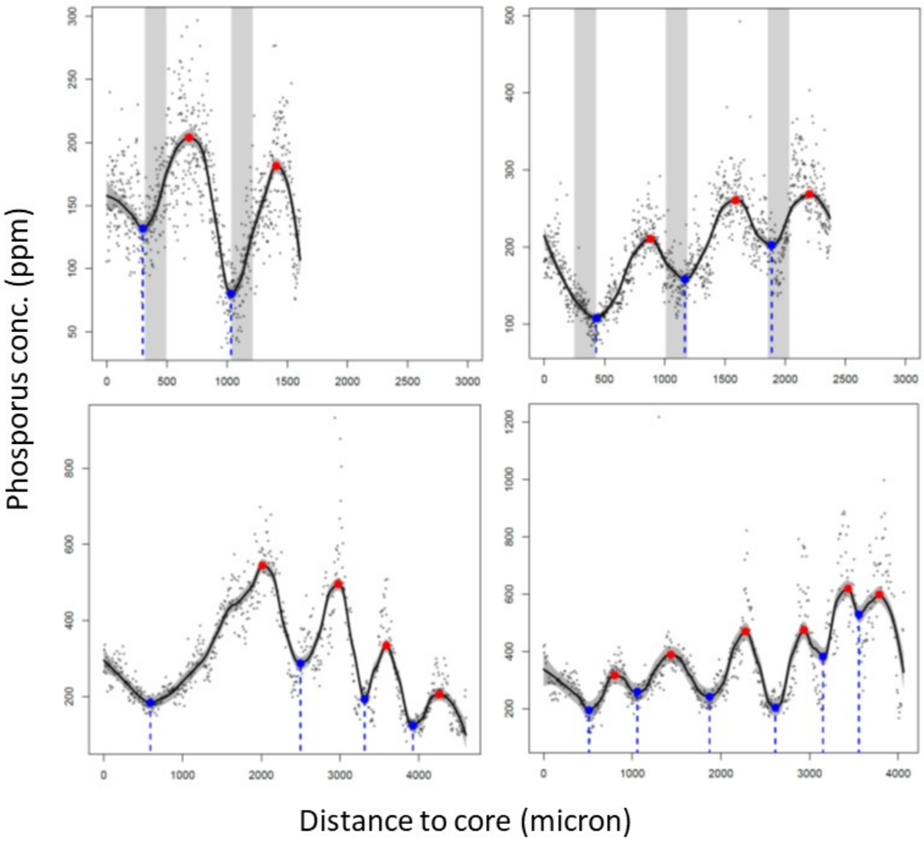


Figure 1.1.2. Examples of phosphorus (P) profiles of four individual fish, where the blue dots represent statistically identified minima in the P profile, red dots represent the corresponding maxima. The top two eastern Baltic cod from the DECODE sample, where the grey vertical bar indicates the winter zone identified from the daily increment analysis, caught in February 2003. These fish were aged 2 years (top left), and 3 years (top right), and minima in chemical profiles correspond with winter zones.The lower two examples are eastern Baltic cod caught in March 2006 and are 5 years (bottom left) and 7 years (bottom right) old. These samples demonstrate that the seasonal signal in the chemical profile persists over the lifespan of the fish. In all four fish the last chemical minima at the edge was not captured by the routines used here, so one year was added to obtain the correct age.

Historic growth patterns

From the sample collection spanning almost an entire decade, individual fish age was estimated by identifying minima in phosphorus and magnesium. Samples were pooled by decade. From the resulting age and length data von Bertalanffy growth curves were estimated (Fig. 1.1.3). The resulting growth curves show that growth of eastern Baltic cod was highest in the 1930s and 1980s, with fish sizes of about 80 cm at age 8. In contrast to this, recent size at the same age is only ca 40 cm! In essence, this means that growth of eastern Baltic cod, based on age estimates from otolith chemistry profiles, has declined by about 50% since the 1980s.

This growth decline mirrors the growth estimates from taggings (Mion et al. 2020a, b). Similar growth pattern is estimated also in present stock assessment for Eastern Baltic cod, where the growth change is estimated based on traditional otolith age readings (ICES 2020). Thus, the results of this project confirm that the growth estimates in the present stock assessment are reasonable.

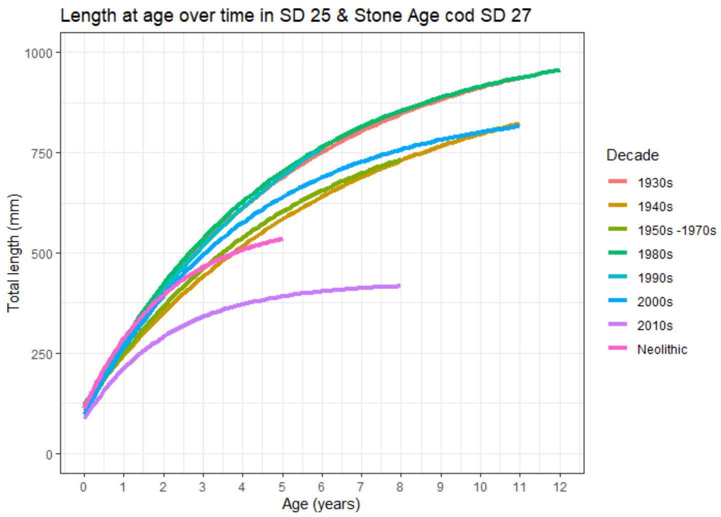


Figure 1.1.3. Preliminary von Bertalanffy growth models fitted to length at age of eastern Baltic cod captured in SD 25, with decades indicated by different colours (data and figure from Y. Heimbrand, SLU Aqua).

Conclusions

These results provide empirical validation for the applicability of trace element concentrations for age and growth estimation of smaller eastern Baltic cod and complement the validation study of the TABACOD project (Hüssy et al., 2020). Thus, we now have confidence for the general applicability of this approach to the entire size- and age range of eastern Baltic cod: The number of minima in phosphorus correspond with the age of the cod.

The application of this method to historic samples of otoliths to obtain objective estimates age and growth further demonstrate that the chemistry-based age estimation method is able to reliably reproduce these parameters not only in contemporary samples, but also in samples from time periods when environmental condition and stock size were different than today.

The growth estimates from microchemistry obtained here are in line with these presently used in stock assessment, confirming reasonable quality of the present assessment with respect to growth. The new approach based on microchemistry can be used to obtain growth updates in future, independent of problematic traditional age readings.

1.1.2 Estimation of fecundity and reproductive capacity

Background

The relative fecundity and egg quality of cod are influenced by fish length/age and condition (i.e. body mass relative to length) (Mion et al., 2018). For this reason, the reproductive capacity of a spawning stock in terms of viable offspring production of a given biomass may differ depending on the demography including female spawner size/age and condition. As the size at sexual maturation and the condition of spawners in the Eastern Baltic cod stock has decreased significantly over the past decades (Casini et al. 2016; Köster et al., 2017), the reproductive potential may be affected. Therefore, the aims of the present project include filling currently remaining knowledge gaps and ascertain data quality in order to quantify changes in reproductive capacity of the EB cod. An objective of the present work is to obtain and validate fecundity estimates, which is also essential input to estimation of the spawning stock biomass based on egg production method (see section 2.1.2).

Our focus here is on implementing stereology as an accurate and precise method for estimating individual fecundity. Then, fecundity of females of different size and condition can be compared. The tasks in this project included 1) sampling ovaries of EB cod, targeting individuals of different size and of different nutritional condition and 2) adapting the stereological method to cod and obtain estimates of individual and relative fecundity. The stereological method involves systematic uniform random sampling (SURS) and histological 3D estimation of the egg cell number (stereology) (Bucholtz et al. 2013). This combined method represents the only fecundity computation that provides the accuracy of the fecundity estimate as well as the accuracy of the method. For this reason, the stereological method is the most reliable fecundity estimation method available.

Due to constrains related to Covid-19, the work in this project focused on sampling and adapting the stereological method to analysis of cod ovaries. An example is provided giving the analysis and calculation procedure for fecundity. Additionally, all collected samples (n=42) have been histologically processed using this methodology and digitalised (scanned). Fecundity estimation of these is ongoing and results will be available for the follow-up EMFF project FREMTOR (33113-B-20-157).

Material and Methods

Samples were collected in the Bornholm Basin during different research cruises in spring 2019 (Fig. 1.1.4).

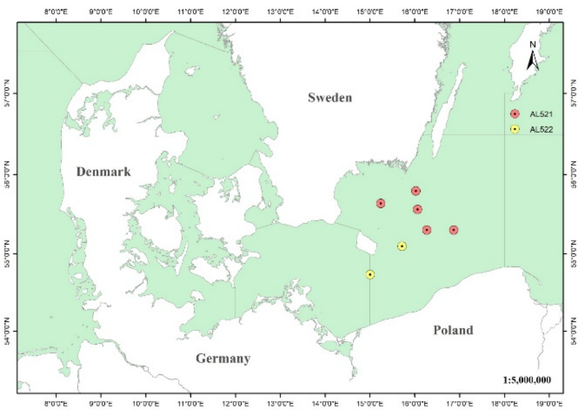


Figure 1.1.4. Trawl haul stations in the Bornholm Basin (ICES Sub-division 25) of the Baltic Sea, where the female cod were sampled for fecundity analyses during research surveys in 2019 with the German research vessel R/V Alkor: AL521 (n=36) and AL522 (n=6).

The data records and sampling of individual female cod included: length, total weight, sex, maturity stage (Tomkiewicz et al., 2003), liver and ovary weight and gutted weight. Only females in maturity stage IV (late vitellogenesis) were sampled. The size distribution ranged from 24 cm to 46 cm with most females obtained for the analysis were in the range 28-39 cm. The ovary was preserved in formaldehyde. In the laboratory, the preserved ovaries were processed histologically. The two ovaries of each individual female were separated and subsequently sampled for stereological analysis of fecundity using the smooth fractionator (Gundersen, 1986, 2002). Depending on the length of the longest lobe, each lobe was dissected into 7-12 equidistant parallel slabs with a random start. The slabs were placed in plastic cassettes and infiltrated in a histokinette. The slabs were subsequently embedded in paraffin blocks. Sampling of embedded ovary slab blocks included that all the blocks were sorted according to size from smallest to largest, after sorting every second block were pushed down a bit producing two rows of blocks. The blocks in the first row were arranged, as before, from smallest to biggest, while the second row was arranged in sequence, but from the largest to the smallest, creating a smooth arrangement of the ovary slabs. Every second to third block, depending on total block number, were now sampled, with a random start between 1 and 2 or 1 and 3, for sampling of dissectors.

The sections with disectors from embedded ovary slab blocks were sampled using the following procedure. The paraffin was trimmed of the blocks with a microtome until the very first tissue was visible. Disectors were sampled for every 1000 section of 5 µm, with a random start, here a random number between 0 and 1000 was found using a random number generator, and if it was e.g. 450, section 450 would be the first section that to be sampled. Section number 450 and 456 were then sampled, representing the first 30 µm disector (section 450 +456). The next disector was sampled 1000 sections of 5 µm further, in the example it would be section 1450 and 1456. The following disector was sampled 1000 sections of 5 µm further in, i.e. section 2450 and 2456. This procedure was repeated until the block was fully sectioned. Thus, there should not be more than 1 or 2 disectors of 30 µm from each block. This procedure was repeated for every block sampled from the individual fish. The sections were placed on a microscope slide, stained with H&E and mounted using Eukitt®

Subsequently, the slides were scanned for stereological analysis of disectors and estimation of total fecundity. The microscope slides with 30 µm disectors were scanned using a Zeiss Axio Scan.Z1. The number of oocytes from the scanned 30 µm disectors were counted in digitally sampled fractions using VIS software (Visiopharm VIS 2020.08) for stereological analysis. All oocytes in developing stages were included: CA – cortical alveoli stage and vitellogenic stages VT1-3 (Tomkiewicz et al., 2003). The total fecundity was estimated from the fractionator equation:

$$N := 1/bsf \cdot 1/ssf \cdot 1/asf \cdot \sum Q^{-}/2$$

where,

N	is the total number of oocyte nuclei i.e. oocytes;
Bsf	the block sampling fraction, i.e. of blocks used from each individual;
ssf	the section sampling fraction, fraction of sections used from each individual, generally given by: ssf = BA/T. In this study, BA equals disector height (BA normally refers to the block advance of the cutting device i.e. microtome). T refers to the distance between sampling of two disectors;

asf the area sampling fraction, fraction of area analyzed given by: asf = total area of counting frames/area of section. In this study asf =0.1, Q^{-}: Disector count i.e number of nuclei counted. As the procedure for disector counting involved counting in both directions, the total disector count was divided by 2.

The coefficient of error (error variance) of the fractionator estimate CE($\sum Q^{-}$) was estimated (Gundersen et al. 1999; Nyengaard, 1999). CE($\sum Q^{-}$) is the variance introduced by the stereological method on the number estimate and consists of two major components, counting noise ("Noise") and VAR_{SURS}(∑area). Noise is the independent variance of a stereological counting procedure, in this case object counting: Noise=$\sum Q^{-}$. The contribution the CE($\sum Q^{-}$) caused by systematic uniform random cutting of blocks, VAR_{SURS}(∑area) is calculated as: VAR_{SURS}(∑area)=(3(A-Noise)-4B+C)/240, where $A = \sum_{i=1}^{n} Q_i^{-} \times Q_i^{-}$, $B = \sum_{i=1}^{n-1} Q_i^{-} \times Q_{i+1}^{-}$ and $C = \sum_{i=1}^{n-2} Q_i^{-} \times Q_{i+2}^{-}$, *i* is the block number. The error variance of the fractionator estimate of oocytes is calculated as:

$$CE(\Sigma Q^{-}) = \frac{\sqrt{Total\ variance}}{\Sigma Q^{-}} = \frac{\sqrt{Noise + VAR_{SURS}(\Sigma area)}}{\Sigma Q^{-}}$$

Based on the morphometric data, Fulton's condition factor (K) was calculated as total body weight/length^3*100, while the gonadosomatic index was calculated as the total ovary weight/body weight*100.

Results

The procedures for estimating fecundity were successfully established combining SURS and the histological sectioning with the VIS analysis of digitalised sections. An example of the calculation of the total and relative fecundity estimated from the fractionator equation is given below using a female of 31 cm and a body weight of 270 g, i.e. F=0.9 and an ovary weight of 23 g.

Total fecundity:
The disector height (equal to BA in this study) was 30 µm, T was 1000 x 5 µm = 5000 µm the total count, $\sum Q^{-}$, was 221 and bsf = 0.5:
ssf = BA/T = 30 µm/5000 µm = 0.006
asf = total area of counting frames/area of section = 0.1
N = 1/bsf × 1/ssf × 1/asf × $\sum Q^{-}$/2
= 1/0.5 × 1/0.006 × 1/0.1 × 221/2 = 368,340 oocytes

Relative fecundity:
The above individual had a total weight of 270 g and an ovarian weight of 23 g. The relative fecundity thus becomes:
368,340 oocytes/270 g = 1,364 oocytes/g fish with ovary;
368,340 oocytes/247 g = 1,491 oocytes/g fish without ovary;
368,340 oocytes/23 g = 16,014 oocytes/g ovary.

Overall, the estimated potential fecundity is within the range observed for cod and matches the model prediction based on length and condition presented by Moin et al. (2018). Here, the fecundity ranges between 350.000 and 400.000 oocytes per fish for the same length and condition. In the present study of CA (previtellogenic oocytes) were included, as the histology-based stereological method can identify specific oocyte developmental stage. This separation is not possible in case of the autodiametric method, which uses an oocyte size separation of undeveloped and developing oocytes. However, this does not appear to affect the estimates of total fecundity. In contrast, the relative fecundity considerably exceeds previously levels (app. 500-900 oocytes/g body weight)(reviewed by Kraus et al., 2002, 2005). In the present case the relative fecundity was estimated to 1,364 oocytes/g fish.

The coefficient of error (error variance) of the fractionator estimate CE($\sum Q^-$) was estimated for the individual above (Bucholtz et al. 2013). The estimation of the coefficient of error will increase its applicability with increasing number of samples.

Block(i)	Q^-	$Q_i^- \times Q_i^-$	$Q_i^- \times Q_{i+1}^-$	$Q_i^- \times Q_{i+2}^-$
1	0	0	0	0
2	18	324	666	918
3	37	1369	1887	1998
4	51	2601	2754	204
5	54	2916	216	1674
6	4	16	124	84
7	31	961	651	155
8	21	441	105	
9	5	25		
Total	$\sum Q^-$=221	*A*=8653	*B=6403*	*C*=5033

Noise=$\sum Q^-$*=221*

VAR$_{SURS}$*(*$\sum$*area)=(3(A-Noise)-4B+C)/240=(3(8653-221)-4x6403+5033)/240=19.65*

$$CE(\Sigma Q^-) = \frac{\sqrt{Total\ variance}}{\Sigma Q^-} = \frac{\sqrt{Noise+VAR_{SURS}(\Sigma area)}}{\Sigma Q^-} = \frac{\sqrt{221+19.65}}{\Sigma Q^-} = 0.07$$

Conclusions

This study has allowed developing a precise and unbiased method for estimating cod fecundity including presenting an example of stereological estimation of fecundity. In near future, analyses of the fecundity of the remaining ovaries prepared in this project will be performed and the results will be related to fish size (weight, length, condition). Additionally, oocyte diameter and atresia will be included in the evaluations and the relation to the hepatosomatic index will be investigated. These results will contribute to the ongoing EMFF project on Eastern Baltic cod (33113-B-20-157) and to relevant ICES Working Groups.

1.2 Western Baltic cod

1.2.1 Accounting for stock mixing in survey indices

One of the main issues with the assessment of cod in SD 22-24 addressed in this project is the mixing of eastern and western Baltic cod stocks within SD24 and how to best account for this in calculation of survey indices to be used as input to stock assessments.

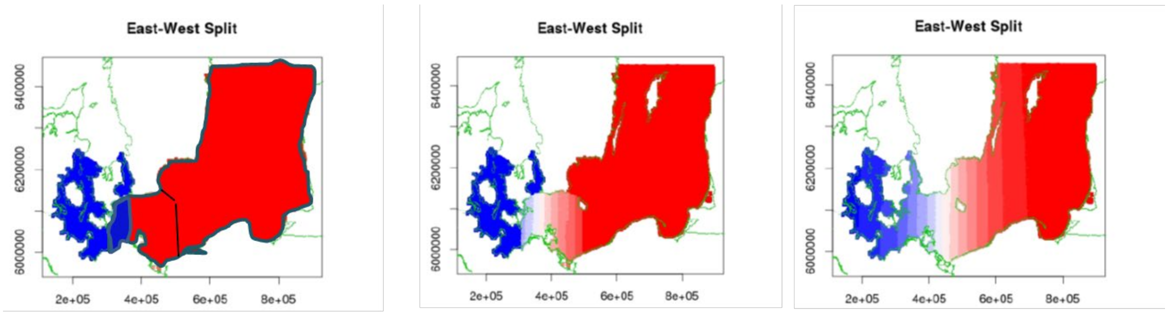
A model for calculating survey indices was developed that accounts for the probability of a cod being from either the western or eastern sub-population of Baltic cod. The purpose of this model is to provide east-west population specific estimates of relative abundance when combined with trawl survey data. The model uses data from otolith shape analyses as well as genetics for east-west stock classification of cod. The model uses time, length of the fish, and longitude as explanatory variables. Details of this model are provided in Appendix A.

To account for mixing of the western Baltic cod with the eastern Baltic cod in SD 24, different options were considered for calculating survey indices, illustrated in Fig. 1.2.1.

13 degree longitude was applied as the borderline, assuming all cod east or west from this line to belong to the eastern or western population, respectively (13 degree);
Mixing proportions were estimated within SD24 only (Hard24),

Both the eastern and western cod were allowed to mix in the entire area of SD22-26 (Soft 24). However, currently there is little genetic evidence of stock mixing beyond SD24, and the mixing beyond SD24 in this exercise in purely based on model extrapolations.

Details of the different stock mixing models and respective results are presented in Appendix A.



13 degree **Hard24** **Soft24**

Figure 1.2.1. Different options explored for accounting for stock mixing in calculating survey indices.

In former stock assessments of the western Baltic cod, the 13 degree approach had been applied. The results from all three models, investigated in this project, were compared for internal consistency to explore whether any of the approaches applied for modelling the stock split in SD24 improved the consistency of the survey index compared to the 13 degree option. The results showed that the internal consistency of survey indices did not improve for survey models ii) “Hard” or iii)Soft for quarter 1 and, in fact, it became much worse for quarter 4 compared to the original survey model applying 13 degree split. These results were discussed and at the latest benchmark for the Baltic cod stocks (ICES WKBALCOD2 2019a).

Conclusion
The conclusion based on the project results, approved at ICES WKBALCOD2, was that among the options explored, it is best to apply the 13 degrees approach for the survey model, i.e. allocating all cod west of 13 degrees longitude to the western stock and all cod east of 13 degrees to the eastern stock. This is due to the best internal consistency of this survey index among the ones investigated. Furthermore, the 13 degrees split approach to the survey is most consistent with the commercial data in terms of dealing with stock mixing. In the commercial data, it is assumed that the western stock in SD24 has the same length/age structure as in SD22, which is similar to the 13-degree split approach in the survey. In contrast, the other approaches to account for stock mixing in survey indices allocate fish to stocks by length, resulting in different assumptions concerning length/age structure of stocks in SD24 than those used for commercial catches.

Future work in this area should consider a common framework, where stock mixing can be accounted for both in commercial catch and in the survey in the same way, allowing to explore different mixing assumptions, while maintaining consistency between catch and survey data.

1.2.2 Recreational catch
A key issue for stock assessment of the western Baltic cod, also addressed at the last benchmark for the Baltic cod stocks (ICES WKBALCOD2 2019a) is the recreational catch. One of the major challenges for including new catch information in stock assessments is that information for a given catch category needs to be available for the entire time period that respective stock assessment covers. This is an issue for recreational catch, were data collection started relatively recently compared to commercial catch registration. At the same time, it is advantageous for stock assessment to cover as long time period as possible, to better capture the stock dynamics through time under different levels of pressures, which is helpful, for example, for setting management reference points. At the benchmark in 2019, a number of assumption were made for the recreational catch back in time, when no data were available (ICES WKBALCOD2 2019a). This issue was followed up in the present project, were we investigated the potential influence of assumptions on recreational catches back in time on management advice regarding catch limits. These analyses are described in section 2.2.

1.3 Kattegat cod

1.3.1 Stock mixing

Background
In previous work, it has been hypothesized that cod of North Sea origin mix with local cod of Kattegat origin in the Kattegat management area for parts of their lifetime, and that the North Sea cod migrate back to the North Sea for spawning (Svedäng *et al.* 2009; Andre *et al.* 2016). In previous projects, these hypotheses have been confirmed and spatial and temporal patterns of population mixing have been estimated using the genetic assignment of fish to population of origin (Hemmer-Hansen *et al.* 2020; EMFF project J. no. 33113-B-16-034). These results have informed that stock mixing occurs and is a substantial issue for stock assessment of Kattegat cod. However, the data have so far not been sufficient to take the mixing into account in stock

assessment, mainly due to lack of time series of quantitative estimates of stock mixing. The present project takes a step further and uses genetic analyses to: 1) generate time series of mixing proportions of juvenile cod and 2) track mixing rates through cohorts. This is to provide data for estimating emigration rates to the North Sea for the North Sea cod, which are used in stock assessment modelling (see section 2.3).

Material and methods

Genetic data and sampling

Information on baseline samples for population assignment has been provided previously (Hemmer-Hansen *et al.* 2020, Hüssy *et al.* 2021). Briefly, the baselines consisted of a total of 586 Atlantic cod collected in spawning season from the North Sea, Kattegat/North Sea-Baltic Sea transition zone and Baltic Sea. Initial genetic analyses of these samples revealed high genetic similarity between samples collected within the North Sea and Kattegat/transition zone, respectively. Consequently, these samples were grouped into reporting groups for assignment purposes, i.e. the "Kattegat" reporting group consisted of baseline fish collected in the Kattegat, Øresund and western Baltic Sea. Consequently, the baseline did not allow an assignment to areas within the transition zone (e.g. between the Kattegat and western Baltic Sea). Work to develop this methodology is in progress (EMFF project FABBIO, J. no. 33113-B-19-140).

Tissue samples from 619 individuals were collected from research surveys in the Kattegat in 2018 and 2019 (Table 1.3.1), and archived otolith samples of 778 juveniles were provided by collaborators at SLU Aqua (Table 1.3.2). From the otolith samples collected specifically for this study, we were able to identify population of origin for 540 fish. The remaining samples were excluded due to missing data or evidence for contamination in the extracted DNA. In addition, we included results from tissue and otolith samples from previous EMFF projects (J. no 33113-B-16-089 and J. no. 33113-B-16-034) to increase total sample sizes and broaden the temporal and spatial coverage of samples available for analyses of stock mixing and related stock assessment modelling. In total, 3711 individual fish assignments were available to the project, with most fish collected in the 4th quarter of the year (Table 1.3.3).

DNA extraction and genotyping

DNA was extracted from tissue samples with Chelex resin (Estoup et al. 1996). For otolith samples, DNA was extracted in a clean laboratory facility with Omega EZNA Tissue DNA kits and genotyped with 4 microsatellite genetic markers to assess potential cross-sample contamination (see also Therkildsen et al. 2013 and Hemmer-Hansen et al. 2019). Only samples that did not show evidence for contamination were used to assess population of origin.

All samples were analyzed for 187 Single Nucleotide Polymorphism (SNP) genetic markers that have been selected because they are informative for identifying population of origin in our baseline consisting of North Sea, Kattegat/transition zone and Eastern Baltic Sea cod populations (Hemmer-Hansen et al. 2020, Hüssy et al. 2021). The original source of the genetic markers were a mix of publications studying cod population structure in the North Sea, Norwegian coastal regions and the Kattegat/Baltic Sea (Nielsen et al. 2012, Heath et al. 2014 and Berg et al. 2016). Data from these publications was extracted and re-analyzed with the specific purpose of identifying genetic markers with high power for identifying populations in the North Sea, Kattegat and eastern Baltic Sea, respectively. Analyses of these baseline samples have previously found that the 187 genetic markers provide independent information for population assignment and collectively provide high power for identifying population of origin of individual fish (see Hemmer-Hansen et al. 2020, Hüssy et al. 2021). Consequently, we expect only few mis-assignments between our baseline population reporting groups.

Assignment to population of origin followed Rannala and Mountain (1997) and was based on comparing genotype likelihoods in the three baseline reporting groups with the programme GeneClass2 (Piry et al. 1996). Population of origin was identified based on the highest assignment score calculated as the ratio between likelihood in a given baseline reporting group divided by sum of all likelihoods.

Table 1.3.1. Contemporary tissue samples collected from research cruises for the current project.

Year	Quarter 1	Quarter 4
2018		259
2019	40	320

Table 1.3.2. Archived otolith samples worked up for genetic analyses in the present project.

Year-class	Sampling time	#Samples	Otolith missing	No DNA	Contamination	No data	Used for population assignment
1985	Q1 1986	68		3	4		61
1991	Q1 1992	59		23	1		35
1998	Q1 1999	59		15			44
1998	Q3 1998	53	20	7			26
2001	Q1 2002	57		7	4		46
2001	Q3 2001	41	8	15			18
2005	Q1 2006	60		2	5		53
2005	Q3 2005	38	14		4		20
2010	Q1 2011	49			10		39
2010	Q3 2010	6	3				3
2011	Q1 2012	52		3	5		44
2011	Q3 2011	24		4	1		19
2011	Q4 2011	45		15	11		19
2012	Q1 2013	54			6		48
2012	Q3 2012	5		1	1		3
2014	Q1 2015	65		1	18	1	45
2014	Q3 2014	7					7
2014	Q4 2014	36		16	5	5	10
Total		778	45	112	75	6	540

Table 1.3.3. Total number of cod with population assignment data analyzed in the current project.

Year	Quarter 1	Quarter 3	Quarter 4
1986	61		
1992	35		
1996		47	
1998		104	6
1999	65		
2001		18	11
2002	75		
2003			12
2004	31		25
2005	39	20	22
2006	88		
2008			92
2010		3	27
2011	39	19	54
2012	44	3	7
2013	48		251
2014		7	120
2015	263		397
2016	83	253	340
2017	141		242
2018			259
2019	40		320
Total	1052	474	2185

Analyses of stock mixing

Temporal and spatial patterns related to inflow of North Sea juveniles to the Kattegat were examined by extracting only juvenile fish from the data set, i.e. age=0 sampled in Q3/4 of the year of spawning or age=1 sampled in Q1 in the following year. These data provided a time series of cohorts at the earliest time when they are captured in surveys. First, we used only yearclasses that were sampled in both Q3/4 and Q1 (1998, 2004, 2005, 2010, 2011 and 2014) with sufficient spatial resolution to examine if quarter of sampling had an effect on mixing proportion. These analyses included a total of 577 fish. We analyzed the data using generalized linear models (using the *glm* function in the R *stats* package) with the probability of assignment to the North Sea modelled as a binomial distribution with ”yearclass”, “quarter” and “latitude” as explanatory variables. Model reductions from the full model including all possible interactions were assessed with the *step* function of the *stats* package in R and through evaluation of the Akaike Information Criterion (AIC) of individual models.

Since we found no significant effect of quarter of sampling (see below), we proceeded with analyses of data pooled across sampling quarters to get a longer time series. This allowed a more thorough evaluation of temporal and spatial effects. In these analyses, we included yearclasses 1991, 1998, 2001, 2003, 2004, 2005, 2010, 2011, 2012, 2014, 2016 and 2019 with a total of 1002 fish. Again, final model selection was based on an evaluation of AIC of alternative models.

We also qualitatively evaluated the recruitment in the neighboring Skagerrak area as a potential driver of the proportion of North Sea juveniles in the Kattegat. This was done by extracting survey data of juveniles (age=0 in Q3) from the ICES DATRAS data base. The reasoning for this analysis was that a high production of juvenile fish in the Skagerrak, which resemble North Sea fish genetically (André *et al.* 2016), could potentially results in an inflow of more North Sea juveniles to the Kattegat.

Further modelling analyses of proportion of Kattegat cod within Kattegat, used in relation to stock assessment modelling are presented in section 2.3.

Results

Of the total of 3711 fish analyzed, only 6 fish (0.2%) were assigned to the eastern Baltic Sea baseline. Hence, these few fish were excluded from further analyses. The remaining fish assigned to the North Sea (48%) or Kattegat (52%) baseline samples.

