BENCHMARK WORKSHOP ON NORTHERN SHELF COD STOCKS (WKBCOD)

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ICES
International Council for the Exploration of the Sea
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Contents

i Executive summary

The North Sea cod stock was last benchmarked in 2021 including a workshop on Stock Identification of North Sea Cod (WKNSCodID) reviewing the population structure information on the cod in the North Sea and adjacent waters. The workshop concluded that the North Sea includes different stock components of Viking and Dogger cod, and that the Dogger cod population extends to the West of Scotland (6.a.N). However, it was not possible to develop spatial approaches in time for the benchmark in 2021 because of (1) unexplained discrepancies between spatially disaggregated data and the data as used in the current North Sea assessment; and (2) the constraint that the 6.a stock was not included in the benchmark process. Nevertheless, the North Sea cod assessment was improved by revising the survey indices, biological data, and SAM assessment model configuration, thus lessening the data and assessment issues that had triggered the benchmark process. ICES recommended that further work be conducted on a data call to consider the different stock components as well as inclusion of the West of Scotland cod stock in the evaluation. This stock was last benchmarked in 2020 at WKDEM (ICES, 2020).

Several pre-data meetings were conducted with the data providers to ensure that the data asked for in the data call met the requirement of the stock assessors, and were realistic to provide for the relevant countries. The data set on landings for the substocks components covering 1995–2021 were evaluated at the data evaluation meeting and was found appropriate to use for the assessment. Presently the North Sea cod time series starts in 1963 and it would therefore be beneficial if the landings by substock could be extended further back in time. For the landings data covering the time period 1963–1995, ICES has a historic database with information on annual cod landings by area. It was decided to investigate if these data could be converted into landings by substock with some country specific assumptions. Also, recreational data were requested in the data call. However, very different quality levels for these data, with many missing years, were submitted by countries; therefore, it was decided that it is currently not possible to incorporate recreational data in the analytic stock assessment. It was concluded that catch level could, as in previous years, be given as a supplementary information in the WGNSSK report. A workshop on including recreational catches in stock assessment has been planned for in April 2023.

As the substocks are considered mixed in Q3-4, a combined index for the whole area was evaluated during the data evaluation meeting. It was decided to combine the survey data for Q3 and Q4 to ensure a full stock area coverage. As the substocks are considered separate in Q1, it was decided to split the Q1 indices based on the assumption that all fish observed during the Q1 surveys can be allocated to substocks based on where they were found. Given mixing is assumed to occur during Q3 and Q4, the decision was made to let the Q3+4 index remain aggregated and representative of the total stock. To allow testing with as many ages as possible in SAM, it was agreed to prepare indices with a 7+ group for the benchmark meeting.

A multi-stock (SAM) model was developed to take into account the substock structure in Northern Self cod stocks. This new model is estimated using substock Q1 survey indices and information about substock fishery catch compositions, as well as catch and survey indices that are only available as a sum for the substocks. For example, yearly catch-at-age data from the North Sea is only available as a sum of the catch of the Southern, Northwestern, and Viking stocks. Furthermore, the model can include genotype data to estimate stock- or catch-compositions.

The benchmark meeting decided to use the BioPar option in the multi-stock (SAM) model for maturity, stock weights, and natural mortality. Three options were explored to address data deficiencies for maturities derived from Q1 surveys prior to 1990. New procedures were used to calculate catch and stock weights-at-age. The stochastic multi-species model SMS estimates of natural mortality rates were used for the three substocks assessed.

Many configurations and sensitivity analyses of the multi-stock model were reviewed during the benchmark meeting. In the final preferred model formulation, stock dynamics were modelled from 1983 onwards. The substock model could not be reliably extended prior to 1983 because of a lack of substock information about landings. Another motivation for truncating the assessment time-series was that there were no maturity estimates prior to 1983 to derive SSB. These values had to be assumed. Hence, the meeting concluded that the assessment model time-period should be constrained to 1983-present. However, the full landings time-series from 1963 onwards still provides some historic perspective on the size of the total stock during 1963–1982.

Estimates from the preferred model indicated that the Southern stock SSB decline steadily from around 28 500 tonnes in 1983 to 3300 in 2020, followed by a small increase in both 2021 and 2022. The Northwestern stock was the largest component; during 1983 to 1997 its SSB fluctuated around 43 500 tonnes, followed by a large decline to 12 700 in 2005 and a generally increasing trend since then, except for 2017–2020. Throughout the period, the Viking stock SSB fluctuated around 21 000 tonnes.

Single combined-stock SAM models were also investigated during the benchmark meeting. Their results were very consistent with the multi-stock model results when combined for the three substocks, but the residual diagnostics were problematic for the single-stock SAM, and the retrospective pattern was at best borderline acceptable. The benchmark concluded that the multi-stock model was better suited to support the intended management options for northern shelf cod.

There is evidence from the literature of three recruitment periods or productivity regimes for cod in the North Sea: before 1988, between 1988 and 1998, and after 1998. The benchmark meeting consensus from the multi-stock model results was that all three substocks had higher recruitment rates (i.e., recruits per spawner) prior to 1997; that is, there were two recruitment regimes since 1983. Hence, the benchmark meeting consensus was that reference points should be based on the stock-recruit times-series since 1997, the last three years for selectivity, and the last 5 or 10 years for other biological parameters. However, agreement to split the stock-recruit time-series was not unanimous, and an alternative perspective is documented in this report.

The reference points derived during the benchmark process are:

Stock	$B_{trigger}$	B_{lim}	B_{pa}	F_{MSY}	$F_{MSYupper}$	$F_{MSYlower}$	B_{MSY}	F_{lim}	$F_{p.05}$	F_{pa}
North-western	28570	21964	28570	0.225	0.352	0.138	124328	0.839	0.689	0.689
Viking	15098	10374	15098	0.197	0.340	0.120	35195	0.502	0.442	0.442
Southern	19786	13504	19786	0.245	0.392	0.161	83231	0.948	0.610	0.610

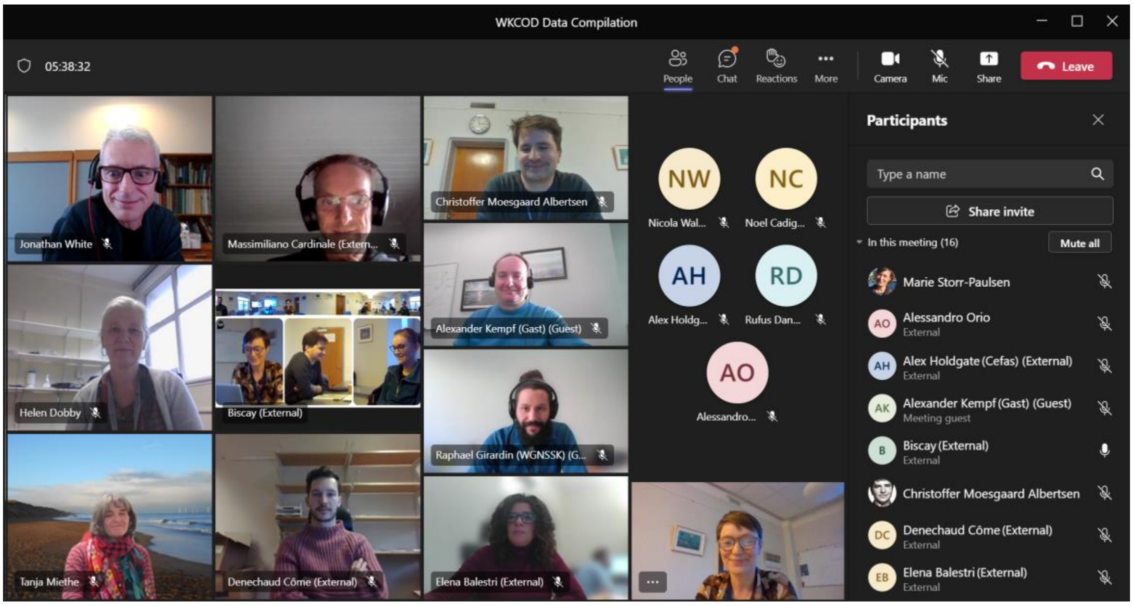
The meeting report documents a minority statement from Swedish participants. They did not agree with the setting of the $B_{trigger}$ reference points, which they suggested were too low and should have been set at 50% of B_{MSY}, at a minimum.

The benchmark process provided many research recommendations dealing with these topics: 1) catch sampling programs that take the new cod substock structure into account, 2) improved genetic sampling information for the substocks, 3) M information for each substock, 4) substock specific landings fractions and catch weights-at-age, 5) further simulation testing of the multi-stock model, 6) fecundity information for the substocks.

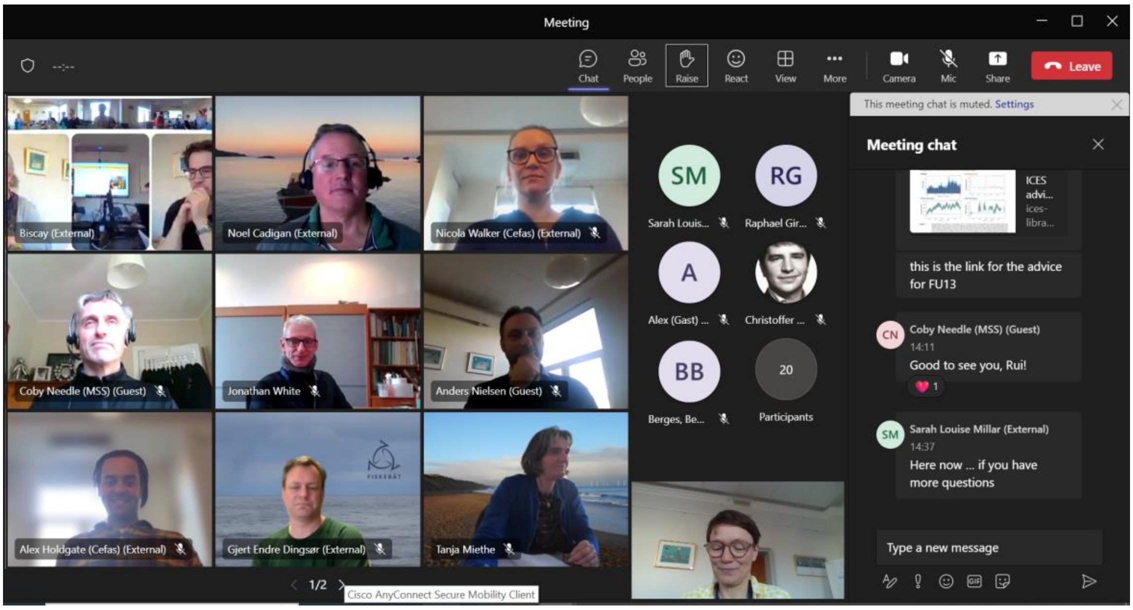
ii Expert group information

Expert group name	Benchmark Workshop for Northern Shelf cod stocks (WKCOD)
Expert group cycle	Annual
Year cycle started	2023
Reporting year in cycle	1/1
Chairs	Noel Cadigan, Canada
	Marie Storr-Paulsen, Denmark
Meeting venues and dates	Data evaluation workshop: 22–24 November, 9 December 2022, and 24 January 2023, Copenhagen, Denmark (hybrid), 20 participants.
	Benchmark workshop: 20–24 February and 27 March, Copenhagen, Denmark (hybrid), 31 participants.

Data evaluation workshop 22–24 November 2022



Benchmark workshop 20–24 February 2023



1 Agenda

1.1 Benchmark workshop

20–24 February 2023, ICES Headquarters, Copenhagen, Denmark, and online

Benchmark workshop chair: Noel Cadigan (noel.cadigan@mi.mun.ca)
Data evaluation workshop chair: Marie Storr-Paulsen (msp@aqua.dtu.dk)
Invited experts: Andrea Havron, USA (andrea.havron@noaa.gov), and Benoit Berges, Netherlands (benoit.berges@wur.nl)
ICES Professional officer: Sarah Millar (sarah-louise.millar@ices.dk)
Supporting officer: Jette Fredslund (jette.fredslund@ices.dk)

Meeting times: 09:00 – 10:30, 11:00 – 12:30, 13:30 – 15:00, 15:30 – 17:00 (2x coffee break of 30min and 60min lunch break)

Monday February 20:
09:00 – 10:00
- Facilities and online participation
- Round of introduction
- ICES Code of Conduct
- Review TORs
- Review Agenda

10:00 – 10:30
- Summary of current single stock assessment frameworks

11:00 – 12:30
- Summary and decisions from Northern Shelf cod data compilation

13:30 – 15:00
- Overview of multi stock SAM
- Northern shelf cod preliminary run – results and diagnostics

15:30 – 17:00
- Requests for additional analyses
- Northern shelf cod preliminary run – reference points
- Questions from reviewers

Tuesday February 21:
09:00 – 10:30
- Working Session

11:00 – 12:30
- Single stock SAM
- Biopar

13:30 – 15:00
- Updates on multi stock SAM

15:30 – 17:00

- Discussion on reference points
- Working Session
- Questions from reviewers

Wednesday February 22:

09:00 – 10:30

- Updates on multi stock SAM

11:00 – 12:30

- Working session

13:30 – 15:00

- Presentation on final model

15:30 – 17:00

- Working session on reference points
- Report writing
- Questions from reviewers

Thursday February 23:

09:00 – 10:30

- Presentation on final model

11:00 – 12:30

- Discussion of multi-stock Sam

13:30 – 15:00

- Comparison of latest multi-stock Sam and updated total stocks SAM

15:30 – 17:00

- Presentation on reference points
- Requests for tomorrow: email or upload research recommendations
- Review Report

Friday February 24:

09:00 – 10:30

- Updates on Reference Points

11:00 – 12:30

- Short-term forecast settings
- Report writing

13:30 – 15:00

- Summary of decisions
- Reviewers feedback
- Stock Annex
- Advice produced (i.e. template, data call).

15:30 – 17:00

- Research Recommendations

- Closing remarks and agreeing on time-line and responsibilities to finish tasks

27 March 2023 online

- Finalize MSY and PA reference points
- Short-term forecast procedures
- Advice Sheet
- Stock Annex

1.2 Data Evaluation Workshop

Hybrid meeting. All Working Documents to be on the WKCOD 2022 sharepoint by 16 November.

Chair: Marie Storr-Paulsen, Denmark (msp@aqua.dtu.dk)

If you do not have access to the share point please contact Supporting officer: Jette Fredslund

Tuesday 22 November

9.30 – opening of online meeting – checking connections

10.00 Start meeting.

Introductions and code of conduct (Marie)

10.30 WKRRCOD

Feed-back on industry workshop (Anna Rindorf)

11.00 Stock summaries

Presentation of the current single stock summaries (Nicola / Helen)

11.30 – 11:45 Coffee break

11.45 Multistock SAM

Genetic data on cod in the North Sea (Jakob Hemmer Hansen)

Presentation on the multistock SAM and frame how the data is used (Christoffer)

12.30 LUNCH

13.30 Data call and commercial catch data

Short introduction to the data call

IC data for both single stock NScod and 6a (Nicola / Helen)

Spatial landing data (Alex)

15.30 Recreational data

Presentation of new / updated recreational data (Kieren/ Zach)

How is data raised

17.00 End of day

Wednesday 23 November

09.30 Summary of work from previous day

Marie

10.00 Survey

Survey indices (Nicola / Helen)

11.00 Maturity

Maturity by area compared to single stock (Nicola / Helen)

12.30 Lunch

13.30 Stock weight

Stock weight by area compared to single stock (Nicola / Helen)

15.00 Coffee break

15.15 Natural mortality

Updated natural mortality

Discussion on the present use of migration M

17.00 revisiting any issues from day 1 or 2

End of day

Thursday 24 November

09.30 Summary of work from previous day

Marie

10.00. Data to be used in the assessment

Ages used in the final assessment (0s and + groups)

Start of the time series

12.30 Lunch Break

13.30 Work plan

Future data calls. 6a data will need to be ready for WGNSSK, we will need to continue collecting spatial landings

A work plan towards the benchmark, including forecasts, reference points

Should there be an online meeting before the benchmark to make final decisions?

Round up of outstanding issues

15.00 Close of meeting

2 Feed-back from WKRRCOD

The Workshops on research needs and a roadmap for further research on cod in the northern shelf seas (including cod in the Celtic Seas) (WKRRCOD) met in Edinburgh, United Kingdom, 1–2 November 2022 to identify evidence needs necessary to achieve management objectives of cod fisheries, share plans for assessments and consider ways to incorporate further knowledge in the advisory process. A total of 35 participants discussed the terms of reference in breakout groups an identified the objectives as a need for good fisheries governance and management that balances social, ecological, economic considerations in management based on agreed perceptions of stock status. The challenges were identified as the Landing Obligation, the use of advice by managers, lack of agreement on stock status, unclear consideration of the effects of changes in cod distribution and inclusion of information from the fishery among other issues. The workshop concluded with six recommendations to address these challenges relating to how industry data can be quality assured and incorporated in the benchmark and assessment process, how the benchmark process can become more transparent to end users, how knowledge from industry can be used to improve assessments through pre-assessment meetings, how managers can become more involved in the advice process and finally how the experience from WKRRCOD can be used for other species.

One of the suggestions from WKRRCOD was a greater use of commercial indices of stock abundance and this was presented at the data evaluation workshop. As an example, estimates of commercial landings per unit effort, LPUE, of potentially spawning cod were estimated from logbook and landings data from Danish trawlers. Timeseries were produced for quarter 1 and the full year using standardization of vessel size (KW) or no standardisation. The data were intended to for potential use in the stock assessment of cod in the Greater North Sea and West of Scotland under the assumption that

$$\overline{LPUE}_{y,a} = q_y SSB_{y,a}$$

Where $\overline{LPUE}_{y,a}$ denotes the average $LPUE$ in year y in area a, $SSB_{y,a}$ is the spawning stock biomass at the onset of year y in area a and q_y is the catchability of spawning cod to the commercial fishery in year y. The catchability changes over time as a result of technical development in the fishery and the average annual technical creep determined by Eigaard *et al.* across a range of fisheries was 3.2% (Eigaard *et al.*, 2014). Other factors may also affect catchability, including density dependence where catchability increases as stock size decreases, though this has not been demonstrated in Danish trawlers (Rindorf and Andersen, 2008). Low quotas in later years may have led to changes in fishing operations to attempt to avoid cod in these years, thereby lowering LPUE without this indicating a change in spawning stock biomass. In opposition to this effect, zero catches were not included, tending to increase LPUE at low spawning stock biomass. Due to all these factors, the implementation of LPUE as indices of spawning stock size should as a minimum be conducted together with a temporal change in catchability, be it linear or stepwise. For the full description, see Section 21.1.

2.1.1 Decisions taken at the DEWK

It was decided during the data evaluation workshop not to include the commercial biomass index as input to the assessment at this point. The commercial CPUE time series did not take 0 catches into account and further that it only covered the Danish trawler fleet. It was however acknowledged that information from commercial CPUE could be beneficial as an index for the older and mature fish and that the time series could be provided to WGNSSK on an annual basis for comparison with the SSB.

3 Stock summaries

3.1 North Sea cod

The North Sea cod stock was last benchmarked early in 2021. This benchmark process began with a workshop on Stock Identification of North Sea Cod (WKNSCodID) to review information on the population structure of cod in the North Sea and adjacent waters. The workshop concluded that the North Sea includes reproductively isolated populations of Viking and Dogger cod, and that the Dogger cod population has some phenotypic structure and extends to the West of Scotland (6.a.N). However, it was not possible to develop spatial approaches in time for the benchmark in 2021 because of (1) unexplained discrepancies between spatially disaggregated data and the data as used in the current North Sea assessment; and (2) the constraint that the 6.a stock could not be considered in that benchmark because it had undergone a benchmark the previous year and, at the time, not received the same attention with regards to stock ID. Nevertheless, the North Sea cod assessment was improved by revising the survey indices, biological data, and SAM assessment model configuration, thus lessening the data and assessment issues that had triggered the benchmark process (conflicting signals in the underlying data and a developing retrospective bias in the assessment).

One of the main changes to the assessment was to introduce an ad hoc adjustment on the natural mortality of ages 3+ from 2011 to account for migration to the West of Scotland area, which could not be included in the assessment area. This adjustment represents a pragmatic solution that was within the scope of the 2021 benchmark and addressed the issue of not dealing with a closed population, as assumed by the SAM assessment model. Essentially, the adjustment removes the fish believed to have migrated away from the North Sea from the modelled population in the North Sea and was shown to result in better model diagnostics. This is seen as an interim solution while spatial approaches are being developed and, in the meantime, substock trends continue to be monitored and presented in the ICES advice.