The spatial distribution of samples and the observed proportion of Kattegat cod is shown in Figure 1.3.1, illustrating that the proportion of North Sea fish decreases around age 3-4 and the oldest fish were primarily of local Kattegat origin. Our analyses of effects of sampling quarter on the proportion of juveniles showed that the full model including three-way interactions provided only a marginally better fit to the data (AIC: 606) than a reduced model without three-way interactions (AIC: 607). The model including two-way interactions could be reduced further to a final model with only main effects “yearclass” and “latitude”, which was found to provide the overall best fit to the data (AIC=597), i.e. effects of “quarter” was found to be non-significant. Further model reductions resulted in poorer model fit to the data. The predicted data under the model including effects of “quarter” is presented in Figure 1.3.2, and illustrate the main effects of both “yearclass” and “latitude” and the non-significant effect of “quarter” on the probability of assigning to the North Sea as a juvenile fish in the Kattegat. For the long time series (1991-2019), we compared a full model with main effects “yearclass” and “latitude” including their interaction (AIC=1194) to a simpler model with no interaction (AIC=1085). Further model reduction was not possible without a significantly poorer fit of models. Consequently, the best model included effects from “yearclass” and “latitude” (Figure 1.3.3). The glm results highlight some outlier yearclasses, for example 2011 which has an overall very high proportion of North Sea fish in contrast to the early years in the time series where proportions were lower.

The analyses of catch per unit effort data for age 0 fish in Q3 from the Skagerrak showed considerable variability between years and general low level after 2011. However, there was no clear relationships between this temporal variation in CPUE and the estimated proportions of North Sea juveniles in the Kattegat across the full time series.

For more results related to the proportion of Kattegat cod within Kattegat, see Section 2.3.

Figure. 1.3.1a. Proportion of cod with Kattegat origin (white) and North Sea origin (blue) from samples in quarter 1. Each pie presents the proportion by sample location. "n" is the total number of cod sampled, "Kat" is the average proportion cod with Kattegat origin and "max" is the number of cod represented by the largest pie on the map.

Figure. 1.3.1b. Proportion of cod with Kattegat origin (white) and North Sea origin (blue) from samples in quarter 3. Each pie presents the proportion by sample location. "n" is the total number of cod sampled, "Kat" is the average proportion cod with Kattegat origin and "max" is the number of cod represented by the largest pie on the map.

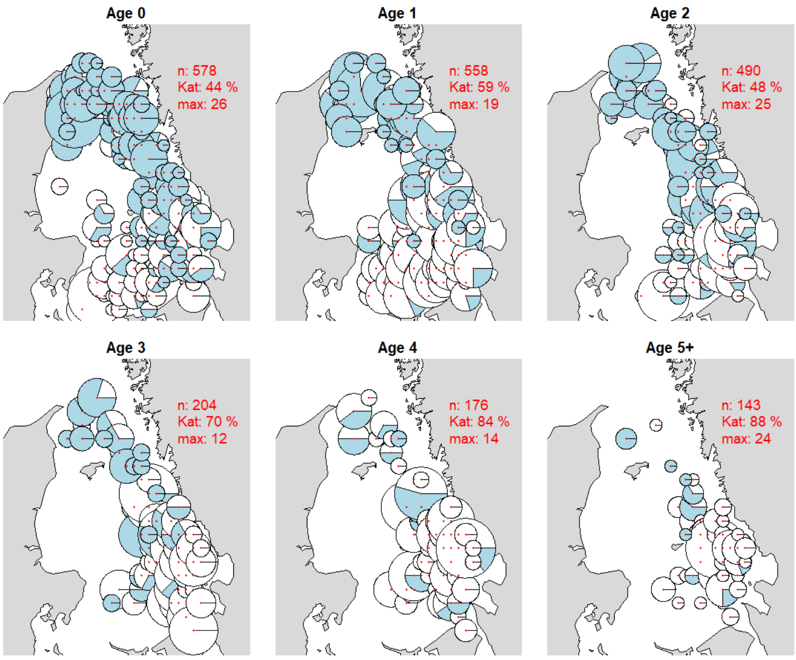


Figure. 1.3.1c. Proportion of cod with Kattegat origin (white) and North Sea origin (blue) from samples in quarter 4. Each pie presents the proportion by sample location. "n" is the total number of cod sampled, "Kat" is the average proportion cod with Kattegat origin and "max" is the number of cod represented by the largest pie on the map.

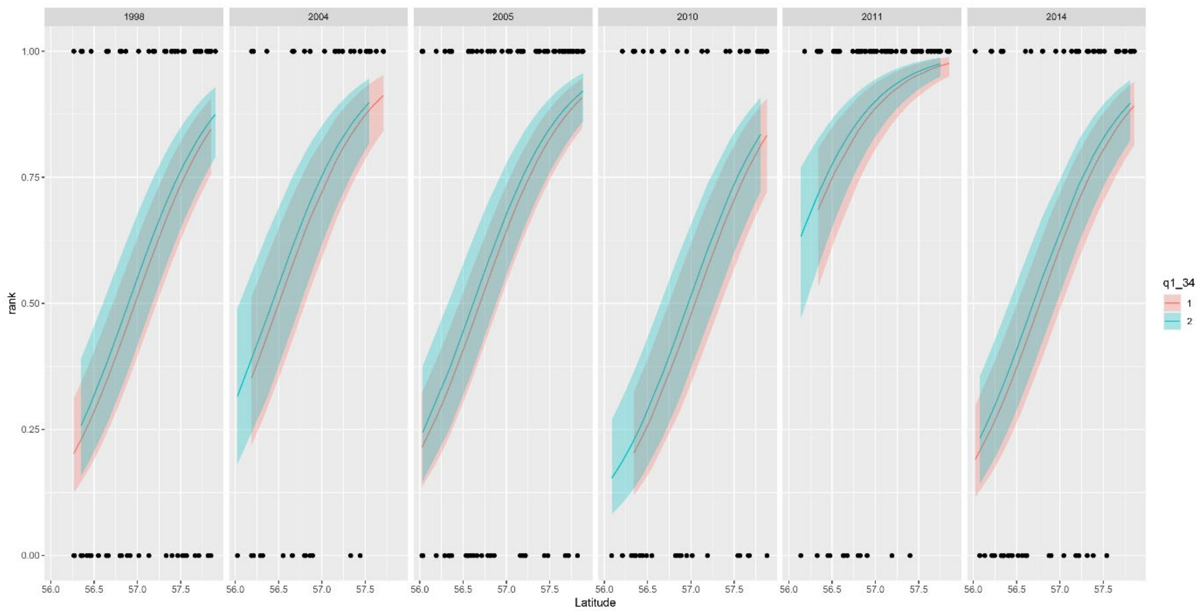


Figure 1.3.2. Predicted probability of assignment to the North Sea (1=North Sea, 0=Kattegat on y axis of plots) as an effect of “yearclass”, “latitude” and “quarter” (red shading=Q1, green shading=Q3/Q4).

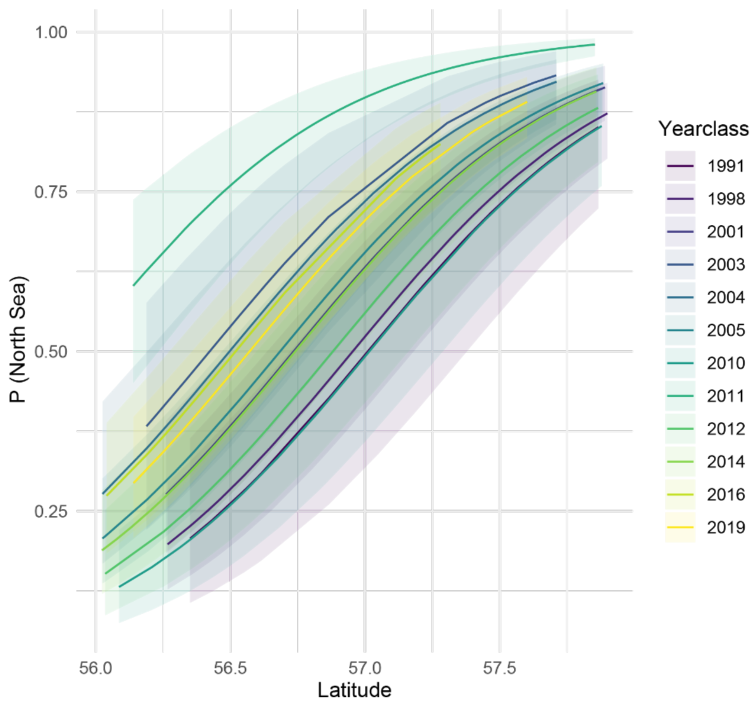


Figure 1.3.3. Predicted probability of assignment to the North Sea (1=North Sea, 0=Kattegat on y axis of plots) as an effect of “yearclass” and “latitude”.

Conclusions

Our genetic analyses found that mixing between North Sea and local Kattegat cod vary both spatially and temporally within the Kattegat. We have confirmed the north to south gradient of mixing proportions with a higher proportion of North Sea fish in the northern parts of the Kattegat. The extended time series provided in the project has also allowed a more detailed understanding of temporal dynamics. Here, we found considerable variability between cohorts, but also that the proportion of North Sea fish tends to decrease around ages 3-4 in the Kattegat. These data are further used in stock assessment modelling (see section 2.3). We were not able to establish a clear role of a potential driver, i.e. production of juveniles in the nearby Skagerrak influencing the inflow of juveniles into the Kattegat. This could indicate involvement of more complex processes and mechanisms in the Kattegat and nearby regions. However, it is possible that future more detailed analyses, for example exploring links to local oceanographic conditions, could reveal relevant links that may be useful for predicting the proportions of North Sea juveniles in the Kattegat. The work in the present project has confirmed genetics as an operational tool for monitoring population components in the Kattegat.

2. Stock assessment analyses

2.1 Eastern Baltic cod - approaches to stock assessment

2.1.1 Analytical stock assessment accounting for changes in stock productivity

An analytical stock assessment for the Eastern Baltic cod was re-established in ICES in 2019 (ICES WKBALCOD2 2019a), after several years of assessment being based on data-limited approaches.

The newly established stock assessment for the eastern Baltic cod uses the features in Stock Synthesis (SS) framework (Methot and Wetzel, 2013) that allow estimating recent changes in natural mortality within the model, as deviations from historical values. To our knowledge, this is so far the only stock in ICES area, for which stock assessment accounts for and estimates changes in natural mortality due to other causes than predation. Similarly to natural mortality, changes in growth parameters are estimated within the assessment model for recent years, as the same factors that increase mortality are also expected to reduce individual growth of the eastern Baltic cod. Technical details of this implementation can be found in ICES (WKBALCOD2 2019a).

Substantial exploratory work was carried out as part of the present project that included exploring among others, different configurations for growth and natural mortality. Age information from traditional age readings is considered uncertain, especially in later years. Therefore, different options for age-length-key, as input to SS model, were explored, and robustness of the assessment results to the uncertainties in age information was evaluated (Fig. 2.1.1). Estimates of growth parameters in recent years from the tagging program (TABACOD project) (Mion et al. 2019, 2020) were also used to validate the change in growth estimated within SS model. The recent tagging confirms the decline in growth compared to the estimates from historical tagging. The exploratory work carried out in the present project contributed to the benchmark process and allowed an analytical assessment for the stock to be re-established. Further details of the exploratory analyses conduced are provided in ICES (WKBALCOD2 2019a).

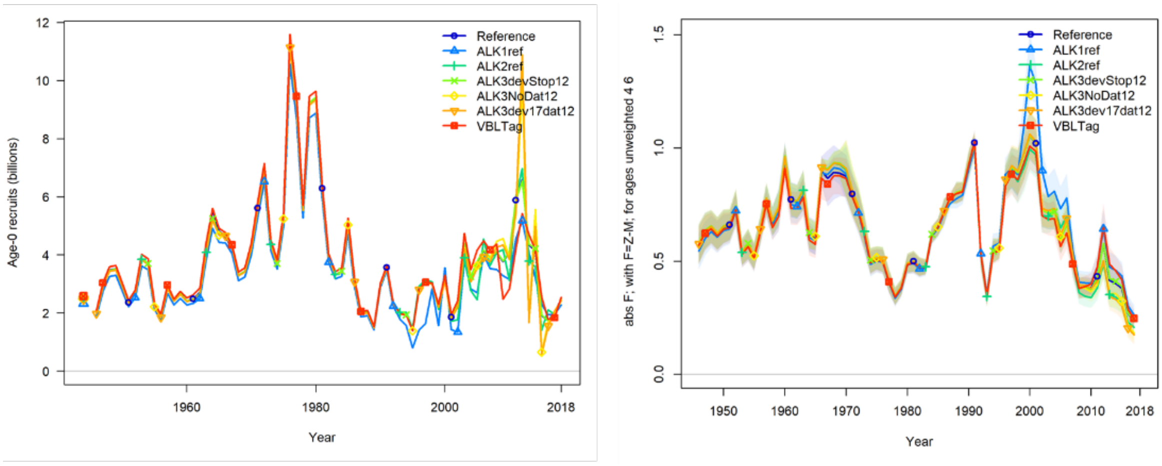


Figure 2.1.1. Recruitment and F estimates from exploratory runs with different growth information (age-length key) (ICES WKBALCOD2 2019*a*).

The results of the established analytical stock assessment revealed a substantial decline in growth and an increase in natural mortality of the eastern Baltic cod (Figure 2.1.2*a*). It is recognized that the two parameters are confounded, also with other parameters of the model, which complicates their estimation. Therefore, validation of the model outcomes with biological evidence is important when accounting for productivity change in a stock assessment model. In case of the eastern Baltic cod, scientific backup to this process was ensured through a series of international workshops dedicated to translating biological knowledge to stock assessment needs (ICES, 2017; 2018). The results of this and earlier related projects (EMFF 33113-B-16-047, 33113-B-17-110, 33113-B-16-071), contributed to this process.

The established stock assessment accounting for reduced growth and increased natural mortality revealed alarming developments in the surplus production of the stock. Surplus production (*SP*) is the net sum of recruitment, growth, and survival from natural mortality, some of which is removed in the form of fisheries catch (*C*). Using the total biomass (*B*) estimated from stock assessment, *SP* for each year *y* can be calculated as:

$$SP_y = B_{y+1} - B_y + C_y$$

Surplus production of the eastern Baltic cod is estimated to have continuously declined since the 1980s, with no surplus production in the stock at present (Fig. 2.1.2*b*).

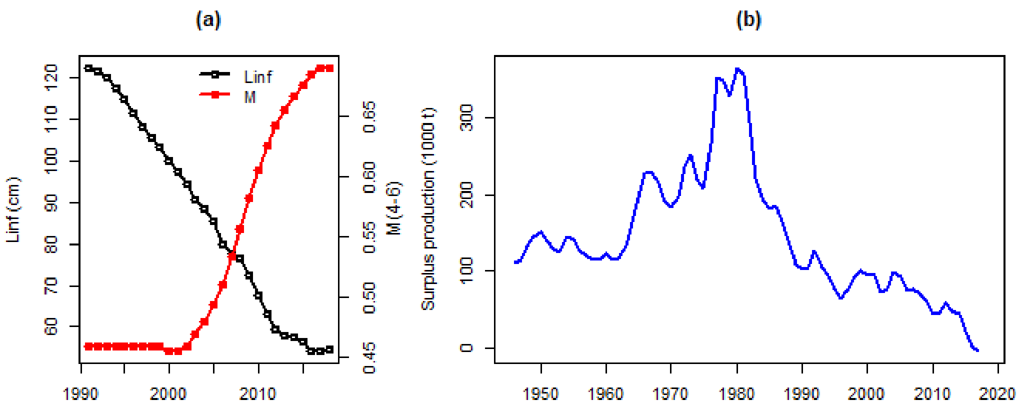


Figure 2.1.2 (a) Developments in natural mortality (M, average for ages 4–6) and von Bertalanffy growth parameter L_{inf} for the eastern Baltic cod, estimated in the stock assessment (ICES, 2019*b*). (b) Surplus production of the eastern Baltic cod, calculated from the stock assessment results (ICES, 2019*b*).

It is recognized that the exact values for growth and natural mortality estimated in the current stock assessment (SS), i.e. separating between the two, is associated with some uncertainty. This is mostly because the age-length-key information to inform growth is imprecise and the two parameters are biologically interlinked and thus confounded in the model. However, the sensitivity analyses conducted as part of this project showed that the results of stock assessment in terms of stock status were robust to these uncertainties associated with separating between natural mortality and growth, i.e. the stock dynamics and estimates were similar for all options explored (Figure 2.1.1). Furthermore, validation of the growth estimates obtained from stock assessment with new method based on microchemistry of the otoliths, conducted within this project (see section 1.1.1), confirms a reasonable quality of the growth estimates used in present stock assessment.

Conclusion

Quantitative stock assessment for the eastern Baltic cod was re-established that revealed alarming developments in productivity of the stock. Natural mortality has substantially increased, growth has declined and there is basically no surplus production in the stock at present to sustain harvest. Today, partitioning natural mortality and growth in stock assessment is still somewhat uncertain (ICES, 2019*a*). However, the stock status obtained from stock assessment is robust to these uncertainties and there is no doubt about that a substantial decline in stock productivity has occurred.

2.1.2 Estimating spawning stock biomass from egg production method

As an alternative approach to obtain information on stock dynamics of the Eastern Baltic cod, egg production methods were developed and applied for the stock. Egg production methods (EPM) allow for estimation of fish stock size based on egg abundance data from ichthyoplankton surveys. Thus, EPMs allow providing fishery independent estimates of spawning stock size and dynamics of fish populations. This is especially useful in situations like the Eastern Baltic cod, where the traditional stock assessment involves uncertainties associated with large changes in growth as well as natural mortality.

Ichthyoplankton surveys have been carried out regularly in the central and eastern Baltic Sea since the 1950s, and have been internationally coordinated since the 1980s, however hitherto not used for stock assessment purposes. For the application of EPMs, we used data for the period 1991–2018 from the current main spawning area of the Eastern Baltic cod, i.e. Bornholm Basin (Köster et al., 2017). Several surveys have been conducted in Bornholm Basin in each spawning season, covering regularly April, May, July and August.

We applied both the annual and daily egg production methods. The two egg production methods, based on annual (AEP) or daily (DEP) egg production require different types of data. The AEPM requires full egg survey coverage of the spawning season to estimate the annual egg production, which is especially demanding in case of species with long spawning season, like the Eastern Baltic cod. The DEPM requires an estimate of the daily egg production at peak spawning time as well as the individual spawning frequency, i.e. how many females participate in spawning at a given date. Both the AEPM and DEPM use additionally a measure of individual egg production, here relative fecundity, i.e. eggs produced per g body weight as well as sex ratios to convert egg production into spawning stock biomass.

In case of the Eastern Baltic cod, application of the DEPM approach is complicated by possible changes in duration of the spawning time in recent years resulting from a truncated size structure of the stock. The AEPM does not make assumptions about the individual spawning duration, however, it requires full coverage of the spawning season, which was achieved in most, but not in all years. Despite some deviations, overall the AEPM and DEPM produced similar stock trends for the Eastern Baltic cod, which are also in line with the stock trends from bottom trawl surveys (Fig. 2.1.3). This confirms that the different uncertainties associated with two EPMs are not seriously compromising the SSB trends. Further, similar stock trends derived from the two EPMs and bottom trawl surveys is assuring that the latter is not seriously affected by catchability changes that has been as concern earlier (ICES, 2014).

Further details on the data and analyses associated with application of the EPMs for the Eastern Baltic cod are provided in Köster et al. 2020.

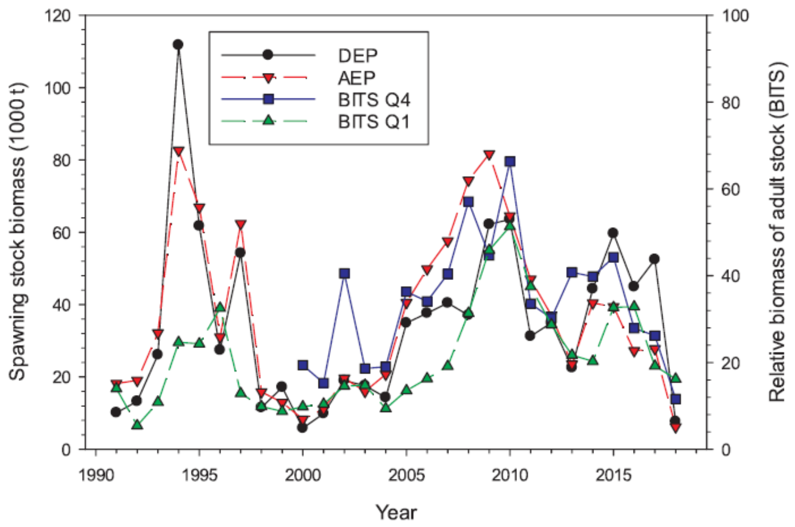


Figure 2.1.3. Spawning stock biomass estimated by the Daily egg production (DEP) and the Annual egg production (AEP) method for the Bornholm Basin in 1991–2018 in comparison to relative trends in adult stock biomass from the 1st and 4th quarter Baltic International Trawl Survey (BITS) in Subdivision 25–32 (from Köster et al. 2020).

Conclusion

The uncertainties in parameters involved in egg production methods (EPMs) impact mainly on the absolute spawning stock size estimates, less on the relative stock trends. Thus, the EPM based estimates can be included as relative stock indices in stock assessments of the Eastern Baltic cod, as implemented in latest benchmark for the Baltic cod stocks (ICES WKBALCOD2 2019*a*). Importantly, the EPM based stock estimates confirm the current poor status of the stock, with the spawning stock biomass estimated close to the lowest in record in 2018. Given the number of uncertainties in traditional stock assessment, e.g. related to changes in growth and natural mortality (ICES, 2019a), the additional information from EPMs on stock status and dynamics is considered highly valuable and useful.

2.2 Western Baltic cod – impact of recreational catch

Data and methods

One of the key data issues for stock assessment of the western Baltic cod is recreational catch, especially the historical part of the time series, which is based on a number of assumptions, because collection of recreational catch information started relatively recently. In this project, we focused on investigating the impact of the assumed historical recreational catch values on evaluation of contemporary stock status as well as on management advice regarding catch limits. To do so, we used the input data and settings as in the official ICES stock assessment from 2019 (ICES 2019*b*) as the basis, referred to as *Baseline* scenario.

The impacts of two variables related to recreational catch input were explored; i.e. the amount of recreational catch in weight (*Recrea*) (Fig. 2.2.1) and age composition of recreational catch (*AgeR*) (Fig. 2.2.2). The impact of both variables in combination was also explored.

Different scenarios were run to investigate the value of adding more years of “correct” information on recreational catch. In other words, we explored, to what extent the stock assessment result moves away from the observed result, when the actual recreational catch information is replaced by random values for certain number of years in the past.

The investigated scenarios included the actual recreational catch data, as used in official stock assessment, for 0 or for the last 1, 3, 5, 10, 15, 20 and 30 years. For the other years in a given scenario, random values were applied. The assessment time series used for these analyses covers 34 years. Thus, the scenario with 30 years of actual recreational catch data applied random values only for the 4 earliest years in the time series. While the scenario with 0 years of actual data applied random values for all the years in the timeseries.

The random values applied in the scenarios were obtained as follows:

> **Recrea:** We randomly varied the annual recreational catch amounts, within the range of observed values. In each scenario, the annual recreational catch was then converted to numbers and incorporated in total catch numbers input for stock assessment.
>
> **AgeR:** The relative age composition of recreational catch applied for a year in a given scenario was randomly drawn from the observed annual age compositions. This age composition was subsequently applied on observed recreational catch amount in a given year, and incorporated in catch numbers input for stock assessment.

For each scenario, 500 replicates were run. For each scenario replicate, the following steps were subsequently applied:

Stock assessment was run with the modified input, using all other inputs as in the official stock assessment and the SAM model with the same settings as applied in formal stock assessment for this stock.

The assessment results from each scenarios (for each of the replicates) were used to estimate corresponding biomass limit reference point (Blim), using the same principal as applied in the current official stock assessment. This implies that Blim was set to average of the 4 lowest SSB values that had given raise to above average recruitment.

As a next step, FMSY was recalculated for each scenario, using the Eqsim program, and following the standard procedures applied for this stock in ICES. Stock-recruitment relationship was defined as a hockey stick, with the break point set to the estimated Blim for a given scenario. Biology (weights, maturity) and fisheries selectivity were used as average for the years 2015-2018.

SSB/Blim and F/Fmsy ratios were calculated for each scenario (for each of the replicates.

Catch advice for one year ahead, corresponding to FMSY, was subsequently calculated.

All scenario results are presented in relative terms, as a percentage difference from the *Baseline* scenario.

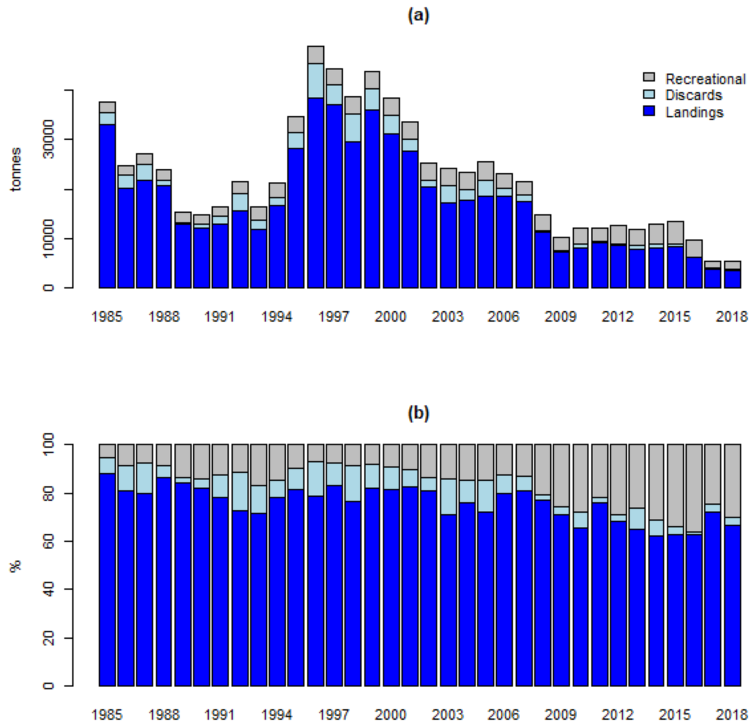


Figure 2.2.1. Panels (a) and (b) show contribution of commercial landings, commercial discards and recreational catch to the total catch from the western Baltic cod stock, in tonnes (a) and in percentage (b). Data from ICES 2019*b*.

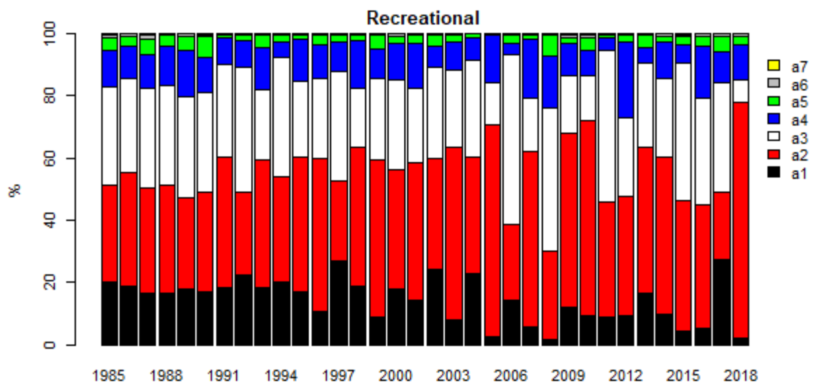


Figure 2.2.2. Relative age composition (in %) of recreational catches. Data from ICES 2019*b*.

Results

Spawning stock biomass

Recreational catch has contributed between 5 - 35% of the total catch of the western Baltic cod stock during the assessment time series from 1985 to 2018. The proportion of recreational catch has generally increased in the later part of the time series, with lower proportions in earlier years. Consequently, when applying random recreational catch amounts to the entire time series from the observed range, largest deviations (>10%) in SSB from the baseline scenario were obtained for the early and later part of the time series, with generally <5% deviations in intermediate years (Fig. 2.2.3). This is probably because in the earlier and later years the scenarios included recreational catch values from the opposite end of the observed range compared to the catches.

Applying random recreational catch amounts for the entire time series resulted in SSB deviations from the baseline mostly below 10%, but with deviations up to 20% in some scenarios in latest years (Fig. 2.2.3). Applying actual recreational catch amount for more years reduced gradually the deviation from the baseline in later years. In scenarios that applied 10 years of actual recreational catch amounts, the deviation from baseline was mostly below 5%, with the exception of some early years in the time series. The deviation up to 10% in biomass in the early years of the time series remained even when applying 30 years of actual catch data.

In scenarios exploring the impact of age composition of recreational catch, the maximum biomass deviation from the baseline in most recent years was higher (>25%) than in scenarios varying catch amounts, when applying random values for all years. However, in the scenarios applying actual age composition for just one or more years, the SSB deviations were generally lower compared to catch amount scenarios. Especially the impact on historical part of the time series was less compared to catch amounts. When applying 10 years of actual age composition data, the SSB deviation was >10 % only in few scenarios in latest year of the time series, otherwise being mostly <5% (Fig. 2.2.3).

In scenarios varying both the recreational catch amounts and age composition at the same time, SSB deviations from the baseline were largest, as expected. When applying random values for all years, deviations in SSB were up to 20% in the historical part and >30% in most recent years. With 10 years of actual data, the SSB deviations were mostly reduced to <10% apart from a few years and scenarios in the early part of the time series.

Fishing mortality

In terms of fishing mortality, most pronounced deviations from the baseline (up to 100%) were obtained for latest years when applying random recreational catch amounts or age compositions for all years (Fig. 2.2.4). The deviations were significantly reduced already with one year of actual data and with 3 years of actual data, the deviations in F were mostly below 10%, with a few exceptions. This is both in scenarios varying catch amounts or age compositions or both. When applying random values for all years, the deviations in F in latest years were larger in catch amounts scenarios compared to age composition scenarios. However, after 3 years of actual data, the deviation in F became generally somewhat lower for catch amounts scenarios compared to age composition scenarios (Fig. 2.2.4). Small deviation (<5%) remained when applying actual data for 30 out of 34 years in the time series (Fig. 2.2.4).

Spawner biomass relative to Blim
For stock status evaluation and catch advice, the impact of recreational catch assumptions on assessment results for the last years in the time series are essentially important. Also, the results should be seen relative to management reference points that maybe influenced by recreational catch values as well. In these analyses, up to 50% deviation from the baseline was obtained for SSB/Blim ratio for first forecast year, when applying both random recreational catch amounts and age compositions for all years in the assessment time series. Most of the deviation was due to varying age compositions, while only up to 25% deviation was obtained from the scenarios of catch amounts. Applying just one year of actual data resulted in a significant drop in the deviations, though still being up to 20% for catch amount and 30% for age composition, and 45% for combination of both. When applying 3 years of actual data, the deviations dropped to below 15%, and remained similar when 20 years of actual data were applied. Only in scenarios applying actual data for most of the years (30 years) in the time series, the deviations in SSB/Blim from the baseline became negligible (Fig. 2.2.5).

Fishing mortality relative to FMSY
For fishing mortality relative to FMSY, the deviations in last assessment year from the baseline were very large when applying random recreational catch amounts (up to 100%) or age compositions (up to 80%), or both (up to 130%) for all years. However, already when applying one year of actual recreational data reduced the deviations in final assessment year to maximum 50% when varying both catch amounts and age compositions and less for the scenarios exploring these individually. Similarly to SSB, when applying actual data for 3-20 years resulted in similar deviations in F/FMSY for final assessment year, i.e. up to 15%, but mostly below 10%. Only when applying actual data for 30 years, reduced to deviations to become negligible (<5%) (Fig. 2.2.5).

Catch corresponding to FMSY
The impact on recreational catch on the total catch corresponding to FMSY two years after the last assessment year, that would correspond to catch advice in ICES was as well investigated. When applying random recreational catch data for all years, the catch advice deviation from the baseline was up to 40% in scenarios varying catch amounts, up to 50% in scenarios varying age composition of recreational catch and up to 60% when varying both. Applying one year of actual recreational data reduced the deviations in catch advice from the baseline to max 25% for catch amounts and 20% for age compositions, still resulting in up to 45-50% deviation when varying both. In scenarios applying actual recreational catch data for 3-20 years, the catch advice deviation from the baseline was similar, i.e. up to ca 15 % for catch amount and age composition individually and up to 20% when varying both. In scenarios applying actual recreational data for 30 years, the deviation of catch advice from the baseline became negligible (mostly far below 5%) (Fig. 2.2.5).

Conclusion
The analyses showed that historical recreational catch amounts as well as age compositions not only impact on the assessment results for particular years in the past, but the impacts are propagated through the time series, impacting also the results for more recent years. This may be due to specifics of the stock assessment model used in these analyses that is making use of the entire time series when fitting the model. Only when applying the actual recreational data for most years in the time series, the deviations of the results from the baseline became negligible.

However, the deviations became remarkably smaller already when applying actual data just for one most recent year, compared to random values for the entire time series. When actual recreational catch values were applied for at least 3 most recent years, the deviations of stock status evaluation or potential catch advice from the baseline where reduced in most cases to below 10-15%, in the analyses investigated. This demonstrates that it is worthwhile to consider improvement of recreational catch data also when it is only possible for few most recent years. Varying catch amounts or age compositions within their observed ranges resulted in generally similar magnitude of deviations, without a clear indication that one of these types of data would be more influential for the results than the other.

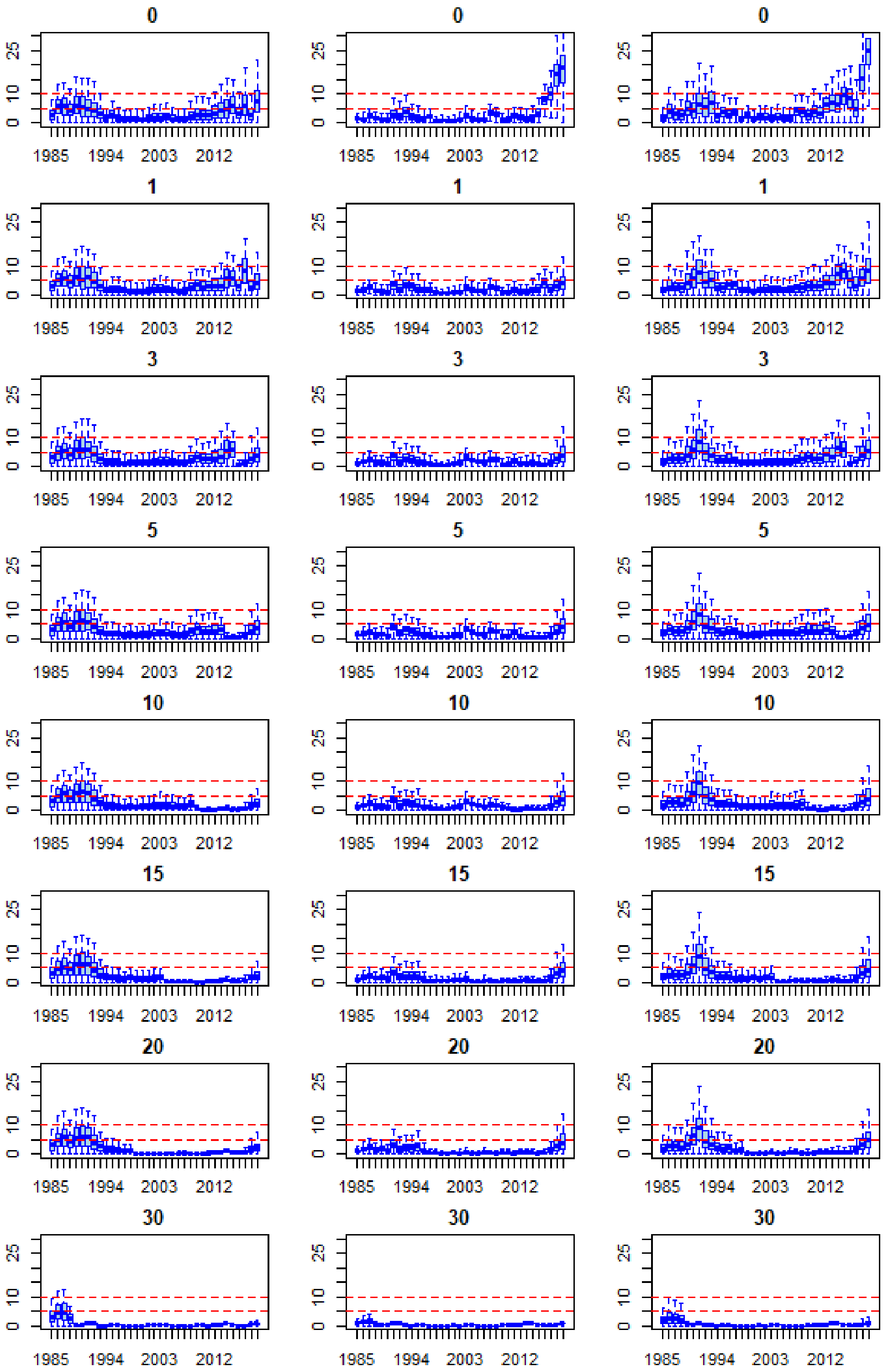


Figure 2.2.3 Spawning stock biomass (SSB) from scenarios relative to official stock assessment (Y-axis shows percentage difference, red lines mark 5 and 10% difference). The panels show scenarios applying actual recreational catch data for 0, 1, 3, 5, 10, 15, 20 or 30 last years in the time series, and randomly selected values for other years. Results are shown separately for recreational catch amounts (left panels), age composition (middle panels) and combination of both (right panels). Bars on panels represent variation of results from 500 replicates run for a given scenario.

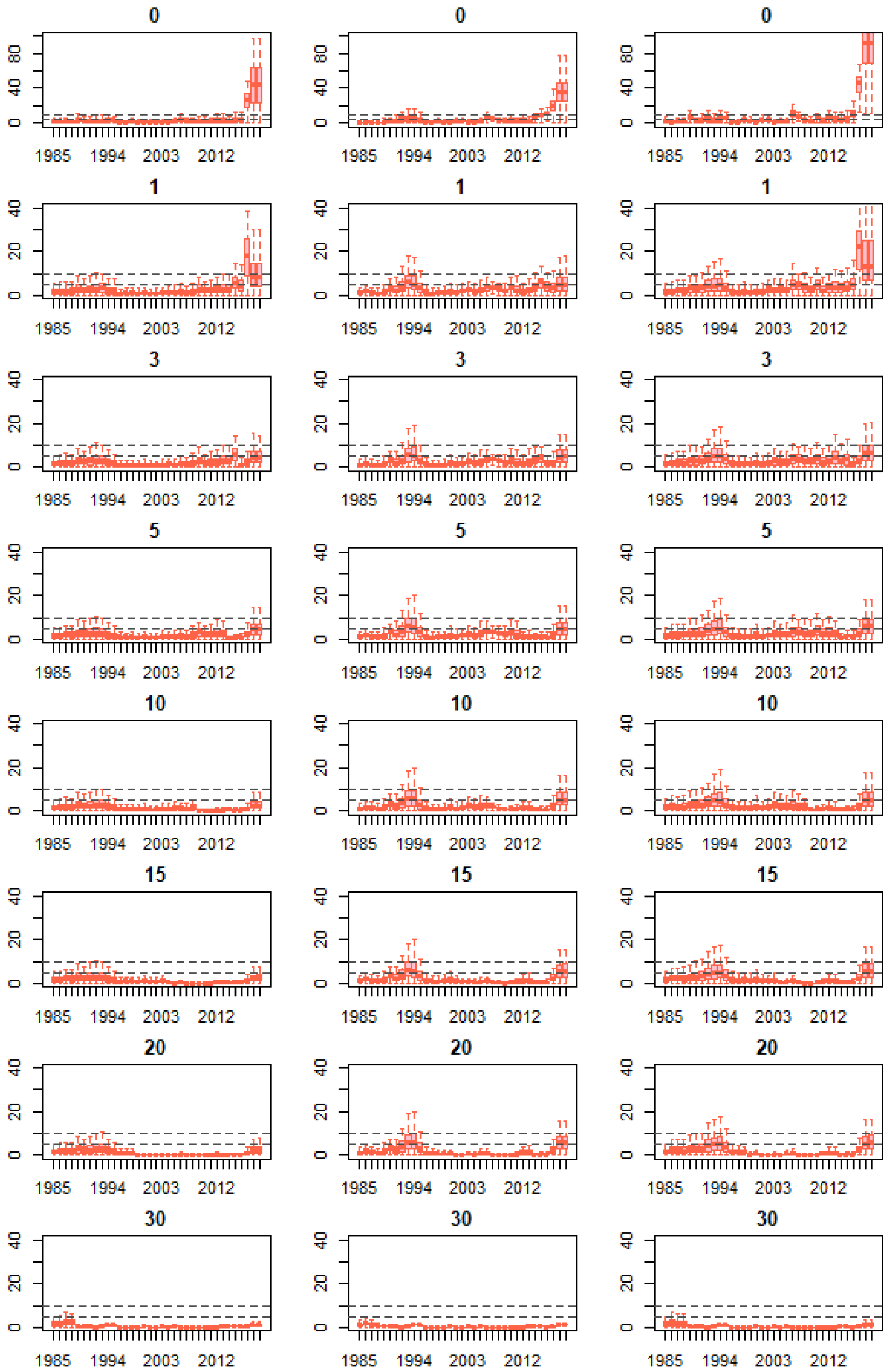


Figure 2.2.4. Fishing mortality (Fbar) from scenarios relative to official stock assessment (Y-axis shows percentage difference). The panels show scenarios applying actual recreational catch data for 0, 1, 3, 5, 10, 15, 20 or 30 last years in the time series, and randomly selected values for other years. Results are shown separately for recreational catch amounts (left panels), age composition (middle panels) and combination of both (right panels). Bars on panels represent variation of results from 500 replicates run for a given scenario.

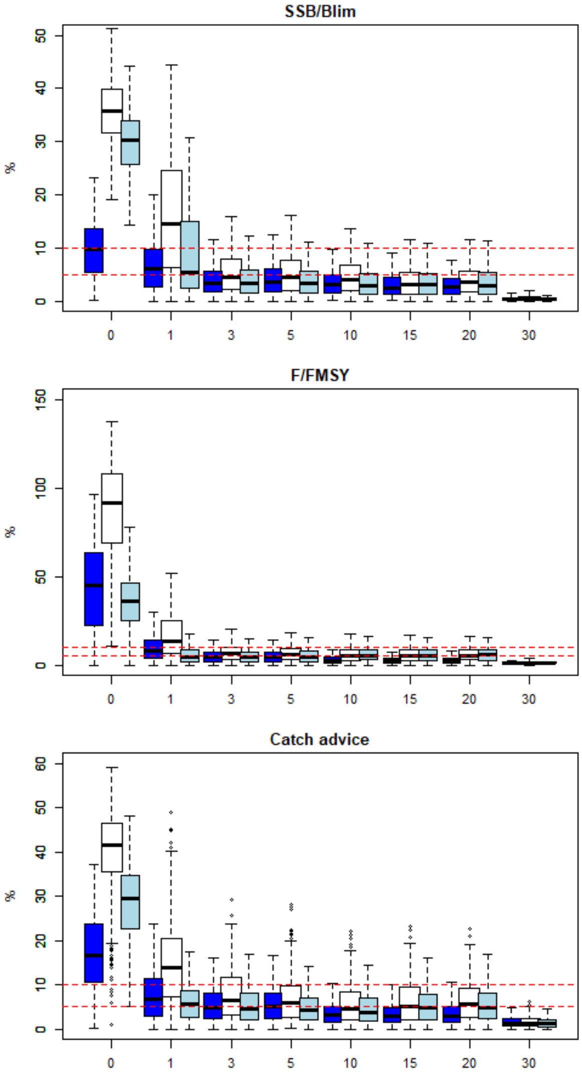


Figure 2.2.5. Impact of recreational catch data on stock status evaluation: SSB relative to Blim in first forecast year (upper panel); Fbar relative to Fmsy in last assessment year (middle panel) and on corresponding FMSY catch advice for two years later then the last assessment year (lower panel). All scenario results, represented by bars, are shown as percentage difference from the *baseline* scenario (Y-axis). The different colors for bars show the results for scenarios varying recreational catch *amount* (dark blue); *age composition* of recreational catch (light blue) and combination of both (white). X-axis shows the number of years for which actual recreational catch data are applied, while applying randomly drawn values for the rest of the years in the time series.

2.3. Kattegat cod – stock mixing

Background

ICES stock assessments of cod in the Kattegat management area have shown that for some cohorts of cod, abundance indices from scientific surveys indicate a much faster stock reduction than possible induced by reported catches. By raising catches (landings and discards) by a year dependent factor estimated by the assessment model (SAM), it has been shown that the model fit become better for both (raised) catch at age and survey indices at age. ICES notes that this “unallocated mortality” due to catch scaling could comprise both unreported catches and biology-driven factors, e.g. migration or predation by seals (ICES 2017b). At present, ICES is not in a position to quantify the proportions of “unallocated mortality” due to fishing or other sources.

Cod migration out the Kattegat area is occurring, possibly linked to natal homing of North Sea cod or food migration. Genetic analysis has shown that for some years, the majority of juvenile (ages 0 and 1) cod in Kattegat are of North Sea origin (spawned in the North Sea) and that the proportion of North Sea cod within Kattegat decreases by age (see section 1.3).

An assessment model for cod in Kattegat should take into account the inflow of North Sea cod and their later return to the area where they were spawned (natal homing). Stock origin in historical catch and survey data has not been sampled sufficiently to model the two components as separate stocks. Instead an “one stock” model like SAM can be modified to handle the assessment of cod in Kattegat given a number of assumptions:

i) Inflow of North Sea cod into Kattegat takes mainly place at the juvenile stage, such that the proportion of juvenile cod within Kattegat with Kattegat origin (P) is practically fixed at age 1 for a cohort.
ii) Migration back to the North Sea of cod spawned in the North Sea is assumed to mainly take place as the cod mature (natal homing), which can be considered as an age dependent process following the rate of sexual maturation. Potential food migrations, in and out of Kattegat, for both components are not explicitly handled, but may be part of the estimated migration.
iii) Natal homing) can be described as a continuous migration with an instantaneous “mortality” rate (L for leave) at age.
iv) Fishing mortality (F) and natural mortality (M) within the Kattegat area are assumed to be the same for the two stock components.

The main purposes of this analysis is to provide data on the relative strength of juveniles for the two stock components (parameter P) for each cohort and secondary to estimate the return migration (parameter L) of the North Sea component. This is done from analysis of samples of individual cod where the origin (Kattegat or North Sea) is known. As sampling of genetic data have not been sufficient in most years, one of the model approach presented assumes a gradual changes in inflow of North Sea, which allow estimation of the P and L for all years. The probably more realistic model where inflow of cod is not correlated between years is also tried, even sampling from some year classes of cod has been very limited or missing. For comparison, the parameter L is also derived without genetic samples, but from data on the proportion of sexual mature individuals, given the assumption of migration due to natal homing.

Data and methods

The analyses presented here include data on genetics of cod caught in the Kattegat area, where each observation for individual cod includes probability for stock assignment (Kattegat or North Sea origin) and various other variables such as, sample longitude and latitude, cod length and age (see also section 1.3). Additionally, data from the ICES stock assessment of the Kattegat cod were used, available from https://www.stockassessment.org, run “codkat2020” and include ages 1 to 6+ for the period 1997-2020.

The proportion of cod in the Kattegat with Kattegat origin (P) and the instantaneous return rate of North Sea cod (L) are estimated from samples of stock origin of individual cod. The estimates of L is compared with and alternative estimate of L derived from the proportion sexual mature as used in stock assessment. Estimated values of P and L are afterwards applied in a modified assessment model for the Kattegat stock.

Proportion of Kattegat cod
The proportion of cod in Kattegat with Kattegat origin (P) at a given age and catch position (longitude and latitude) was modelled using a Generalized Additive Model (GAM) with a binomial distribution and a logit link function. Two models were explored:

$$P \sim \alpha + random(yearclass) + f1(lon, lat) + f2(age) + \varepsilon \quad (1)$$
$$P \sim \alpha + f3(yearclass) + f1(lon, lat) + f2(age) + \varepsilon \quad (2)$$

where f1, f2 and f3 are smoothing functions, “yearclass” is a covariate and reflects the proportion of recruits present in Kattegat with Kattegat origin for a given year class or cohort. This term is modelled as a random effect in model 1, such that each cohort may have a unique value, or as a numerical values in model 2, where the smooth function f3 allows a gradual change in year class effect between years. “age” is the age of the cod in continuous time, assuming “birthday” the 1. January.

For assessment modelling, the year class model term provides proportion of Kattegat cod at recruitment age and the f2(age) model term provides estimates on the change in proportion over ages and thereby a measure for parameter L. Model 1 can only estimate P for the year classes sampled, while model 2 estimates P values for all years, given the assumption that proportion of North Sea recruit in Kattegat is mainly determined by the relative strength of the spawning biomass for the two cod populations, which will gradually change between years. The average population P at ages for each cohort were calculated as a mean of predicted P at a given location weighted by the relative population density estimated from another GAM model of survey trawl catch. This population model used a Tweedie distribution and a power function link, with model terms as shown below:

$$catch \sim \alpha + yearclass + f1(lon, lat, age) + f2(age) + f3(depth) + survey + \varepsilon \quad (3)$$

the model term “catch” is the number of caught cod at age, “survey” is one of four surveys (ICES NS-IBTS, ICES BITS, Danish Cod survey and Danish Sole survey), and depth is the average depth at the fished location. The logarithm of the duration of the haul was used as offset variable in the model. 3725 hauls from the period 1997-2020 and quarters 1, 3 and 4 were used as input to the model.

The survey catches, and the genetic samples mainly done during these surveys, cover the main distribution area of cod. With the assumption that the surveys cover the main distribution area, all trawl stations from the entire time series were used to make a set of 1 minutes (longitude and latitude) grid cells, such that each grid cell includes at least one survey trawl haul. The centre of these grid cells from this set, together with the mean depth within the cell, was used to predict local abundance of cod from model 3 and the proportion Kattegat cod from model 1 or 2. The average proportion cod of Kattegat origin within the Kattegat stock area was finally calculated as a weighted mean of the predicted proportions weighted by the predicted abundance in each grid cell.

When the average proportion of Kattegat origin is known, the instantaneous rate of return (L) of the North Sea component to the North Sea can be determined:

$$L_{y,a} = -\log(\frac{P_{y,a}}{1-P_{y,a}} / \frac{P_{y+1,a+1}}{1-P_{y+1,a+1}})$$

Return migration estimated based on maturity

Given the assumption that migration is due to natal homing and that no migration back to the Kattegat

takes place after spawning in the North Sea, the observed proportion sexual mature at age as used in the assessments (Table 2.3.1) can be used to estimate migration.

Table 2.3.1. Average proportion mature by stock and age since 1997, as derived from ICES assessment data.

	Age 1	Age 2	Age 3	Age 4	Age 5	Age 6+
North Sea	0.03	0.30	0.64	0.84	0.95	1
Kattegat	0.00	0.49	0.82	0.95	1.00	1

Given the assumption of natal homing migration follows the proportion mature for the North Sea and, e.g. 30% of the age 1 stock of North Sea origin will have returned to the North Sea at spawning time (1st January) at age 2, while the rest (70%) will remain in Kattegat.

The instantaneous return rate (L) can be calculated from proportion mature (S) for the first age that matures as:

$$L_{y,a} = log(\frac{1}{1-\ S_{y+1,a+1}})$$

For older ages L becomes:

$$L_{y,a} = log(\frac{1-S_{y,a}}{1-S_{y+1,a+1}})$$

Modifications to stock assessment model

The developed assessment model for cod in Kattegat is an extension of the presently used SAM model, which operates with one stock only and does not provide input data like catches or survey indices by stock components. The inflow of North Sea cod as recruits by year (y) and thereby the annual proportion of recruits (age=1) with Kattegat origin (Py,a=1) is assumed known for some, but not all cohorts, so the vector P is a combination of parameters to be estimated within the SAM model and input values. Recruiting stock numbers (N) with Kattegat origin (O=kat) are determined from total stock number within the Kattegat area and the proportion with Kattegat origin (Py,a).

$$N_{o=kat,\ y,\ a=1} = N_{y,a=1} * P_{y,a=1}$$

Similarly for the North Sea component (O=nor)

$$N_{o=nor,\ y,\ a=1} = N_{y,a=1} * (1 - P_{y,a=1})$$

The proportion of Kattegat cod for older ages in the first assessment year (Py=first year, a>1) is also a parameter to be estimated by the model or given as input.

Cod are spawning in the first quarter of the year, but for model purposes it is assumed that spawning takes place the 1st January. Natal homing are described by an instantaneous rate of migration (La), (L for leave) such that stock numbers of the North sea component within Kattegat becomes

$$N_{o=nor,y+1,a+1} = N_{o=nor,y,a} * e^{-(F_{y,a}+M_{y,a})} * e^{-(L_a)}$$

While stock number for the Kattegat component is just reduced by natural mortality (M) and fishing mortality (F)

$$N_{o=kat,y+1,a+1} = N_{o=kat,y,a} * e^{-(F_{y,a}+M_{y,a})}$$

M and F are assumed the same for the two stock components.

With known P and L, the total stock number one time step ahead for a cohort is the sum of the Kattegat and North Sea components:

$$N_{y+1,a+1} = N_{o=kat,y+1,a+1} + N_{o=nor,y+1,a+1}$$

$$\begin{aligned} &= N_{y,a} * P_{y,a} * e^{-(F_{y,a}+M_{y,a})} + N_{y,a} * (1 - P_{y,a}) * e^{-(F_{y,a}+M_{y,a})} * e^{-L_a} \\ &= N_{y,a} * e^{-(F_{y,a}+M_{y,a})} * (P_{y,a} + (1 - P_{y,a}) * e^{-L_a}) \\ &= N_{y,a} * e^{-(F_{y,a}+M_{y,a}+m_{y,a})} \end{aligned}$$

Where m is defined as

$$m_{y,a} = -log(P_{y,a} + (1 - P_{y,a}) * e^{-L_a})$$

Catch numbers at age (C) within a year becomes the sum of catches from the two components:

$$\begin{aligned} C_{y,a} &= \frac{F_{y,a} * N_{y,a} * P_{y,a} * (1 - e^{-(F_{y,a}+M_{y,a})})}{F_{y,a} + M_{y,a}} + \frac{F_{y,a} * N_{y,a} * (1 - P_{y,a}) * (1 - e^{-(F_{y,a}+M_{y,a}+L_a)})}{F_{y,a} + M_{y,a} + L_{y,a}} \\ &= F_{y,a} * N_{y,a} * \left(\frac{P_{y,a} * (1 - e^{-(F_{y,a}+M_{y,a})})}{F_{y,a} + M_{y,a}} + \frac{(1 - P_{y,a}) * (1 - e^{-(F_{y,a}+M_{y,a}+L_a)})}{F_{y,a} + M_{y,a} + L_a}\right) \end{aligned}$$

Stock numbers at time t within a year, used in SAM to predict survey observations from stock numbers are calculated from the two components in a similar way:

$$\begin{aligned} N_{y+t,a} &= N_{y,a} * P_{y,a} * e^{-t*(F_{y,a}+M_{y,a})} + N_{y,a} * (1 - P_{y,a}) * e^{-t*(F_{y,a}+M_{y,a}+L_a)} \\ &= N_{y,a} * e^{-t*(F_{y,a}+M_{y,a})} * (P_{y,a} + (1 - P_{y,a}) * e^{-t*L_a}) \end{aligned}$$

P for the next time step can be calculated from the previous P in the cohort and migration:

$$P_{y+1,a+1} = \frac{N_{o=kat,y+1,a+1}}{N_{y+1,a+1}}$$
$$= \frac{N_{y,a} * P_{y,a} * e^{-(F_{y,a}+M_{y,a})}}{N_{y,a} * e^{-(F_{y,a}+M_{y,a})} * (P_{y,a} + \ (1 - P_{y,a}) * e^{-L_a})}$$
$$= \frac{P_{y,a}}{P_{y,a} + \ (1 - P_{y,a}) * e^{-L_{y,a}}} = \frac{P_{y,a}}{e^{-m_{y,a}}}$$

Stock assessment runs

To the modified SAM model, 3 additional sets of data must be given as input or estimated within the SAM model. This includes:

i) $Pold_a$ - Proportion of Kattegat cod for older ages in the first assessment year ($P_{y=\text{first year}, a>1}$).
ii) $Pjuv_y$ - Proportion of Kattegat cod for recruiting year-class in all assessment years ($P_{y, a>1}$).
iii) L_a - Return rate by age of North Sea cod, assumed independent of year.

Several model configurations of the modified SAM model were evaluated:

Default: SAM configuration as applied by ICES official assessment (ICES 2021), with and without catch scaling for the period since 2003.

conf01: $Pold_a$, calculated from average P_a, as input. $Pjuv_y$ and L_a estimated by Model 2. For the years without $Pjuv_y$ data, an average Pjuv was used. Runs were made with and without catch scaling.

conf02: As conf01, but $Pjuv_y$ were estimated within SAM for years without data. With and without catch scaling.

conf03: As conf02,but $Pjuv_y$ were additionally estimated within SAM for the up to years with low sampling of the year class. Runs made only without catch scaling.

conf04: Return rates of North Sea cod derived from proportion mature as used in the ICES assessment. $Pjuv_y$ were estimated within SAM with assumed constant values in 4 blocks with 9, 5,5, and 5 years. With and without catch scaling.

Results

Proportion of Kattegat cod

The two models for proportion Kattegat origin gave similar results, but model 2 gives a slightly better fit on the cost of a much higher number of parameters:

	df	AIC	Dev. explained	R-sq.(adj)
model 1	45.9	3220.0	0.30	0.36
model 2	102.9	3194.9	0.34	0.38

All model terms were significant, except the age term in model 2, which was finally excluded.

Model 1 estimates of the age effect on a logit scale show a clear increase by age in the proportion of cod with Kattegat origin up to age 6. Year class effect is modelled as a random intercept that allows different inflows of recruits from the North Sea cod each year. There is almost no difference in the year class effect estimated by model 1 and model 2.

Model 1 has a year independent spatial distribution (on a logit scale) which is scaled by the year class strength and age effects, while model 2 allows a gradually temporal change in the spatial distribution between ages. The estimated spatial distributions are therefore different for the two models. Examples of estimated proportion Kattegat origin for the year classes 2010-2015 with relative high sampling level (Figure 2.3.1) show that the proportion of Kattegat cod is lower than 50 % for most of the northern Kattegat for ages 1-3. The proportion of Kattegat cod increases by age such that a rather limited area of Kattegat has less than 50 % Kattegat cod for cod older than 3. There is a large difference between year classes, for example, the 2010 year-class had a relatively low, and 2011 year-class a high proportion of North Sea cod (Fig. 2.3.1)

The stock distribution, irrespective of origin, estimated from model 3 shows a gradual change in spatial distribution with age, with recruits mainly distributed in the northern Kattegat, while older cod are mainly found in the south-eastern part. Model 3 assumes that the spatial distribution by age is independent of year, so the estimated spatial distribution is the same for all years, while the absolute abundance will change by year. The estimated average proportion Kattegat cod predicted from model 2, weighted by the relative cod abundance (model 3), show (Table 2.3.2 and Figure 2.3.2) increasing proportion cod with Kattegat origin by age, but also high variation between year classes. The lowest proportion Kattegat 1-group cod is estimated for the 2011 year class (22 % 1-group with Kattegat origin) and the highest proportion (55%) for the 2018 year class. The proportion of Kattegat cod origin increases between age 0 and 1 for all year classes, indicating that 0-group North Sea cod entering the Kattegat may leave Kattegat before they become 1 year old. The stock assessment uses 1 year old cod as youngest age (recruits), so only proportion and migration rates for 1-group and older cod will be used for assessment purposes.

Estimated return migration

The estimated instantaneous return rates estimated for North Sea cod are shown in Table 2.3.3. The highest rates are estimated for the 0-group (quarterly return rate in quarter 4), and for ages 3 and 4 (annual values, 1. January to 31. December) which are the ages with steep increase in proportion mature. Return rates for age 2 are zero or negative indicating a net inflow of Kattegat cod from the North Sea. Model 1 and 2 provide similar estimates of proportion Kattegat cod and return rates (Figure 2.3.3).

The estimated return mortality estimated from proportion mature (Table 2.3.4) depends very much on stock specific maturity data used. The Kattegat stock mature at an earlier age and over a shorter age span than for the North Sea stock, which gives higher return migration rates. Return rates estimated from observations of stock origin are quite similar to the return rates estimated from the proportion mature data for ages 3-4, but the comparison clearly show that natal homing cannot fully explain the model results.