3.2 West of Scotland cod

The West of Scotland cod stock assessment was last benchmarked in 2020 at WKDEM (ICES, 2020) and while that process addressed a variety of issues which improved the stock assessment and basis for advice, it was acknowledged that several issues remained:

- Stock structure is complex, and a number of different subpopulations are known to occur within this area. The stock assessment therefore represents an assessment of multiple substocks with the northern component (which is linked to the N Sea) accounting for most of the landings since the mid-2000s.
- Since the early 1990s the most significant data issue for the assessment of West of Scotland cod has been with commercial catch data. Incorrect reporting of landings, species, quantity and management area, is known to have occurred. In an attempt to reduce bias in the assessment, a combination of externally estimated misreported landings data and model estimated catches are used. In addition, discards have been extremely high and these are typically poorly sampled for age compositions (due to low observer coverage). All these issues contribute to making the catch data highly uncertain for this stock.
- There are multiple scientific research surveys covering this stock, but the change in survey design and ground gear of the Scottish surveys in 2011 means that there are currently no continuous indices over the whole assessment time period. Additionally, catch rates

from the recent surveys are characterised by high numbers of zeros and occasional large catches, resulting in highly uncertain survey indices.

- There has long been debate about the impact of seal predation on West of Scotland cod. Hammond and Wilson (2016) estimated cod consumption by seals to be of a similar order of magnitude to the estimated stock size and it has been suggested that seals may be impairing the recovery of this stock. However, there is uncertainty as to whether the seals are actually exploiting the same population as the fishery with limited overlap between seal foraging and the fishery (Russell *et al.*, 2017). Natural mortality clearly remains a major source of uncertainty in this assessment and incorrect assumptions regarding its trend and magnitude can have a significant impact on estimates of stock status.
- The input data for this cod assessment are particularly uncertain (both survey indices and commercial data) and as a result, the data can be interpreted in different ways by different assessment methods which make very similar assumptions. Cook (2019) and a number of exploratory assessments presented at WKDEM show a stock which by 2016 had recovered to levels consistent with those of the 1990s in contrast to the agreed SAM assessment. Given these model uncertainties, the benchmark considered that estimates of uncertainty from the final SAM assessment are therefore unlikely to adequately reflect the true uncertainty in the estimates of stock biomass and fishing mortality for this stock.

4 Multistock SAM

4.1 Genetic data

We used genetic data to investigate mixing of cod populations in the North Sea and adjacent areas, with a specific focus on juveniles to evaluate specific model assumptions. We used a genetic marker panel with 187 single nucleotide polymorphism (SNP) markers, specifically designed to identify North Sea vs. Kattegat and eastern Baltic Sea cod populations, and hence it was not specifically designed to identify sub-populations within the North Sea. Yet, power analyses showed that the panel is sufficiently powerful to identify the two main sub-populations within the North Sea ("Viking" and "Dogger"), although stringent individual assignment level thresholds resulted in the loss of some individuals that could not be assigned to populations with high assignment scores. Additional detail on the methodology and the application to North Sea populations can be found in Wright *et al*. (2015).

→ We analysed juveniles collected on IBTS Q3 2021 (Figure 4.1) and compared results to juveniles collected in 2013–2015. Results showed mixing of Viking and Dogger juveniles within the North Sea, with a geographical pattern indicating a dominance of Viking juveniles in the Skagerrak. However, Viking juveniles were also found in the southern and central parts of the North Sea. It should, however, be mentioned that samples sizes were quite low for some locations and that geographical sampling coverage is still limited in most of the North Sea.

→ Further developments are underway to develop, through full genome sequencing, more powerful genetic marker tools to identify the cod sub-populations within the North Sea. Preliminary results are promising and indicate that a highly powerful and operational tool can be developed for assisting population-based stock assessments in the North Sea and adjacent regions.

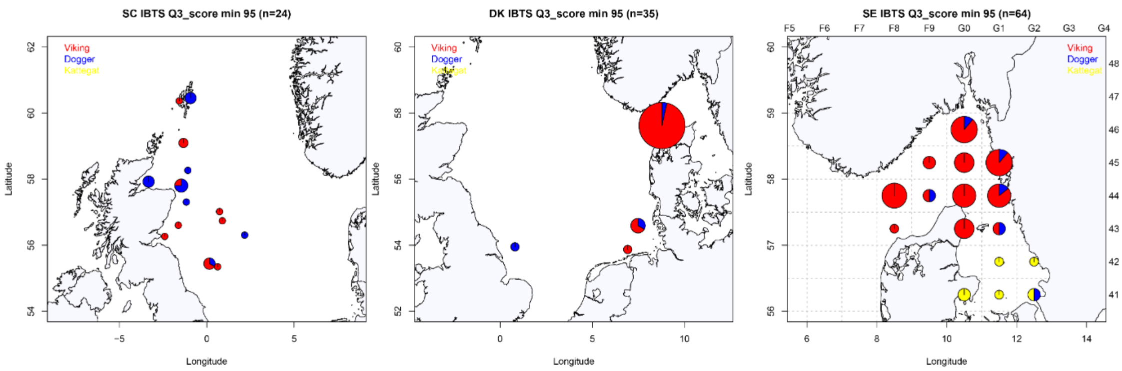


Figure 4.1. Genetic samples of juveniles IBTS 2021 Q3.

4.2 Technical Overview of Multistock SAM

Several cod stocks inhabit the North Sea and adjacent areas. However, since the three cod stocks in the North Sea have been assessed as one, sufficient data is not available to split catch data between the three mixing stocks.

Recent developments extending the SAM model to multiple stocks were presented. The SAM model has been extended to fit several assessments concurrently. The abundance processes of the assessments can either be fitted independently or be correlated (Albertsen *et al*., 2018). The multi-stock model requires only the same data, in the same format, as a single-stock SAM model. The multi-stock model gives the same results when fitted to a single stock.

The multi-stock model has been developed to allow data that is only available as a sum of the stocks. For example, yearly catch-at-age data from the North Sea is only available as a sum of the catch of the Southern, Northwestern, and Viking stocks. Further, the model can include genotype data to estimate stock- or catch-compositions. For this benchmark, the model was extended to allow data on stock compositions in landings. Likewise, an option was developed to incorporate area compositions in landings which, in turn, is converted to estimated stock compositions within the model.

A more complete description of the model is provided in Section 21.2.

5 Data call and commercial data

The data call for WKCOD 2023 (Annex 2) requested national landings data disaggregated by year, quarter, cod area and ICES rectangle, to consider a substock approach to stock assessment. Given no discards or age data were requested, the idea is to investigate the possibility to use the new disaggregated landings to portion the existing catch data for Northern Shelf cod (consisting of single stock data for the 6.a and North Sea stocks) into substocks based on cod area (Figure 5.1).

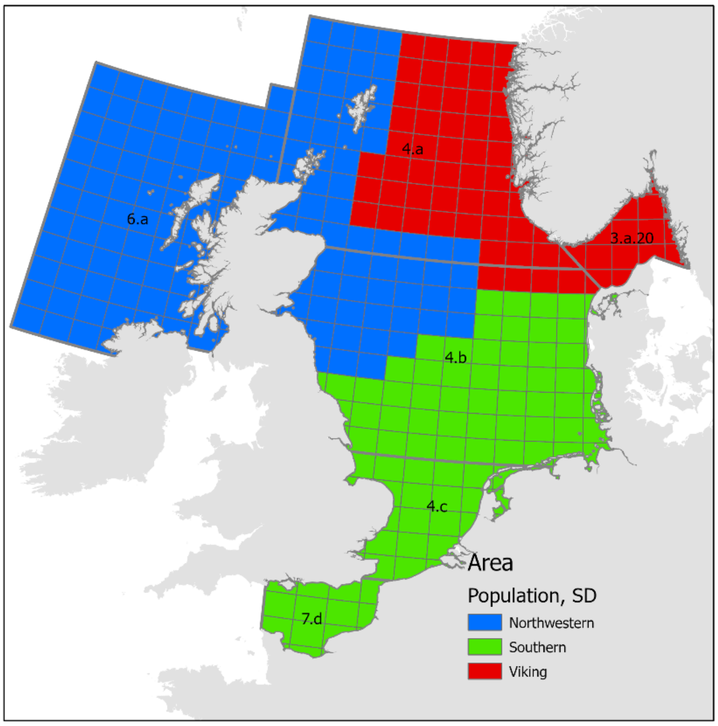


Figure 5.1. Three substock components have been considered in the data call. Note, all three substock areas include a portion of 4.b, while both the Northwestern and Viking substock areas include a portion of 4.a.

5.1 Single stock data 6.a cod

The time series of commercial data in the current West of Scotland stock assessment begins in 1981. As part of the 2020 benchmark, a data call was issued and data from 2003 onwards are available in Inter-catch. Sampling of landings and discards is limited to relatively few countries/fleets for this stock (typically Scotland, Ireland and more infrequently France & N Ireland). Given that sampled data for the two Scottish fleets (the main exploiters of the stock) are provided only on an annual basis, estimation is carried out on an annual basis within Intercatch. Allocation of discard ratios to unsampled fleets is conducted by grouping fleets together such that e.g., all unsampled large mesh demersal target fleets are allocated a discard-landings ratio on the basis of the weighted average of all available ratios from large mesh demersal target fleets (typically Scottish, Irish & French when available). Other groupings used are small mesh fleets, longline fleets, and 'other' miscellaneous fleets. The allocation of age compositions to unsampled landings and discards proceeds in a similar manner. For those years for which IC data are available (2003 onwards), catch-at-age data and associated weights-at-age are available over an extended age range (up to, for example, age 15 and including age 0 when available). However, the historical data (pre-2003) are only available in the assessment input files and are available for ages 1 to 7+ only.

Reported landings of cod in Division 6a are considered to have been significantly impacted by area misreporting since the mid-2000s (that is, cod which are caught in Division 6a are incorrectly reported as being taken from the N Sea and elsewhere, resulting in the reported landings being an underestimate of actual landings from Division 6a). At the 2020 benchmark an approach was agreed which utilised VMS data and associated daily reported landings records to estimate an amount of area-misreported landings. Catch data used in the West of Scotland assessment are adjusted to account for area-misreporting i.e., the area-misreported quantity is added to the reported landings for Division 6a, and an equivalent quantity has been subtracted from the N Sea landings in most years. Late availability of estimated area-misreported landings between 2019 and 2021 meant that only landings for the West of Scotland cod stock were adjusted to account for this in these years. This is likely therefore to result in a small amount of double accounting when summing Intercatch data for 6a cod and N Sea cod for these years (< 2% of total landings in 2019 and 2020, and < 0.5% in 2021).

Further details of these data and issues can be found in Section 21.3 and in ICES (2020).

In order to allow the new combined stock assessment to make use of the full time series of North Sea cod commercial data, approaches for deriving a historical time series of catch-at-age data (and associated mean weights) for the West of Scotland were considered.

For the period 1966–1980, landings numbers-at-age and landings mean-weights-at-age were obtained from a historical assessment WG report (ICES, 2002) (Figure 5.1.1). These data had previous been used in a landings-only TSA assessment, but had subsequently been excluded from more recent catch-based assessments due to a lack of associated discard data for these years. Two options were considered for calculating historical numbers discarded-at-age: i) an average 6a discard fraction at age making use of data from a more recent time period, and ii) applying the N Sea discard fraction. Figure 5.1.1 compares the discard fraction by age for North Sea and West of Scotland cod over time. Given the differences (WoS typically lower in the early part of the time series), it was deemed most appropriate to utilise an average West of Scotland discard rate and utilise this when calculating discards- and catch-at age from the historical landings-at-age data. A 10-year average (1981–1990) discard fraction at age of West of Scotland data was applied to the historical landings numbers-at-age to derive total catch numbers-at-age. Historical discard weights-at-age were also assumed equal to the 10-year average.

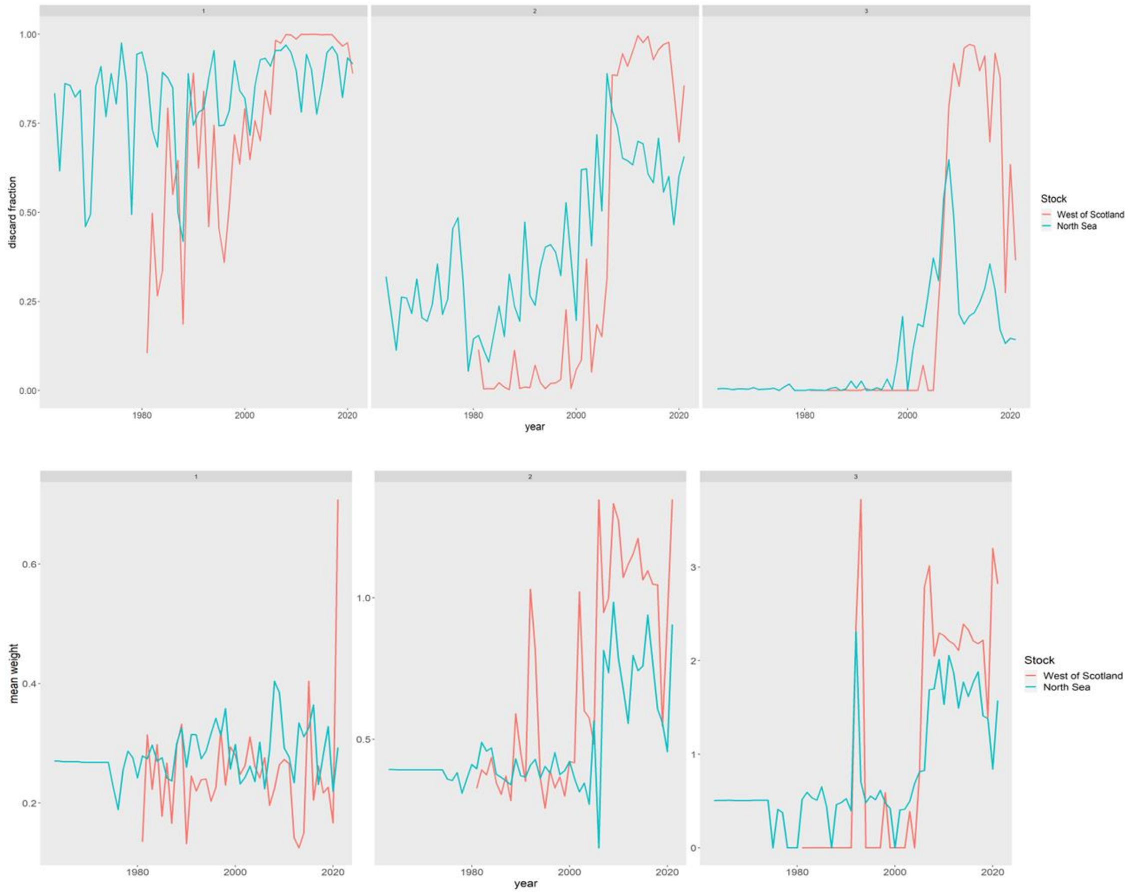


Figure 5.1.1. Proportion of catch discarded at ages 1–3 (upper row) and discard mean weight-at-age for ages 1–3 (lower), for North Sea (blue) and West of Scotland (red).

For the period 1963–1966, there are no commercial age composition data available for the West of Scotland stock, and only officially reported landings are available. A consideration of the countries which have reported landings for these years (i.e. countries are consistent across time period), suggests that these data are likely to be of reasonable quality. They indicate that the landings from the West of Scotland are only a very small percentage of the total West of Scotland + North Sea landings (Figure 5.1.2). Given this, and the relatively similar landings-at-age distributions in the two areas during the time period when data are available for both (1966–2021) (Figure 5.1.3), the WK considered that it was appropriate to use the North Sea landings-at-age composition applied to the West of Scotland for this period (1963–1966).

Figure 5.1.4 shows that the various assumptions (about the West of Scotland catch composition) actually make very little difference to the resulting total catch number-at-age for the whole Northern Shelf (6a+N Sea) due to the very low level of total catches from the West of Scotland compared to the North Sea.

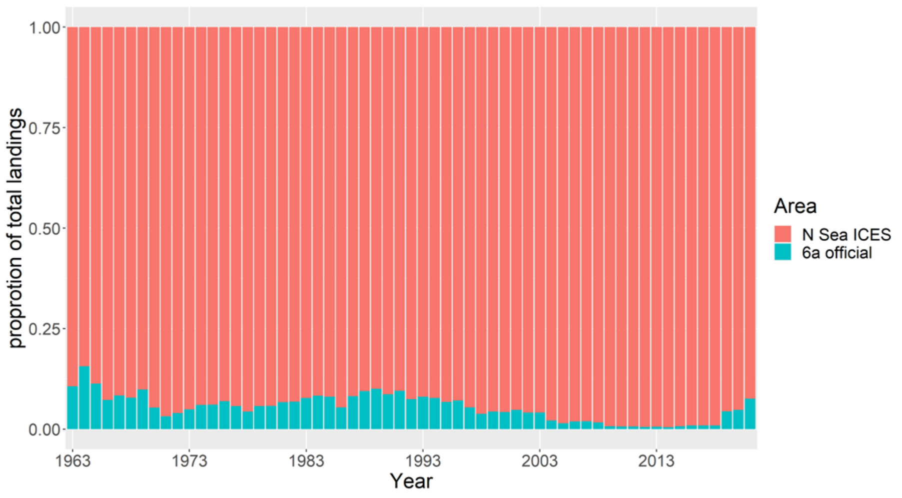


Figure 5.1.2. West of Scotland cod official landings as a proportion of total cod landings from Northern Shelf area (6.a official landings + N Sea ICES landings).

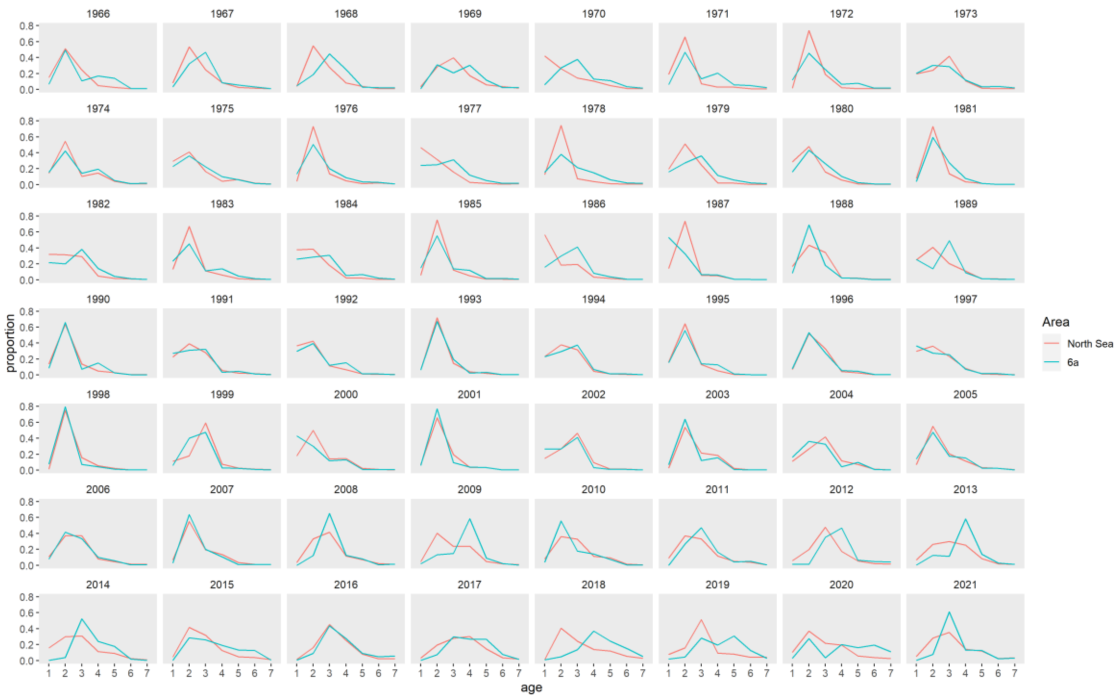


Figure 5.1.3. Landings-at-age proportions by year for North Sea (red) and West of Scotland (blue).