Stock assessment analyses

The use of estimated parameters for proportion of Kattegat cod and return rate of North Sea cod did not in general improve the statistical fit of the modified SAM assessment models, compared to official ICES assessment. The statistical fit including estimates of $Pjuv_y$ and L_a (Figure 2.3.4) (*conf01*) were slightly poorer than for *Default* for the configuration with catch scaling and slightly better for the model without catch scaling, but the differences were small. The assessment results depend more on the use of catch scaling than the use of data on genetic origin, and the estimated catch scaling factors were almost independent of the use of genetic origin parameters. Including the estimated stock origin parameters gave a higher recruitment for the runs with catch scaling, while the opposite was the case for the run without catch scaling.

When the missing $Pjuv_y$ parameters were estimated within SAM (*conf02*), the likelihood improves marginally, but as the degree of freedoms increases with the added parameters, the quality of the model did not improve based on the AIC values. Using the within SAM estimates of $Pjuv_y$ for the years with less observations instead of the external estimates (*conf03*) had a very limited effect on the assessment results. The likelihood increases with increasing number of SAM estimates, but the AIC values from the models are lowest for the model with $Pjuv_y$ given as input. The SAM estimates of $Pjuv_y$ are in general higher than the input values of $Pjuv_y$, especially for the beginning of the time series with rather few observations of genetic data.

When return rate derived from proportion mature data are used, and $Pjuv_y$ by year blocks are estimated within SAM (*conf04*), the assessment results depend mainly on the use of catch scaling. The estimated proportion of Kattegat cod at age 1 ($Pjuv_y$) shows two different temporal developments. With no catch scaling, SAM estimates an initial (1997-2004) high proportion of Kattegat cod followed by a decline such that the proportion of Kattegat cod is close to zero in 2020. If catch scaling is applied, the opposite is seen with a lower proportion of Kattegat cod in the beginning of the time series followed by an almost 100 % Kattegat origin for the most recent years. Model likelihoods and AIC are slightly better when return rates and $Pjuv_y$ in year blocks are applied compared to the default ICES configurations.

Conclusions

Genetic analysis of more than 3000 cod caught in the Kattegat shows a mix of cod spawned in the Kattegat and cod from the adjacent North Sea area. For the juveniles, the proportion of “true” Kattegat cod is close to zero in the northern Kattegat and close to 100 % in the southern Kattegat. By increasing cod age, the average proportion of “true” Kattegat cod increases in all areas of Kattegat, 73-92% of the cod in Kattegat at age 6+ is of Kattegat origin.

Stock assessment results and model diagnostics depend mainly on the use of catch scaling, while the proportion of Kattegat cod at age 1 and return rates of North Sea cod used as input or estimated within SAM have a limited effect. For all assessment runs, with or without data on stock origin, SSB and recruitment are reduced to a very low level in recent years. Fishing mortality is estimated at a high level throughout the time series except for a few years around 2014. Therefore, for a one-stock, one-area management, the choice of the model is not crucial.

The results from this analysis are however important for a better understanding of the situation for cod in Kattegat and for e.g. spatial management measures. Observations on stock origin clearly show that the proportion of cod with Kattegat origin changes between years and between ages. Model results provide a robust estimate of spatial distribution of stock proportions at age and could be used directly, if a spatial management to protect cod of Kattegat origin is targeted. The estimates of stock proportion for the whole Kattegat area become more uncertain as the spatial weighting factor (the local abundance at age and time of the year) ignores that the spatial distribution of cod in Kattegat is probably correlated to the inflow of North Sea cod.

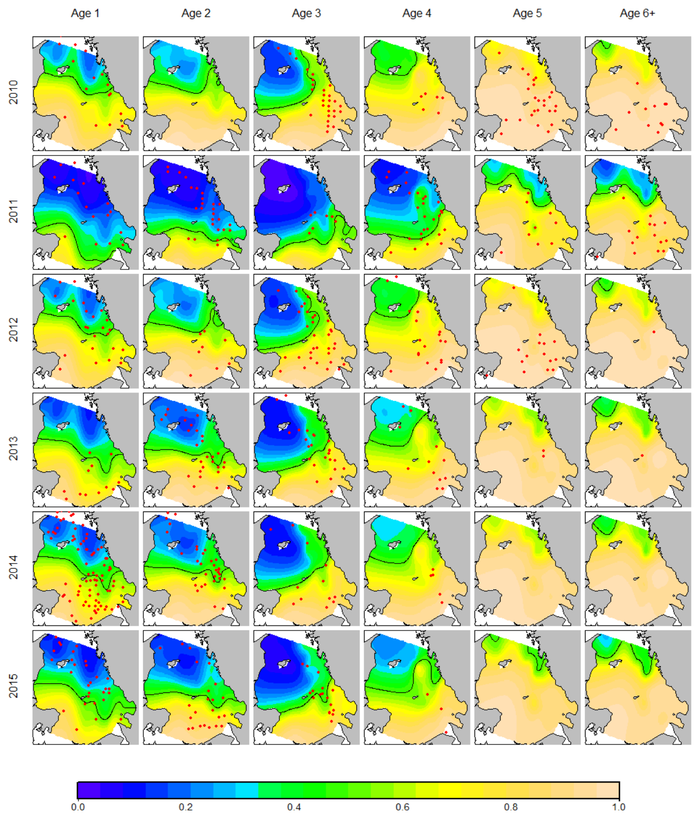


Figure 2.3.1. Estimate of proportion cod with Kattegat origin at the beginning of the year, by year class as estimated from model 2. All maps use the same scale shown at the bottom of the figure. The red dots show sampling locations for all cod from the given year class and age. The black line is the 50% contour line.

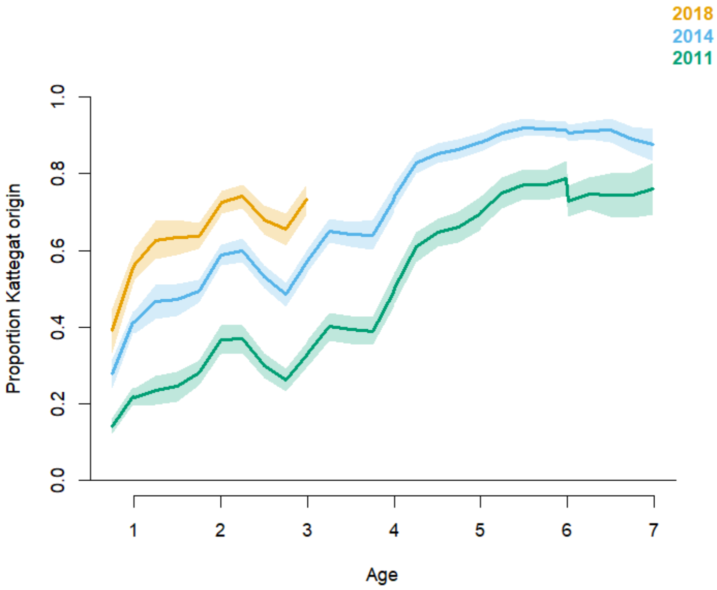


Figure 2.3.2. Estimate of average proportion of cod in Kattegat with Kattegat origin by age for three year classes as estimated from model 2 using weighting factors from model 3 using quarterly time steps. The 95% confidence limits of the average proportion are also shown. Weighting factors for age 6 are the same as for age 5 which explain the sudden change in proportion for age 6.0.

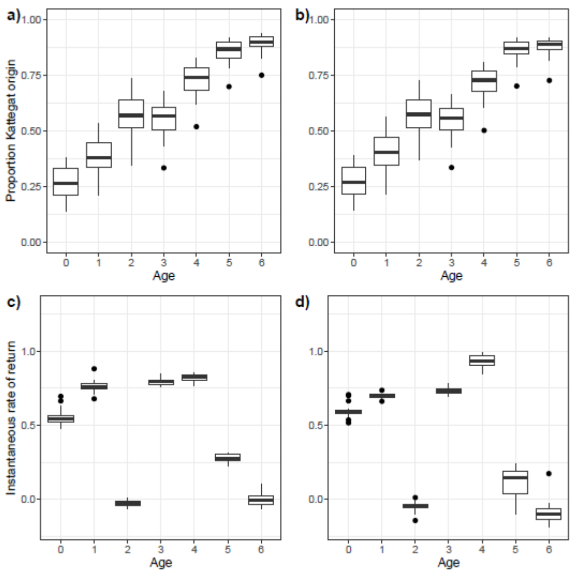
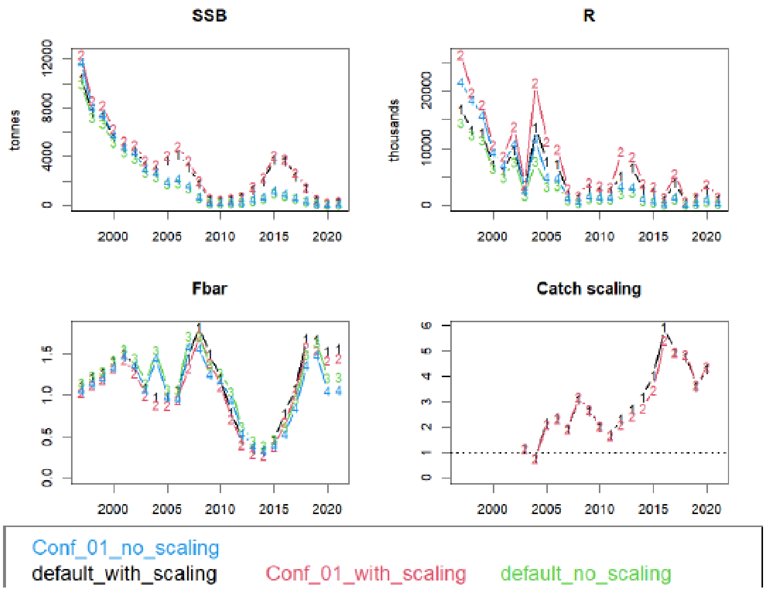


Figure 2.3.3. Box plots of estimated annual proportion of cod with Kattegat origin (panel a, for model 1 and panel b for model 2), and return migration rate of North Sea cod (panel c for model 1 and panel d for model 2).



	log Lik.	df	AIC
default_with_scaling	-690.6	45	1471.3
Conf_01_with_scaling	-692.9	45	1475.8
default_no_scaling	-734.3	27	1522.6
Conf_01_no_scaling	-734.3	27	1522.5

Figure 2.3.4. Results from *Conf01* compared to *Default* (official ICES assessment, 2021*),* for runs with and without catch scaling are also shown.

Table 2.3.2. Percentage of cod in Kattegat with Kattegat origin by year class and age, estimated from model 2 and weighted by abundance estimates from model 3. Values are by the beginning of the year except for age 0 which is by the 1. October.

	Age 0	Age 1	Age 2	Age 3	Age 4	Age 5	Age 6
1998	34	48	64	63	79	91	92
2001	27	40	58	56	73	88	89
2003	18	29	45	43	61	79	82
2004	22	33	50	49	66	83	85
2005	25	38	55	54	71	86	89
2008	36	50	67	66	81	92	92
2009	28	41	58	57	73	87	87
2010	36	50	66	67	81	91	90
2011	14	22	37	34	50	70	73
2012	34	47	64	63	78	90	90
2013	27	40	57	56	73	87	89
2014	28	41	59	58	74	88	91
2015	21	34	52	51	68	85	-
2016	23	35	52	51	68	-	-
2017	21	35	51	51	-	-	-
2018	39	56	72	-	-	-	-
2019	26	38	-	-	-	-	-

Table 2.3.3. Instantaneous rate of return migration of North Sea cod by year class and age, estimated from model 1 and weighted by abundances estimates from model 3. Annual values except for age 0, where the rate is for half year.

	Age 0	Age 1	Age 2	Age 3	Age 4	Age 5	Age 6
1998	0.56	0.66	-0.06	0.78	0.98	0.15	-0.30
2001	0.58	0.69	-0.08	0.76	0.96	0.14	-0.18
2003	0.59	0.71	-0.10	0.72	0.88	0.18	-0.03
2004	0.59	0.70	-0.06	0.71	0.91	0.20	-0.12
2005	0.60	0.69	-0.04	0.73	0.97	0.24	-0.26
2008	0.58	0.70	-0.01	0.76	0.97	0.00	-0.20
2009	0.58	0.69	-0.02	0.73	0.90	-0.02	-0.07
2010	0.59	0.68	0.01	0.75	0.91	-0.10	-0.09
2011	0.52	0.74	-0.14	0.69	0.85	0.12	0.17
2012	0.56	0.69	-0.04	0.73	0.93	0.05	-0.10
2013	0.61	0.69	-0.05	0.73	0.92	0.16	-0.17
2014	0.60	0.70	-0.04	0.75	0.96	0.24	-
2015	0.67	0.71	-0.04	0.71	0.99	-	-
2016	0.59	0.71	-0.06	0.73	-	-	-
2017	0.71	0.69	-0.02	-	-	-	-
2018	0.70	0.71	-	-	-	-	-
2019	0.54	-	-	-	-	-	-

Table 2.3.4. Average return mortality estimated from GAM models and from proportion mature data by stock and age.

	Age 0	Age 1	Age 2	Age 3	Age 4	Age 5	Age 6
Model 1	0.56	0.76	-0.03	0.80	0.82	0.28	0.00
Model 2	0.60	0.70	-0.05	0.73	0.93	0.12	-0.12
Proportion mature North Sea	0.03	0.33	0.66	0.81	1.10	-	-
Proportion mature Kattegat	0.00	0.68	1.05	1.27	-	-	-

3. Considerations on management reference points

3.1 Reference points under changing stock productivity

Biomass reference point - Blim

Defining fish biomass reference levels for fisheries management purposes is generally tightly connected to recruitment. Biomass reference points are in ICES usually set by examining the observed relationship between spawning stock size (SSB) and corresponding recruitment (R), to identify at which stock level R may be impaired by too low SSB (ICES, 2018*b*). Within the time period used for defining biomass reference points, stock-recruitment (S-R) relation is considered stable.

For Eastern Baltic cod, the time period to be used for S-R has always been a subject for discussion. This is because including or excluding the data from 1970s-1980s in S-R have potentially a large impact on Blim determination. At previous benchmark in 2013, it was recognized that considerable hydrographic and ecological changes have occurred since 1968 in the eastern Baltic Sea including large changes in the distribution of cod. It was considered that a low fishing mortality was unlikely to be sufficient to reverse these distributional changes under the current environmental conditions and hence only a restricted time period should be used for the stock recruitment relationship (ICES WKBALT 2013). However, changes in different variables occurred gradually and in slightly different time periods, which complicated defining the exact year since when to include the S-R data in Blim determination. 1989 was then identified as the year where the distributional change was completed and was chosen by WKMULTBAL meeting in 2012 as the appropriate breakpoint for S-R time series (ICES WKMULTBAL 2012). This marks also the years of so-called regime shift, that is suggested to have occurred in the central Baltic Sea (Möllmann *et al*., 2008).

At present, setting Blim for the eastern Baltic cod is further complicated by changes in quality of SSB and related possible parental effects on R, which are generally not considered in reference point determination, as only the biomass of the spawning stock is measured. Eastern Baltic cod is an example where these usual practices for defining biomass reference points may be inappropriate due to the pronounced changes in biology of the stock. These aspects were investigated and considered in the present project, which results contributed to the Blim discussion at benchmark in ICES in 2019 (WKBALCOD2 2019*a*).

It was recognized that it is no longer relevant to consider the entire time-series from the late 1980s onwards for S-R, as has been done in the past, as also the period after this is likely not homogenous in terms of the SSB effects on R due to changes in parental condition (Fig. 3.1.1).

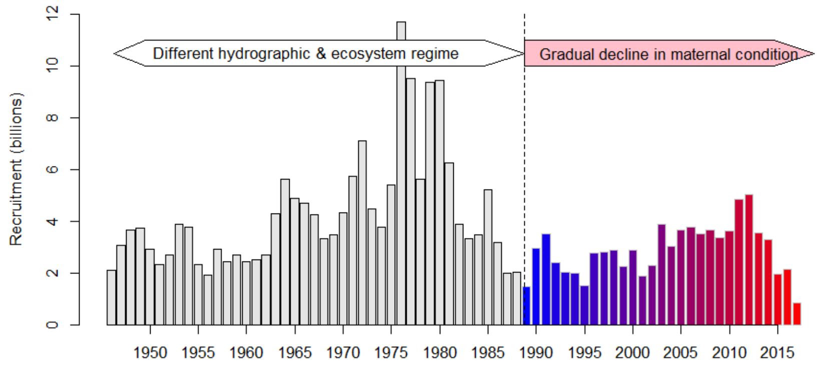


Figure 3.1.1. Recruitment of the eastern Baltic cod, highlighting the periods of changes in the ecosystem and parental conditions, expected to impact on recruitment (data from ICES, 2019*b*).

First, SSB in later years is not only reflecting the dynamics in stock size, but is additionally strongly influenced by the reduced size at maturation (Fig. 3.1.2). The SSB in recent years contains a large proportion of small individuals that were not yet part of SSB in former years (before 2000s). The biomass of the relatively larger cod that formed the spawning stock before the 2000s is currently at a historic low level (Fig. 3.1.2). The eggs of young female Eastern Baltic cod have considerably lower survival at poor hydrographic condition compared to the eggs of older females (Hinrichsen *et al.,* 2016).

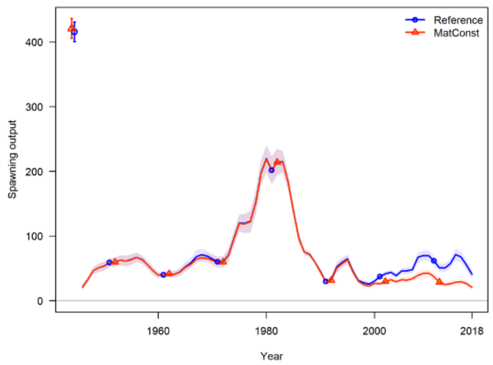


Figure 3.1.2. SSB (females only) taking into account the observed reduced size at maturation (reference run, blue line) compared to the biomass of the same size of cod that corresponded to the SSB before 2000s (L_{50} at 38 cm) (red line). (From ICES WKBALCOD2 2019a).

Furthermore, the condition of spawners has much deteriorated in later years, due to low nutritional condition and high infestation with parasites. Thus, the reproductive capacity of a specified amount (tons) of SSB today (consisting of small individuals at poor condition) is likely not equal to the reproductive capacity of the same amount of SSB in the past (Mion et al. 2018).

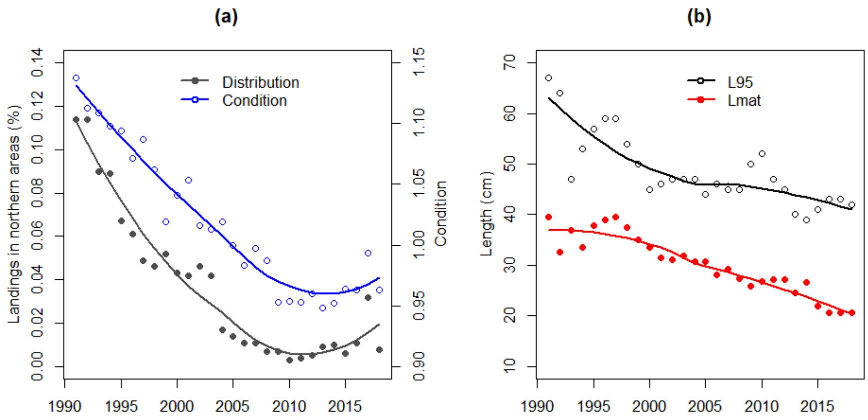


Figure 3.1.3. (a) Proportion of commercial landings of eastern Baltic cod in northern areas of the Baltic Sea (ICES subdivisions 27–32), illustrating contracted stock distribution. LeCren condition factor (based on data from International Bottom Trawl Survey (BITS) in the 1st quarter). (b) Length of cod at 95 percentile of length distribution (L95), and size at which 50% of the population become mature (Lmat). Data are from BITS survey in the 1st quarter. The dots show annual observations while the lines represent smoothed trends.

The recruitment of the eastern Baltic cod has been continuously declining since 2012 (Fig. 3.1.1). Although there is no apparent relationship between SSB and R (ICES, 2019*a*), the recruitment could currently be impaired by the quality of the parent stock rather than the quantity of adult fish in the population.

The biological characteristics of Eastern Baltic cod likely to influence its reproductive capacity have gradually deteriorated since the 1990s (Fig. 3.1.3), resulting in no period when the SSB effects on R would be comparable. At best, the period would be confined to only a few latest years when much of the decline in the biological parameters had already taken place. There are currently no procedures in place in ICES for defining biomass reference points considering other characteristics of the SSB than the total amount.

It was concluded that Blim should currently not be set lower than the most recent SSB that was still able to produce a strong year class, when much of the adverse developments affecting the quality of the SSB had already taken place. The latest relatively strong year class was formed in 2012 (Fig. 3.1.1). Therefore, SSB estimated for that year is currently the basis for Blim, adopted at benchmark in ICES in 2019 (ICES WKBACOD2 2019*a*).

Due to the presently very dynamic biological situation for the Eastern Baltic cod, the current Blim is considered to be applicable only in short term. The reproductive capacity of the stock needs to be closely monitored in coming years, and when new information becomes available, the Blim value needs to be re-evaluated.

Fishing mortality reference point

Fishing mortality that in a long term gives maximum sustainable yield (MSY) is the main pillar in many current fisheries management frameworks, also included in the EU multi-annual management plan for the Baltic Sea. MSY concept involves an assumption of long-term equilibrium, i.e.

variations in stock productivity are assumed to be centered around a stable average, at a given harvest (Skern-Mauritzen *et al*., 2016). Therefore, the meaning of MSY is challenged in situations when productivity is changing beyond the ordinary inter-annual variations.

For eastern Baltic cod, exploratory analyses conducted prior to last benchmark (ICES 2019a) revealed that no F_{MSY} value could be defined as sustainable in long term, at present productivity of the stock. The future biomass and potential recovery of the eastern Baltic cod are largely dependent on development in stock productivity (growth, natural mortality and recruitment). This is demonstrated by medium term projections of stock development under contrasting productivity scenarios. These analyses used the stock estimates from the ICES assessment (ICES, 2019*b*) and applied growth and natural mortality in forecast years i) at present levels, and ii) at historical levels, before the pronounced changes were estimated to have occurred (i.e. before the year 2000 for natural mortality and 1991 for growth). Both scenarios applied recent five-year average recruitment and zero fishing in forecast years. The results illustrate that, at present productivity, the stock biomass would remain at a historic low level even in the absence of fishing (Fig. 3.1.4). In contrast, improved growth and reduced natural mortality, corresponding to their past levels, would allow the stock biomass to increase substantially. Thus, the potential for the stock to support sustainable fisheries in future is much dependent on the ecosystem processes affecting stock productivity (Eero et al. 2020).

The eastern Baltic cod example demonstrates that long-term goals such as F_{MSY} are not well suited for management of stocks undergoing large and rapid productivity changes. In such situations, a more dynamic and flexible approach may be required that allows adapting to a changing biology. For eastern Baltic cod, a risk based approach was adopted at benchmark in 2019 (ICES, 2019*a*), estimating catch levels that are associated with low probability of the stock being below certain reference level in the short term. In this approach, biomass reference point is still required, which in this case represents an escapement target, i.e. the biomass that is desired to be kept in the sea. However, no fishing mortality reference point is defined in this setup and the possible harvest is determined by the amount of biomass in excess to the reference level. A similar approach is usually applied for short-lived species where harvest opportunities are much dependent on incoming year-classes. The eastern Baltic cod example shows that under ecosystem change, similar principal may become relevant for long-lived species, especially those at the edge of their distribution range or experiencing the effects of climate change. The eastern Baltic cod case is, to our knowledge, the first time where such approach has been applied for a long-lived species as cod.

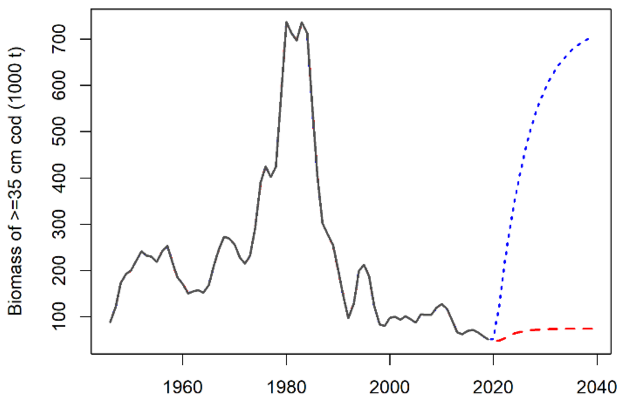


Figure 3.1.4. Historical time series of biomass of marketable size (>= 35 cm in length) eastern Baltic cod (black solid line; from ICES, 2019*b*) and deterministic medium term projections for two contrasting productivity scenarios. The scenarios applied growth and natural mortality i) as estimated for most recent years (red dashed line) and ii) as observed before the substantial decline in stock productivity (blue dotted line) (i.e. before the year 2000 for natural mortality and 1991 for growth). Both scenarios applied zero fishing in forecast years (from Eero et al. 2020).

Conclusion

The potential for the eastern Baltic cod stock to support sustainable fisheries in future is much dependent on the ecosystem processes affecting stock productivity. The eastern Baltic cod example demonstrates that the present standard practices and frameworks for determining management reference points are not well suited to account for severe rapid productivity changes. Parental effects on recruitment need to be considered when determining B_{lim}, and alternative approaches are needed to identify potential sustainable harvest in situations when no F_{MSY} can be defined. The current solutions adopted for the eastern Baltic cod provide useful input and inspiration to further development of principals and frameworks for reference point determination under dynamic ecosystem conditions affecting stock productivity. Such developments including advances in related research are needed so that future management frameworks can be better prepared for such productivity changes in a timely manner, when these occur in other areas or species. Finally, stock productivity needs to be regularly monitored to be able to adjust management to dynamic ecosystem conditions.

3.2 Sensitivity of reference points to various data inputs

Background

Estimation of biological reference points for biomass (Blim) involves stock-recruitment relationship, which for many stocks is unclear. ICES has developed guidelines for determining Blim under different stock-recruitment types. However, in specific cases various additional aspects may need to be considered, e.g. related to variable productivity (see section 3.1), implying that determination of Blim is not straightforward. Western Baltic cod is among the stocks were stock-recruitment relationship does not provide a clear indication at which SSB level the recruitment becomes impaired by too low spawning stock size (Fig. 3.2.1). At low stock sizes, both relatively high and low recruitments have been observed. As no breakpoint in S-R could be defined, ICES benchmark in 2019 (ICES WKBALTCOD2 2019a) decided by to use an average of the lowest SSBs in 4 years corresponding to above average recruitment (the 1991, 1993, 2003 and 2016 year class) (Fig. 3.2.1).

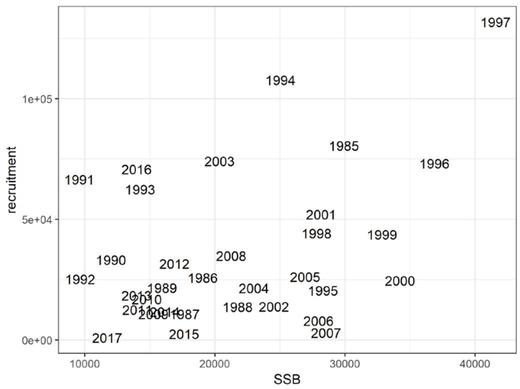


Figure 3.2.1. Stock-recruitment relationship for the western Baltic cod (ICES 2019a).

Material & Methods

In this project, we investigated the impact of uncertainties in various data inputs on stock status evaluation (see chapter 5). To do so, we modified different input variables (Discards and recreational catch and their age compositions, and biological information on weights, maturity and stock mixing) to stock assessment by drawing randomly annual values for a given variable from the range of observations in the time series (see Approach1 described in detail in Chapter 5). The results were then compared to the baseline, for which we used the results of the official stock assessment from 2019 (ICES 2019b). These analyses were conducted to investigate whether stock status evaluation is more or less sensitive to exact annual values of some inputs compared to others, which could be used to prioritize annual data updates. In this context, it is also relevant to consider sensitivity of biological reference points to variability in data inputs.

In this section, we report on the results of these analyses specific to the robustness of Blim, set in such a way as it is currently done for the western Baltic cod stock. As it is defined based on a relationship between recruitment and spawning stock size, the Blim value is potentially sensitive to data inputs affecting the stock assessment results, i.e. the values for R and SSB. In the scenarios modifying data inputs, we re-calculated Blim following the same principles as currently done in ICES, i.e. Blim was set to an average of the 4 lowest SSBs values in the time-series corresponding to above average recruitment.

Results

The analyses showed that Blim deviations from the baseline were roughly up to 20% in the scenarios modifying age structure of recreational catch (*AgeR*) ,maturity (*Maturity*), discards relative to landings (*Discard*) and proportion of eastern Baltic cod in catches from SD24 (*Mixing*) (see chapter 5 for further explanation of the scenario variables) (Fig. 3.2.2). From a few scenarios modifying age structure of discards (*AgeD*), up to 35% deviations from the baseline were obtained. In terms of the variable modified in the scenarios, recreational catch amount (*Recrea*) and individual weight (*Weight)* seemed to have least impact on Blim value (Fig. 3.2.2). The Blim was changing in scenarios mostly because a different year-class and corresponding SSB got included among the 4 values being used for Blim calculation.

Fishing mortality reference points, i.e. FMSY, was insensitive to the scenarios conducted for all other variables, apart from Weight, where up to 20% deviation from the baseline as obtained.