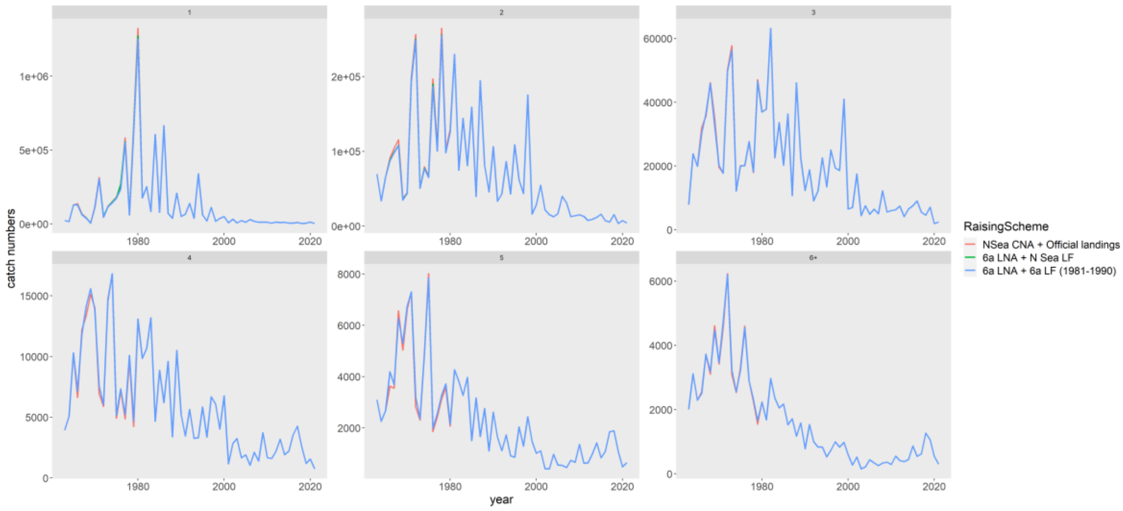


Figure 5.1.4. Comparison of total catch numbers-at-age (total N Sea + West of Scotland) with different estimation assumptions. Red: assumes N Sea catch-at-age composition for all pre-1981 data, Green: utilises West of Scotland landings numbers-at-age 1966–1980 combined with N Sea annual discard fraction. Blue: utilises West of Scotland landings numbers-at-age 1966–1980 with West of Scotland average discard fraction. The latter (blue) are the data proposed for use at the benchmark.

5.2 Single stock data North Sea

The North Sea cod catch time-series starts in 1963. Prior to the use of InterCatch for discard estimation, discard numbers-at-age were estimated for areas 4 and 7.d by applying the Scottish discard ogives to the international landings-at-age, while those in Subdivision 3.a.20 were based on observer sampling estimates. Estimation of landings age compositions, as well as the estimation of both discards numbers and age compositions for 2002–2021 was performed in InterCatch. The approach used for discard ratio allocation is to do it by area (4, 3.a.20) and treat FDF métiers separately where prominent (between 2009–2016). Then, within each of these categories, ignoring country and season, where métiers have adequate samples, these are pooled and allocated to unsampled records within that métier. At the end of this process, any remaining métiers are allocated an all-samples pooled discard ratio for the given area. A similar approach is used for allocating age compositions, except that there are double the number of categories because discards are treated separately to landings. Full details are given in Section 21.4.

5.3 Combined data and how to prolong further back

The new SAM modelling framework proposed for Northern Shelf cod requires total landings by the different substock areas. Eleven countries in total submitted landings data to accessions in response to the data call for Northern Shelf cod (i.e. Belgium, Denmark, England, France, Germany, Ireland the Netherlands, Northern Ireland, Norway, Scotland and Sweden). Data are available across all years for each of the proposed substock areas, including the inshore/offshore split of the Northwestern substock population. Comparisons between the landings data submitted to accessions and the landings data currently used in the individual assessments of North Sea cod and West of Scotland cod available in InterCatch showed good consistency with negligible differences in total landings across all years (Section 21.5). Similar consistency was observed between the accessions data and the combined InterCatch data representing the Northern Shelf cod meta-population (Figure 5.3.1). Full details, including country-level comparisons are presented in Section 21.5. Subsequently, accessions landings data from Q1 for the period 1995 onwards were used to calculate the relative substock proportions over time as it is assumed that the substock components do not mix in Q1 (Figure 5.3.2).

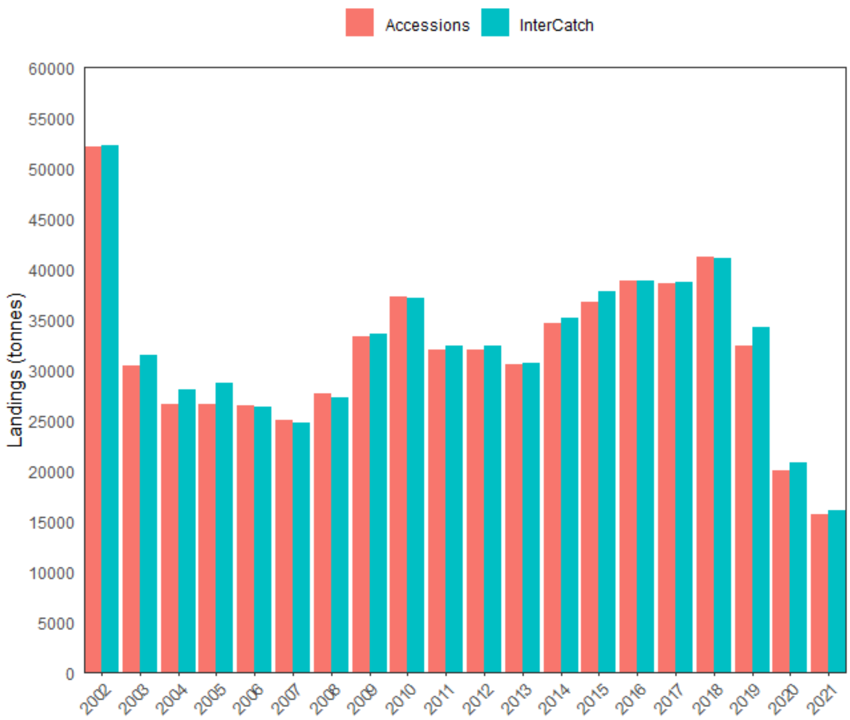


Figure 5.3.1 Accessions data and the combined InterCatch data representing the Northern Shelf cod meta-population.

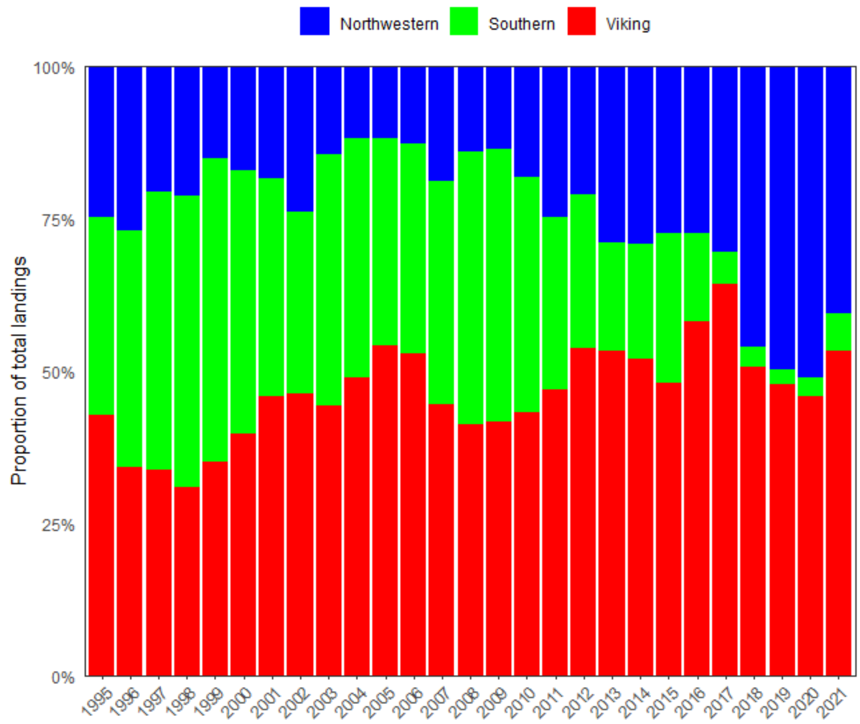


Figure 5.3.2. Proportion of total landings by stock component in Q1.

Historical cod landings by country and area for the years 1963–1994 were obtained from the ICES landings database (https://www.ices.dk/data/dataset-collections/Pages/Fish-catch-and-stock-assessment.aspx). The historical annual landings were available for different combinations of countries and areas with the spatial resolution of the historical landings variable for different years. To obtain the most reliable estimate of the split of the historical landings by the different substocks, assumptions for each country have been made to split the aggregated areas into single ICES divisions.

The historical landings split by area after assumptions have been made to split areas into divisions. Area 7.d,e in every year represented always less than 2% of the total landings, area 7.d-k less than 0.5% while area 3.a less than 1.5%. Therefore, we decided to keep them in the total landings and consider the potential contamination of cod catches from neighbouring stocks as negligible.

Due to the geographical distribution of the different substocks, all the landings coming from areas 3.a and 3.aN were assumed as Viking substock landings. All the landings coming from areas 4.c, 7.d, 7.d,e and 7.d-k were assumed as Southern substock landings.

The proportion of different substocks for areas 4.a and 4.b for each country were calculated from the Q1 Accessions data. For each country the first three years of available accessions data for each area were used to produce average proportion of the different substocks in the different areas and applied to the historical landings.

Some countries in the historical landings do not have accessions data so the following assumptions have been made. For Belgian historical landings in 4.a, the Dutch proportions were used. For the Faeroese, Icelandic and Irish historical landings, the Scottish proportions were used. For the Polish historical landings, the German proportions were used. For the Russian historical landings, the Norwegian proportions were used. For the Spanish historical landings, the French proportions were used. It is important to note that several sources of uncertainty need to be considered when using these results. Most importantly, the proportion of substocks in the different areas come from Q1 accessions data but are used to split annual landings data and the historical landings used include, although in negligible amounts, cod landings from neighbouring stocks. For further details, see the Section 21.6.

5.3.1 Decisions taken at the DEWK

The data set on landings for the substocks components covering 1995–2021 were evaluated at the data evaluation meeting and was found appropriate to use for the assessment. There was relatively small difference between the new substock dataset compared to the historic data set. Some of the differences were caused by historic corrections due to suggested area misreporting and some to lack of data in specific years by minor cod catching countries. Four countries missed information from the beginning of the period and after investigating the country specific landing pattern it was decided to prolong the four countries time series back to 1995 based on a 3 year mean for the first years with data.

Presently the North Sea cod time series starts in 1963 and it would therefore be beneficial if the landings by substock could be prolong further back in time. For the landing data covering the time period 1963–1995 ICES has a historic database with information on annual cod landings by area. It was decided to investigate if these data could be converted into landings by substock with some country specific assumptions. Denmark and Sweden had some missing years in the historic database, and this should be corrected before 9 December to an online meeting. Max and Alessandro will at the meeting 9 December present a suggestion on how to allocate the country specific historic landing to substock.

For historic catch at age in WoS cod the conclusions were: i) to utilise historical landings numbers and weights-at-age (available from historical WG report) for 1966–1980, ii) to estimate landings numbers-at-age for 1963–1965 using the N Sea cod age compositions (on the basis of similarities in the earlier time period), and iii) to assume a fixed discard fraction-at-age and weights-at-age (1963–1980) based on a 10 year mean (1981–1990, the start of the time series of data) from the WoS. Given that the WoS cod only contributes 7% on average of the total landings during this period, the assumptions have little impact on the overall catch numbers at age for the combined NSea and WoS.

6 Recreational data

The North Sea cod assessment required the reconstruction of marine recreational fishing (MRF) catches. Nine countries including Belgium, Denmark, France, Germany, Netherlands, Norway and the UK (Table 6.1). Most catch data was provided per ICES area and subpopulation, but due to the larger number of subpopulations accessible to UK MRF and low sample sizes when splitting the data to that spatial scale all the UK's data were aggregated to the whole population. Furthermore, the number of recreational fishers providing catch data in 6a in the UK survey was low, so the catches were separated out. The MRF data collected by all countries was patchy and often had large confidence intervals (See Figure 6.1). To address this issue, the time series was reconstructed using the relative portion of each country's catch compared to the Danish catch data, which ran back to 2010. The total reconstructed MRF catch estimate was 1993 tonnes (or 1846 tonnes excluding area 6a catches; Table 6.2). Due to the patchiness of the time series, inability to reconstruct back to the beginning of the timeseries and large confidence intervals, it was not possible to include the MRF catches in the assessment model and were only presented as part of the advisory process.

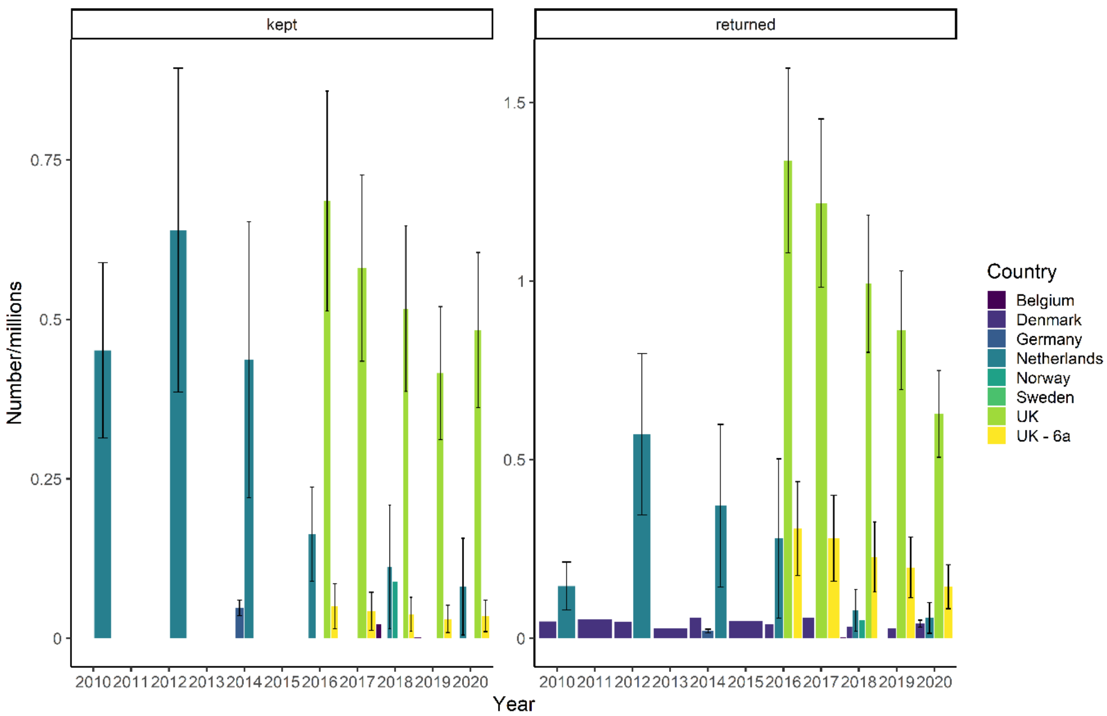


Figure 6.1. The recreational catch data submitted by each country per year. Error bars are 95% CI.

Table 6.1. A summary of the recreational catch data submitted, how the data were collected and the data available.

Country	Years	Method	Sectors	Ret wt	Rel wt	Ret No	Rel Nos	Lengths	Notes
Belgium	2017–21	Onsite	All	Yes	Yes	Yes	Yes	Yes	Analysis underway
Denmark	2009–21	Online recall	Residents	Yes	No	No	Yes	No	Adjusted for recall bias
France	2006–7	Recall	Residents	No	No	Yes	Yes	No	Not used
Germany	2014–15	Diary	Residents	Yes	No	Yes	Yes	No	Few diarists
Netherlands	2010, 12, 14, 16, 18, 20	Diary	Residents	Yes	No	Yes	Yes	Yes	
Norway	2018	Onsite	Tourists	Yes	No	No	No	Yes	Coastal cod & tourists
Sweden	2013–21	Recall	Residents	Yes	Yes	Yes	Yes	No	Large variances
UK	2012 (Eng) / 2016–21	Onsite / Diary	All / residents	Yes	Yes	Yes	Yes	Yes / Yes	Possible positive bias
UK – 6.a	2016–21	Diary	All / residents	Yes	Yes	Yes	Yes	Yes	Possible positive bias

Table 6.2. The total recreational catches per year in tonnes. Calculated by reconstructing all countries missing years with the relative portion of catches compared with the Danish catch estimates.

Year	Retained	Dead Released	Removed
2010	1430	275	1705
2011	1240	325	1565
2012	1467	320	1787
2013	2039	171	2210
2014	3194	361	3555
2015	2324	300	2624
2016	1867	286	2154
2017	1605	298	1903
2018	1336	185	1521
2019	1172	199	1372
2020	1250	134	1384
2021	1252	160	1413
Average	**1681**	**251**	**1933**

6.1.1 Decisions taken at the DEWK

As the recreational data by country was submitted in very different quality levels with many missing years, it was decided that at the present state it would not be possible to incorporate the recreational data in the analytic stock assessment. It was concluded that catch level could as in former years be given as a supplementary information in the WGNSSK report and that it was important to continually monitor the recreational catch levels in the future. A workshop on including recreational catches in stock assessment has been planned for in April 2023.

7 Survey Indices

Standardised age-based survey indices were calculated based on GAMs and Delta-distributions. The general methodology is described in Berg and Kristensen (2012) and Berg *et al*. (2014) and is implemented in Microsoft R Open 4.0.2 based on the DATRAS (http://rforge.net/DATRAS/) and surveyIndex packages. The model formulation currently used for the North Sea cod stock was retained and comprises a high resolution stationary spatial model with low resolution yearly independent deviations and includes ship, year, depth, time of day and haul-duration effects. The Delta-GAM was fit to the survey data for quarters 1 (NS-IBTS, SWC-IBTS and SCOWCGFS), 3 (NS-IBTS) and 4 (SWC-IBTS, SCOWCGFS and IE-IGFS) separately, including a gear effect in the models for Q3 and Q4 to account for use of the Aberdeen Trawl between 1992–1997, and to the data for quarters 3+4 combined to give full area coverage. For Q1, the Delta-GAM was fit to ages 1–6+, for quarter 3 and quarters 3+4 to ages 0–5+ and for quarter 4 to ages 1–4+. Indices by substock were obtained by summing the relevant predicted abundances on a grid of haul positions. A more complete description of the models and results is provided in Section 21.7.

7.1.1 Decisions taken at the DEWK

As the substocks are considered mixed in Q3–4, a combined index for the whole area is needed. During the data evaluation meeting, it was therefore decided to combine the data for Q3 and Q4 to ensure full stock area coverage. It was noted, however, that there will be some extrapolation in Division 6.a early in the time series due to the later start of the Q4 surveys covering that area (1996 for the SWC-IBTS and 2003 for the IE-IGFS), and for the youngest and oldest ages due to less samples of those ages in Division 6.a. These extrapolations are expected to have a small impact at the stock level and when assuming mixing.

As the substocks are considered separate in Q1, it was decided to split the Q1 indices based on the assumption that all fish observed during the Q1 surveys can be allocated to each substock based on where they were found. Given mixing is assumed to occur during Q3 and Q4, the decision was made to let the Q3+4 index remain aggregated and representative of the total stock.

To allow testing with as many ages as possible in SAM, it was agreed to prepare indices with a 7+ group for the benchmark. The updated indices are presented in Section 21.8.

8 Maturity-at-age

Area-weighted annually varying maturity ogives have been used in the assessment of North Sea cod since 2015. The methodology has been refined for North Sea cod as other North Sea gadoids have gone through benchmarks, and a more standardised approach is now being used in the assessments of North Sea whiting, Northern Shelf haddock and West of Scotland cod. This more standardised approach was applied to Q1 survey data (NS-IBTS, SWC-IBTS and SCOWCGFS) for Northern Shelf cod to derive maturity ogives by substock and for the total stock combined (see Section 21.9) but the GLMs were found to fit the data poorly. Using the same data weightings (consisting of area weighted mean catch rates by substock and statistical weights to account for length stratified sampling), four alternative models were explored during the data evaluation meetings to summarise the data:

1. A GLMM with a main age effect and a iid random intercepts and slopes each year
2. A GLMM with a main age effect and a AR(1) random intercepts and slopes each year
3. A GLM estimating a parameter for each age and year
4. A GLMM with fixed age effects and iid random effects for year and age-year deviations

The first two models assumed that the logit of the proportion mature-at-age increased linearly with age, while the last two models included parameters for each age-year combination and the parameter estimates were therefore essentially data summaries. Model 4 was found to perform the best based on AIC for the Southern substock and BIC for all substocks. This model produced more realistic confidence intervals compared to model 3.

Reproductive potential

Upon introduction of annually varying maturity ogives, ICES WKNSEA (2015) raised concerns that accounting for the increase in maturity may give the impression that the spawning stock is in better condition than it is given the possibility of lower fecundity of younger age groups and the potential for a maternal age effect on survival.

8.1.1 Decisions taken at the DEWK

It was decided to consider maturity data from 1983 for consistency with when the Q1 index starts, before which the IBTSWG considers the survey data to be inconsistent due to use of various gear types. It was acknowledged that there was no biological sampling in the Skagerrak (3.a.20) prior to 1991 and in 6.a prior to 1996, and that data quality may be poorer prior to 1990. However, excluding the earlier data would ignore increasing trends in maturity-at-age evident during the 1980s and potentially lead to an overestimation of historic SSB.

Three maturity options will be explored for the benchmark:

- An external biopar model with age, year and cohort effects that can be integrated in SAM.
- Use of a GLMM with fixed age effects and iid random effects for year and age-year deviations (Model 4) to provide a data summary of observations for the SAM biopar facility.
- Knife-edge maturity at age 3 (sensitivity).

9 Stock and catch weights-at-age

The current assessments for North Sea (NS) cod and West of Scotland (WoS) cod take different approaches in their calculation of stock weights-at-age. In the North Sea, for ages 1 and 2, stock weights are derived from the Q1 survey; for ages 3 and above, weights are based on Q1 catch mean weights-at-age. Where survey weights are scarce (pre-2002), the mean ratio-at-age from 2002–2019 between the Q1 survey and annual catch weights was used to scale the annual catch weights to the level of the survey weights for ages 1 and 2. Similarly for ages 3 and above, quarterly catch mean weights are available only from 2002 onwards and so the mean ratio-at-age from 2002–2019 between the Q1 catch mean weights and the annual catch mean weights is used to scale the annual catch weights back in time. In contrast, in the WoS, stock mean weights are estimated as gam smoothed annual catch mean weights-at-age for all ages (1 to 7+). The current stock mean weights show substantial differences between the two stock assessments which could be indicative of real spatial differences in mean weight but could also be related to the types of data used (targeting and timing of fishery data).

Despite having previously rejected the use of survey data for estimating stock mean weights at older ages (3 and above) at previous NS cod benchmarks (2015 and 2021), the data were revisited here as: i) historical literature suggests that there are spatial differences in growth rates (Daan, 1974; Rijnsdorp *et al*.,1991), and ii) these are the only data from which substock dependent mean weights can be derived. There are additional difficulties associated with the use of survey data for stock mean weights-at-age in that the surveys start in the mid-1980s while the stock assessment starts earlier. Although the start year for a combined assessment has yet to be agreed, the current NS cod assessment begins in 1963 and the WoS in 1981. An approach for deriving historical substock weights-at-age is proposed.

The general approach to deriving mean weights-at-age from the survey is described in detail in Section 21.10. It involves calculating substock specific length-weight relationships (restricted to data from 2011 onwards when sampling of individual weights became more widespread) to calculate weight-at-length and then using this and the annual and substock specific length-at-age distributions to derive weights-at-age. Confidence intervals were derived by bootstrapping the hauls. Estimated weights-at-age for the Viking substock appear significantly lower than those for the South over most ages (with the Northwest in between).

In order to derive historical stock weights-at-age (for those years for which survey length at age data are not available, i.e., pre-1983), a substock and age dependent scaling factor based on the average ratio (average over 1983 to 2021) between substock area survey weights-at-age and the annual catch weight-at-age for the combined stock was calculated. This was applied to the historical annual catch weights-at-age (1963 onwards) to derive historical stock weights-at-age.

9.1.1 Decisions taken at the DEWK

The conclusions from the data compilation WK were to utilise the Q1 survey derived stock mean weights-at-age, extended back in time through scaling the annual catch weights-at-age. Two options will be explored at the benchmark meeting:

1. Use these mean weights-at-age (and potentially the associated estimated standard deviations) with the biopar feature in SAM
2. Externally smooth the mean weights-at-age and use a 5-year running mean within the assessment model.

10 Natural mortality rate

The current stock assessments for North Sea and West of Scotland cod use different methods to estimate natural mortality-at-age. Since 2009, variable natural mortality rates at age estimates produced using the stochastic multi-species model SMS (Lewy and Vinther, 2004) have been used in the assessment for North Sea cod. The model is formulated and fitted to observations of total catches, survey catch-per-unit-effort and stomach content data for the North Sea area. New natural mortality rate estimates are produced by the Working Group on Multi Species Stock Assessment Methods (WGSAM) every three years in so-called 'key-runs', with the latest estimates produced in 2020 (ICES, 2021). In the assessment for North Sea cod, the raw estimates of natural mortality from the latest SMS key-run are smoothed to reduce the effects of interannual variability whilst maintaining overall trends (see Section 21.11). For West of Scotland cod, age-dependent natural mortality-at-age was first implemented in the assessment in 2012, where M-at-age was derived from mean stock weights-at-age using Lorenzen parameters for fish in natural ecosystems (Lorenzen, 1996). Due to trends observed in the stock weights, time-varying M-at-age estimates derived from the stock weight-at-age (i.e., the modelled mean catch weight-at-age) have been used in the assessment for West of Scotland cod since 2019. Comparisons of the M-at-age estimates derived using both methods for each stock individually, and both stocks combined into the Northern Shelf meta-population, showed poor consistency, with the Lorenzen method estimating lower M-at-age at younger ages and slightly higher M-at-age for older ages compared to SMS. However, despite SMS being parameterised for the North Sea area, there is evidence from the literature that suggests it can capture some of the trends in M-at-age for West of Scotland cod (e.g. increased M due to a larger grey seal population). Comparisons between SMS and predation models parameterised for West of Scotland cod showed similar trends in M-at-age for younger age groups, albeit with different magnitudes. Furthermore, many stocks currently assessed by ICES with distributions that include the West of Scotland (i.e. ICES area 6.a) use the latest SMS estimates of M produced by WGSAM in their assessments (e.g. Northern shelf haddock and West of Scotland herring). The fact that SMS uses the same input data as the single-species stock assessments and the robust methodological background of the model are cited as sufficient justification for using its outputs in assessments covering the West of Scotland.

10.1.1 Decisions taken at the DEWK

It was decided to include natural mortality based on the SMS runs from the North Sea. There was a recommendation to ensure the increased seal population size should be updated in the future key runs.

11 Work-plan towards the benchmark

An online meeting was conducted 9 December 14.30–16.00, which mainly focused on the maturity and historic landings by substock. An additional online meeting was held the 24 January 09.30–12.00, with the agenda:

- Data / plus group options and managing the number of runs.
- Criteria for including / not including survey ages.
- Single stock SAM.
- Multi-SAM and preliminary model runs.
- Reference points.
- Status of the DEWK Report

12 Combined northern shelf cod SAM runs

Several explorative single stock SAM runs were conducted using the combined data for northern shelf cod. The settings of these are briefly summarized in the Table 12.1. The model results were very consistent, but the residual diagnostic was problematic and the retrospective pattern was at best borderline acceptable. It was concluded that the three-stock model was better suited to support the intended management options, had less problematic model diagnostic, and was overall a better description of the biological reality.

Table 12.1. Summary of settings for explorative single stock SAM runs for the combined northern shelf cod stock. The runs differ with respect to data selection (plus group 7+ or 6+), and key model configuration options.

Name	Plus Gp.	Maturity	Surveys	CorStr	F-coupling	Extra
fit99	7+	process	q1+q34+R	all obs independent	sep F all ages	
fit1	7+	process	q1+q34	all obs independent	two last ages same	
fit3	6+	process	q1+q34	all obs independent	two last ages same	
fit4	6+	process	q1+q34+R	all obs independent	two last ages same	
fit5	7+	ave	q1+q34	all obs independent	two last ages same	
fit6	7+	ave	q1+q34+R	all obs independent	two last ages same	
fit7	6+	ave	q1+q34	all obs independent	two last ages same	
fit8	6+	ave	q1+q34+R	all obs independent	two last ages same	
fit9	7+	process	q1+q34+R	Catch ID, surveys AR	two last ages same	
fit10	7+	process	q1+q34+R	Catch ID, surveys AR	sep F all ages	
fit11	7+	process	q1(1-5)+q34(1-4)+R	all obs independent	two last ages same	
fit12	6+	process	q1(1-5)+q34(1-4)+R	all obs independent	two last ages same	
fit95	7+	process	q1+q34+R	all obs independent	sep F all ages	-cn 19,20
fit96	7+	process	q1+q34+R	all obs independent	sep F all ages	-I 19,20
fit97	7+	process	q1+q34+R	all obs independent	sep F all ages	-I 17,18
fit98	7+	process	q1+q34+R	all obs independent	sep F all ages	-cn 17,18
fit100	7+	process	q1+q34+R	all obs independent	sep F all ages	M=.4, >04,>3
fit50	7+	process	q1+q34+R	all obs independent	sep F all ages	short
fit51	7+	process	q1+q34+R	all obs independent	sep F all ages	short, sd

12.1 Reference model

The selected (best) combined stock model, the "reference model" (fit99 in Table 12.1), is a state-space model, which include catch-at-age observations C_{ay} (ages 1–7$^+$, years 1963–2021), a quarter 1 index-at-age $I^{(1)}_{a,y}$ (ages 1–7$^+$, years 1983–2022) a combined quarter 3&4 index-at-age $I^{(2)}_{a,y}$ (ages 1–7$^+$, years 1992–2021), and a combined recruitment index $I^{(3)}_{1,y}$ (years 1993–2022). All observations are assumed independent and normally distributed at the logarithmic scale, where the mean values are defined as:

$$E(\log C_{ay}) = \log F_{ay} - \log(F_{ay}+M_{ay}) + \log(1-\exp(-F_{ay}-M_{ay})) + \log N_{ay}$$

$$E(\log I^{(1)}_{ay}) = \log Q^{(1)}_{a} + \log N_{ay} - (F_{ay}+M_{ay})/8$$

$$E(\log I^{(2)}_{ay}) = \log Q^{(2)}_{a} + \log N_{ay} - (F_{ay}+M_{ay})3/4$$

$$E(\log I^{(3)}_{1y}) = \log Q^{(3)} + \log N_{ay}$$

Here F are the fishing mortalities, N are the stock numbers, M are the natural mortalities (assumed known), and Q are the catchability parameters which are estimated within the model. The catchabilities for ages 6 and 7$^+$ are assumed to be the same within each of the two age-based indices $Q^{(1)}_{6} = Q^{(1)}_{7+}$ and $Q^{(2)}_{6} = Q^{(2)}_{7+}$. The variance parameters are separate for each of the 4 fleets but assumed to be the same across ages within each fleet.

The fishing mortalities F and the stock sizes N are unobserved random variables in this model. The log-scale fishing mortalities are assumed to follow a multivariate random walk where an AR(1) correlation structure across ages is assumed for the process increments. Defining $F_y = (F_1,\ldots,F_{7+})$ the process can expressed as:

$\log F_{y+1} \sim N(\log F_y\ , \sigma_F^2 C)$, where $C_{aa'}=\rho^{|a-a'|}$ (defined to 1 if a=a').

$C_{7\times7}$ is the correlation matrix for the AR(1) structure. σ_F^2 is a variance parameter and $-1<\rho<1$ is a correlation parameter and both are estimated within the model.

The processes for the stock-sizes are defined as:

$\log N_{1,y+1} \sim N(\log N_{1,y}\ , \sigma_R^2)$

$\log N_{a+1,y+1} \sim N(\log N_{ay}-F_{ay}-M_{ay}\ , \sigma_S^2)$ for a = 2,3,4,5,6

$\log N_{7+,y+1} \sim N(\log(\exp(\log N_{6y}-F_{6y}-M_{6y})+\exp(\log N_{7+,y}-F_{7+,y}-M_{7+,y}))\ , \sigma_S^2)$

All the process increments are assumed independent and the two additional variance parameters are estimated within the model.

This defines the model (except for the maturity model used to smooth the maturity observations and predict the missing maturities). The random effects are integrated out via the Laplace approximation and the model parameters are maximum likelihood estimates.

12.2 Results

The reference model converged and produced results which were broadly in line with the total estimates from the multi-stock SAM model (see comparison in Section 1.6). The retrospective pattern for SSB had a Mohn's rho of 22% (exceeding 20% threshold in ICES guidelines), but was judged to be acceptable, because it was predominantly caused by a single point (the assessment ending in 2017) and because the 3 most recent peels were unproblematic.

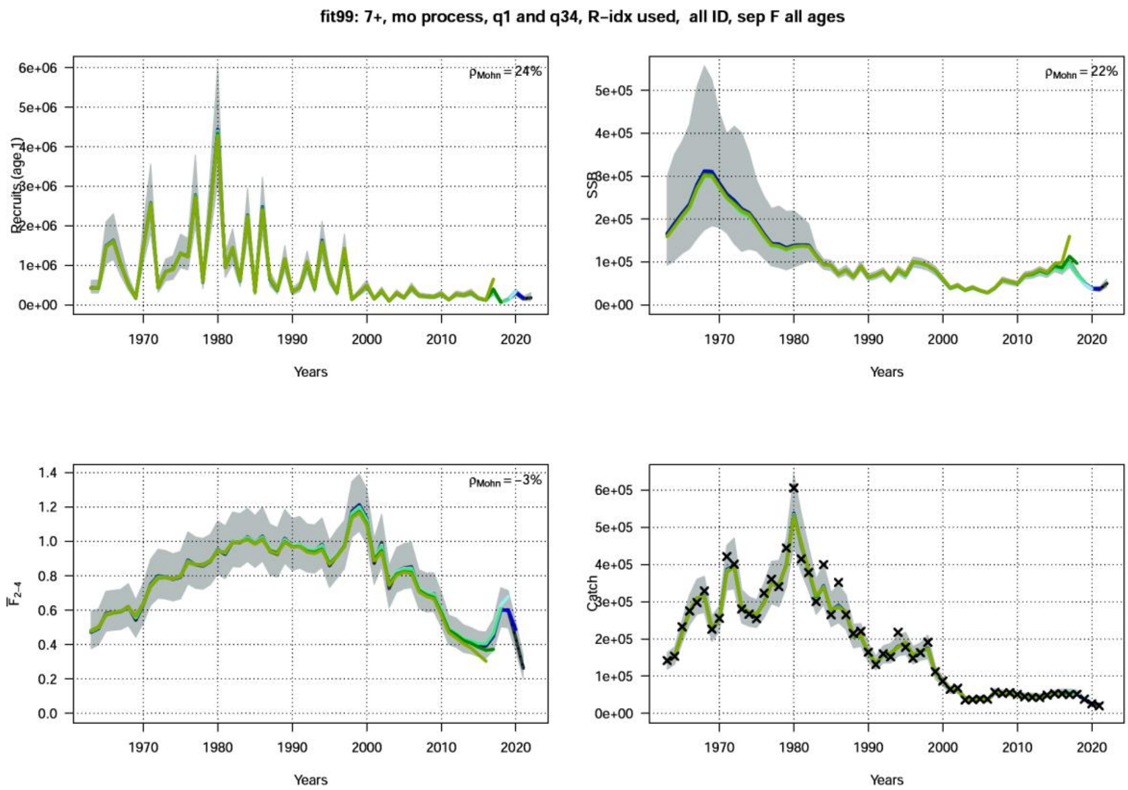


Figure 12.1. Model results (black line with shaded grey confidence area) and retrospective pattern (coloured solid lines) for the reference model.

The residual pattern (one-observation-ahead predictions) for the reference model (Figure 12.2) was problematic. A clear pattern of negative residuals (predictions smaller than observations) exists for the 2 or 3 oldest age groups in the last 10–15 years in both catches and in the quarter 1 survey indices. This residual pattern is the main problem for the combined assessment, and no standard changes to configuration options resolved this issue.

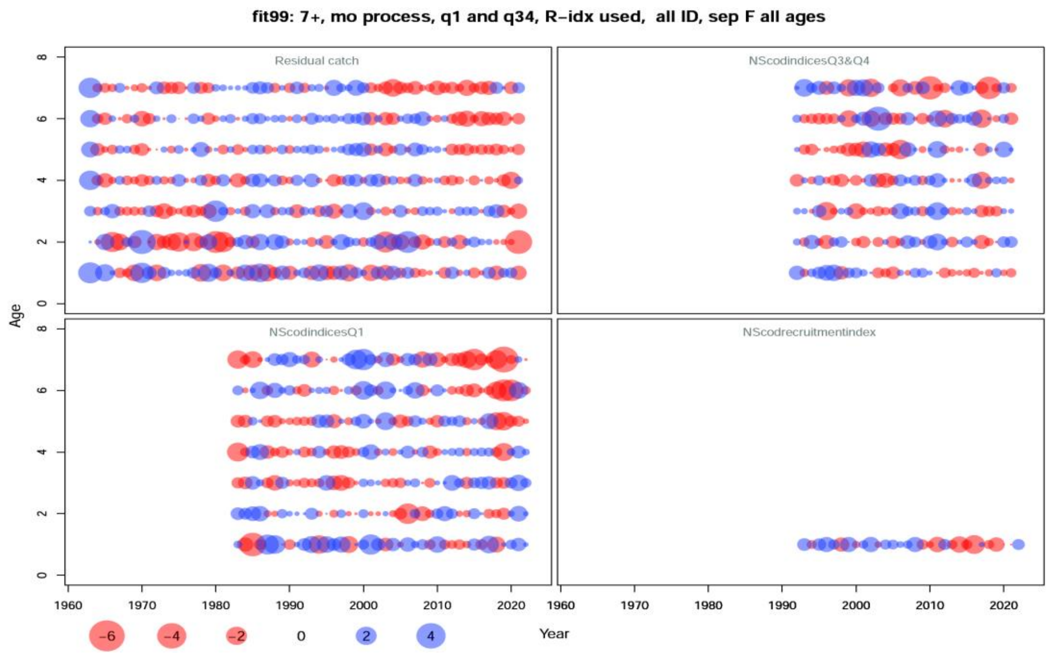


Figure 12.2. One-observation-ahead residuals for the reference model.

12.3 Sensitivity runs

Sensitivity runs were preformed to identify the effect of excluding the recruitment index, defining the plus group at age 6+ instead of 7+, using a shorter time series, and various other configuration options. In addition, some sensitivity runs focused on excluding specific observation years (identified as potentially problematic), and one run focused on adjusting M (a list of all runs are in Table 12.1).

All sensitivity runs were consistent and gave similar estimates of recruitment, spawning stock biomass, fishing mortality, and catch (Figure 12.3). Including or excluding the recruitment index and defining the plus group at 6+ or 7+ did change the results noticeably. Using a shorter time series (from 1983) also produced almost identical estimates.

There are no estimates of maturity-at-age prior to 1983. Two solutions were compared: 1) using the age-specific averages over all observed years, and 2) smoothing the maturity internally in SAM. These two options gave different SSB estimates prior to 1983 (pink lines in SSB part of Figure 12.3) but did not affect other model outputs. This difference is to be expected. The only other configuration option that gave visually different estimates were to allow correlation (i.e., AR1 structure) in the two age-specific survey indices, which resulted in higher estimated fishing mortality in the years 2005–2015 and correspondingly lower SSB in the same years (purple lines in Figure 12.3).

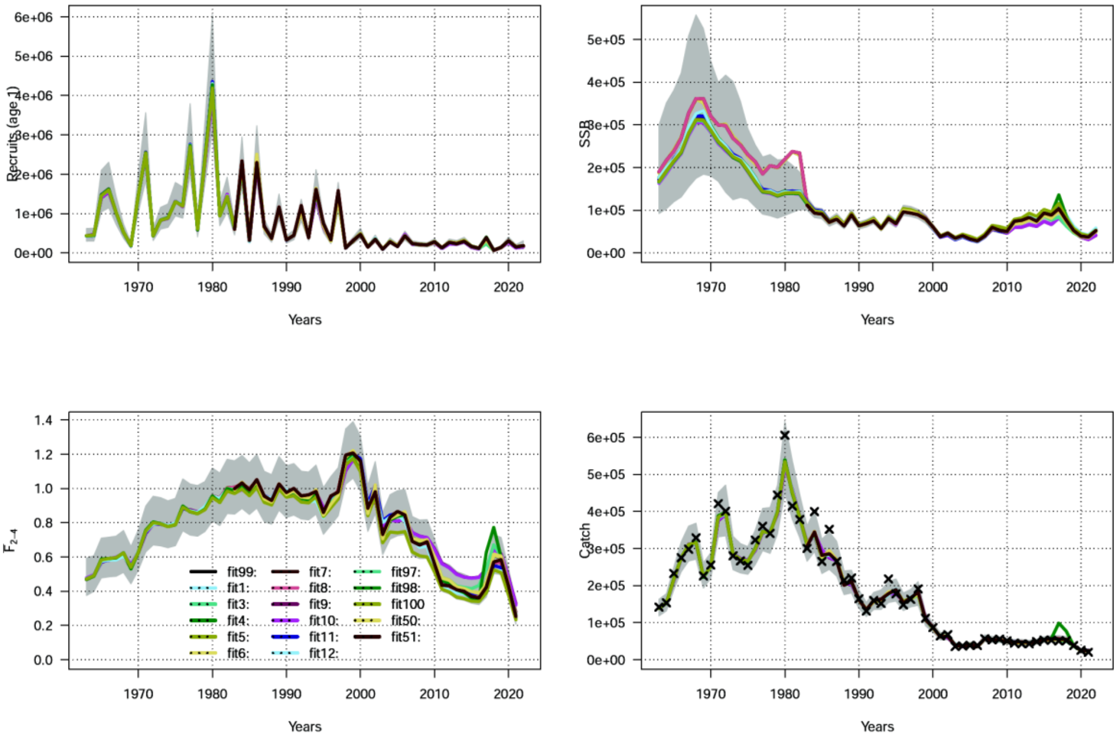


Figure 12.3. Consistency of sensitivity runs w.r.t. Recruitment, spawning stock biomass, fishing mortality and catch predictions.