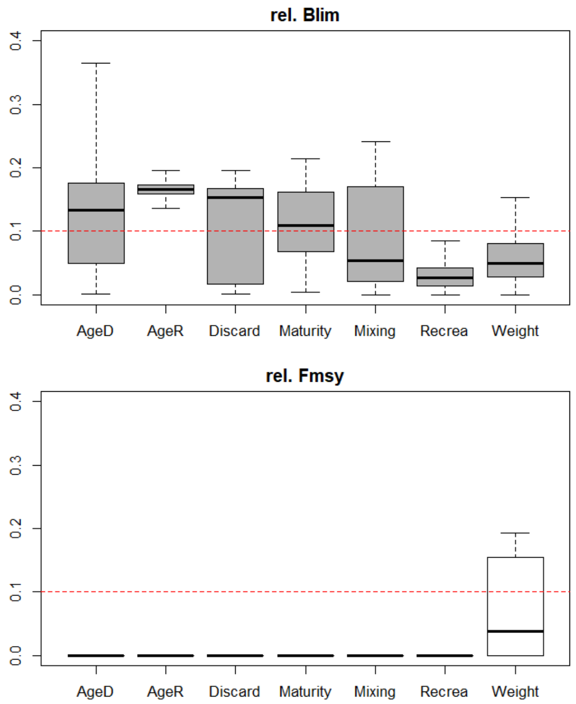


Fig. 3.2.2. Blim (upper panel) and FMSY (lower panel) relative to the baseline (proportion difference), obtained from the scenarios modifying annual values for input variable for stock assessment shown in x-axis, randomly drawn from the observed range. Baseline refers to Blim and FMSY applied in official stock assessment (ICES 2019b). Boxplots show variability from the scenarios, further described in Chapter 5 in this report. Red dashed lines mark 10% deviation from the baseline, for illustration.

Conclusion

Similarly to stock assessment outputs, the associated biomass reference points can be sensitive to uncertainties in data inputs. In the example for western Baltic cod, relatively similar magnitudes of impacts on Blim were found when modifying age structure of recreational catch, maturity, discard amounts relative to landings, or the proportion of eastern Baltic cod in catches. Modifications in individual mean weight and recreational catch amounts had relatively less impacts on Blim. The estimates of FMSY were not affected by investigated modifications to data inputs, with the exception of modification to mean weight.

4. Effects of supplementary management measures on cod

4.1 Spawning closures

Fisheries management measures often include spatio-temporal closures during the spawning period of the fish with an overarching aim of improving the stock status. However, the effects of such closures on stock status often remain unclear. The different mechanisms how a spawning closure potentially can influence the stock are often not explicitly considered when designing such closures. In this project, we reviewed and synthesized the available data and knowledge on potential effects of the implemented spawning closures on cod in the Eastern Baltic Sea.

In the Western Baltic Sea, spawning closures have also been implemented, and were extended in some recent years. Its effects on cod spawning and resulting recruitment remain so far unresolved, and relatively little is known about recruitment processes of Western Baltic cod in general. In this project, we investigated the drivers for recruitment of Western Baltic cod, especially in light of the relatively large interannual contrasts in recruitment in later years, when spawning closures have also been implemented. Improved knowledge on recruitment processes and its main drivers is important to evaluate the relative influence of measures such as spawning closures on recruitment and subsequently on stock status.

4.1.1. Review of potential impacts of spawning closures on Eastern Baltic cod

Both spatial and temporal spawning closures have been implemented for the eastern Baltic cod since the 1990s, and their location and timing have varied over the years. The overarching aim of the cod spawning closures in the Baltic Sea is improving the stock status. The legislations do not specify further, which parameters of stock status the closures are intended to improve, and through which mechanisms. According to the literature, potential benefits of spawning closures as a supplementary management measure can include greater reproductive output, positive effects on stock structure, reduced evolutionary effects of fishing and reduced impact on spawning habitat (e.g. van Overzee and Rijnsdorp, 2015 and references therein). We focused our analyses on the potential effects of the spawning closures on cod recruitment, distinguishing between three different mechanisms.

These included direct effects of the closures on:

i) the quantity and quality of egg production by ensuring undisturbed spawning activity;
ii) preserving the spawners whose offspring have a higher survival probability;
iii) increasing the proportion of larger/older individuals in the stock.

A number of scientific publications over the past decades have addressed cod recruitment in the Baltic Sea, including aspects relevant for evaluating the spawning closures. In this project, we synthesized these findings and conducted additional analyses, using data on egg abundances from ichthyoplankton surveys and cod catch information from the Baltic fish stock Assessment Working Group in ICES. Recognizing the general difficulty in assessing the realized effects of spawning closures, we instead evaluated their potential effects. In this approach, we focused on identifying whether or not there is an overlap between the closure and the stock component intended to be protected, in time and space. If such overlap is lacking, the closure can impossibly be beneficial. If the overlap is present, this implies that the closure can potentially contribute to improving the stock status through a certain mechanism.

The results, summarized in Table 4.1, demonstrated that designing appropriate spawning closures can be more complicated than hitherto thought, as a spawning close that is beneficial for the stock through one mechanism may at the same time compromise other aspects of the stock status.

The present area closure in the main spawning ground of the Eastern Baltic cod (Bornholm Basin) allows part of the stock to spawn undisturbed. However, this would not necessarily increase the recruitment, if the offspring spawned outside the closure would have a higher survival probability due to better environmental or feeding conditions. In such situations, the area closure may in fact increase disturbance and fishing pressure on those spawners whose offspring would otherwise have a greater chance to survive. This is because fishing effort is likely to be concentrated in the areas outside the closure. Expansion of the area closure to cover most of the spawning could avoid the potential negative effect of the closure in relation to offspring survival. However, an area closure only in SD 25 could also cause fishing effort reallocation to SD 26, increasing the fishing pressure on the remaining larger cod found in this area, with negative impacts on stock structure (Table 4.1).

Seasonal closures in the main cod distribution area (SDs 25-26) that do not cover all months of peak spawning season may cause temporal fishing effort reallocation to those months of spawning that re not covered by the closure. However, this could be avoided simply by adjusting the timing of the closure to cover the entire peak spawning.

Table 4.1. Summary of the potential positive and negative effects of the implemented area closure (*AC*) in Bornholm Basin (BB) and the seasonal closure (*SC*) in SDs 25–26 (as implemented in 2018) on the eastern Baltic cod (from Eero et al 2019).

Closure	Potential positive effects	Potential negative effects
AC: BB May 1–Oct 31	Undisturbed spawning of part of the stock.	Part of spawning activity, high survival of offspring, and larger cod occur in areas outside the closure, where fishing effort may reallocate.
SC: July 1- August 31 (SDs 25–26)	Partly undisturbed spawning; somewhat reduced proportion of larger cod in fisheries catch.	Possible reallocation of fishing effort to June, i.e. increased disturbance of peak spawning in this month.

Further details of these analyses and results are provided in Eero et al. 2019. This synthesis of the effects of spawning closures also contributed to the ICES workshop to evaluate the effect of Conservation measures on Eastern Baltic cod (Gadus morhua) (WKCONGA) (ICES 2018c) and corresponding ICES advice on this matter (ICES 2018d).

Conclusion

Regular monitoring has demonstrated that the most intensive spawning activity of eastern Baltic cod is variable in time and space, implying that closures covering relatively small areas or short time periods have a low chance of matching the peak spawning in all years. The highest concentration of spawning activity is not always corresponding to the highest survival probability up to juvenile stage, further complicating the design of spawning closures covering relatively small areas. Small area closures cause fishing effort reallocation to other stock components with a risk of unintended negative effects via the mechanisms that may not have been accounted for when designing the closure. To avoid these counterproductive effects, a closure would need to be sufficiently large. Quantifying the actual effects of spawning closures likely remains a challenge also in future. Therefore, if spawning closures are chosen to be applied as a supplementary management measure, these should be designed in a way that allows their potential benefits to occur, while avoiding potential counteracting effects. The Baltic cod example suggests that the closures covering most of the distribution area of the stock during its peak spawning time are better suited for this purpose rather than those covering small areas.

4.1.2 Recruitment processes of Western Baltic cod

Material & Methods

Data

In this study, we used time series of larval abundance with associated hydrographic information, data on spawning stock size and recruitment, zooplankton composition and information of strength of Atlantic water inflow.

There were three different data sets available from ichthyoplankton surveys carried out in the period from 1923 to 2019. The first data set spans the years 1923-1929 (Poulsen, 1931). The second and third data set are raw data from ichthyoplankton surveys that spans the years 1993-2005 and 2014-2019. The analyses focused on SD 22, unless otherwise stated.

Data on spawning stock size (SSB) and recruitment (abundance of 0, 1 and 2-year old fish) were obtained from ICES (2020). To test the impact of inflow strength on recruitment in 1993-2018, we used the volume of saline water inflow from the Baltic saline barotropic inflows (SBI) dataset (Mohrholz, 2018), in the spawning time of western Baltic cod. For most recent time period, i.e. 2014-2019, additionally, data on zooplankton abundances were available, obtained from Leibniz Institute for Baltic Sea Research, Warnemünde.

Analyses

Identification of life stage where recruitment is determined: Abundance of four life stages were available: larva, 0-group, 1-group and 2-group. A series of sequential linear regressions in abundance between all these life stages was carried out using ANOVA. Cases where there is no significant relationship in abundance between two consecutive life stages is considered to indicate the time in the cod’s life where recruitment is determined.

Impact of spawning stock biomass: In order to test, whether larval abundance depends on spawning stock biomass, mean larval abundance was calculated for each year as the sum of larva abundance, divided by the number of stations sampled. The relationship between mean larval abundance and SSB was analysed using linear regression for each of the time series separately.

Impact of geographic and hydrographic conditions: The impact of geography and hydrography on larval abundance was tested using a Generalised Linear Model approach (GLM), including all available variables in the initial model:

$$A_{larvae} = T_{air} + T_{surf} + T_{bot} + S_{surf} + S_{bot} + O_{surf} + O_{bot} + D_{haul} + D_{bot} + long + lat + year + \varepsilon$$
, where $\varepsilon \sim N(0,\sigma^2)$

T = temperature in ^{0}C., *S* = salinity in psu, *O* = oxygen in % saturation, *D* = depth, *long* = longitude of sample station, *lat* = latitude of sampling station, *year* = sampling year was included as a factor to account for effects that were not included in the measurements available to this study, and $\varepsilon(0,\sigma)$ = error term. Subscripts *air*, *surf* and *bot* indicate whether the measurements were taken in the air, the surface (water depth 1m) or at the bottom (1 m above bottom), and D_{haul} = maximum depth of the haul taken. A reduced model model included only variables that were not correlated and had the highest degree of explanation. This model was then further reduced to the final model through stepwise forward reduction of parameters.

Impact of Atlantic water inflow: The impact of Atlantic inflow strength on recruitment of western Baltic cod was analysed using linear regression between recruitment estimated from stock assessment, and mean inflow volume over the months January, February and March, corresponding to spawning time of respective year-class.

Impact of availability of suitable prey: The availability of prey suitable for in particular the early larvae, where 0-group abundance seems to be regulated (see results), was assessed by qualitative comparison of zooplankton prey composition and abundances covering the years 2014 – 2019.

Results

Life stage where recruitment is determined: The abundances of 0-group, 1-group and 2-group juveniles was plotted against larval abundances for all analysed time periods. The regression analysis revealed that for 1923 - 1929, a significant positive relationship between larval abundance and age 0, 1 and 2 year old cod exists (ANOVA, df = 3 to 8, all $p < 0.05$, $r^2 = 0.74$ to 0.89). For the years 1993 – 1997 a significant relationship was found between age 0 and age 1, though it is important to note, that the data in this period are too limited to be conclusive. In 1998 - 2005 and 2014 – 2019, no significant relationship between larval abundance and any of the subsequent life stages was found (ANOVA, all $p > 0.05$, all $r^2 < 0.1$), but correlations between age 0 and older were highly significant for both time series (ANOVA, all $p < 0.05$, all $r^2 < 0.96$). These results suggest that in more recent years, recruitment of western Baltic cod has been regulated between the larval and the demersal 0-group stage.

Impact of spawning stock biomass: A significant relationship between larval abundance and SSB was only found for the years 1993 – 1997 (ANOVA, df = 2, $r^2 = 0.93$, $p < 0.05$). For other parts of time series, no such relationship was evident. SSB does therefore not appear as a key factor regulating larval abundance of western Baltic cod.

Impact of geographic and hydrographic conditions: For the year 1923 – 1929, Poulsen (1931) claimed that bottom temperature was the key driver of larval abundance. Our analyses showed that bottom temperature was indeed the variable with the highest explanatory power, but the effect was not significant (ANOVA, df = 4 and 2, $p > 0.05$). For years 1998 – 2005, significant effects of bottom depth and surface salinity were found, in addition to a year and latitude effect (ANOVA, $F = 19.21$, df = 4 and 313, adjusted $r^2 = 0.20$, $p < 0.05$). In 2014 – 2019, surface salinity was also found to have statistically significant effects on larval abundance, in addition to temperature and year (ANOVA, $F = 17.69$, df = 3 and 157, adjusted $r^2 = 0.15$, $p < 0.05$)

*Impact of Atlantic water inflow: W*e used the mean volume of saline water inflow from the Baltic saline barotropic inflows (SBI) as proxy for inflow strength. The temporal pattern in inflow volume shows how dynamic the hydrography in the Belt Sea is, with volume strength varying by a factor of 5 over the time series available. Recruitment strength was not found to be linearly related to this inflow index (ANOVA, df = 33, $r^2 = -0.029$, $p = 0.85$).

Impact of availability of suitable prey: The bulk of the zooplankton abundance (> 95%) consisted of different life stages of copepods, except for 2016 (only ca. 60%). Most frequently occurring copepod species were *Acartia* spp, *Balanus* spp, *Oithona similis* and *Centropages* spp. In 2016, the most notable difference compared to the other years is the large abundance in *Synchaeta* sp., making up approximately 40% of the abundance in zooplankton. Zooplankton abundance separately for life stages suitable as prey for smaller and larger cod larvae illustrate the same patterns, with 2016 standing out with a relatively high abundances of Synchaeta available both for smaller and larger larvae (Figure 4.1.1). Synchaeta is used in aquaculture as first prey for earliest larvae for different fish species, thus it can be considered an important food item especially for early larval stages. In addition to Synchaeta, Temora suitable for smaller cod larvae was relatively abundant in 2016 compared to adjacent years.

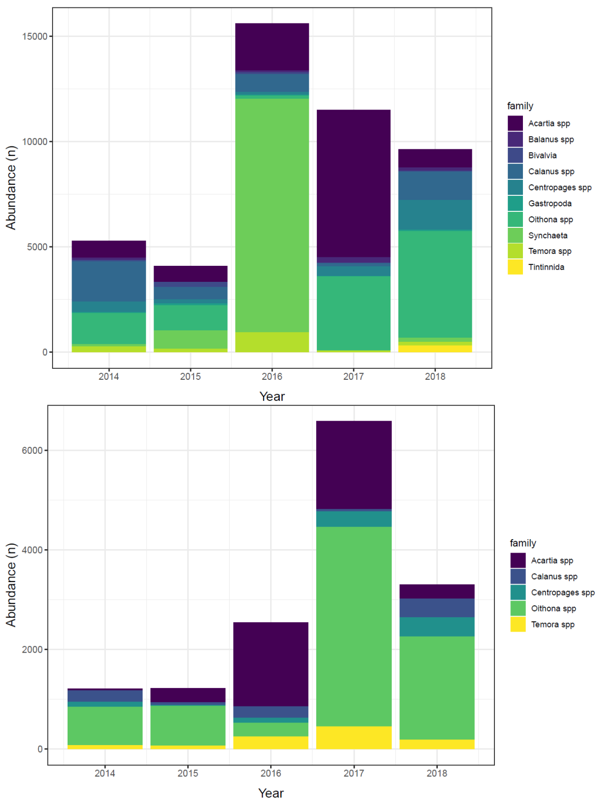


Figure 4.1.1. Abundances of the most frequently occurring species and life stages of zooplankton in the Fehmarn belt area, separated by life stages suitable as prey for smaller cod larvae (left panel) and larger cod larvae(right panel).

Conclusion

Recruitment of Western Baltic cod has been low in several most recent years, with the exception of 2016 year-class that is estimated to be relatively large (ICES 2020). The results of the analyses conducted in this project suggest that recruitment is determined between the larval and the demersal 0-group stage. Among the drivers explored, prey composition in 2016, especially with a high abundance of Synchaeta, was clearly different from that in the neighbouring years. This suggest that the relatively higher year-class in 2016 is related to abundance of suitable prey for larvae. Hydrographic conditions were also found to have significant impacts on recruitment. There are large differences in realized recruitment in adjacent years (e.g. by factor 10 differences in year-class strength in years 2016-1018) when spawning closures have similarly been applied. This suggests that a spawning closure is not a major driver determining recruitment dynamics of western Baltic cod, and the potentially existing impacts probably remain hard to detect and disentangle from the more prominent impacts of hydrography and prey abundance.

4.2. Size selectivity of fisheries

One of the most dramatic negative changes in the eastern Baltic cod stock in later years is truncation of the size structure. A combination of reduced growth of individual fish as well as increased natural mortality have likely contributed to this development. However, it has been argued in scientific literature that size selective fishing has also played a role (Svedäng and Hornborg 2014). In the Eastern Baltic Sea, a relatively large mesh size has been used in the cod fisheries in later years, which implies that fishing mortality has been directed towards larger cod. Furthermore, selective removal of largest individuals has been suggested to cause density-dependence among the remaining smaller cod and deteriorate their growth and condition (Svedäng and Hornborg 2014). In this project, we investigated potential contribution of fisheries to the changes in cod size structure by focusing on the following research questions:

i) How has the size structure of eastern Baltic Sea cod population changed over two decades of fishing?
ii) Can we identify fishing effects on population size structure by analyzing commercial and fishery-independent survey data?

4.2.1 Data and Methods

Scientific survey data on cod were available through the Baltic International Trawl Surveys program (BITS). The data are collected during the first and fourth quarter of the year, available from DATRAS database in ICES. We used data for relative abundance and biomass by haul, for 1990-2019 for Q1 and 1993-2019 for Q4. Additionally, data on catch at length in commercial fisheries for 2000-2019 were used, as reported to the Baltic Fisheries Stock Assessment Working Group in ICES. Thus, altogether three datasets were used, the survey at first quarter (Survey Q1), the survey at last quarter (Survey Q4) and the commercial data (Com). We only used data for >35 cm cod, which were available both in survey and commercial data.

Population size indices

For each year y and dataset, we computed the community-weighted mean (CWM) length of the cod population, using the abundance at length $D_{t,l}$ reported in the different datasets:

$$CWM_t = \frac{1}{\sum_{l=35}^{l=l_{max}} D_{t,l}} \times \sum_{l=35}^{l=l_{max}} D_{t,l} \times l$$

This index would typically decrease if large size individuals disappear from the population (Shin et al. 2005). We also calculated the Large Fish Indicator (LFI):

$$LFI_t = \frac{\sum_{l=40}^{l=l_{max}} B_l}{\sum B_l}$$

Size spectrum

For each dataset and year, we constructed the size spectrum of cod population based on the log10-transformed abundance at length and log10-transformed individual length. For each year t and dataset, the size spectrum slope a is computed from linear regressions. A linear model was applied to quantify the shape of the size spectrum of cod on each yearly size spectrum across the three datasets. The size spectrum is particularly characterized by its slope and origin. Typically, strong changes in the size structure of a population or a community would be characterized by a change in the slope of the size spectrum (Andersen 2019; Gislason and Rice 1998; Shin et al. 2005; Bianchi 2000).

Analysis of temporal signals

To follow the change in the size spectrum slope through time, we plotted the estimated slope from linear models against years and quantified changes by linear regressions. Temporal variations in the size spectrum slope were compared across the different datasets (especially between the two surveys and the commercial data). To identify the potential fishing effect on the recent decrease in large individuals in the population especially after 2011 (ICES 2019), we compared the slopes of the size spectrum between the survey (Q1 or Q4) and the commercial data through time. This analysis assumes that survey data reflect the ecosystem state, while the commercial data reflect fishing activities.

A fishing effect would be marked by an increase in the size spectrum slope a in the commercial data (FD), where fisheries target large individuals from year t_1 to year t_2.This would then be followed by a decrease in the slopes for both survey (FI) and commercial datasets (FD) at year t_3 (Fig. 4.2.1), indicating a decline in large individuals both in the ecosystem and in the fisheries catch. An environmental or indirect fisheries effect would typically be marked by a decrease in the size spectrum slope simultaneously in survey and commercial datasets, therefore excluding a direct fisheries effect (Fig. 4.2.1).

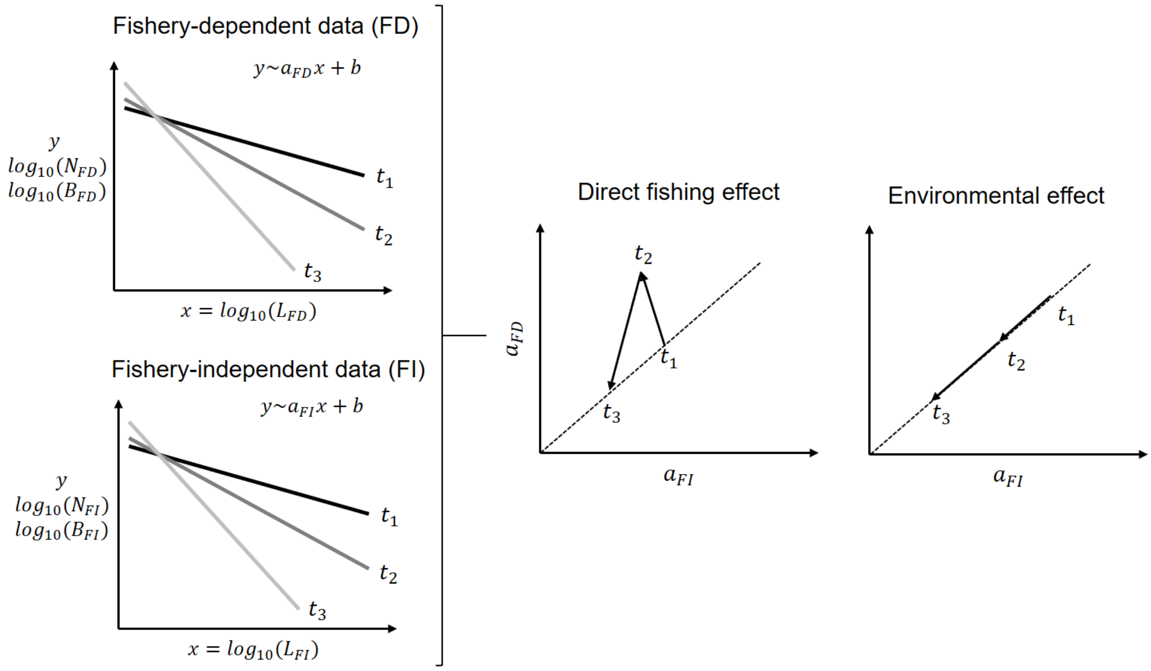


Figure 4.2.1. Schematic illustration of methods and hypotheses used to investigate the potential fisheries impact on the strong decline of large-size cod in the eastern Baltic Sea.

4.2.2 Results

Change in cod population size structure

Size spectra slopes constructed with the abundance and length of individuals are generally lower in commercial data, which is probably due to differences in selectivity or fishing strategy. In both survey (FI) datasets in Q1 and Q4 and in commercial (FD) data, there is a strong decrease in the size spectrum slope from 1990 to 2018 (Fig. 4.2.2). Furthermore, there is a strong drop in the commercial data since 2010, indicating a stronger recent decline in large individuals (Fig. 4.2.2 c and f). The temporal decrease in the size spectrum slope seems to be slightly higher in the case of the commercial data (Fig. 4.2.2 d, e, and f).

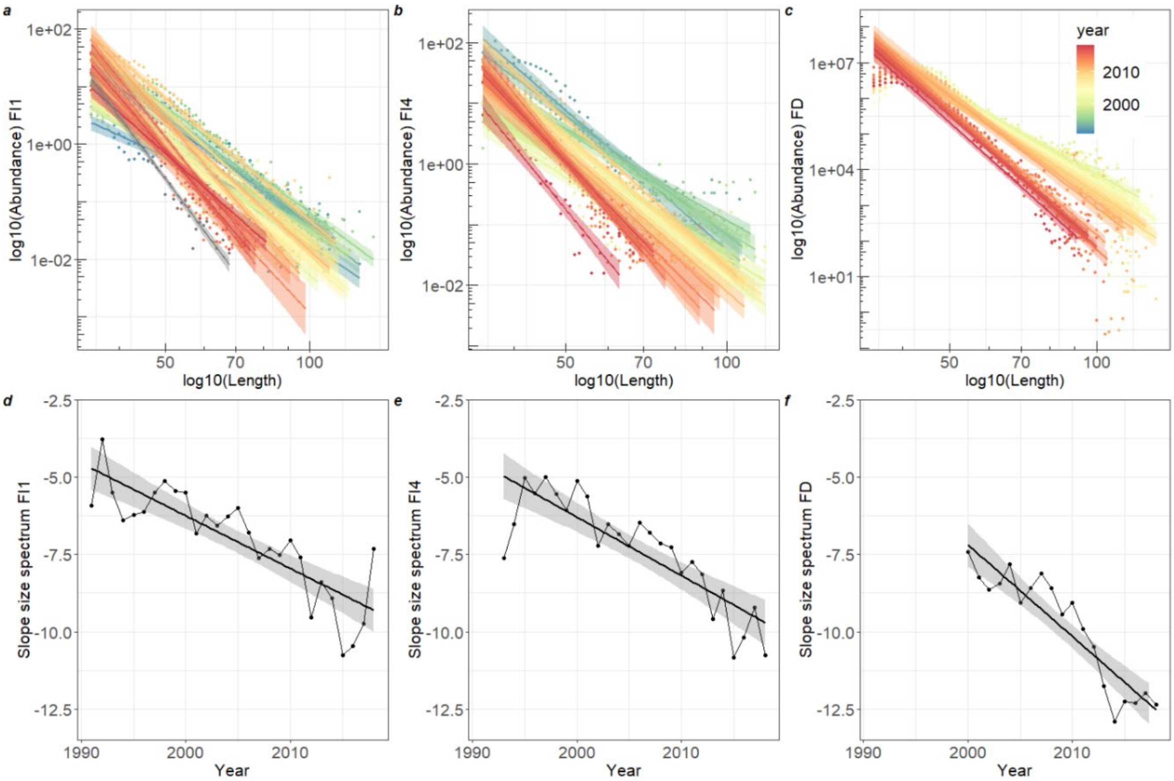


Figure 4.2.2. Temporal change in eastern Baltic Sea cod population size structure based on survey data quarter 1 (a, d), survey data quarter 4 (b, e) and commercial data (c, f). Population size spectra built with linear regressions on log10-transformed abundance and log10-transformed lengths (a, b and c). Color scale indicates the year. Linear regressions on temporal decrease in the size spectra slopes (d, e, and f). Slopes of the temporal decrease in slopes are -0.27 for the survey FI Q1 (d), -0.24 for the survey FI Q4 (e) and -0.30 for the commercial data FD (f).

Qualitative analysis of fishing effects

The comparison between the size spectra slopes across commercial and survey data may suggest some fishing effects on decline in large individuals in the eastern Baltic Sea cod population in some years, however the results are not consistent across the datasets. The analyses show an overall drop in the size spectrum slope in commercial data and in both surveys from 2000 to 2018 (Fig. 4.2.3). Some periods in the time series seem to indicate an increase in the slope in the commercial data (large individuals caught during fisheries operations compared to scientific surveys) before a simultaneous drop in both datasets. For instance, there was an increase in the slope in commercial data during 2005-2007, followed by a drop in the slope from 2009 onwards (Fig. 4.2.3a). However, in the period when largest decline in larger cod occurred, i.e. between 2011 and 2013, the results in terms of fishing effect are not conclusive across both surveys. Comparison of slopes between commercial data and Q4 survey showed an increase in slope in fisheries data in 2009-2010, followed by a strong drop in the slope from 2011 to 2013 (Fig. 4.2.3b). Similar pattern is not apparent for Q1 survey, although there seems to be a smaller decline in slope in fisheries data from 2011 to 2012 compared to Q1 survey data (Fig. 4.2.3 a). Recent years (2014, 2017) seem to indicate an increase in the size spectra slopes in scientific surveys, but not necessarily in the commercial data (Figure 4.2.3).

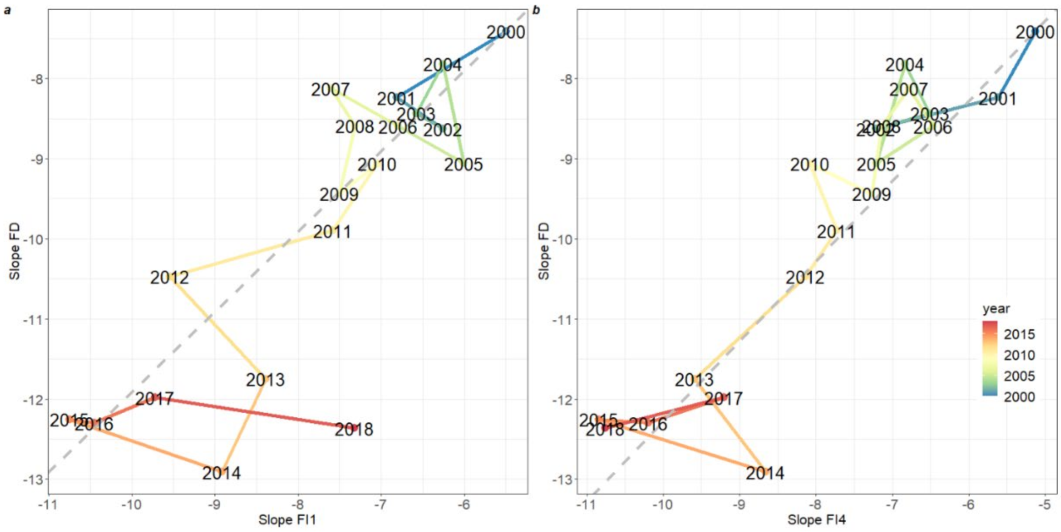


Figure 4.2.3. Comparison of temporal change in cod population size spectra slopes across datasets: (a) slope change from scientific surveys Q1 FI versus commercial data FD and (b) slope change from scientific survey Q4 FI versus commercial data FD. The grey dotted line indicates a simultaneous changes in both datasets relative to 2000 (slope of 1). The color scale indicates years.

Conclusion

The abundance and biomass of large individuals of the eastern Baltic Sea cod population have drastically decreased since 2000. Comparisons of size spectrum slope and size-based indicators temporal variations from fishery-independent (survey) and commercial data indicated fishing effects on decline in size structure in the stock in some years. Fishing potentially contributed also to the largest drop in abundance of larger cod (2011-2013), however the results are not entirely conclusive, and other factors must have contributed as well, as the size structure deteriorated both in survey and commercial catch at the same time.