None of the standard configuration options improved residual or retrospective patterns. Additional experimentation to illustrate possible causes for residual and retrospective patterns included leaving out years of data for surveys or catches (2017–2018 or 2019–2020) and doubling the assumed M for ages 4–7+ in years 2005–2022. Changing M improved both the residual and the retrospective patterns, and leaving out catches in 2017–2018 improved the retrospective, but not the residual patterns. Neither of these scenarios were considered realistic options.

13 Northern shelf cod multi-stock SAM assessment model

13.1 Model development and preliminary runs

Based on the discussions at the data compilation workshop, a preliminary multi-stock assessment model was presented at the benchmark workshop (See Section 21.12 for full details). The model included mixed-stock catch-at-age data from 1963 to 2021 and ages 1–7+, stock-wise quarter 1 indices from 1983 to 2022 and ages 1–7+, a mixed-stock quarter 3 index from 1992 to 2021 and ages 1–7+, stock-wise quarter 3 forward-shifted recruitment indices, stock composition from quarter 1 total landing weight from 1995 to 2021, full year stock area landing composition from 1963 to 1994, and proportion of landed weight per quarter from 1995 to 2021. Furthermore, mean stock weight-, maturity-, and natural mortality-at-age were modelled internally by Gaussian Markov random fields.

The model was manually configured to minimize AIC in a stepwise procedure. The best configuration obtained had an AIC improvement of over 300 from the initial configuration. Besides AIC, model configurations were only considered an improvement if the fit had a positive definite Hessian and residuals could be computed using the "oneStepGaussianOffMode" method in TMB.

With this model, spawning stock biomass of the Southern stock was estimated to increase from 1963 to 1970 (Figure 21.12.4), followed by a large decline until the mid-1980s. This period was followed by a steady decline until an all-time low in 2020. The Northwestern stock was estimated to be at a lower level than the Southern stock in the early data period, followed by a steady decline from the 1970s to the mid-2000s. Since then, the stock was estimated to slowly recover. Finally, the Viking stock was estimated to decline during 1970 to the late 1980's, and then remained at a steady level since then. The estimated trends in SSB for the entire stock complex were similar to the currently used single-stock model for the North Sea cod. Likewise, overall trends in F (Figure 21.12.6 and 21.12.7), catch (Figure 21.12.8), and recruitment (Figure 21.12.9) were similar to the currently used single-stock model. The model was validated through one-step-ahead quantile residuals and retrospective analysis. In general, the residuals had few systematic patterns (Figure 21.12.11). The main exception is the stock proportions from 1995 onward, that give higher one-step predictions in the beginning and lower predictions in the end. For the Northwestern stock, Viking stock, and total stock complex, no discernible retrospective patterns were present in SSB (Figure 21.12.12), F (Figure 21.12.13) or catch (Figure 21.12.14). Consequently, Mohn's rho was low in all cases. For the Southern stock, Mohn's rho for SSB was 0.236, while it was 0.120 for catch and -0.065 for F.

Through 76 additional model runs (described in Section 21.12.9), the sensitivity to input data and assumptions was tested. The main sensitivity run tested the assumptions made to include stock area compositions from 1963 to 1994. Similar to the stock composition in quarter 1 landings from 1995 to 2021, these data aggregated landings by stock areas. These methods were described in Section 5.3. However, since historical landings were only available at a yearly scale, all quarters were combined, implicitly assuming limited mixing of the stocks in quarters 2–4. As a sensitivity analysis, yearly historical landings were aggregated by ICES division, and assumptions were made about mixing for each division. With this model, the Viking stock was estimated to have the largest abundance in the early period (Figure 13.1). From the 1980s, where surveys are available, estimated trajectories were similar for the two runs. In general, the results from the 1980s onward were robust across sensitivity runs (Figures 21.12.16–21.12.43). Some difference in estimated stock composition was observed, but stock-wise trends and results for the total stock complex were similar across runs.

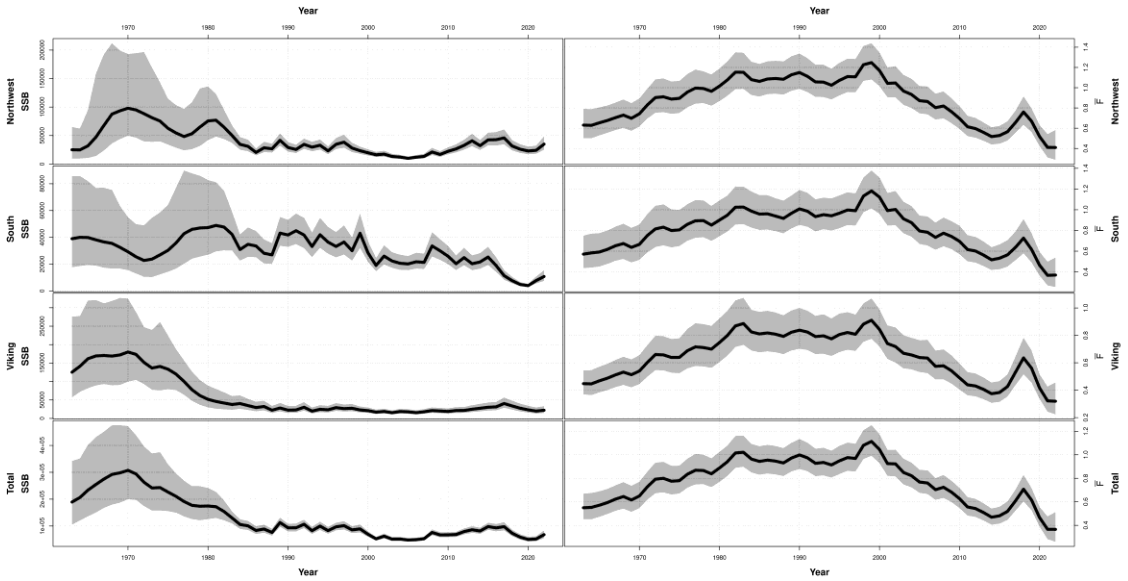


Figure 13.1. Estimates of SSB and Fbar for a multistock SAM model using yearly historical landings aggregated by ICES division.

The substock model could not be reliably extended prior to 1983, because of a lack of substock information about landings. Another motivation for truncating the assessment time-series to start in 1983 is there are no maturity estimates prior to 1983 to derive SSB. These values would have to be assumed, and the assumptions will be subjective. Hence, the meeting concluded that the assessment model time-period is constrained to 1983-present. However, the full landings time-series from 1963 onwards still provides some historic perspective on the size of the total stock during 1963–1982.

At the benchmark meeting there were substantial concerns and discussions about how landings prior to 1995 were assigned to substocks. Historic substock size estimates were very sensitive to how the pre-1995 landings were used (i.e. substock proportions or aggregated by ICES divisions). Three additional runs were requested: 1) Using catch area proportions 1983–1994, using substock proportions 1983–1994, and 3) using no proportions in 1983–1994. These three model configuration options all included information on substock dynamics from the Quarter 1 surveys which are available since 1983 and cover the entire timeframe of the assessment model. All configurations included information on quarter one landings by substock from 1995–present. The meeting concluded that the assumptions used for options 1) and 2) were tenuous and unnecessary since option 3 performed about as well in terms of model diagnostics, including retrospective patterns (Table 13.1). Therefore, the benchmark meeting concluded that option 3) was the preferred multi-stock model configuration, which did not include substock specific information about landings for 1983–1994. However, the model was fit to catch numbers for all substocks during 1983–present. Outputs from these models are illustrated in Figure 13.2.

Table 13.1. Mohn's rho for SSB and Fbar for the Northwestern stock (3rd column), the Southern stock (4th column), Viking stock (5th column) and the total stock (3 components added; 6th column). Model formulations: SA_SA used substock catch proportions for 1983–1994 and 1995–2021; CA_SA used catch area proportions for 1983–1994 and substock catch proportions for 1995–2021; NA_SA did not use substock or catch area proportions for 1983–1994, but used substock catch proportions for 1995–2021. The smallest rho is in bold.

	Model	NW	Southern	Viking	Total
	SA_SA	0.108	**0.254**	0.116	0.128
SSB	CA_SA	0.093	0.275	0.106	0.114
	NA_SA	**0.053**	0.340	**0.100**	**0.096**
	SA_SA	**-0.030**	-0.078	**-0.054**	-0.055
Fbar (2–4)	CA_SA	-0.034	**-0.065**	-0.059	-0.052
	NA_SA	-0.032	**-0.065**	-0.055	**-0.051**

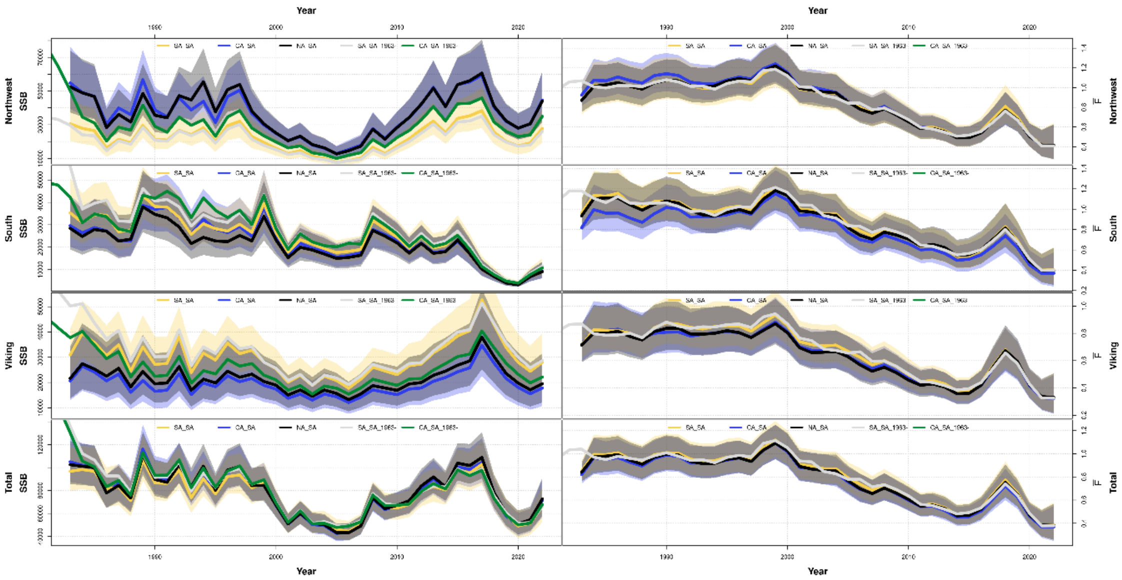


Figure 13.2. Estimates of SSB (left column) and Fbar (right column) for the Northwestern stock (1st row), the Southern stock (2nd row), Viking stock (3rd row) and the total stock (3 components added; 4th row). Line colours indicate model formulations: SA_SA used substock catch proportions for 1983–1994 and 1995–2021; CA_SA used catch area proportions for 1983–1994 and substock catch proportions for 1995–2021; NA_SA did not use substock or catch area proportions for 1983–1994; SA_SA_1963 used catch data from 1963 to 2021 with substock catch proportions for 1963–1994 and 1995–2021; and CA_SA_1963 used catch data from 1963 to 2021 with catch area proportions for 1983–1994 and substock catch proportions for 1995–2021.

The third model option was further refined from the preliminary configuration described in Section 21.12. Index uncertainty was not used as a model input in the third option, and some age 7 indices had high uncertainty. During the benchmark meeting, the survey index CV's were included in the model estimation. Some additional reconfigurations were also applied to improve model fit. The specific configuration is described in Section 13.2. The benchmark meeting concluded that this was the preferred model configuration. Some other configurations were discussed that did not lead to improved fits, which provided further justification to accept the preferred model configuration.

Another assessment model option was a SAM applied to total stock catch and indices (see Section 12). There was substantial debate during the benchmark meeting about the advantages and disadvantages of the combined stock SAM compared to the multi-stock model. The combined model does not address substock structure and there is clear evidence of this. This model cannot provide advice that reflects substock issues. Overall, the meeting concluded that the multi-stock SAM fit the data better than the combined stock SAM, and the multi-stock model had slightly better retrospective patterns. The lack of fit of the multi-stock model to the 1995-present quarter 1 landings proportions by substock was a concern. However, a participant noted that the multi-stock model used the whole stock landings fractions, which may not apply to substocks. This could affect fitting of landings proportions. The discard fraction is different for the substocks. A sensitivity run that did not use the 1995-present quarter 1 landings proportions gave similar assessment results, so the meeting concluded that this aspect of lack-of-fit for the preferred multi-stock model was not a serious concern. There was also concern about differences in observed and predicted total catches for all components. This could be caused by substock differences in catch weights, and this needs further exploration. There were also differences in index catchabilities between substocks, perhaps because of differences in growth rates for the substocks. If substock size relative to each other changes over time then this will mean the combined stock index catchability may change, which is another possible problem with the combined stock SAM. The benchmark meeting was satisfied that, although the preferred multi-stock model was not simulation self-tested, there has been substantial testing of the model during development.

13.2 Final model formulation and results

During the benchmark, it was decided to exclude data prior to 1983 as well as stock proportion data prior to 1995. Therefore, the final model included mixed-stock catch-at-age data from 1983 to 2021 and ages 1–7+, stock-wise quarter 1 indices from 1983 to 2022 and ages 1–7+, a mixed-stock quarter 3 index from 1992 to 2021 and ages 1–7+, stock-wise quarter 3 forward-shifted recruitment indices, stock compositions from quarter 1 total landing weights from 1995 to 2021, and the proportion of landed weight per quarter from 1995 to 2021. Further, mean stock-weight-, maturity-, and natural mortality-at-age were modelled internally by Gaussian Markov random fields. The model mostly used the same configuration as the initial models, but parameters related to survey catchability and observation variances were re-configured in a manual, stepwise procedure based on AIC. The final model configuration is written in full detail in the stock annex (See Annex 3).

In the final model, trends in estimated SSB and fishing mortality rates (Figure 13.3) were similar to the estimates in preliminary models. For the Southern stock, a steady decline was estimated in SSB from around 28 500 tonnes in 1983 to 3300 in 2020, followed by a small increase in both 2021 and 2022. The Northwestern stock was estimated to be the largest component of the stock complex. From 1983 to 1997, SSB was estimated to fluctuate around 43 500 tonnes, followed by a large decline to 12 700 in 2005. Since then, there has been a generally increasing trend in SSB, except for 2017–2020. Throughout the period, the SSB of the Viking stock has been fluctuating around 21 000 tonnes. Consequently, trends in the total stock complex SSB followed the trends in the Northwestern stock.

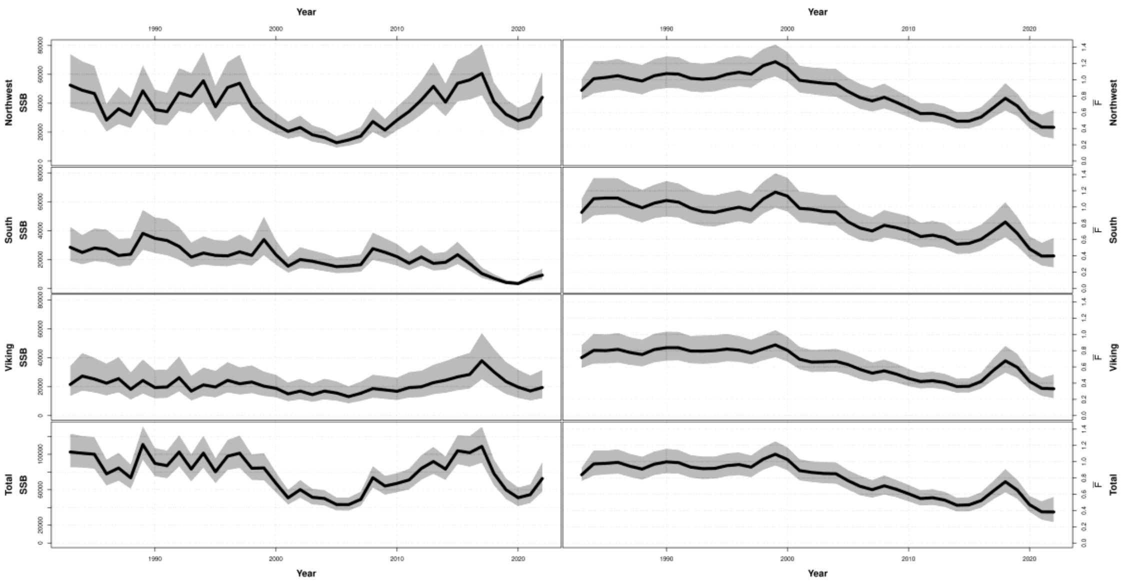


Figure 13.3. Estimated spawning stock biomass (SSB) and average fishing mortality (F) trajectories from the final model.

Trends in average fishing mortality rate from age 2 to 4 ($\bar{F}$) were similar across stocks (Figure 13.3). For all three stocks, F was steady or slightly increasing from 1983 to1999, followed by a decline until 2014. F increased for all stocks during 2014 to 2018, but decreased since then for all stocks. Throughout the period, F was estimated to be lower for the Viking stock than the two other stocks. The level of F was estimated to be similar for the Northwestern and Southern stocks, but with periodic differences.

The final fit was validated by one-step-ahead quantile residuals using the "oneStepGaussianOff-Mode" method in TMB (Figure 13.4). Visually, the overall distribution of all residuals followed a normal distribution as expected for a good model fit. Residual values ranged from -4.49 to 3.89, which is not an unreasonable range for 1547 values from a standard normal distribution. For most fleets, the residuals showed no discernible patterns. However, for the stock composition data from total Q1 landings, there was a tendency to over-predict one of the stocks in the beginning and under-predict in the end.

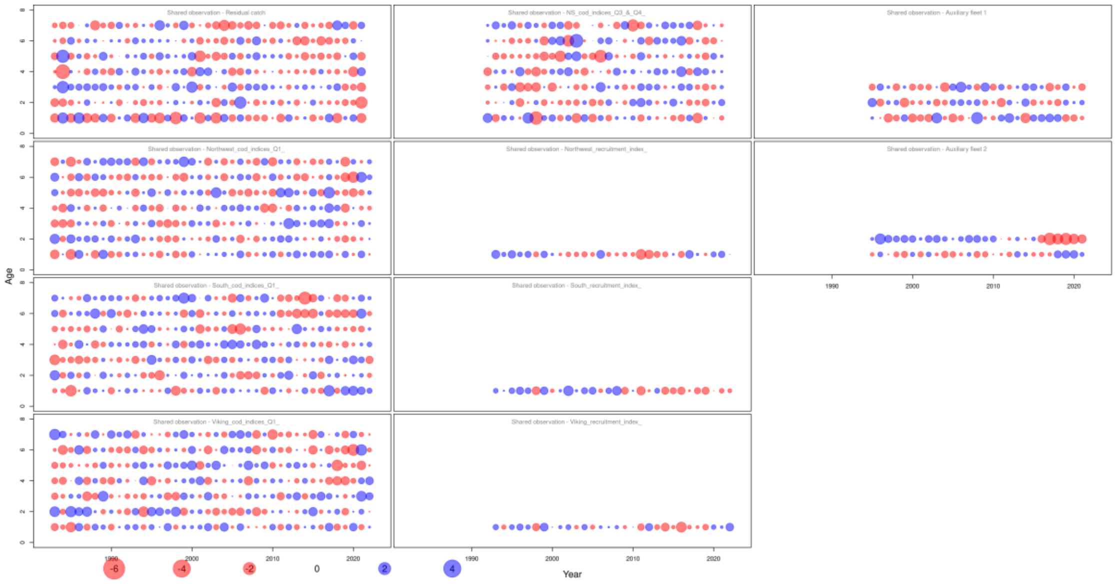


Figure 13.4. One-step-ahead quantile residuals for the final model fit. Residual values ranged from ranged from -4.49 to 3.89.

In retrospective runs, all estimated SSB and F trajectories from retrospective peels were within the confidence intervals of the assessment model fit. For F, Mohn's rho was close to zero for all three stocks and for the total stock complex. In all four cases, Mohn's rho was no further from zero than -0.065. For SSB, Mohn's rho was 0.053 for the Northwestern stock, 0.340 for the Southern stock, 0.1 for the Viking stock, and 0.096 for the total stock complex. In all eight cases, the worst years, in terms of retrospective patterns, were 2017 and 2018, which is similar to the previous assessment and the combined single-stock model. For the Southern stock, the SSB trajectories from the 2017 and 2018 peels had different levels than the four other fits. This was also reflected in the estimated survey catchabilities. However, the trajectories were within the confidence intervals of the final fits.

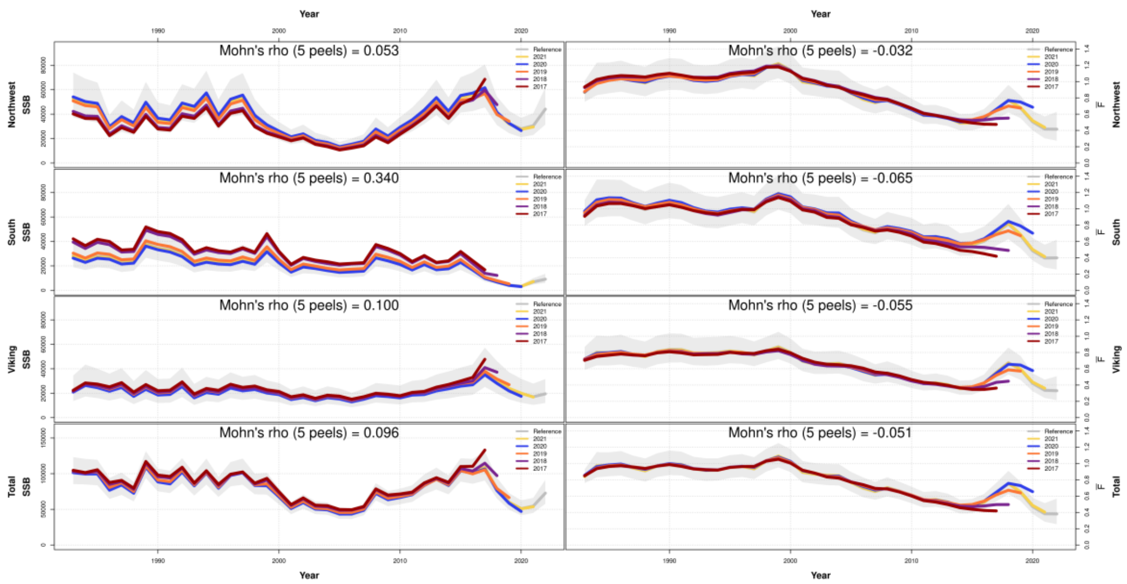


Figure 13.5. Retrospective peels of the final fit for spawning stock biomass (SSB) and average fishing mortality rate (F).

14 Methods for short term outlook

Forecasting catch scenarios are an essential part of scientific advice in fisheries. Both the single-stock and multi-stock SAM models are statistical time-series models. Therefore, the model formulation directly determines how to forecast the modelled system. However, there are different ways to handle the forecast of catch scenarios, including future biological inputs and recruitment. These options are described in Section 21.13, and settings for the Northern Shelf cod stock are proposed in Section 21.13.3.

The benchmark meeting recognized that the forecast procedures will need to be fine-tuned by the Northern Shelf working group. Issues to resolve include:

1. Table 2 in Section 21.13 appears to have mixed up Viking and Southern substocks, if compared to other estimates (slide 10 of WKBCOD_followUp_RP_v3.pptx in presentation folder).
2. It may not be correct to add COD/4N-S62 to the TACs (that was not done for the “old” NS cod stock).
3. There are large changes reflected for e.g. headline advice in the “% Catch change” column, and it would be useful to understand why that is, given F is well above F_{MSY} and needs to be reduced to that level.
4. There are some apparent inconsistent values of the probability of being below B_{lim}, with lower values sometimes associated with higher median catches.
5. Concerns were noted about which year was treated as the base year in forecasts.
6. The landing fraction was the average of the last 3 years, whereas previously only the last year was used.

15 MSY and PA reference points for cod substocks

The results of the preferred multi-stock SAM described in Section 13.2 were used for estimating precautionary approach (PA) and maximum sustainable yield (MSY) reference points for category 1 stocks. Stock recruit models were fit "externally" because internal estimation within the multi-stock SAM model did not converge well.

ICES recommends that the full time series of SR pairs should be used to estimate reference points unless there is very strong evidence to truncate (e.g., regime shift or change in productivity). There is evidence from the literature of three recruitment periods or productivity regimes for cod in the North Sea: before 1988, between 1988 and 1998 and after 1998.

In 2007, STECF examined the influence of broad-scale environmental changes in the Northeastern Atlantic on cod productivity and concluded that a regime shift in the North Sea ecosystem occurred in the mid-1980s (STECF, 2007), with many supporting studies suggesting that cod recruitment has been negatively impacted by changing environmental and climate conditions in the area (e.g. O'Brien *et al.*, 2000; Reid *et al.*, 2001; Beaugrand, 2004; Kempf *et al.*, 2009; Olsen *et al.*, 2011; Akimova *et al.*, 2016). As such, the reference points agreed upon at the 2015 WKNSEA benchmark for North Sea cod (ICES, 2015) were based on SR pairs from 1988 onwards, with B_{lim} = SSB in 1996, as this was deemed to be the last SSB associated with 'reasonably sized' recruitment which excluded the gadoid outburst of the 1960s and 1970s and was consistent with the change in productivity in the 1980s. However, cod productivity in the North Sea has further declined over the last 25 years, with estimated recruitment being lower than explained by SSB alone, and recent studies have provided evidence that an additional regime shift may have occurred in the North Sea around 1998 (Weijerman *et al.*, 2005; Alvarez-Fernandez *et al.*, 2012; Beaugrand *et al.*, 2014). Informed by the findings presented above, the 2021 benchmark for North Sea cod decided to truncate the SR series to start from 1997 SSB onwards (ICES, 2021).

STECF described how "biological parameters and reference points are dependent on the time period over which they are estimated", noting that estimates of F_{MSY}, MSY and B_{MSY} were lower for North Sea cod when considering SR pairs from the more recent warm period after 1988 compared to the earlier cooler period. STECF noted that the decline in F_{MSY}, MSY and B_{MSY} can be expected to continue due to the continued predicted warming of the North Sea, and stock assessments (and therefore reference point estimation procedures) should account for this. In relation to this, STECF concluded from modelling outputs that reference points based on fishing mortality were more robust to uncertainty than those based on biomass when accounting for climate change (STECF, 2007).

As described earlier, the multi-stock SAM modelled stock dynamics from 1983 onwards; however, the benchmark meeting consensus was that all three substocks had higher recruitment rates (i.e., recruits per spawner) prior to 1997; that is, there were two recruitment regimes. The evidence for this conclusion is documented in Section 21.14. This included a statistical test of differences in mean recruitment rates in the two regime periods, which produced highly statistical significance for the three substocks (Table 21.7). The decision to truncate the time series to 1997 SSB (1998 recruitment) for all three substocks is also supported based on the literature findings presented above. However, the consensus on the recruitment rate regimes was not unanimous, and an alternative perspective is provided at the end of this section.

Analysing the SR pairs from 1997+ led to a consensus that a of Type 2 stock definition for the Northwestern (Figure 21.9 and Figure 21.10) and Southern stocks (Figure 21.17 and Figure 21.18). There was no consensus on stock-type definition when considering the ICES guidelines for the Viking sub-stock, both for the full time series (1983+; Figure 21.12) or the truncated time series

(1997+; Figure 21.14) of SR pairs. For this substock, the benchmark meeting agreed to set B_{lim} as the mean SSB in the lower 50th percentile producing above average recruitment, and then the SR relationship is modelled as a segmented regression with the breakpoint fixed at this B_{lim} (Figure 21.15). This approach is consistent with the method used to define B_{lim} during the benchmark for Western Baltic cod (WKBALTCOD2 2019).

The most recent 3 years of selectivity estimates were selected from which to resample for the simulations due to trends in the selectivity pattern for all three sub-stocks. There were minimal recent trends in biological parameters (i.e., mean weights, proportion mature and natural mortality) for the Northwestern (Figure 21.11) and Viking stocks (Figure 21.16); hence, the previous 10 years of data were selected to resample future biological parameters. For the southern substock, there were trends in stock weights and maturities (Figure 21.19) so the benchmark meeting agreed to do a reference point sensitivity analysis using either the previous 10 years or 5 years of biological data. This analysis indicated practically the same F reference points (Table 21.6), but a period of 5 years was selected for the Southern substock. The reference points values in Table 15.1 (also see 1997+ in Table 21.6) are the values recommended by the benchmark meeting.

Table 15.1. Reference points for the three Northern Shelf cod substocks (NW – Northwestern; V – Viking; S – Southern). These are based on the stock-recruitment time-series since 1997, the last 10 years for biological parameters, and the last three years for selectivity. Autocorrelation in recruitment was included in the reference point calculations.

Stock	$B_{trigger}$	B_{lim}	B_{pa}	F_{MSY}	$F_{MSYupper}$	$F_{MSYlower}$	B_{MSY}	B_0	F_{lim}	$F_{p.05}$	F_{pa}
NW	28570	21964	28570	0.225	0.352	0.138	124328	493356	0.839	0.689	0.689
V	15098	10374	15098	0.197	0.340	0.120	35195	156895	0.502	0.442	0.442
S	19786	13504	19786	0.245	0.392	0.161	83231	331835	0.948	0.610	0.610

The reference calculations in Table 15.1 included autocorrelation in recruitment residuals, which is a standard approach using EqSim. However, for the Northwestern and Viking stocks, the autocorrelation was estimated to be low but negative. There was a concern about the lack of a generating mechanism for a negative lag one autocorrelation; however, negative lag 1 autocorrelations are not rare and could be caused by inter-cohort competition for resources (see Rindorf *et al.*, 2020). Reference points were also estimated without autocorrelation (Table 21.8) to check their sensitivity to the negative estimates of autocorrelation.

15.1 Reproductive potential

There was concern at the benchmark meeting that recent increases in the proportion mature-at-age could result in calculated SSB's that do not reflect the reproductive potential of the stock components. Times series of recruitment per age 6+ SSB did not indicate a regime change. While there was agreement that the quality and quantity of spawning products produced by younger fish will be less than produced by older fish, the benchmark meeting still concluded that overall, there was a regime shift in recruitment rates, consistent with published literature outlined above.

15.2 Minority Statement on MSY $B_{trigger}$

Swedish experts present at the meeting did not agree with the setting of the MSY $B_{trigger}$ reference point as explained in Section 21.15. The ratio between MSY $B_{trigger}$ and B_{MSY} is below 25%, except for the Viking stock using the shorter 1997+ time series. According to best practice and in line with ICES guidelines for SPiCT models, MSY $B_{trigger}$ should be set as a minimum at 12.5% B_0 or be set as a minimum at 50% B_{MSY}. When following the current ICES guidelines for this stock, the major issue is how B_{lim} is set, which in turn affects the value of MSY $B_{trigger}$. If B_{lim} is set too low, then MSY $B_{trigger}$, which is directly related to B_{lim}, is also set too low. WKREBUILD (ICES, 2020) pointed out that if B_{lim} and MSY $B_{trigger}$ are too close to each other, small reductions in biomass below MSY $B_{trigger}$ can lead to large changes in F with little time for the stock to adapt/respond. Therefore, if MSY $B_{trigger}$ is set too low, F only declines when it is too late, which invalidates the reason for the MSY $B_{trigger}$ existence.

16 Advice Sheet

A draft advice sheet is provided on the sharepoint site in the report folder. It did not display well with the format of this report.

Comments from the Benchmark meeting were:

1. If catch estimates from the multi-stock SAM model are included in a figure then confidence intervals should also be provided. The caption should clarify that these are model estimates of catch and not reported catch for each substock.
2. The advice sheet should have a table of total catches (3 substocks) because there is a figure.
3. Official substock codes will be required.

17 Independent Reviewer Reports

Reviewers: Andrea Havron, NOAA, USA, and Benoit Berges, WUR, NL.

Atlantic cod in the north is a challenging fish stocks complex amid its population structure. To date, the stock has been assessed using a single stock assessment framework in Subarea 4, Division 7.d, and Subdivision 20. WKCOD comes in the context of two preceding workshops, WKNSCodID and WKNSEA.

Held in 2020, WKNSCodID evaluated the stock structure based on available data and the body of literature available, and concluded that the current stock unit is not a closed homogeneous population. Three populations were identified: "Viking cod", Northwest "Dogger cod" (labelled Northwestern) and southern "Dogger cod" (labelled Southern). It is important to note that the Northwestern stock is inclusive of the West of Scotland area (6.a.N), an area that has been assessed separately as the West of Scotland cod stock. It is understood that whilst the Atlantic cod populations in the North Sea and in 6a are spatially separated in the first quarter of every year, large mixing occurs in the third and fourth quarters. To date, this population structure underpins the rationale for the assessment framework.

Using the information from WKNSCodID, the stock then went through a dedicated benchmark (WKNSEA) in 2021. WKNSEA resulted in improved data and assessment methods, but was still assessed as a single stock. The reason for this setback was twofold: 1) the commercial data made available in 2021 did not allow for disaggregation by individual stocks, 2) the ToR of this workshop did not allow the combining with the West of Scotland cod stock (6.a area). The use of the single stock assessment model was unsatisfactory because of unaccounted stock structure but also large retrospective patterns.

In that context, the aim of WKCOD is to devise an assessment framework that best accounts for stock structure and revise the advice process accordingly.

Prior to WKCOD, a data evaluation workshop was held on 22–24th November 2022, leading to the workshop meeting on 20–24th February 2023.

17.1 Biology

- Genetic data collected during the IBTS-Q3 bottom trawl survey confirmed the mixing between the Viking and Dogger populations across the North Sea and in Kattegat. This further corroborates the stock mixing hypothesis in Q3/Q4. However, the effort in genetic sampling over both the IBTS-Q1 and IBTS-Q3 should continue to further the understanding of the spatial distribution of each population but also better monitor temporal and spatial changes in mixing and substock dynamics.
- The inclusion of the 6.a area allows addressing the issue of stock containment within the North Sea, which was inherent to assessing the Atlantic cod in the North Sea and in the 6a area separately. In recent years, this aspect became problematic because of the change in spatial distributions with a substantial part of mature fish being observed in 6.aN. During WKNSEA, because of the two separate cod assessments, the approach of altering natural mortality to account for changes in spatial distributions was used. This aspect was identified as a temporary solution until the two areas are combined. The inclusion of the 6a area to the Northwestern stock now resolves this discrepancy.
- The natural mortality considered is the one estimated by the SMS multi-species model for Cod in the North Sea, not inclusive of the 6.a area. This discrepancy was deemed acceptable because of similarities in temporal trends. However, this should be revisited

when the SMS is next run in order to be consistent with the combining of the North Sea and 6a areas.

- Maturity for the stock is calculated from the Q1 survey for each stock from 1983 onward.

17.2 Data inputs

- In order to allow for the application of a stock assessment model by substock, the disaggregation of commercial data by area and quarters was needed. During the data evaluation workshop, the group was able to resolve the discrepancy experienced at WKNSEA between aggregated and stock disaggregated landings. It is important to note two aspects. First, catch at age data are not directly disaggregated by substock. Instead, the landings by area in quarter 1 are used to infer the proportion of each substock in the catch. A clear improvement would be to achieve a direct disaggregation of catch at age data which would inform the stock assessment model more directly. Second, the disaggregation by substock could only be performed from 1995 onward. Prior to 1995, quarterly data by area were not made available (only yearly data). The use of an historic database might allow the group to revisit this and build a longer time series of landings by substocks.
- Indices from bottom trawl surveys are available over Q1 and Q3/Q4. Data from different surveys are combined to build the indices, now including surveys covering the 6a area. Similarly, to WKNSEA, a delta-GAM model was used to calculate numbers-at-age from observed number-at-length and spatially variable age-length keys. The hypothesis is that the substocks are separate in Q1 and exemplify large mixing in Q3 of each year. Under this assumption, the indices in Q1 were disaggregated by substocks, using the spatial delimitations from WKNSCodID whilst the indices in Q3/Q4 are combined for all stocks.

17.3 Model

- The single stock assessment model (SAM) indicated several diagnostic issues. There were strong retrospective patterns in SSB which has been a long-lasting issue for this assessment. Additionally, one-step-ahead residuals demonstrated large trends in catch-at-age, suggesting a discrepancy between the data and the model predictions. More particularly, the years 2017 and 2018 were found to be conflicting with respect to model diagnostics. Attempts to resolve these issues within the model were not satisfactory. Moreover, a single stock model does not account for the underlying sub population structure. Following the data evaluation workshop, the expert group decided to move toward a multi-stock state space model (SAM).
  - **Multi-stock Model Selection**.
    - Two major decisions were made related to the multi-stock SAM model. Substock catch proportions were derived using a fleet-to-stock key calculated from Q1 survey and landing proportions based on the assumption that substocks were separated by area in Q1. Data used to inform catch proportions came from Q1 survey indices, available from 1983 and onwards, and catch proportions from landing data, available form 1995 and onwards. Given this limitation in data, it was necessary to decide how to account for unobserved catch proportions in the historic time period (prior to 1995) and whether or not to truncate the time series.
    - Three methods were considered to project substock catch proportions back in time. Decisions on method and truncation were made based on *a priori* assumptions of each method.

        - The stock area proportions method (SA) calculated historical (prior to 1995) catch proportions using information per country with the mean of substock proportions from over three years. This method therefore assumes similar historical proportions that mimic the proportions observed in the early portion of the 1995–2021 time period. This method was rejected due to this strong yet inappropriate *a priori* assumption.
        - The catch area proportions method (CA) estimated proportions in the model based on the probability a given stock being available in each catch area. This method assumes stable stock distribution over time.
        - Landings data from the 1983–1995 time period were not assigned to substocks (NA). This method had the least assumptions and largest uncertainty.
    - Four model runs were compared in detail: Using either the CA or NA method to project catch proportions in combination with using either the full historical time period (from 1963) up until 1995 or truncating the time series to 1983 and onwards, using either the CA or NA method to project catch proportions during the 1983–1994 time period. Out of these options, the group decided to use the model using the 1983 onward period without any assumption on substock catch proportions (NA).
        - Several reasons were provided for rejecting the two model runs with the full historical time period and deciding to use the 1983 onward period:
            - The NA method from the full historical time period had issues with instability.
            - Back allocated stock proportions were highly sensitive to calculation methods and their associated assumptions. Importantly, they appeared to have effects on the recent time period.
            - Maturity estimated prior to 1983 was sensitive to methods, some of which resulted in unrealistic maturity curves for the historical time period. This issue could be related to the bioPar method, which may be better for forecasting opposed to hindcasting.
            - There were concerns expressed about truncating the time series and losing the historical perspective, however, a clear method was not identified that would have appropriately apportioned the stock into sub-components back in time. Any information on the historical time is best represented in aggregation and can still be included in the advice sheet in this form.
        - The NA method was selected over the CA method for projecting catch proportions for the 1983–1994 period as the uncertainty in this approach was more reflective of the true state of knowledge about this system.
    - Issues were identified with the truncated model that used the NA method to project stock proportions during the 1983–1994 time period, and SA method for calculating stock proportions when Q1 survey and landings data were not available.
        - The Viking substock showed evidence of doming, suggesting cryptic biomass. This was in conflict with knowledge that this subspecies was smaller than the Dogger subspecies.
        - Survey uncertainties were not included in the updated SAM model, which was flagged as a problem due to poor external consistencies in the plus group for Viking and Q3/Q4 surveys. The uncertainties were not originally included due to model convergence issues, but this only

happened when the entire time series was used. It was recommended to re-run the truncated model with survey uncertainties included.