5. Sensitivity of stock assessment to selected data inputs and robustness of management advice

Stock assessment of Western Baltic cod has become increasingly complex in later years since 2015, including more different kind of data inputs than most standard stock assessments conducted in ICES. Mixing with the Eastern Baltic cod in the management area of the Western Baltic cod requires partitioning of catches in the mixing area of the two stocks. Furthermore, the assessment of the Western Baltic cod has recently included information on recreational catch, as one of the few stocks in ICES. Additionally, the assessment includes annually varying biological information on weights and maturity, and information on discards. This altogether results in relatively high demands for annual data collection and preparation, to obtain regular stock assessments updates.

In this project, we investigated whether some of these data inputs are relatively more influential for stock assessment results and subsequent management advice compared to others. This information is considered useful in case annual data updates need to be prioritized in situations of limited resources.

5.1 Material and methods

5.1.1 Data and scenarios

We investigated the influence of seven different variables on stock status evaluation. These variables are associated with different types of input data, listed in Table 5.1, together with the abbreviations used in this report. Survey data and commercial landings at age where considered the main inputs for stock assessment, and thus these variables were not included in scenario analyses, which focused on other catch components (discards, recreational catch) and biological information on weights, maturity and stock mixing. In the scenarios conducted, only one variable was modified at a time, including its propagated effects, e.g. on catch numbers, while keeping the rest of the data as used in official stock assessment of the western Baltic cod in 2019 (ICES 2019b).

Table 5.1. Variables modified in scenario analyses and their abbreviations.

Abbreviation of scenario variables	**Description**
Base	Input and output from official stock assessment (ICES 2019)
Discards	Total amount of commercial discards relative to landings in weight
AgeD	Age composition of discards
Recrea	Total amount of recreational catch in weight
AgeR	Age composition of recreational catch
Mixing	Proportion of western Baltic cod stock in total commercial catch of cod in SD24
Weight	Mean weight at age, both in fisheries catch and in the stock
Maturity	Proportion mature at age

The scenarios were defined in a way that these would be realistic, i.e. taking into account links between variables or age groups, to avoid too unrealistic scenarios. The aim of these scenarios was to demonstrate the range of results that could be obtained within reasonable range for certain input variable, avoiding unrealistic scenarios. Three different approaches to modifying selected input variables were investigated:

i) **Approach 1:** For each year in the time series, values were randomly drawn from the entire range of observed values. In these scenarios, we investigated the impact of applying annually "incorrect" variability within a given range to certain input data.
ii) **Approach 2:** For all years in the time series, we applied the same values for a given parameter, randomly drawn from the observed range. Here we investigated the impact of ignoring annual variability in the time series.
iii) **Approach 3:** We took into account long term trends in the time series, but not inter-annual variability. Thus, we identified when shifts in the time series had occurred, and chose random values only from within a given "regime". In these analyses, we investigated the impact of ignoring inter-annual variability within a period after taking into account major changes in a parameter over time.

We run 100 replicates for each case, where relevant. This relatively low number of replicates was chosen for practical reasons, to save computation time, and was considered sufficient for the purpose of these analyses, to obtain an overview of the range of deviations of results from the baseline and differences between the variables and approaches. Below further specifics regarding the scenarios conducted for each of the 3 approaches are described.

Approach 1: Random values from the entire observed range
Discards: Discard amounts have been closely connected to the amount of landings (r^2=0.81 in the observed data) for this stock. Therefore, annual discard amounts were not varied randomly, but instead we varied the amount of discards relative to landings, i.e. discard ratio. In scenarios, discard ratio in each year was set to a random value in the range of maximum and minimum observed in the time series. The corresponding discard amount was then converted to numbers, and incorporated in catch numbers input for stock assessment.

AgeD: The relative age composition of discards applied for a year in a given scenario was randomly drawn from the observed annual age compositions. This randomly drawn age composition was subsequently applied to convert the discard amount observed in a given year to numbers at age, and incorporated in catch numbers input for stock assessment.

Recrea: Recreational catch has been independent from commercial catch in the observed time series. Therefore, we randomly varied the annual recreational catch amounts, in the range of observed values. In each scenario, the annual recreational catch was then converted to numbers using the observed age structure for a given year, and incorporated in total catch numbers input for stock assessment.

AgeR: Similar to age composition of discards, the relative age composition of recreational catch applied for a year in a given scenario was randomly drawn from the observed annual age compositions. This age composition was subsequently applied on observed recreational catch amount in a given year, and incorporated in catch numbers input for stock assessment.
Mixing: In scenarios, the annual proportion of eastern Baltic cod stock in total cod catches (including those from western Baltic stock) in SD24 (pct_EBC) was randomly drawn from the

range of observed values in the time series. Landings in numbers at age as well as total cod landings in tons separately for SD 22 and 23, were derived from ICES WGBFAS. Catch in numbers was modified in each scenario, corresponding to different pct_EBC. This was done as follows:
Landings of Wester Baltic cod (WBC) in tons in SD 24 were calculated as:
Landings_WBC= Landings_24- (Landings_24*pct_EBC)

Landings in numbers in SD 22 were then upscaled by the fraction of tons of WBC in SD24, and thereafter landing numbers in SD23 were added, to obtain total landings in numbers for the WBC stock. Similar procedure was done for discards, using the same mixing proportions in scenarios (pct_EBC) as for landings. The scenario landings and discards at ages were subsequently summed and incorporated in catch at age, as input to stock assessment.

Weight: Catch weights (sw) and stock weights (sw) are set equal in stock assessments for WBC for ages 4 and older. For ages 1-3, cw and sw differ, being sampled from catches and research surveys, respectively. There is no correlation between cw and sw for ages 1-3 ($r^2<0.1$), therefore, in scenarios, these were varied independently from one another. Also, there is no significant correlation between the different age groups. Thus, the annual values for both cw and sw for each age were randomly sampled from the observed range for a given age.

Maturity: In scenarios, maturity ogive for each year was sampled from the observed annual maturity ogives.

Approach 2: Constant values
For comparison with Approach 1, scenarios were run where instead of random values for each year, the same constant value was applied for all years. This constant value to be applied for all years was randomly drawn from the observations, as in Approach1. In case of age compositions (*AgeR, AgeD*), 34 replicates were possible in these analyses, that corresponds to the length of time series, and thus to the number of unique age compositions from which the age structure to be applied for all years was drawn. In case of *Maturity*, only 20 unique maturity ogives were available in the dataset, and correspondingly 20 replicates were run.

Approach 3: Taking into account major shifts in the data
For four selected variables (i.e. *Discard*, *AgeD*, *Mixing* and *Maturit*y), runs were made, applying otherwise random values from the observed range, as in Approach1, but taking into account major shifts that had occurred in the time series. For *Discard* and *Mixing,* two periods were identified using STARS analyses, with breakpoints in 2007 and 2006, respectively (Fig. 5.1). For *Maturity*, we separated the period from 2009 onwards, which is an average breakpoint identified for ages 1-3 in STARS analyses. It corresponds to a change in maturity for age2, where also the largest change in proportion mature is detected among the age groups and where maturation mainly occurs. For *AgeD*, a shift in the proportion of Age 1 in discards was identified to have occurred in 1999 that was applied to separate periods for randomly choosing the age structure for discards.

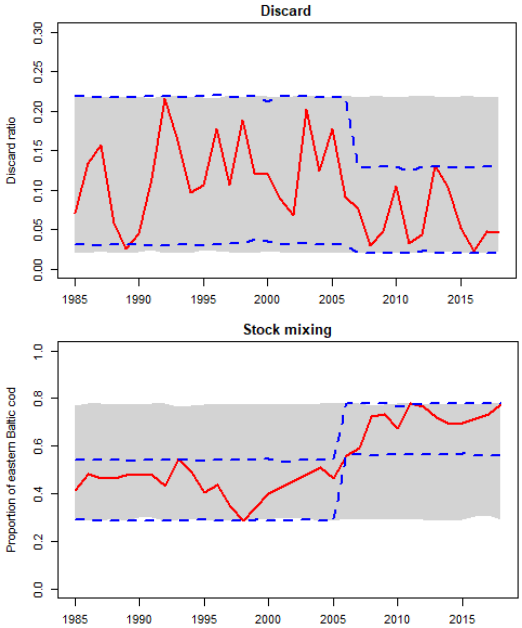


Figure 5.1. Illustration of the range of values applied in scenarios for Approach1 (grey zone) compared to Approach 3 (blue lines). Red lines show the actual time series for *Discards* and *Mixing*.

5.1.2 Analyses

In the analyses investigating the influence of different variables on stock status evaluation, the following steps were followed:

i) Respective input file to stock assessment (catch numbers, weights or maturity) was modified according to the scenarios described above.
ii) Stock assessment was run with the modified input, using all other inputs as in Base and the SAM model with the same settings as applied in formal stock assessment.
iii) The assessment results from each scenario (for each of the replicates) was used to estimate corresponding biomass limit reference point (Blim), using the same principal as applied in the current official estimates. It means that Blim was set to the average of the 4 lowest SSB values that had given raise to above average recruitment.
iv) As a next step, FMSY was recalculated for each scenario, using the Eqsim program, and following the standard procedures applied for this stock in ICES. S-R was defined as hockey stick, with a break point set to the estimated Blim for a given scenario. Biology and selectivity were used as averages for the years 2015-2018.
v) Then SSB/Blim and F/Fmsy ratios were calculated for each scenario (for each of the replicates) for each variable investigated.
vi) Finally, forecast was conducted, where F in intermediate year was set to status quo and to the estimated Fmsy in the following year. Catch corresponding to FMSY advice for the year after was compared for the scenarios.

The results are presented in relative terms, as percentage difference from the Base scenario.

5.2 Results

Comparison of the impact of different variables on stock status evaluation
The deviations in SSB from the baseline were generally largest for *Weight* and *Maturity*, where up to 50% deviations in the time series occurred (Fig. 5.2). For *Mixing* scenarios, up to 30% deviations were obtained. For *Discard* and *Recrea*, SSB deviations were mostly below 10 %, with a few exceptions for some years in some scenarios. Also, for age composition scenarios (*AgeD* and *AgeR*), the SSB deviations from the baseline were generally relatively small (below 10%) in the historical part of the time series, but up to 30% in the latest years.

The deviation in fishing mortality (Fbar) from the baseline were generally small (<10%) in historical part of the time series for all variables investigated. However, larger deviations from the baseline were obtained for most recent years in the time series, especially for *Recrea* and *AgeR* (up to >50%), and somewhat less for *Discard* and *AgeD*. In scenarios for *Mixing*, the Fbar deviations from the baseline were mostly <10% for the entire time series. *Maturity* and *Weight* do not affect the F estimates from stock assessment. The large impact on F in latest years for some variables is likely related to a peculiar age structure of the stock in recent years, with one year-class (from 2016) largely dominating the catches (ICES 2019b). Therefore, the F in final years is extra sensitive to modifying the age structure of the catches in scenarios compared to the observed unusual age structure.

When looking at the results of stock status in terms of SSB relative to Blim and F relative to FMSY, in some cases larger deviations from the baseline were obtained, compared to looking at SSB or F alone. For SSB, this was the case for *Discard* and *AgeD*, where up to 20-30% deviations from the baseline for SSB/Blim were obtained compared to mostly <10% deviations for SSB. Also, for *AgeR*, the deviations from the baseline generally became larger for SSB/Blim. This is because Blim was changing in the scenarios as well, corresponding to the assessment results, and in these cases the deviations from the baseline where amplified when accounting for both Blim and SSB changes. For *Maturity* and *Mixing*, the impact of Blim changes in scenarios was propagated differently in different parts of the time series. For *Maturity*, the SSB deviations from the baseline were smallest for later years in the time series, while the deviations of SSB/Blim were, on opposite, largest in the later part of the time series (Fig. 5.3). This is because in early part of the time series, the changes in SSB and Blim were balancing out one another, resulting in lower overall deviation of SSB/Blim, compared to later part of the time series, where SSB was changing relatively less. Similar pattern is seen for *Mixing*, with larger deviations in SSB/Blim in the historical part of the time series and smaller in later years, compared to SSB. For F, there is not much difference in deviations from the baseline when looking at Fbar or Fbar/FMSY, which is because of smaller impact of the scenarios on Fmsy compared to Blim.

Further discussion on the impact of the scenarios on reference points is provided in Section 3 in this report.

Impact of annually varying vs constant values on stock status evaluation
Comparison of Approach1 (annually varying random values) and Approach2 (annually constant random values) did not reveal major differences in SSB/Blim deviations from the baseline for *Discard*, *AgeR* and *Mixing* (Fig. 5.4). Although, on average over the time series, somewhat

wider range of results was obtained from Approach1 (Fig. 5.6.a). For other variables, the average and maximum deviations from the baseline were more clearly smaller in Approach2 compared to Approach1 (Fig. 5.4, Fig. 5.6a). This is best seen for *Maturity* (Fig. 5.6a) and historical part of the time series for *Weight* (Fig. 5.4). The range of SSB/Blim values obtained from the scenarios for a given year was generally smaller for Approach2 compared to Approach1, for all variables, as expected.

In case of F/FMSY, the large deviations from the baseline in latest years for *Discard* (up to 50%) in Approach1 did not occur in Approach2 (mostly <10%) (Fig. 5.5). Also, when aggregated across years, the results from Approach1 showed wider range of values compared to Approach2 (Fig. 5.6b). For *Mixing*, the deviations in the entire time series were clearly smaller in Approach2 compared to Approach1 (Fig. 5.5, 5.6b). Opposite, for *Weight*, the maximum deviations of F/FMSY from the baseline in Approach 2 were larger compared to Approach1 (Fig. 5.5), which is due to scenario impact on FMSY value.

The SSB/Blim values from Appraoch3 (taking into account long-term changes in variables) showed clearly smaller deviations from the baseline compared to Approaches 1 and 2 for *Maturity* and *Mixing*, however were similar to the other approaches for *Discard* and *AgeD* (Fig. 5.6a). The F/FMSY values from Approach3 were similar to Approach2 for *Mixing*. For *Discard* and *AgeD*, the differences between the approaches were less clear (Fig. 5.6b).

Impact on potential catch advice

The potential catch advice corresponding to FMSY from the scenarios conducted showed up to 50% deviation from the baseline (Fig. 5.7). However, there were large differences between variables explored. In Approach1, largest deviations (up to 50%) from the baseline were obtained for *AgeR*. Smallest deviations occurred for *Maturity* (<10%), while the deviations for other variables were up to 25-40%. In Approach2, largest deviation (up to 50%) was obtained for *Weight*, which is probably due to these scenarios impacting on FMSY value. For other variables, the maximum deviations from the baseline were slightly smaller than in Approach1. The deviations obtained from Appraoch3 were generally relatively similar to Approach2. In all analyses, smallest deviations of FMSY catch from the baseline were obtained from the scenarios varying *Maturity*. This is due to no impact of maturity on F, which is most influential for FMSY advice.

Conclusion

Varying some of the investigated variables had larger impact on biomass, others on fishing mortality, making it difficult to conclude on overall impact for stock status evaluation. The larger impacts (>10%) on biomass occurred over the entire time series, while fishing mortality was mostly affected for latest years, however in some cases by large extent (>50%). Given that fishing mortality in latest years is the main basis for FMSY based catch advice, accurate information for the variables having most impact on F in latest years could be considered most essential. These were the variables related to age composition (*AgeR* and *AgeD*) as well as the amount of catch for those catch components which age structure differs from that of the landings, thereby indirectly influencing the age composition of the total catch (*Recrea*, *Discard*). In situations when reference points are re-estimated, the biological information, e.g. on *Weight*, can also have a large impact on FMSY catch advice by influencing the FMSY value. In terms of potential catch advice following FMSY, *Maturity* seems to be least influential among the variables investigated, at least in situations when stock biomass is above the biological reference limit and maturity is not influencing the stock status being above or below Blim. In case of lack of correct information on annual variability, applying constant values may be advantageous, resulting in generally smaller deviations from the “truth”, compared to scenarios applying incorrect annual variability.

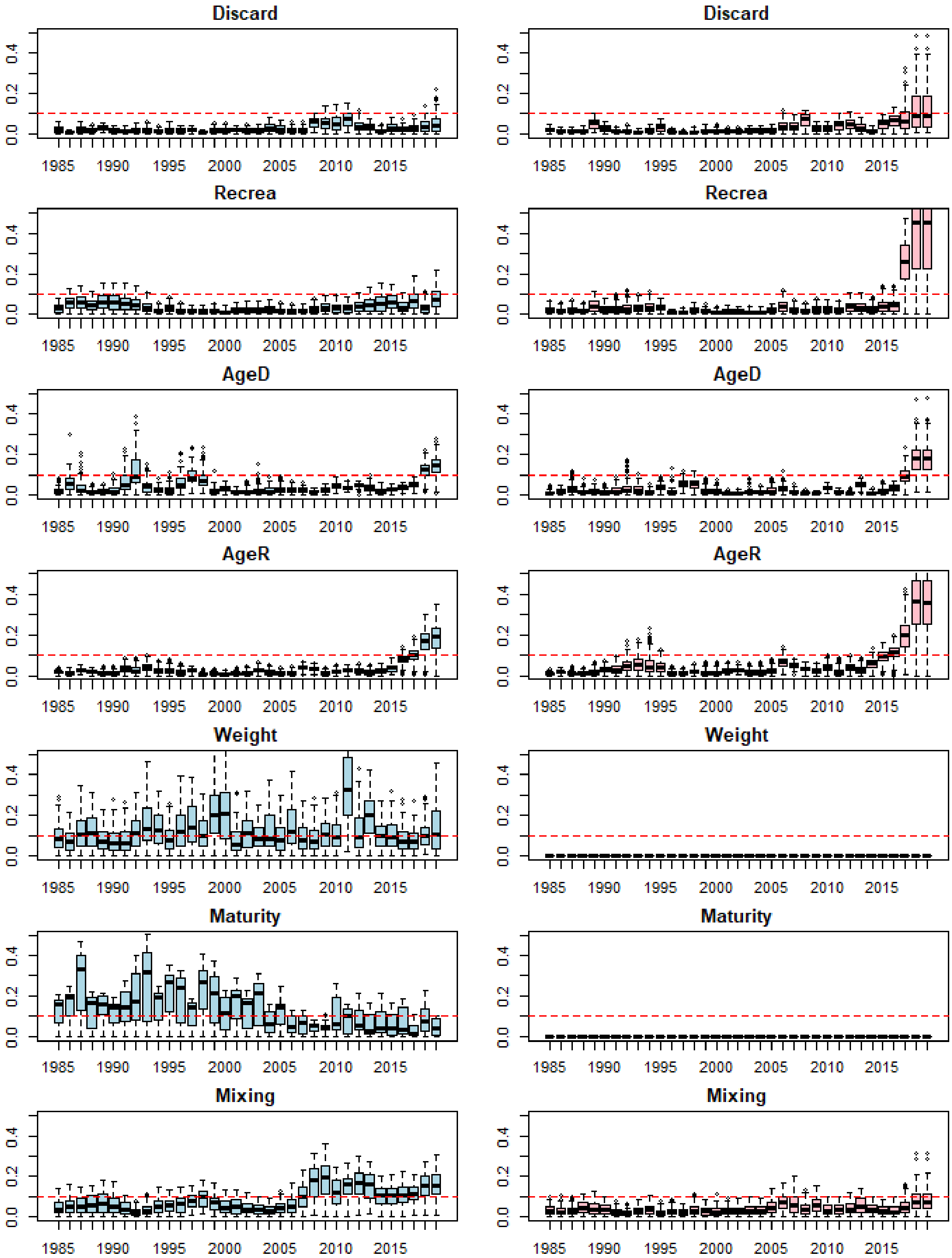


Figure 5.2. SSB (left panels) and Fbar (right panels) values relative to the baseline (proportion difference), from Approach 1 (see Material and Methods for explanation). Boxplots show variation from different scenarios, varying the variable shown in different panels. Red lines depict 10% deviation from the baseline, for illustration.

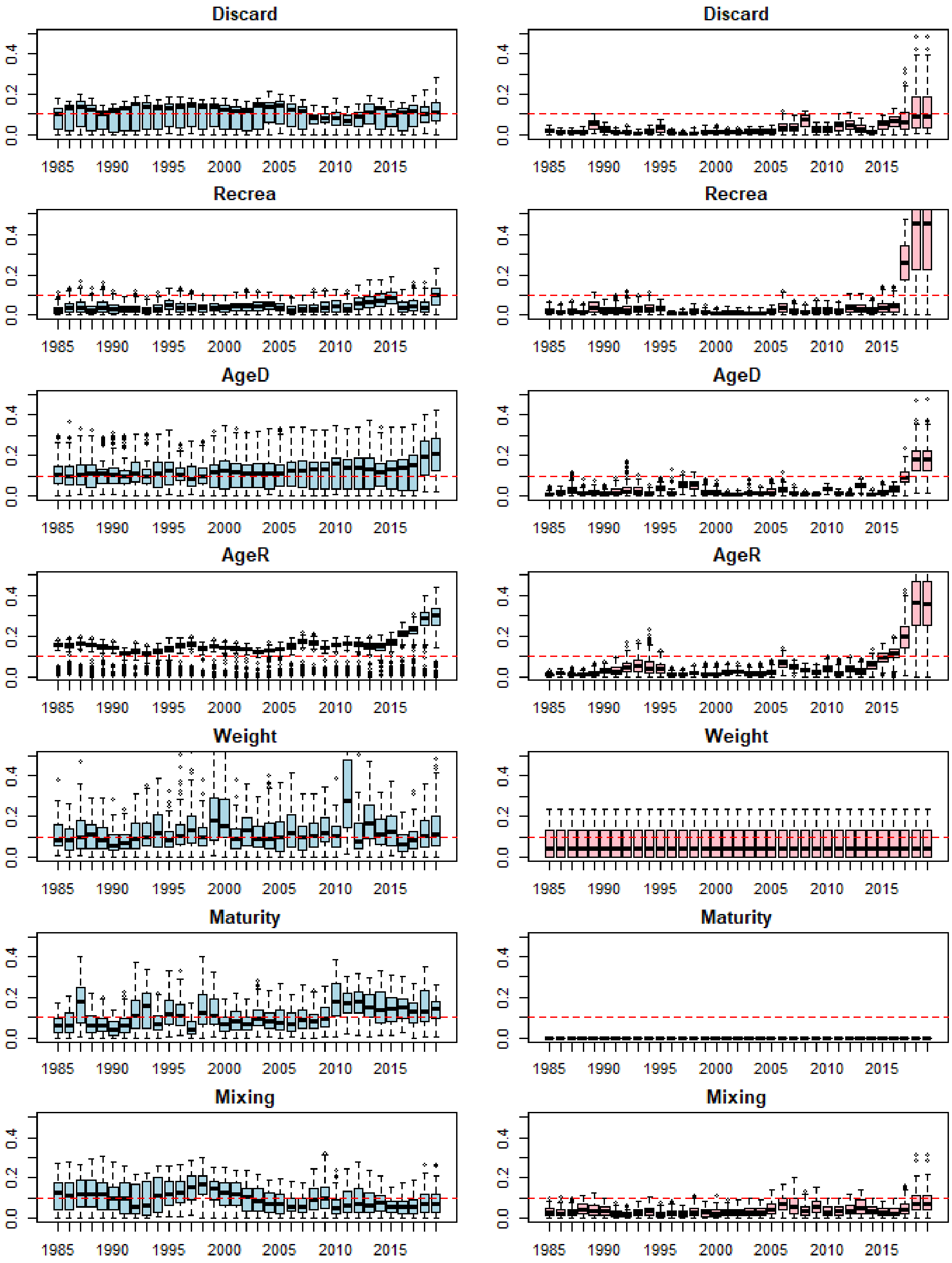


Figure 5.3. SSB/Blim (left panels) and Fbar/FMSY (right panels) values relative to the baseline (proportion difference), from Approach 1 (see Material and Methods for explanation). Boxplots show variation from different scenarios, varying the variable shown in different panels. Red lines depict 10% deviation from the baseline, for illustration.

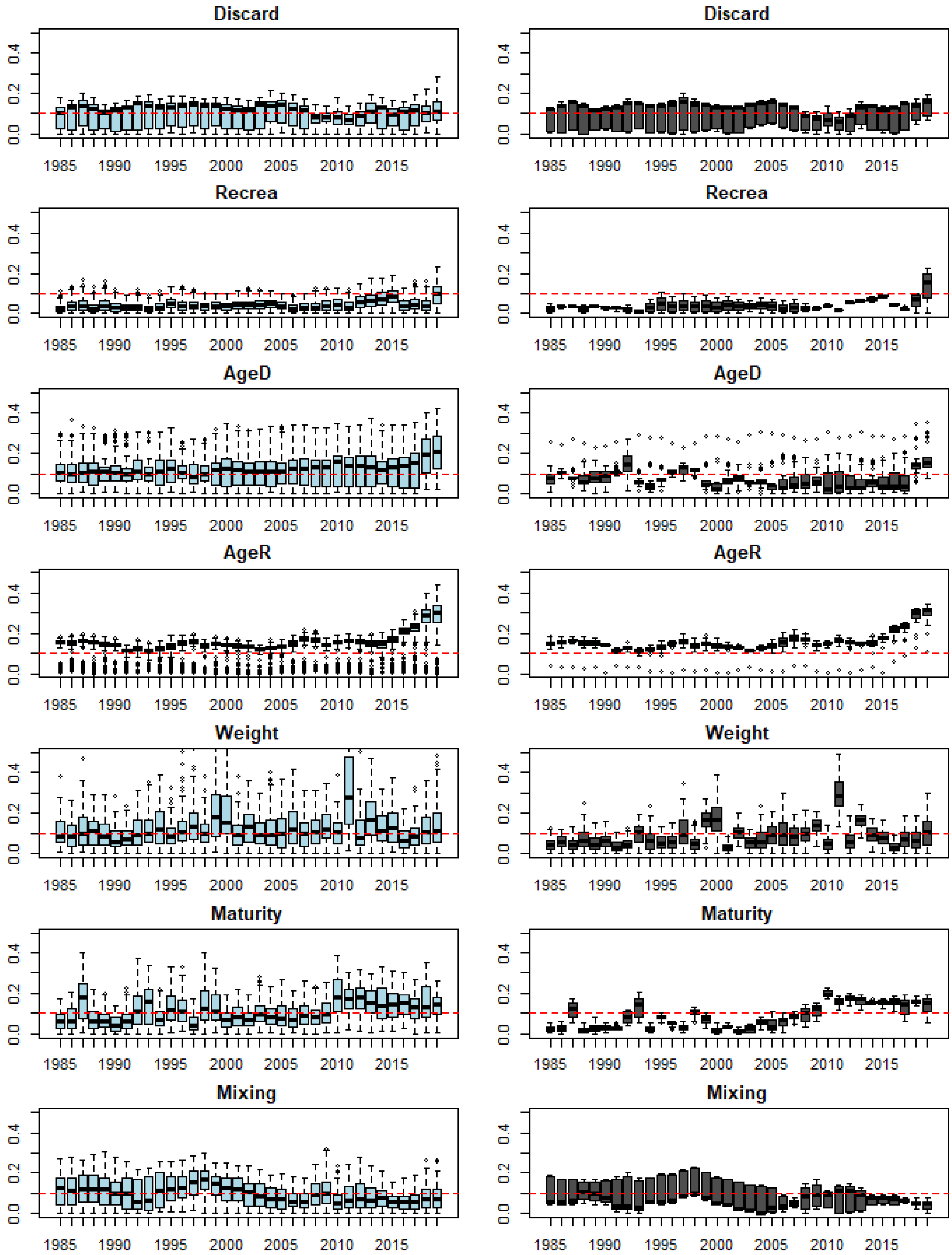


Figure 5.4. SSB/Blim from Approach 1(left panels) and Approach 2 (right panels) relative to the baseline (proportion difference) (see Material and Methods for explanation of the Approaches). Boxplots show variation from different scenarios, varying the variable shown in different panels. Red lines depict 10% deviation from the baseline, for illustration.

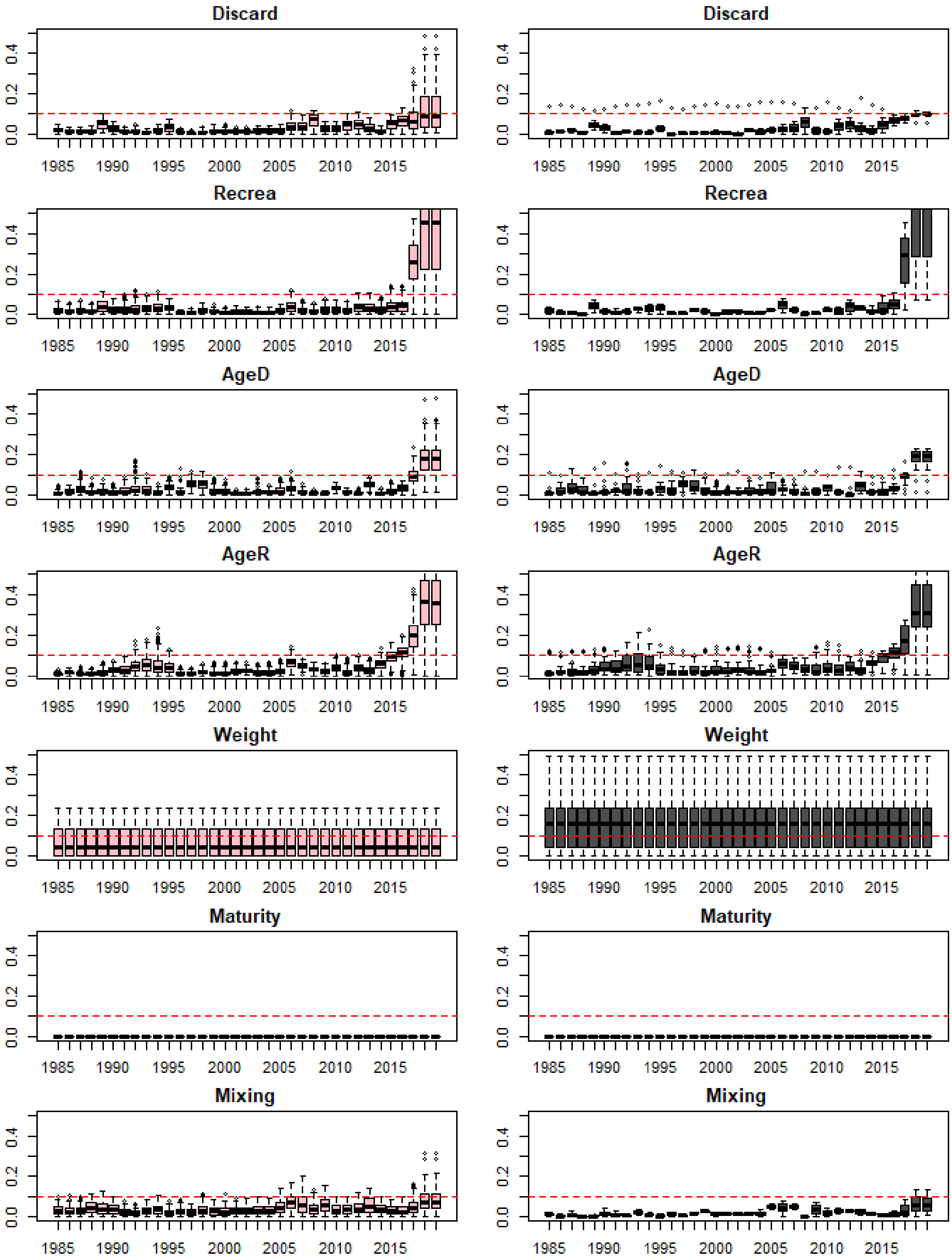


Figure 5.5. F/FMSY from Approach 1(left panels) and Approach 2 (right panels) relative to the baseline (proportion difference) (see Material and Methods for explanation of the Approaches). Boxplots show variation from different scenarios, varying the variable shown in different panels. Red lines depict 10% deviation from the baseline, for illustration.