- **Multi-stock Model**
  - Raw unsmoothed maturity at age is imputed to the assessment model by sub-stocks. Similarly to the single fleet assessment model, the smoothing of these values are handled internally to the assessment model by treating maturity as a state-space process (bioPar functionality in SAM). The main advantages of such a method is the direct use of maturity at age data, accounting for uncertainties, negating the need for a priori assumptions for the historical period (1963–1983) and allowing statistical forecasting of maturity. However, an important caveat is that maturity will tend toward the long-term mean for the entire available time series in case of lack of values. In the case of historical values, this aspect requires an evaluation.
  - The time series was truncated from 1983 onward. Q1 survey data were used to inform substock dynamics from 1983-present while Q1 landings data were used only from 1995-present (NA method). The decision to truncate was made based on the lack of consensus about the best way to project catch proportions back in time when data were not available. It is recommended, therefore, that this decision to truncate should be revisited in the next benchmark, especially if new historical data sets are identified.
  - The inclusion of survey index uncertainties improved issues seen in previous model runs, in particular, there was no longer a doming pattern in the Viking selectivities.
  - Consistent scaling through the whole time series was seen in the retro patterns, where there was a lack of convergence between the peels and the original time series back in time. This scaling pattern was most pronounced in the southern substock. Large uncertainties seen in catchabilities (resulting from less data available in the south) could result in this change of scale in SSB.
  - Overall, retrospective patterns in total SSB and Fbar were improved relative to the single-stock assessment. Multiple year retros were outside the confidence interval for the single-stock assessment while all retros were within the confidence interval of the multi-stock assessment. The improvement in retrospective might reflect a better agreement between the multi-stock assessment and the underlying sub-population structure. In light of this, the change of model framework to a multi-stock model seems sound.
  - When looking at retro patterns by substock, the southern substock had large mohn's rho values. This pattern was partially due to low population numbers resulting in high uncertainty. More research is recommended on retrospective analysis best practices when partitioning by substock.
  - Less residual pattern was seen in the survey index residuals from the multi-stock model compared to the single-stock model.
  - The added benefit of the multi-stock over the single stock model is that the sub-stock proportions are handled within the model allowing any uncertainties to propagate to those of final estimates
  - The multi-stock model appears at the time of this workshop as the most viable modelling framework. However, issues inherent to the model remain, an aspect that will be alleviated with improved data inputs (e.g. catch at age by substock, as opposed to catch proportions) but also with the increased genetic data wealth which should lead to a better understanding of sub-population dynamics.

17.4 Reference points

- Reference points were finalized through a dedicated online meeting after the in person WKCOD meeting. The reviewers could not take part in the online meeting and therefore could not take part in the full discussion process.
- Following the rationale for the multi-stock assessment model, reference points were evaluated separately for each stock. Whilst based on the multi-stock assessment model outputs, the calculations of the reference points were done independently, following ICES guidelines and using the eqSim software. Within this framework, two assumptions are central: the type of S-R relationship and the time series used (e.g. based on potential regime shift). Of importance here is the analysis of the productivity regime (R/SSB) for all three stocks that exemplified a statistically significant shift around 1997. This motivated the testing of both the 1983 onward and 1997 onward periods.
- Viking stock. The S-R relationship for this substock is poorly defined which motivated a derivation for B_{lim} which deviates from eqSim calculations. Instead, B_{lim} was set as the mean SSB in the lower 50th percentile producing above average recruitment. Such a decision is sound and is justified by the small dynamic range in SSB available, for both the 1983 onward and 1997 onward periods. The use of the 1997 was backed by the significance in regime shift, though more tenuous than for the Southern substock.
- Southern stock. For the Southern stock, the shift in productivity regime was clearly identified in 1997 with a large drop in average R/SSB around this point. As a result, only the 1997 onward time series was considered, an approach that is sensical for this substock. However, the choice of S-R relationship was the most influential and triggered more discussions. The stock recruitment pairs seem to indicate a type 2 relationship but this is subject to the interpretation of stock impairment which might be ill defined in that instance. The stock has exemplified a substantial drop in SSB and has been at low levels in recent years. It is important to note that this substock appears particularly vulnerable due to the combination of environmental conditions and fishing pressure.
- Northwestern stock. Whilst the S-R relationship for the Northwestern substock was clearly identified as type 2, the time series truncation is a source of concern as it is very influential in the derivation of both B_{lim} and MSY $B_{trigger}$. The Northwestern substock is currently driving the trends in combined SSB as it is the largest substock component. For this substock, whilst statistical significance for productivity regime shift was found around 1997, this transition is less pronounced than for example for the Southern substock. Of importance is that B_{lim} and MSY $B_{trigger}$ are particularly sensitive to the 1997 truncation in time series with a halving for both quantities (compared to using 1983 onward). Beyond the effect of not considering the 1983–1997 years for the calculations, the high sensitivity is also partly due to the sporadically high productivity in 2005, a clear outlier since 1997. The decision of only using the 1997 onward period is pivotal to the evaluation of the stock. The reviewers think that the uncertainties and sensitivity on the time series truncation should have warranted the use of precautionary measures in the derivation of PA and MSY reference points for this substock.

17.5 Short-term forecasts

- Short term forecasts could only be evaluated based on the draft report available. This aspect limited the ability of the reviewers to assess the forecast procedure. Moreover, at the stage of the review, the documentation and tools provided were also only in preliminary form.

- The multi-stock assessment model allowed for the evaluation of short-term forecasts at the substock level.
- The total allowable catch (TAC) for the assessment area was based on the intermediate year catch assumption rather than individual substocks due to population mixing. TACs could be allocated by substock for certain regions: COD/5BE6A would only be fishing on Northwestern stock, COD/07D would only be fishing on the southern stock, and COD/03AN and COD/4N-S62 would only be fishing on the Viking stock. The remaining areas assumed uniform distributions of all stocks in proportions related to stock in 4a-c.
- The short-term forecast updated the method for forecasting natural mortality from an average of the final three years to the GMRF (bioPar) process. The previous benchmark conducted in 2021 (WKNSEA) noted that the bioPar functionality in SAM worked well for projecting natural mortality in short-term forecasts but was not implemented as it was unclear how the M-adjustment used in the 2021 assessment would affect this functionality. Given that 6.aN was included in the current assessment, negating the need for the M-adjustment, the bioPar functionality can successfully be applied to forecast natural mortality.
- The previous 2021 assessment simulated F with 0 variability. The functionality was updated in the current assessment to simulate F from simulation using a stationary covariance using the final year.
- Large confidence intervals were noted in the reported percent catch change from an example short-term forecast (eg. Table 3. MSY approach. % Change: -100.0%-610298.3%).
- The short-term forecast example also contained inconsistencies with respect to higher catches associated with lower probabilities of falling below B_{lim} in 2024 (eg. Table 5, MSY approach: Catch - 10672, p below B_{lim} - 0.3% vs. $B_{trigger}$: Catch - 7433, p below B_{lim} - 0.6%).

17.6 Future recommendations

- While the multi-stock model is an improvement over the single-stock, we would not consider any decisions in this benchmark as precedent for future North Sea cod or multi-stock models. The multi-stock SAM approach requires additional improvements and will certainly benefit from additional and improved data input in the future. Consequently, decisions made herein should be revisited (e.g. truncation of time series, improved method for projecting stock proportions back in time).
- As stock assessment models are growing in complexity, ICES should review its benchmark structure. More time is required to review multi-stock compared to single-stock models as there are more configurations and more modelling methods to explain to the benchmark committee.
- Ideally, new data and information on stock proportions should be proposed that could improve model runs, especially for Q3 and Q4
- The use of the multi-stock SAM model is novel on the modelling front but it also brought novelty in the setting of reference points and the handling of catch advice by separate stocks. Whilst the application of this new model addresses key underlying issues inherent to the North Sea cod stock complex, it is important to remember that uncertainties in the process are introduced. Most notably, uncertainties remain on the new forecasting tool to be introduced and the setting up of reference points is particularly sensitive to the assumptions taken. The latter was largely debated and led to conflicting views among the group. These uncertainties should warrant a precautionary approach for the management of the stock together with regular evaluations of the model, the short term forecast and the reference points.

18 Recommendations for future improvements of the assessment methodology and data collection

1. National catch sampling programs should take the new substock structure into account when planning future commercial catch sampling. This would ensure catch in numbers at age and catch weight at age by substock. Currently the information is only needed by substock in quarter 1. This recommendation should be directed to RCG NS&EA and the ICES WGCATCH. The substock map (Figure 5.1) should be included.
2. Start sampling genetic information from North Atlantic cod on a regional basis. Since we assume the stocks are not mixing in Q1, it is especially important to sample from Q2–4. This could be conducted from both the Q3 and Q4 survey and from the commercial catches. The sampling should be coordinated throughout the entire area. This recommendation should be addressed to WGBIOP and to RCG NS&EA.
3. Investigate the magnitude of mixing between substocks in Q2–Q4 to evaluate the assumption that only Q1 surveys and catches can be used as substock specific.
4. Further work is conducted to split natural mortality to substock, either by explicitly modelling three substocks in the SMS multispecies model or by postprocessing the outputs of the multispecies key run. This recommendation should be addressed to WGSAM.
5. Research is conducted to quantify seal predation on the Northwestern substock.
6. Investigate if the optimal multi-stock SAM is different for each component.
7. Conduct simulation self-tests of the preferred multi-stock SAM for Northern Shelf cod stocks.
8. The SAM biopar fits to maturities could be improved.
9. Investigate how to improve the multi-stock SAM model fits to the 1995–present quarter 1 landings proportions by substock. This may involve substock specific landings fractions or catch weights-at-age.
10. There have been large changes in estimates of the proportion mature-at-age for all the Northern shelf cod substocks. There are concerns that younger fish may contribute less to the reproductive potential of the stocks than their weight indicates, compared to older cod. Research is required about the fecundity versus weight and egg quality of these substocks.

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21 Working Documents

21.1 Estimation of cod commercial CPUE in Danish trawlers

Josefine Egekvist and Anna Rindorf

Introduction

Estimates of commercial landings per unit effort, LPUE, of potentially spawning cod are estimated from logbook and landings data from Danish trawlers. Timeseries are produced for quarter 1 and the full year using standardization of vessel size (KW) or no standardisation. The data are intended to for potential use in the stock assessment of cod in the Greater North Sea and West of Scotland under the assumption that

$$\overline{LPUE}_{y,a} = q_y SSB_{y,a}$$

Where $\overline{LPUE}_{y,a}$ denotes the average $LPUE$ in year y in area a, $SSB_{y,a}$ is the spawning stock biomass at the onset of year y in area a and q_y is the catchability of spawning cod to the commercial fishery in year y. The catchability changes over time as a result of technical development in the fishery and the average annual technical creep determined by Eigaard *et al.* across a range of fisheries was 3.2% (Eigaard *et al*., 2014). Other factors may also affect catchability, including density dependence where catchability increases as stock size decreases, though this has not been demonstrated in Danish trawlers (Rindorf and Andersen 2008). Low quotas in later years may have led to changes in fishing operations to attempt to avoid cod in these years, thereby lowering LPUE without this indicating a change in spawning stock biomass. In opposition to this effect, zero catches are not included, tending to increase LPUE at low spawning stock biomass. Due to all these factors, the implementation of LPUE as indices of spawning stock size should as a minimum be conducted together with a temporal change in catchability, be it linear or stepwise.

Input data

Data used were individual logbook records from Denmark (1987–2021). The logbooks indicate catch per day in specific statistical rectangles. The observations are individual fishing days on individual trips and the rectangle allocation is used to divide the data into Southern, Viking and Northwestern cod.

Non-standardised data

The non-standardised data are simple averages of ln(landings per fishing day) across individual records within area and quarter 1 of the year for the quarterly time series and within area and the year for annual data. The variance and the number of observations are also given. Under this approach,

$$\overline{LPUE}_{y,a} = exp\left(\frac{\sum_{j=1}^{J_{y,a}} ln\left(LPUE_{y,a,j}\right)}{J_{y,a}}\right)$$

Where $J_{y,a}$ is the total number of records in year y in area a and j denotes record j.

Standardising effort with respect to vessel ID effects

Often a vessel will catch consistently more than another vessel, leading to inherent correlation in catch rates taken by a single vessel. This can be addressed by estimating the area and year specific catch rates in a model that includes random effects of vessel ID:

$$ln(LPUE_{y,a,ID,j}) = k_{0,y,a} + \lambda_{ID} + \varepsilon_j$$

Where λ_{ID} and ε_j are normally distributed parameters, each with a mean of 0 and a separate standard deviation.

Standardising effort with respect to engine size

The standardised data are based on the observed increasing relationship between engine size in KW and $LPUE_{y,a,j}$ (Figure 1), corresponding to the relationship,

$$ln(\overline{LPUE}_{y,a,KW}) = ln(q_y SSB_{y,a}) + b_y ln(KW)$$

The engine power effect *b* was estimated in the generalised linear model:

$$ln(LPUE_{y,a,KW,j}) = k_{y,a} + b_y ln(KW) + \lambda_{ID} + \varepsilon_j$$

Where λ_{ID} and ε_j are normally distributed parameters, each with a mean of 0 and a separate standard deviation. The value of b_y was used to estimate standardised *LPUE* of trip observation *j* as

$$ln(LPUE_{y,a,KW=375,j}) = ln(LPUE_{y,a,j}) + b_y ln\left(\frac{375}{KW_j}\right)$$

The value of 375 was the average KW of all observations. Average standardised LPUE for the year and area was then estimated as

$$\overline{LPUE}_{y,a,KW=375} = exp\left(\frac{\sum_{j=1}^{J_{y,a}} ln(LPUE_{y,a,KW=375,j})}{J_{y,a}}\right)$$

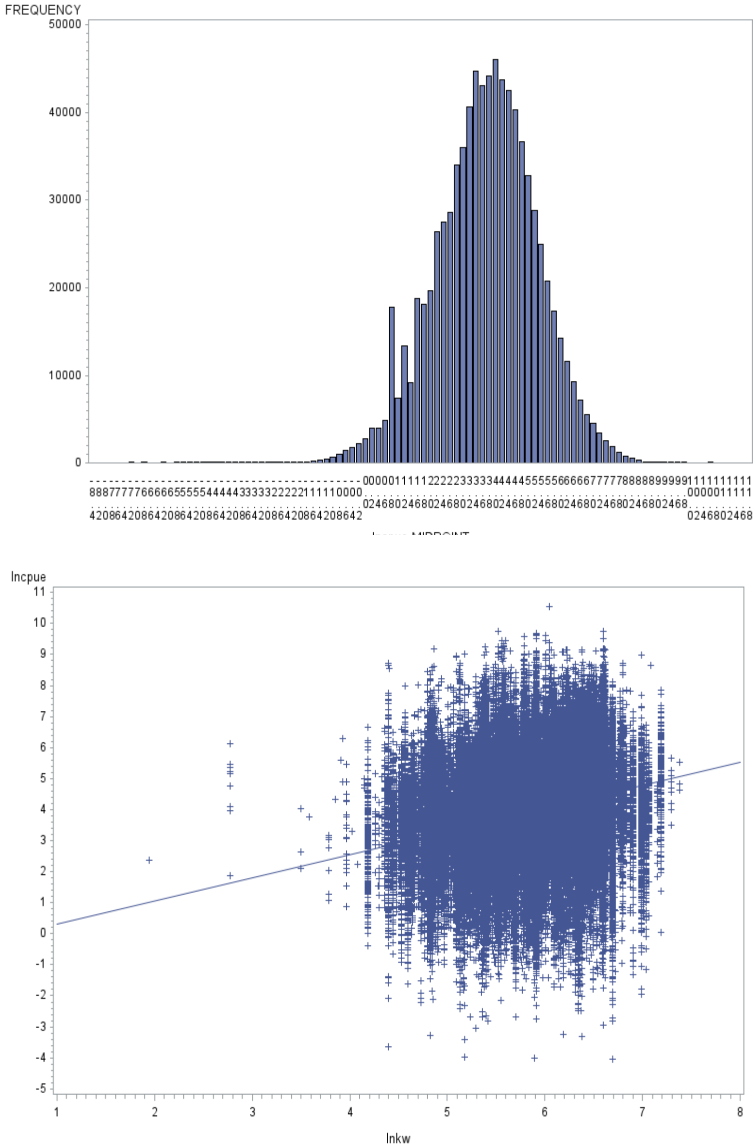

Figure 1. Histogram of all ln(LPUE) observations (left) and relationship between $LPUE_{y,a,j}$ (relative to the average for the area and year) and KW across all data (right).

Results

The amount of variation explained by the fixed effects in the model was relatively modest (r^2=0.15). However, the variation explained by KW exceeded that explained by area and year (area and year alone r^2=0.054). Residuals were examined for signs of non-linearity in the relationship between *LPUE* and *KW*, but no such signs were found though there was a tendency for heavy tails. The parameter estimates of *b* are given in Figure 2. The temporal development in the time series of effort were very similar between the different standardisation (Figure 3). All standardised time series showed a greater decline than the non-standardised series.

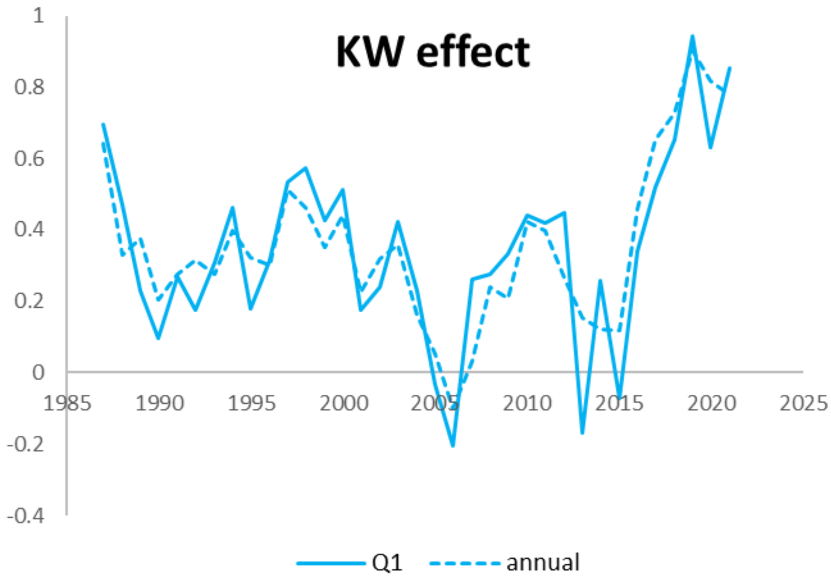

Figure 2. Parameter estimates for *b* (effect of ln(KW) ln Ln(LPUE).

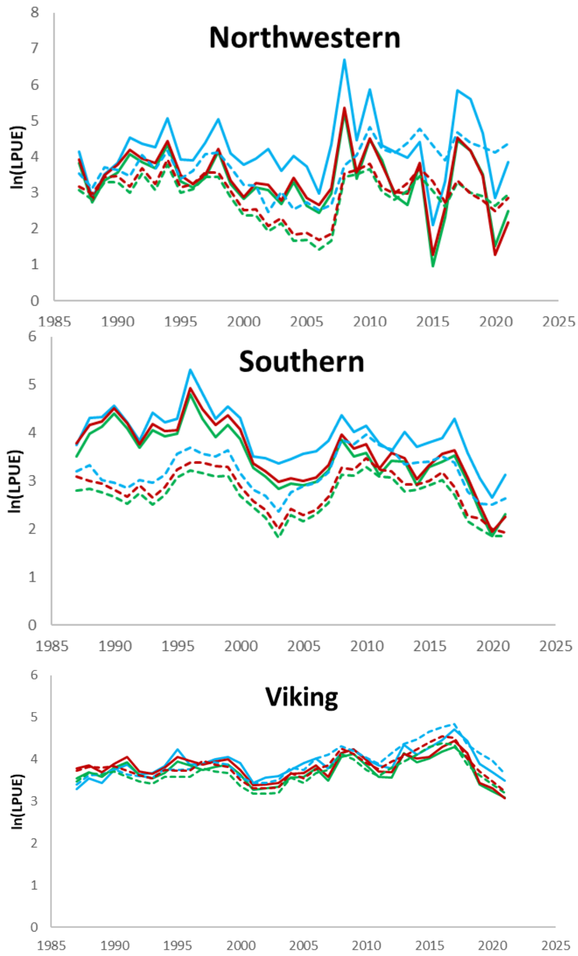

Figure 3. Ln(LPUE) observed (blue) and standardised by mixed effects of vessel ID (green) and vessel ID and KW (red). Solid lines are quarter 1 values, dotted lines annual values.