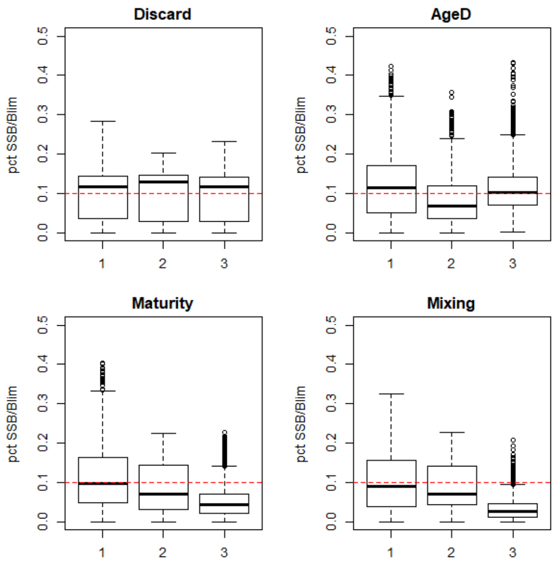


Figure 5.6a. SSB/Blim deviations from the baseline (proportion difference), aggregated over the timeseries. Boxplots show variation from different scenarios, varying the variable shown in different panels. Red lines depict 10% deviation from the baseline, for illustration. X-axis corresponds to Approach1, Approach2 and Approach3 (see Material and Methods for explanation of the Approaches).

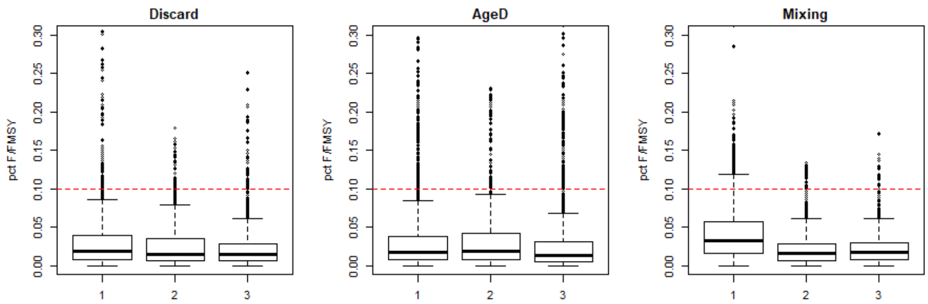


Figure 5.6b. F/FMSY deviations from the baseline (proportion difference), aggregated over the timeseries. Boxplots show variation from different scenarios, varying the variable shown in different panels. Red lines depict 10% deviation from the baseline, for illustration. X-axis corresponds to Approach1, Approach2 and Approach3 (see Material and Methods for explanation of the Approaches).

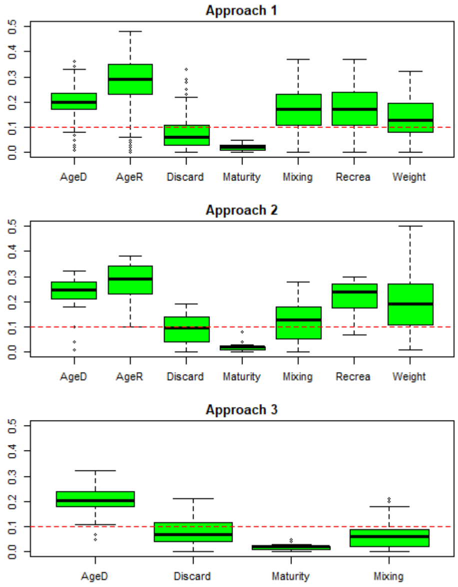


Figure 5.7. Catch advice corresponding to FMSY from the three approaches (see Material and Methods for explanation of the approaches). Boxplots show variation from different scenarios, varying the variable shown in x-axis. Red lines depict 10% deviation from the baseline, for illustration.

6. Communication and dissemination

Communication and dissemination of the results of this project involves three main platforms, i.e. i) international scientific community through stock assessment related work in ICES; ii) international scientific literature and iii) meetings with relevant stakeholders.

The work conducted in this project has been tightly coupled to stock assessment related activities in ICES, for the three cod stocks, i.e. eastern and western Baltic cod and cod in the Kattegat. This is important for international recognition of the outcomes of the project, and ensures most optimal implementation of the results. For eastern and western Baltic cod, the work conducted in this project provided a major contribution to the ICES benchmark in 2019 (ICES WKBALCOD2 2019*a*). For eastern Baltic cod, the work of this project contributed to re-establishing quantitative analytical assessment for the stock. This allowed to reveal aspects of severe stock status that were not visible when applying data limited approaches to stock assessment as was done in previous years. For western Baltic cod, also several improvements to the stock assessment were achieved at the benchmark in 2019, that made use of the contributions of this project. This included extended inclusion of recreational catch and identification of most appropriate way to deal with mixing between eastern and western Baltic cod, given the current scientific knowledge and data. For the Kattegat cod, the activities of this project, focusing on mixing with the North Sea cod, largely emerged from the needs identified at last ICES benchmark for this stock (ICES WKBALT 2017a). The new knowledge produced in this project on that matter is a prerequisite for potential improvement of assessment and management of this stock in future.

Several aspects and issues addressed in this project go beyond what is generally considered in routine fish stock assessments. This is especially the case for the eastern Baltic cod, that has experienced outstanding productivity changes in later years, invalidating some standard approaches involved in stock assessment and management. Therefore, communication of the current situation and potential solutions to a wider audience of both scientists, managers, stakeholders and other interested audience is considered important. This helps to generate common understanding of the challenges faced and possible solutions and thereby facilitates buy-in to management regulations that may be necessary. Publication of the project results in scientific literature was therefore prioritized. The results published so far include the application of the egg production method for eastern Baltic cod (Köster et al. 2020) as a useful supplement to evaluate stock status in situations where standard stock assessment is associated with relatively higher uncertainties. Furthermore, the eastern Baltic cod stock situation has resulted in increased focus on alternative management measures, such as spawning closures. Publication of the review of potential effects of the spawning closures on Baltic cod (Eero et al. 2019), supported by the present project, allows this knowledge to be utilized not only for the particular case of Baltic cod but also elsewhere.

Communication of the stock situation of the eastern Baltic cod is essentially important also in relation to the advice of zero catch from the stock, as has been advised by ICES since 2019. Without deeper insights to the stock situation, the advice of zero catch may be counterintuitive, in the light of the management efforts and resulting substantial decline in fishing pressure of the Eastern Baltic cod that has taken place since 2000s (Fig. 6.1). This could be expected to have improved the stock status. However, here it is important to understand and communicate that, in parallel to reduced fishing pressure, stock productivity has substantially declined to a historic low level (Fig. 6.1).

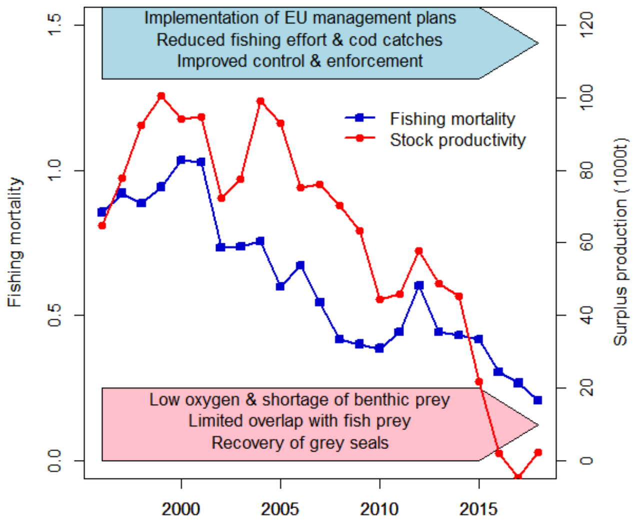


Figure 6.1. Illustration of synchronous declines in fishing mortality and productivity of the eastern Baltic cod (based on the official stock assessment (ICES 2019*a*)); and the fisheries (on the top) and ecosystem (at the bottom) factors suggested to have contributed to respective developments over time (from Eero et al. 2020).

Presently, there is no surplus production in the stock to support harvest, which explains the advice of zero catch. At present low growth and high natural mortality, the stock biomass is projected to remain low, even in the absence of fishing (Fig. 3.1.4). Thus, the future development in this stock and its potential recovery are largely dependent on ecosystem drivers likely contributing to the presently poor state of the cod stock. It is important to understand and communicate these ecosystem drivers as some of these and associated impacts on cod may be possible to influence by management measures. These may, however, not be straightforward to implement. In the frame of this project, we shared with a wider audience the new management challenges emerging from ecosystem changes affecting cod in the Baltic Sea (Eero et al. 2020). The Baltic cod case exemplifies the complexity of questions emerging for management as well as for scientific advice under rapidly changing ecosystem conditions, where traditional fisheries management alone may have a limited potential to rebuild a fish stock.

The eastern Baltic cod example also demonstrates that science is lagging behind in being able to quantify possible benefits to the stock resulting from management interventions influencing the ecosystem conditions. This is due to a high complexity of the ecological processes involved, and combinations of drivers and stock developments that have not been present, and thus not in focus for research in the past (Eero et al., 2015). The research related to managing fish stocks has been traditionally much focused on fishing impacts. This priority and focus on fisheries in scientific development in the past is justified, as fishing is often a dominant pressure on commercial fish, as has also been the case for the Baltic cod. However, no quantitative models are presently available that would be capable of addressing processes relevant for the eastern Baltic cod, which are related to physiological stress, food limitation and parasites, to be able to compare their relative impacts on fish growth, mortality and reproduction, and evaluate associated management measures.

Similar pronounced changes in productivity as recently observed for the eastern Baltic cod may become more common in future in other areas and species, for example under climate change.

The eastern Baltic cod example could inspire and motivate management frameworks as well as supporting science to become better prepared to handle new questions and emerging management challenges in a timely manner in future. This involves continuous monitoring of various ecosystem parameters to obtain early warnings, and adaptive scientific frameworks to allocate efforts to new questions as they emerge, e.g. the effects of parasites or food limitation in the case of Baltic cod. Finally, it may be relevant to consider whether stock productivity declines due to unfavourable ecosystem conditions are reversible at all by ecosystem management, and how far should such interventions go. This may involve consideration and balance between associated costs, societal values connected to certain species or ecosystem structure, as well as the potential ecosystem services under alternative ecosystem configurations (Eero et al. 2020).

The participants of this project also took part in several meetings with fishing industry, NGO-s and managers, where topics relevant to the three cod stocks included in this project were discussed. There include local annual meetings in Danish Fishermen's organization; BSAC meetings, dialog meeting on the future for Danish fisheries in the Baltic Sea, and regular meetings with the ministry and fishing industry. Finally, the Baltic cod situation was also communicated in Our Baltic conference in Sept. 2020, that brought together ministers, decision makers, scientists and stakeholders from NGOs and industry in the region and across the EU to discuss the challenges faced by the Baltic Sea.

Acknowledgements

We thank SLU Aqua, Sweden, for collaboration in relation to stock assessment modelling and grown analyses of the eastern Baltic cod, as well as in relation to data and samples used in the analyses of cod stock mixing in the Kattegat. We also thank Thünen Institute for Baltic Sea Fisheries, Rostock, for contributing data used in the analyses of recruitment of Western Baltic cod, and GeoMar, Kiel, for organising and coordinating the sampling of Eastern Baltic cod for fecundity analyses.

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Annex A: A model for East-West cod stock classification in the Baltic Sea

A model for East-West cod stock classification in the Baltic Sea

Casper W. Berg

November 20, 2018

1 Summary

This document describes a model for the probability of a cod being from either the western or eastern sub-population of Baltic cod. The purpose of the model is to provide east-west population specific estimates of relative abundance when combined with trawl survey data. The model is fitted to east-west classifications based on otolith shape analysis as well as genetics. The model uses time, length of the fish, and longitude as explanatory variables.

The model is then used for allocating a stock to all length and age samples of cod from BITS, either by expected probability (soft cut) or by the most likely stock (hard cut).

Samples classified as belonging to the western stock are then used to calculate standardized indices of abundance by age. Only the western stock is considered in this respect because ageing is unreliable for the eastern stock component. Indices of abundance based on a fixed geographical area where it is assumed that the majority of samples are belonging to western stock are also calculated for comparison. Finally the different indices are compared based on internal and external consistencies.

2 Data

All available classifications based on otolith shape from the German part of the BITS are used. Three versions of the otolith shape data were provided:

1. Original genetic baseline (only German data). No length effect correction.
2. Updated genetic baseline and length effect correction (German and Danish data).
3. Updated genetic baseline without length effect correction (German and Danish data).

The original genetic baseline was updated with Danish genetic samples because the German data alone contained relatively few samples of small cod. The length effect correction was added because other work with east/west classifiers from otolith shape suggested that improved classification success could be achieved by including the fish length in the model. Initially only data set 1 and 2 were provided, and only with the binary classifications as the response variable. After the first

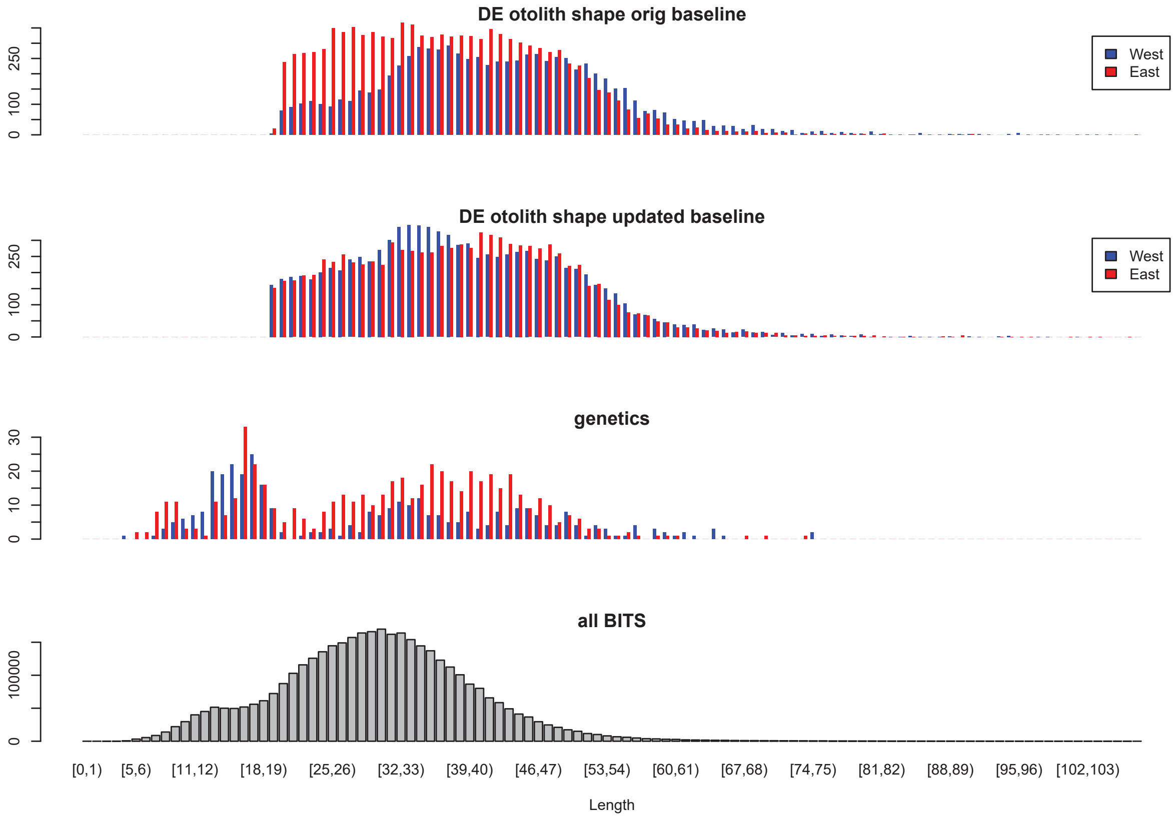

Figure 1: Assignment by length and data source. The two top plots show data sets 1 and 2.

data meeting classification probabilities and data set 3 were also provided. It was decided to omit the length effect correction, because it did not seem to produce more reliable results.

For the genetic classifications we only consider samples that are taken within the time-period when BITS is conducted. Both data sources are useful, since they cover different parts of the populations. The otolith data only contains samples of individuals larger than 20 cm but covers the whole time-span of BITS, whereas the genetic data spans the whole length spectrum but with incomplete coverage over time (see tables in the appendix).

3 Model

This section describes the model for the probability of east/west stock allocation. In the first attempt the response variable was only provided as the categorical classifications of east/west, and a binomial model had to be fitted. However, the otolith classifications comes from another model, which provides the more informative classification probabilities. After these probabilities were provided, a beta regression model was fit to the probabilities rather than the binary classifications. The same mean value formula was used for binomial and beta regression models:

$$\text{logit}(E(p_i)) = \mu + f_1(t_i, l_i) + f_2(t_i, l_i)\theta_i \quad (1)$$

where p_i is the probability of belonging to the west stock for the ith individual, μ is the overall mean, f_1 and f_2 are tensor product splines, t is time, l is the length of the fish, θ is the longitude. Both tensor product splines use Duchon spline bases [3] with 1st order derivative penalities. These spline bases "go flat" outside the data range as opposed to cubic or thin-plate splines which will follow linear trends, which may produce unrealistic predictions. Duchon splines were chosen because extrapolation outside the range of sampled longitudes and time-periods will be needed. The model formulation is known as a varying coefficient model [4], because for a given time and length (t, l) the model is a simple logistic regression as a function of longitude θ. The spline terms allows smooth changes in the intercept (f_1) and slope (f_2) as a function of time and size of the fish. All splines are subject to a zero mean constraint such that the common intercept μ is identifiable. Estimation is performed using the `gam` function from the `mgcv` package in `R`. Smoothness selection in the beta regression model is performed by minimizing the negative REML score. For the binomial model smoothness selection was estimated using the UBRE criterion, or a further penalized version of that. The latter is achived through the "gamma" argument to "gam", which multiplies the model degrees of freedom in the UBRE criterion. A justification for enforcing more smoothness in the binomial models is that the errors/uncertainties in the classifications are not accounted for. The following valus of the "gamma" argument are tried: 1.4 (recommended default), 5 (roughly equivalent to smoothness selection by BIC), 10 and 20.

The following combinations of data and splitting model are tried:

1. Binomial classifications. Data set 1. Smoothness selection: $\gamma = 1.4$.
2. Binomial classifications. Data set 1. Smoothness selection: $\gamma = 5$.
3. Binomial classifications. Data set 1. Smoothness selection: $\gamma = 10$.
4. Binomial classifications. Data set 1. Smoothness selection: $\gamma = 20$.
5. Binomial classifications. Data set 1, but excluding otolith classifications for lengths < 35 cm . Smoothness selection: $\gamma = 10$.
6. Binomial classifications. Data set 2. Smoothness selection: $\gamma = 1.4$.
7. Binomial classifications. Data set 2. Smoothness selection: $\gamma = 5$.
8. Binomial classifications. Data set 2. Smoothness selection: $\gamma = 10$.
9. Binomial classifications. Data set 2. Smoothness selection: $\gamma = 20$.
10. Probability classifications. Data set 1. Smoothness selection by REML.
11. Probability classifications. Data set 3. Smoothness selection by REML.

In addition to the settings for the split models (Table 1) the effect of a soft split versus a hard split is also investigated. A soft split is one where survey numbers-at-length (calculated as described in [2]) are multiplied with the probability of being east/west for each point in time and space. A hard split is one where instead of multiplying with probabilities we multiply with the most probable stock, such that all hauls where the probability is less than 0.5 are excluded completely. We also consider a fixed geographical split at 13° longitude as well as using the current method for the

Western Baltic cod, which also uses a fixed geographical split at 13° longitude but an age-based CPUE standardization model (Configs 19 and 21 in the table below). Finally, model 20 assumes that east/west mixing only occurs in area 24, whereas areas 23 and 23 are 100% western cod and areas 25–29 are 100% eastern cod. The same assumption was made when splitting the commercial catches for the assessment, which is why this was the preferred option during the data meeting.

Config	Split model	Otolith shape	Longitude	Soft/Hard	Model type
1	1	Orig (1)		Soft	Length
2	2	Orig (1)		Soft	Length
3	3	Orig (1)		Soft	Length
4	4	Orig (1)		Soft	Length
5	5	Orig (1)		Soft	Length
6	6	Updated (2)		Soft	Length
7	7	Updated (2)		Soft	Length
8	8	Updated (2)		Soft	Length
9	9	Updated (2)		Soft	Length
10	1	Orig (1)		Hard	Length
11	2	Orig (1)		Hard	Length
12	3	Orig (1)		Hard	Length
13	4	Orig (1)		Hard	Length
14	5	Orig (1)		Hard	Length
15	6	Updated (2)		Hard	Length
16	7	Updated (2)		Hard	Length
17	8	Updated (2)		Hard	Length
18	9	Updated (2)		Hard	Length
19			13	Hard	Length
20	2	Orig (1)		Soft24/Hard	Length
21			13	Hard	Age

Table 1: Indices compared. Indices 1–18 are based on time-varying splitting and length-based standardization. Configs 19 and 21 uses 13° longitude fixed split. Configuration 21 is using the currently used age-based standardization model (data from 2001 and onwards only).

At present, no indices were computed using splitting models 10 or 11, because these data were not available initially, however the results are expected to be comparable to using model 2 (see results section).

To calculate Western Baltic cod indices from the numbers at length (after splitting by stock), age-length keys are needed as well. Spatially varying age-length keys are estimated as described in [1], except that the age-samples are weighted with the probability of being of western origin using the same model as for splitting the length data.

4 Results

Models fit to original baseline data (1–4) display a strong dependence on length, small cod are predicted to be east cod, whereas large cod are from the western stock (2). Model 5, which also uses the data from the original baseline but excludes otolith classifications for lengths < 35 cm, gives more mixed predictions of small cod. This indicates a conflict between the Danish genetic data and the otolith classifications based on the original genetic baseline. Models fit to data using the updated baseline with length correction (6–9) have less pronounced length effects, in fact model 9, which has the highest smoothness penalty imposed, removes the length effect completely from the model. The effect of longitude is more similar between the original baseline and the updated one (figures 2 and 3 bottom rows). The results from models fit to the classifiction probabilities rather than binary classfications (10 and 11) are shown in figures 5 and 6. These two models give very similar results, probably because the updated baseline is not much larger than the original. It is also worth noting that the plots from models 10 and 11 look quite similar to those obtained from using model 2 (compare figure 2 with 5 and 6).

The results of using various fixed longitudes (using the current age-based standardization approach using years 2001–2018) are shown in figure 7. There is a clear local maximum at 13° longitude, which confirms the currently used fixed cut point as being the most appropriate among possible values.

Figures 8 and 9 show the age-based indices for Western Baltic cod in quarter 1 and 4 respectively (scaled to have mean 1 for all ages) for a subset of the examined models. There are some clear discrepancies between the indices from different models, especially for quarter 4 and for the older age groups. The largest differences are found between models that uses the soft split (1–9) and models with hard or soft24/hard (9–21). Specifically, all indices indicate that there was a high recruitment to age 0 in 1997, but this strong cohort is disappearing for the older ages when using the hard cuts but not when using the soft cuts. This effect is most pronounced for the Q4 indices. This is also evident in figure 10, which shows the internal and external consistencies for all the indices. There is a clear tendency that models 1–9 (soft cuts) have better internal consistencies for Q4. The previously used age based model (21) actually has the best average consistency, although this may be due single high valued data points that are driving the correlation. Models (1–5) are the best among the length based models with respect to concistencies, although there are alternatives using hard cuts that are almost as good, e.g. model 20. It is also worth noting, that model 20 using the soft24/hard split has slightly higher consistencies than model 19, which does not use splitting data at all, but simply a fixed hard geographical split.

The reason for why the soft versus hard splitting alternatives yield quite different results is illustrated in figure 11: There are substantially higher abundances of cod in area 25 compared to any of the other areas, so even when only a small percentage of the cod in area 25 are assumed to be western cod it has a large impact on the indices of abundance. This is also evident from the spatial plots (see Appendix), which clearly illustrates the differences between soft and hard cuts. It should however be kept in mind, that no data (genetics or otolith shape) were available from outside area 24, so the predicted split percentages in area 25 are made by extrapolating the model beyond the data range. It must therefore be recommended that samples outside area 24 should be obtained, most importantly from area 25.

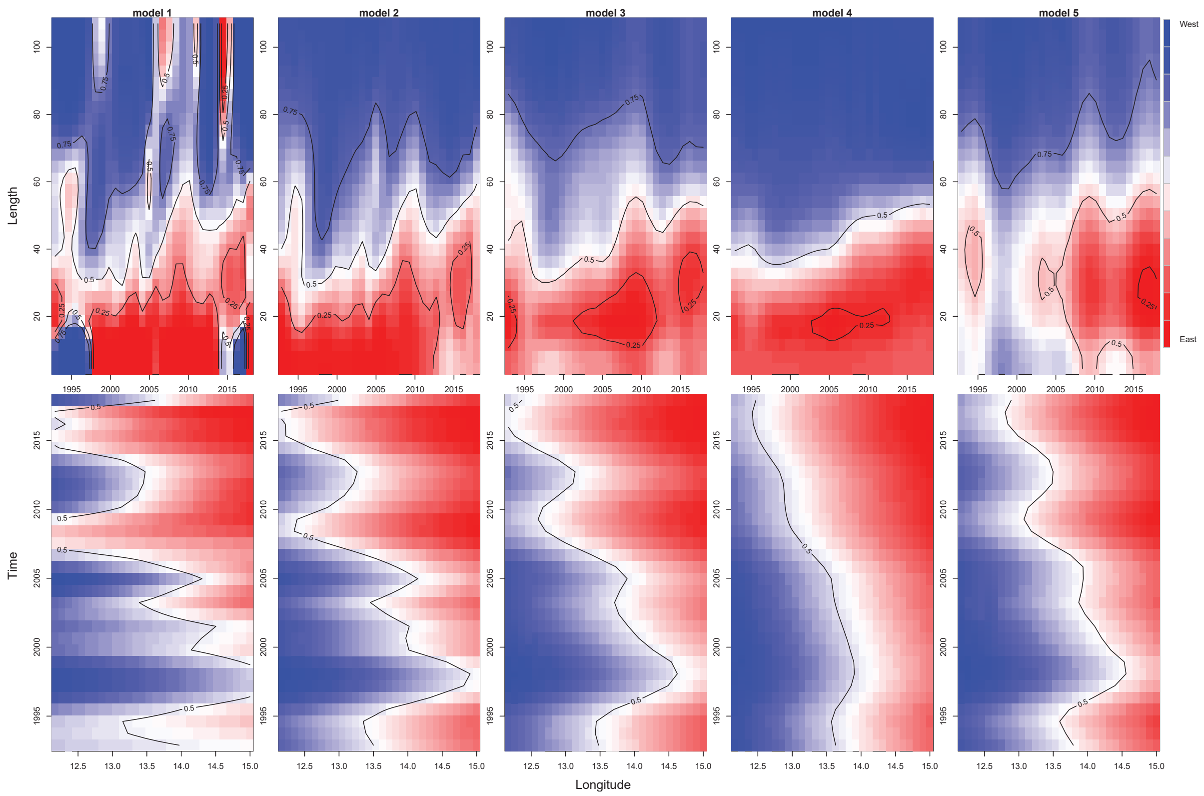

Figure 2: Top row: Estimated east/west probability as a function of time (x-axis) and length (y-axis), given the longitude being 13°. Columns represent models 1–5.
Bottom: Same but as a function of longitude (x-axis) and time (y-axis) given a cod of 38 cm in length.

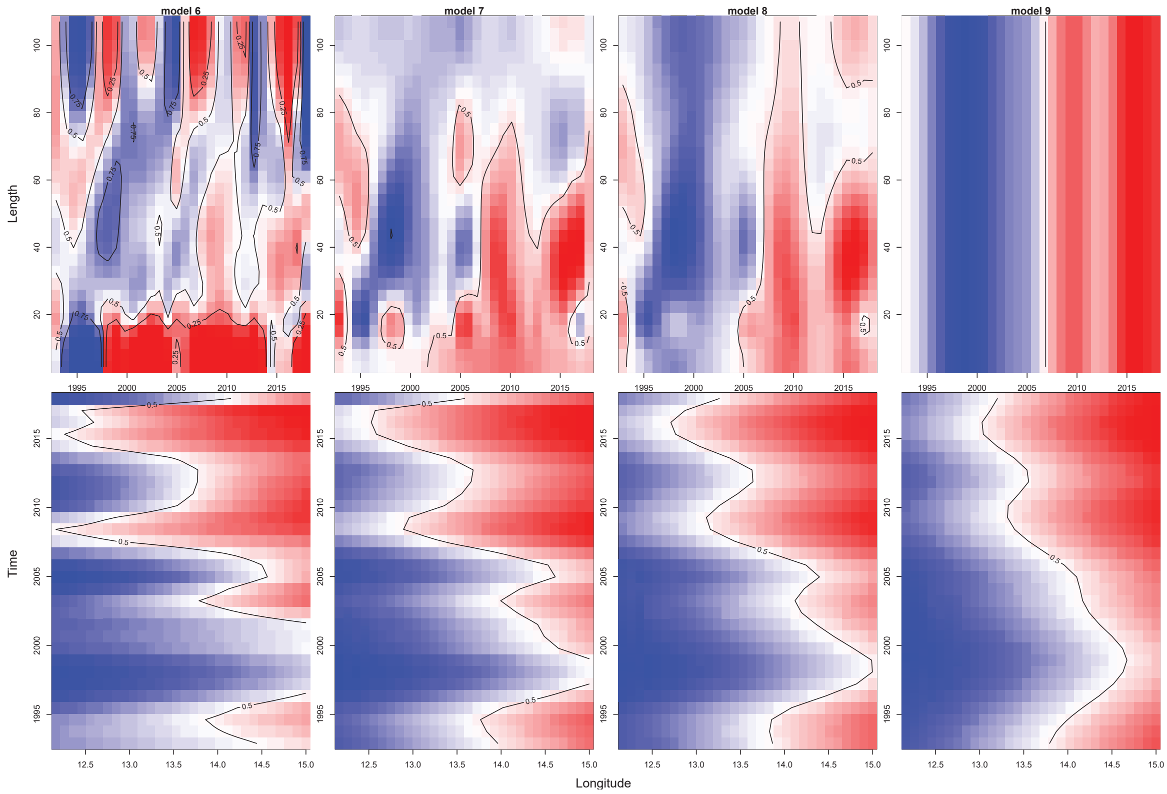

Figure 3: As figure 2, but for models 6–9 (updated baseline).

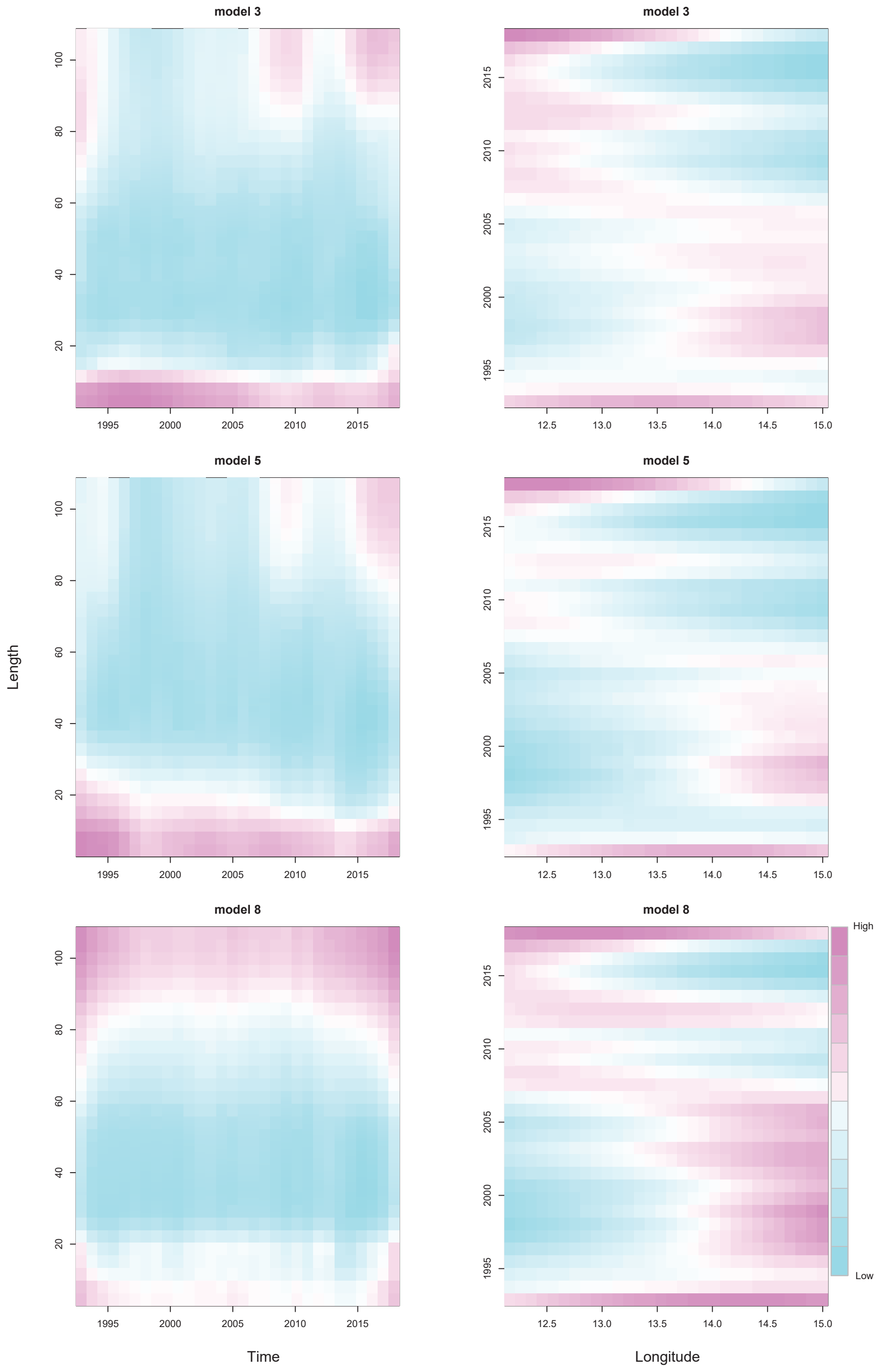

Figure 4: Prediction standard deviation for EW splitting models 3, 5 and 8.

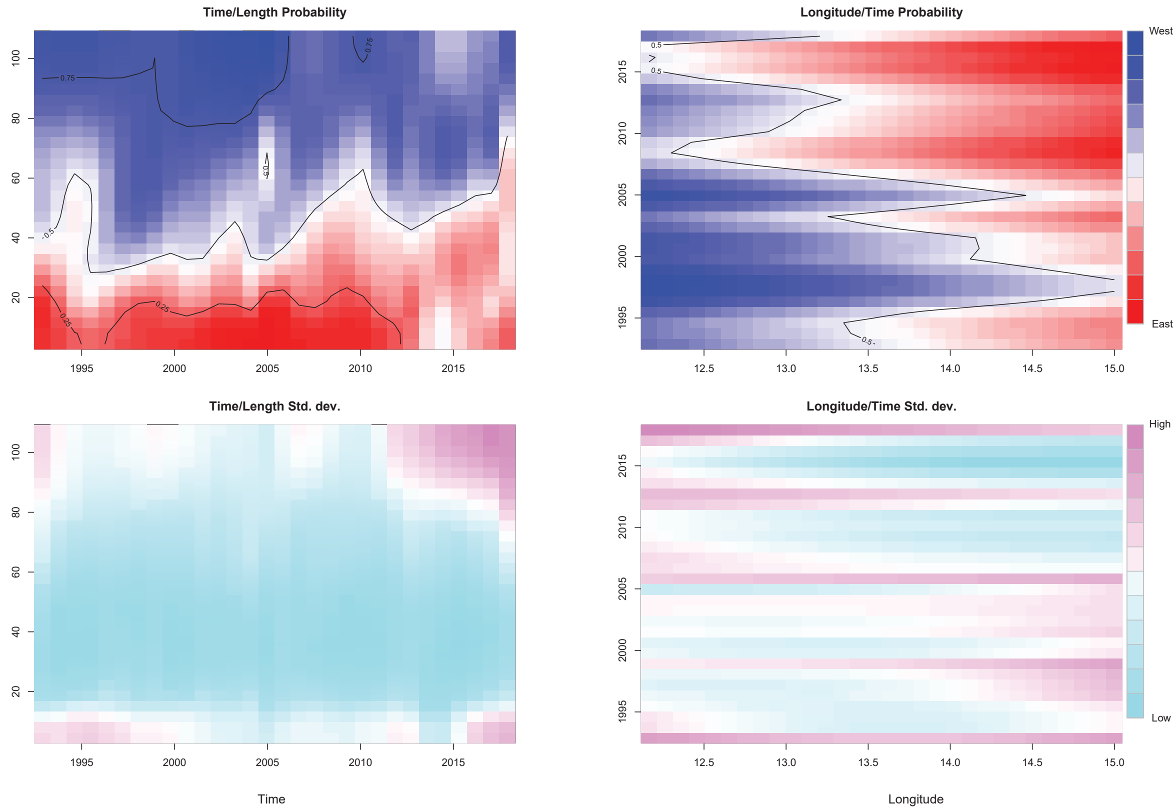

Figure 5: Top row: Estimated east/west probability as a function of time (x-axis) and length (y-axis), given the longitude being 13° for beta regression model (probabilistic classifications, data set 1, model 10).
Bottom row: Same as top except showing the prediction standard deviations rather than the probabilities.

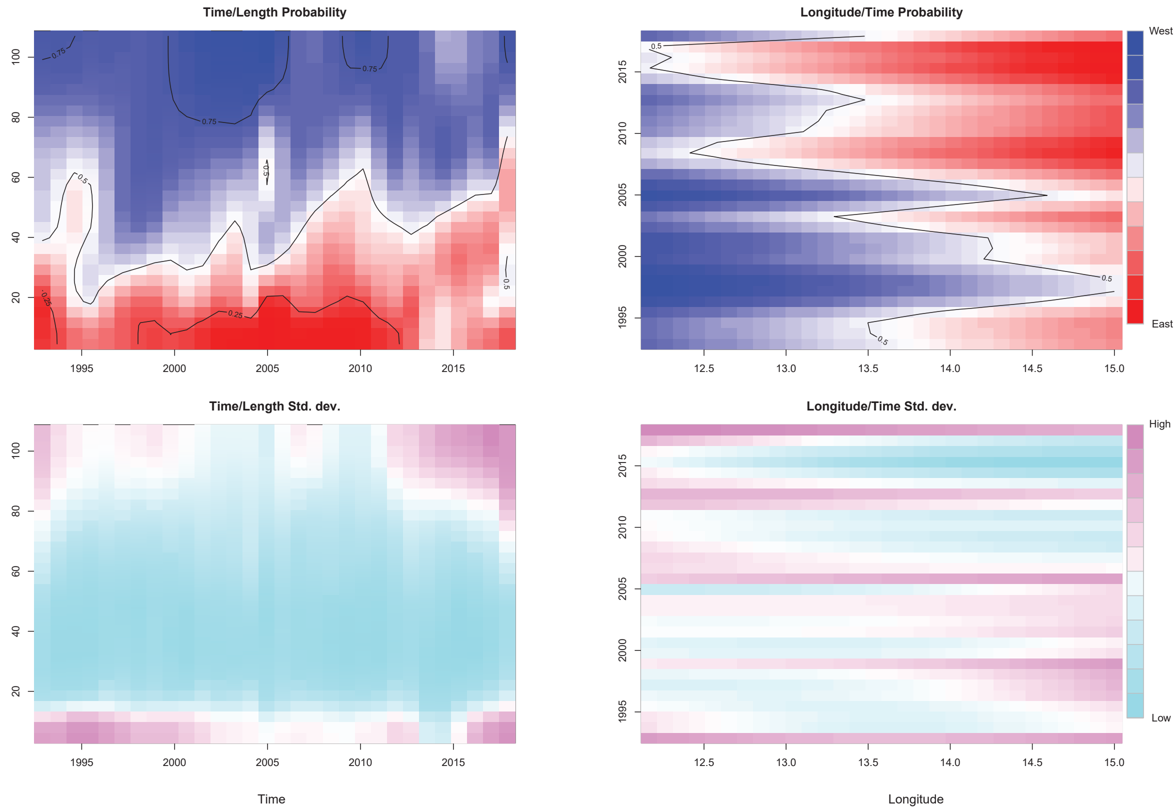

Figure 6: Top row: Estimated east/west probability as a function of time (x-axis) and length (y-axis), given the longitude being 13° for beta regression model (probabilistic classifications, data set 3, model 11).
Bottom row: Same as top except showing the prediction standard deviations rather than the probabilities.

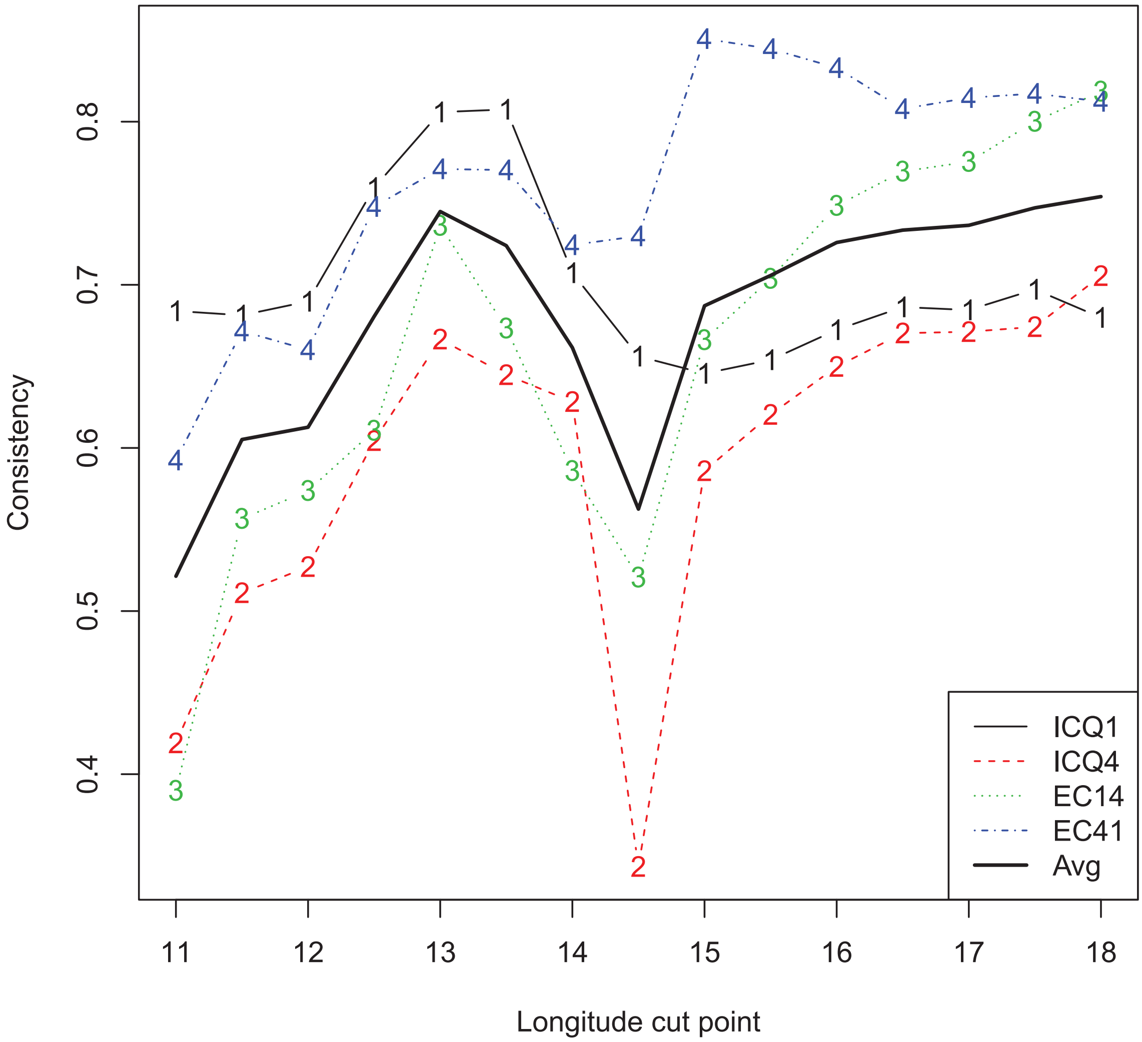

Figure 7: Internal (IC) and external (EC) consistencies averaged over ages 0–4 for varying fixed longitude split using the age based standardization model

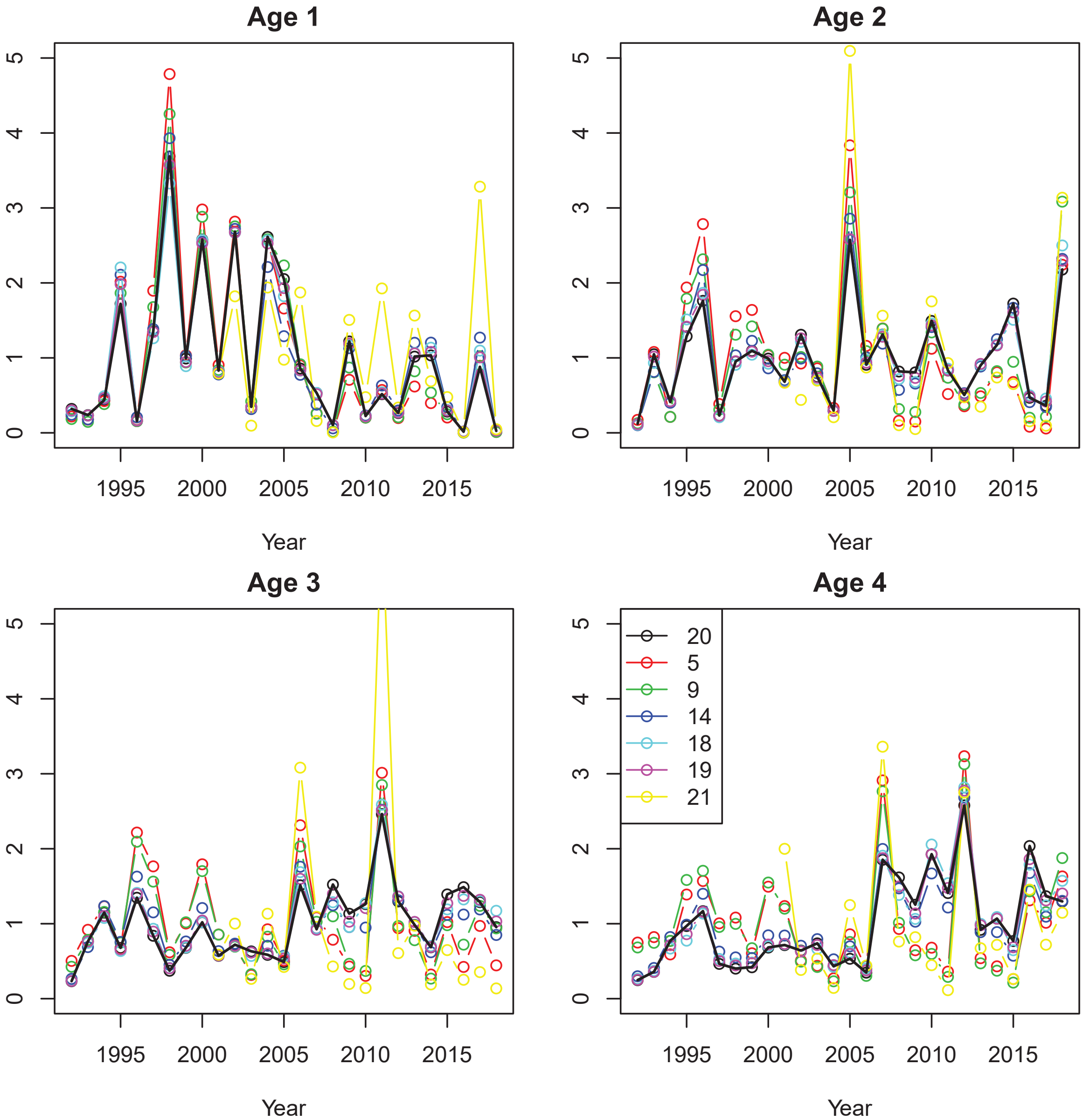

Figure 8: Q1 mean scaled indices for 8 selected configurations

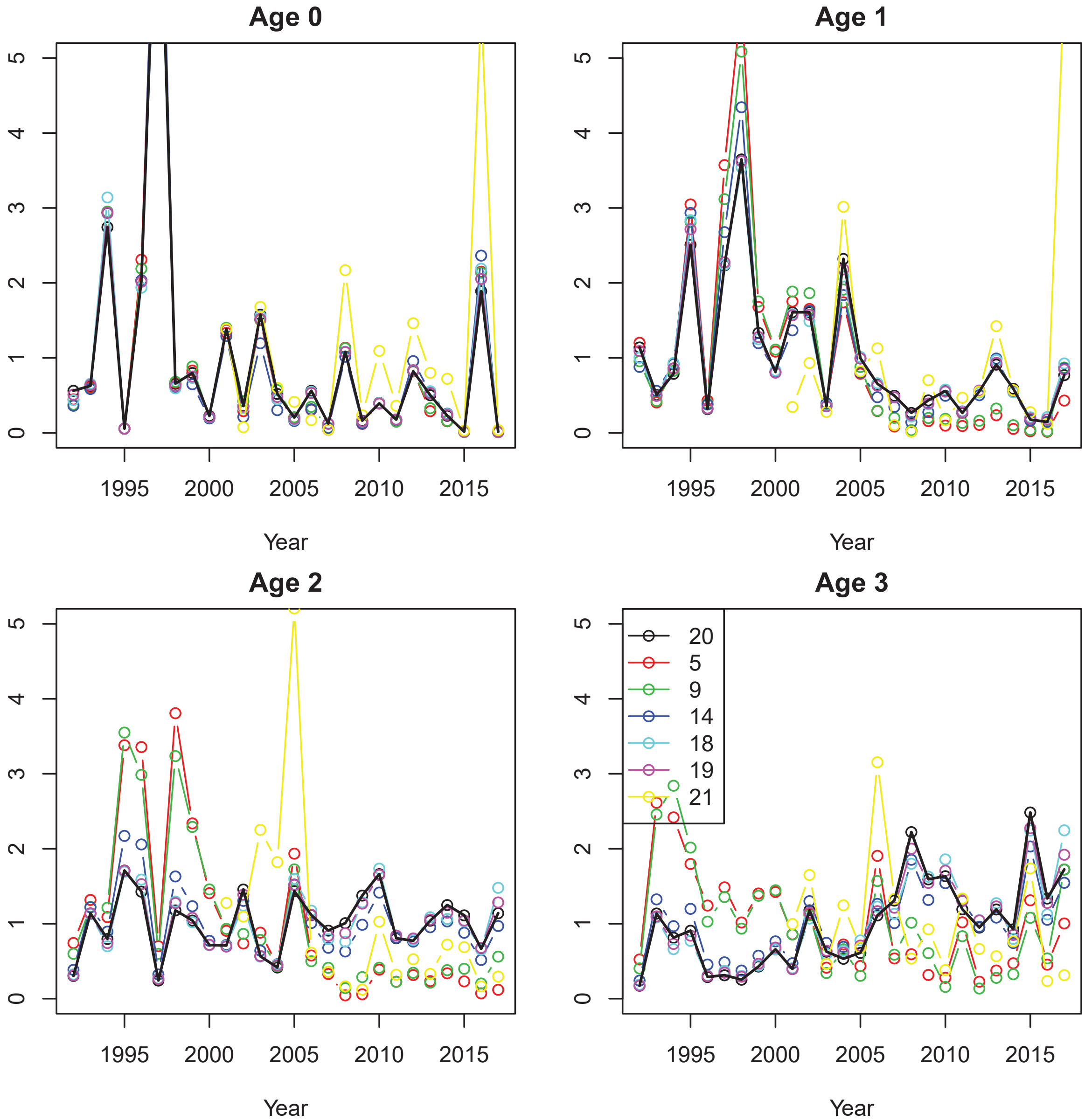

Figure 9: Q4 mean scaled indices for 8 selected configurations

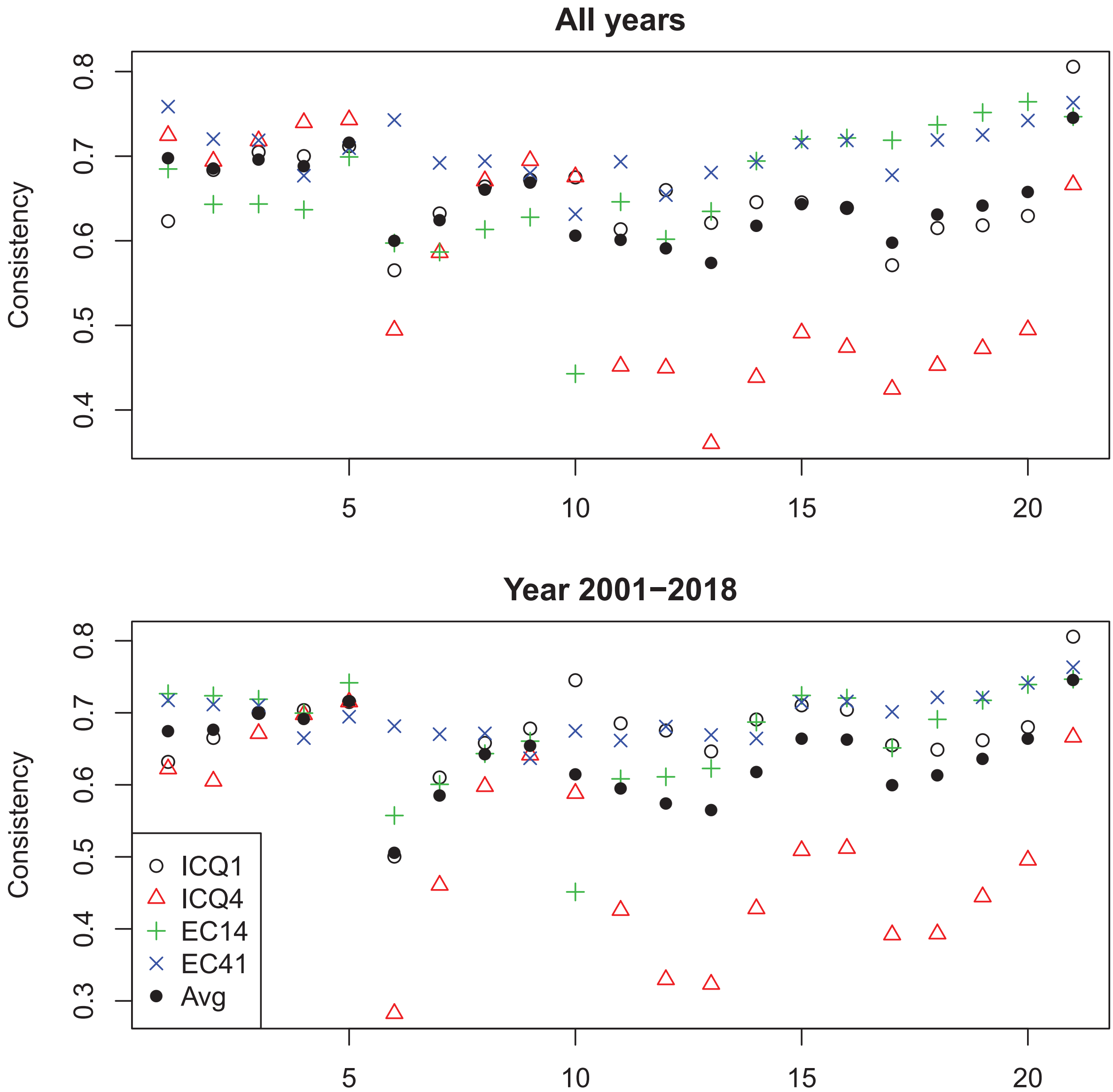

Figure 10: Internal (IC) and external (EC) consistencies averaged over ages 0–4 for each of the configurations (x-axis).

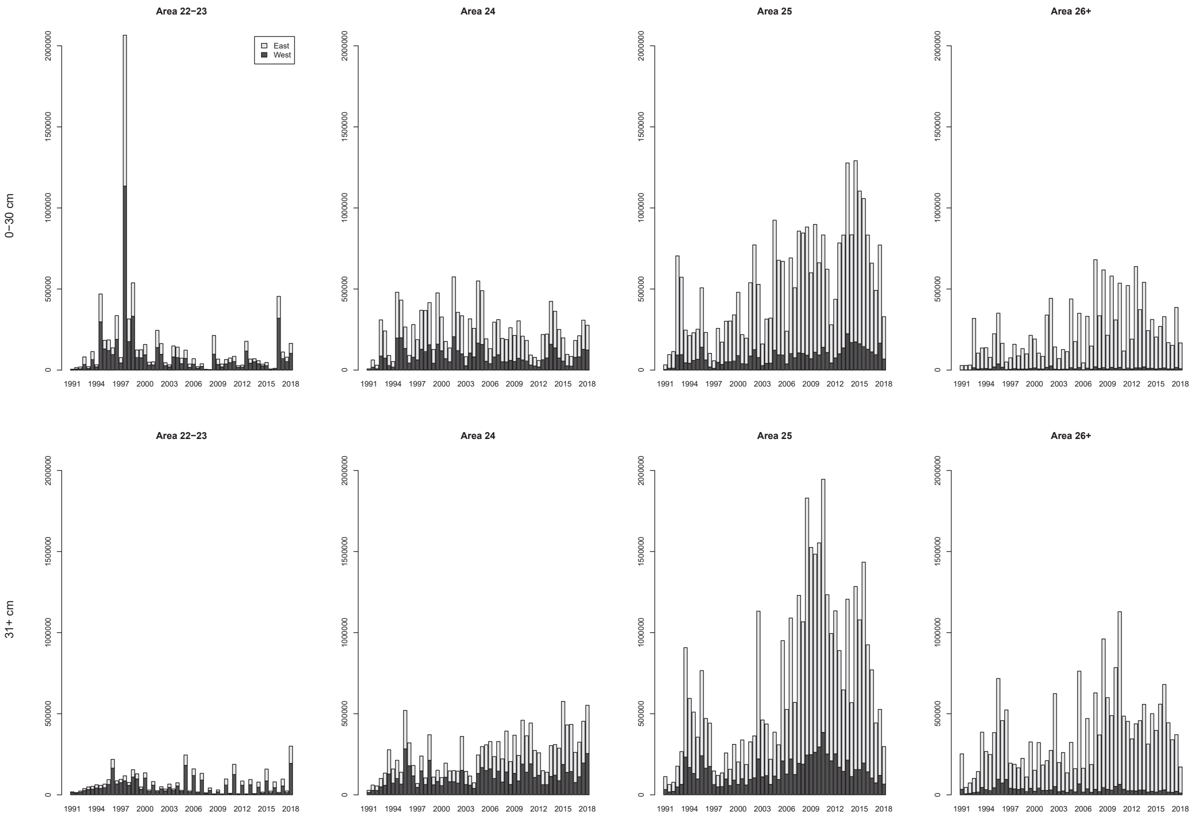

Figure 11: Total number of cod by ICES area and stock using a soft split model. Top rows show smaller cod (0-30 cm) and bottom rows larger cod (31+ cm).

References

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[3] Jean Duchon. Splines minimizing rotation-invariant semi-norms in sobolev spaces. In *Constructive theory of functions of several variables*, pages 85–100. Springer, 1977.

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