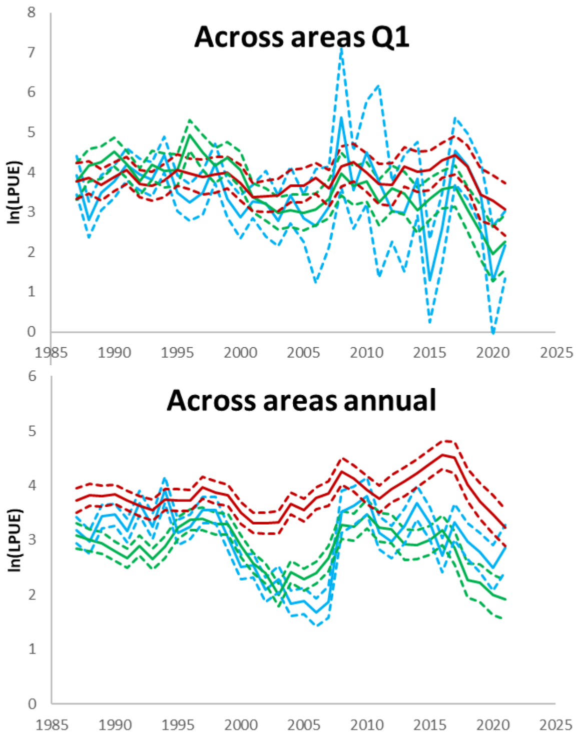

Figure 4. Comparison across areas for quarter 1 and annual data and ID+KW standardisation.

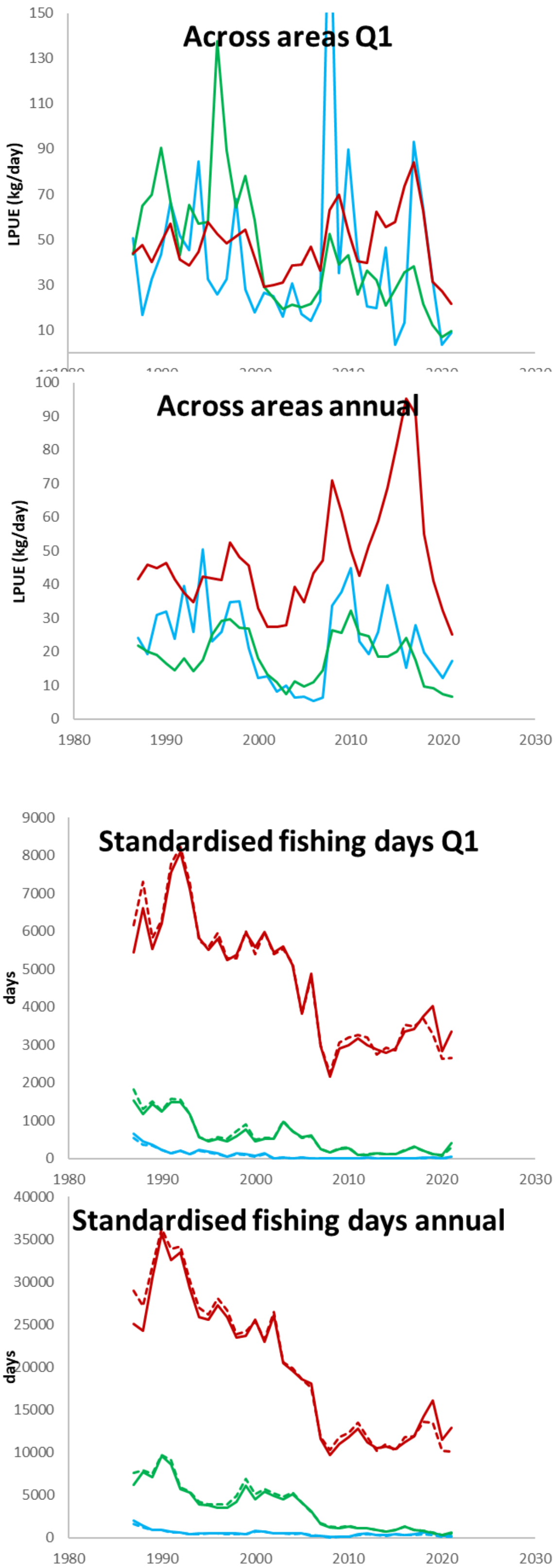

Figure 5. Comparison of LPUE on a natural scale (top) and development in standardised number of fishing days (bottom solid) and non-standardised number of fishing days (bottom dotted). Viking (red), southern (green) and northwestern (blue).

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21.2 Short technical overview of the stock assessment and multiStockassessment R packages

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Short technical overview of the stockassessment and multiStockassessment R packages

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1 Introduction

The state-space assessment model SAM (Nielsen and Berg 2014) is widely used in ICES. The model treats single-stock fish abundance and fisheries induced mortality rates as unobserved stochastic processes that are connected to data via observational likelihoods. The model has been extended to a multi-stock setting where abundance processes are linked through partial correlations (Albertsen, Nielsen, and Thygesen 2018). The single-stock SAM model is implemented in the open source R package `stockassessment` (Nielsen et al. 2023), while the multi-stock SAM model is implemented in the open source R package `multiStockassessment` (Albertsen 2023). For a single stock, the two packages give the same results. Since the initial model formulations, both packages have been developed to allow further data sources and biological processes. Below, the current model framework implemented in the two packages is described.

2 Fishing mortality process

In both models, the fishing mortality rate process is modeled independently of other parts of the model. For notational simplicity, ages are indexed from 1 to n_a, years from 1 to n_y, fleets from 1 to n_f, and stocks from 1 to n_s.

2.1 Single-stock model

The single-stock SAM includes two options for modeling the fishing mortality rate vectors, $\mathbf{F}_{y,f} = (F_{1,y,f}, \ldots, F_{n_a,y,f})$. The fishing mortality rate vectors are indexed by year (y) and fleet (f), and are constrained to have positive elements.

2.1.1 Random walk

The default option in the SAM model is to let the fishing mortality process follow a multivariate random walk on log-scale by fleet,

$$\log \mathbf{F}_{y,f} = \log \mathbf{F}_{y-1,f} + \boldsymbol{\epsilon}_{y,f}^{(F)}$$

Here, $\boldsymbol{\epsilon}_{y,f}^{(F)} \sim N_{n_a}(0, \boldsymbol{\Sigma}_f^{(F)})$. The covariance matrix, $\boldsymbol{\Sigma}_f^{(F)}$, can be parameterized with a diagonal, compound symmetry, AR(1) (see Nielsen and Berg 2014; Nielsen et al. 2023), or separable structure (similar to Aanes et al. 2007). Fishing mortality rates are independent between fleets.

2.1.2 VAR(1)

Alternatively, the fleet-wise fishing mortality rate can be modeled as a one-step vector auto-regressive process on log-scale,

$$\log \mathbf{F}_{y,f} - \boldsymbol{\mu}_f^{(F)} = \alpha_f^{(F)} \left(\log \mathbf{F}_{y-1,f} - \boldsymbol{\mu}_f^{(F)} \right) + \boldsymbol{\epsilon}_{y,f}^{(F)}.$$

Within fleets, the process is restricted to have the same scalar auto-correlation parameter for all ages, $0 < \alpha_f^{(F)} < 1$. Similar to the random walk model, $\epsilon_{y,f}^{(F)} \sim N(0, \Sigma_f^{(F)})$. The covariance matrix can be parameterized with a diagonal, compound symmetry, or AR(1) structure (see Nielsen and Berg 2014; Nielsen et al. 2023).

2.2 Multi-stock model

The multi-stock SAM model allows the same per-stock options as the single-stock SAM. Further, additional options are implemented to link fishing mortality rates between stocks.

2.2.1 Random walk

Similar to the single-stock SAM, the multi-stock SAM default is to model stock-wise fishing mortality rates by multivariate random walks on log-scale,

$$\log \mathbf{F}_{y,f,s} = \log \mathbf{F}_{y-1,f,s} + \epsilon_{y,f,s}^{(F)}.$$

Again, $\epsilon_{y,f,s}^{(F)} \sim N_{n_a}(0, \Sigma_{f,s}^{(F)})$ and can be parameterized with a diagonal, compound symmetry, AR(1), or separable structure. The process increments are independent between stocks and fleets.

2.2.2 VAR(1)

Besides the random walk model, a vector AR(1) on log-scale is available,

$$\log \mathbf{F}_{y,f,s} - \boldsymbol{\mu}_{f,s}^{(F)} = \alpha_{f,s}^{(F)} \left(\log \mathbf{F}_{y-1,f,s} - \boldsymbol{\mu}_{f,s}^{(F)} \right) + \boldsymbol{\epsilon}_{y,f,s}^{(F)}.$$

Parameters are as defined above.

2.2.3 Constraining multi-stock F processes

For multi-stock settings where stock-wise observations are not available (See "Stock mixture observations" below), full fishing mortality rate processes per stock may not be identifiable. For these cases, the multi-stock SAM offers different configurations to connect the processes between stocks. In all options, the F processes of the first stock follows either a random walk or a VAR(1) model as described above.

2.2.3.1 Shared F process In the first configuration option, the same F process is used for all stocks such that

$$\log F_{a,y,f,s} = \log F_{a,y,f,1}, s > 1.$$

This option is similar to assessing the stocks in a combined single-stock model.

2.2.3.2 AR(1) deviances The second configuration option is to let the deviations in F follow independent AR(1) processes. In this case,

$$\log F_{a,y,f,s} = \log F_{a,y,f,1} + \tau_{a,y,f,s}, s > 1$$

where

$$\tau_{a,y,f,s} - \mu^{(\tau)}_{a,f,s} = \alpha^{(\tau)}_{f,s}\left(\tau_{s,a,y-1,s} - \mu^{(\tau)}_{a,f,s}\right) + \epsilon^{(\tau)}_{s,a,y}$$

where $\epsilon^{(\tau)}_{s,a,y} \overset{iid}{\sim} N\left(0, \left(\sigma^{(\tau)}_s\right)^2\right)$.

2.2.3.3 Scaled selectivities with flexible $\bar{F}$ Finally, the stock-wise selectivities can be scaled by parametric functions, while the average fishing mortality rate is scaled by a stochastic process,

$$\log F_{a,y,f,s} = \log F_{a,y,f,1} + \beta_{a,y,f,s} + \tau_{y,f,s}, s > 1$$

where $\tau_{y,f,s}$ can be modeled by a random walk,

$$\tau_{y,f,s} = \tau_{y-1,f,s} + \epsilon^{(\tau)}_{y,f,s},$$

an AR(1) process,

$$\tau_{y,f,s} - \mu^{(\tau)}_{f,s} = \alpha^{(\tau)}_{f,s}\left(\tau_{y-1,f,s} - \mu^{(\tau)}_{f,s}\right) + \epsilon^{(\tau)}_{y,f,s},$$

or be left out. In both the random walk and AR(1) processes, $\epsilon_{\tau,s,y} \sim N\left(0, \sigma^2_{\tau,s}\right)$.

Unlike $\tau_{y,f,s}$, the parametric scaling of selectivities, $\beta_{a,y,f,s}$, is modeled by a linear function,

$$\beta_{a,y,f,s} = \boldsymbol{b}_{f,s}\boldsymbol{X}_{f,s}(a,y),$$

where $\boldsymbol{b}_{f,s}$ is a vector of parameters and $\boldsymbol{X}_{f,s}(a,y)$ is a design matrix that can depend on age and year. Note that the function is linear in the parameters, and not necessarily in age or year. As a special case, $\beta_{a,y,f,s}$ can be omitted to assume the selectivity is the same for all stocks, similar to a combined single-stock assessment of the stocks.

2.3 Seasonal F process

For fleets where the fishing mortality rate is assumed to be constant throughout the year, the F processes above are used without modification. Otherwise, the fishing mortality rates above are parameterized to represent the full year effect on survival from fishing. Therefore, seasonal modifications to F are constrained such that the effect over a year is 1,

$$\int_0^1 F_{a,y,f,s} \cdot S_{a,y,f,s}(t)dt = F_{a,y,f,s}.$$

Here, $S_{a,y,f,s}(t)$ is the seasonal effect at time t of year y. Seasonal variation in fishing mortality rates can be included in three ways. The first way is to let a fleet be active in part of the year. In this case, $S_{a,y,f,s}(t) = 0$ before and after the fleet is active. The second way is to estimate $S_{a,y,f,s}(t)$ as piece-wise constant fixed effects. Finally, $S_{a,y,f,s}(t)$ can be estimated as transformed AR(1) processes. Similar to the second option, the effects are piece-wise constant over the year corresponding to seasons. For each season, the effect follows an AR(1) process across years. In turn, the AR(1) processes are transformed to fulfill the full-year constraint above.

3 Population process

Similar to the fishing mortality rate, fish abundance is treated as an unobserved stochastic process in the SAM models.

3.1 Single-stock abundance process

The first age in the model is modeled by a recruitment relationship,

$$\log N_{1,y} = R(SSB_{y-a_R}, y, \log N_{1,y-1}) + \epsilon_{1,y}^{(N)}.$$

The recruitment relationship can depend on the spawning stock biomass in the spawning year (SSB_{y-a_R}, where a_R is the age of recruitment), the previous recruitment, and the year (See section "Stock-recruitment relationships" for details). The last model age is typically modeled as a plus group, aggregating all fish at that age or older,

$$\begin{aligned}\log N_{n_a,y} = &\log\left(\exp\left(\log N_{n_a-1,y-1} - \sum_{f=1}^{n_f} F_{n_a-1,y-1,f} - M_{n_a-1,y-1}\right) + \right.\\ &\left.\exp\left(\log N_{n_a,y-1} - \sum_{f=1}^{n_f} F_{n_a,y-1,f} - M_{n_a,y-1}\right)\right) + \epsilon_{a,y}^{(N)}\end{aligned}$$

Finally, middle ages are modeled by

$$\log N_{a,y} = \log N_{a-1,y-1} - \sum_{f=1}^{N_f} F_{a-1,y-1,f} - M_{a-1,y-1} + \epsilon_{a,y}^{(N)}, 1 < a < N_a.$$

In the equations above, $F_{a,y,f}$ are instantaneous fishing mortality rates defined above, $M_{a,y}$ is the instantaneous natural mortality rate, and $\epsilon_{a,y}^{(N)} \overset{iid}{\sim} N\left(0, \left(\sigma_a^{(N)}\right)^2\right)$, It is possible, but not recommended, to change the mean assumption of $\epsilon_{N,a,y}$ such that the calculated survivors correspond to either the mean or mode of $N_{a,y}$ instead of the default median.

3.2 Multi-stock abundance process

Similar to the single-stock SAM, the multi-stock SAM defines the abundance processes by

$$\log N_{1,y,s} = \log R_s(SSB_{y-a_R,s}, y, \log N_{1,y-1,s}) + \epsilon_{1,y,s}^{(N)}$$

for recruitment,

$$\log N_{n_a,y,s} = \log\left(\exp\left(\log N_{n_a-1,y-1,s} - \sum_{f=1}^{n_f} F_{n_a-1,y-1,f,s} - M_{n_a-1,y-1,s}\right) + \exp\left(\log N_{n_a,y-1,s} - \sum_{f=1}^{n_f} F_{n_a,y-1,f,s} - M_{n_a,y-1,s}\right)\right) + \epsilon_{a,y,s}^{(N)}$$

for the plus group, and

$$\log N_{a,y,s} = \log N_{a-1,y-1,s} - \sum_{f=1}^{N_f} F_{a-1,y-1,f,s} - M_{a-1,y-1,s} + \epsilon_{a,y,s}^{(N)}, 1 < a < N_a.$$

for middle ages. The mean assumptions of $\epsilon_{a,y,s}^{(N)}$ can be adjusted similar to the single-stock model. However, in the multi-stock SAM, $\epsilon_{a,y,s}^{(N)}$ can be correlated between ages and stocks (see Albertsen, Nielsen, and Thygesen 2018). With these abundance processes, each stock represent a separate genetic or biological spawning unit. As such, there is no transfer of individuals between stocks and recruitment is only influenced by spawning biomass from the same stock.

3.3 Stock-recruitment relationships

In both SAM models, recruitment can be modeled as a function of SSB, last years recruitment and age. Currently, 32 recruitment models are implemented in the SAM models. In the descriptions below, stock subscripts are omitted from parameters for simplicity. However, the same recruitment models are available for the single- and multi-stock SAM models. By default, the random walk on log-scale is used.

3.3.1 Random walk on log-scale

The random walk on log-scale recruitment model (e.g., Nielsen and Berg 2014) is implemented as

$$\log R(SSB_{y-a_R,s}, y, \log N_{1,y-1,s}) = \log N_{1,y-1,s}.$$

3.3.2 Ricker

The Ricker recruitment model (Ricker 1954) is implemented as

$$R(SSB_{y-a_R,s}, y, \log N_{1,y-1,s}) = \alpha SSB_{y-a_R,s} \exp\left(-\beta SSB_{y-a_R,s}\right)$$

where $\alpha, \beta > 0$.

3.3.3 Beverton-Holt

The Beverton-Holt recruitment model (Beverton and Holt 1957) is implemented as

$$R(SSB_{y-a_R,s}, y, \log N_{1,y-1,s}) = \frac{\alpha SSB_{y-a_R,s}}{1 + \beta SSB_{y-a_R,s}}$$

where $\alpha, \beta > 0$.

3.3.4 Piece-wise constant mean

The piece-wise constant mean recruitment model is implemented as

$$R(SSB_{y-a_R,s}, y, \log N_{1,y-1,s}) = \mu_{\gamma(y)}$$

where $\mu_{\gamma(y)} > 0$, $\gamma(y) = \sum_i \mathbb{1}(b_i \leq y)$, b_i is a sequence of break points, and $\mathbb{1}(b_i \leq y)$ is an indicator function that is 1 if $b_i \leq y$ and 0 otherwise.

3.3.5 Logistic hockey stick

The logistic hockey stick recruitment model (Barrowman and Myers 2000) is implemented as

$$\begin{aligned} R(SSB_{y-a_R,s}, y, \log N_{1,y-1,s}) =& \alpha \cdot m \cdot t \cdot (1 + \exp(-1/t)) \cdot \\ & (SSB_{y-a_R,s} \cdot m \cdot t - (1 + \exp((SSB_{y-a_R,s} - m)/(m \cdot t))) \\ & \cdot (1 + \exp(-1/t)) \end{aligned}$$

where $\alpha, m, t > 0$.

3.3.6 Hockey stick

The hockey stick recruitment model (e.g., Barrowman and Myers 2000) is implemented as

$$R(SSB_{y-a_R,s}, y, \log N_{1,y-1,s}) = \alpha B_{lim}(SSB_{y-a_R,s} - \frac{1}{2}(SSB_{y-a_R,s} - B_{lim} + |SSB_{y-a_R,s} - B_{lim}|))$$

where $\alpha, B_{lim} > 0$.

3.3.7 AR(1) on log-scale

The hockey stick recruitment model is implemented as

$$\log R(SSB_{y-a_R,s}, y, \log N_{1,y-1,s}) = \mu + \alpha(\log N_{1,y-1,s} - \mu)$$

where $-1 < \alpha < 1$.

3.3.8 Bent hyperbola (smooth hockey stick)

The bent hyperbola (smooth hockey stick) recruitment model (Mesnil and Rochet 2010) is implemented as

$$\log R(SSB_{y-a_R,s}, y, \log N_{1,y-1,s}) = \mu + \alpha(\log N_{1,y-1,s} - \mu)$$

where $-1 < \alpha < 1$.

3.3.9 Compensatory power function

The compensatory power function (e.g., Cushing 1971) is implemented as

$$R(SSB_{y-a_R,s}, y, \log N_{1,y-1,s}) = \alpha SSB^{\beta}_{y-a_R,s}$$

where $\alpha > 0$ and $0 < \beta < 1$.

3.3.10 Depensatory power function

The compensatory power function is implemented as

$$R(SSB_{y-a_R,s}, y, \log N_{1,y-1,s}) = \alpha SSB^{\beta}_{y-a_R,s}$$

where $\alpha > 0$ and $1 < \beta$.

3.3.11 Shepherd

The Shepherd recruitment (Shepherd 1982) is implemented as

$$R(SSB_{y-a_R,s}, y, \log N_{1,y-1,s}) = \frac{\alpha SSB_{y-a_R,s}}{1 + (SSB_{y-a_R,s}/\beta)^{\gamma}}$$

where $\alpha, \beta, \gamma > 0$.

3.3.12 Hassel/Deriso

The Hassel/Deriso recruitment (Hassell 1975; Deriso 1978; Schnute 1985) is implemented as

$$R(SSB_{y-a_R,s}, y, \log N_{1,y-1,s}) = \frac{\alpha SSB_{y-a_R,s}}{(1 + \beta\gamma SSB_{y-a_R,s})^{\gamma}}$$

where $\alpha, \beta, \gamma > 0$.

3.3.13 Saila-Lorda

The Saila-Lorda recruitment (see e.g., Iles 1994; Needle 2001) is implemented as

$$R(SSB_{y-a_R,s}, y, \log N_{1,y-1,s}) = \alpha SSB^{\gamma}_{y-a_R,s} \exp(-\beta SSB_{y-a_R,s})$$

where $\alpha, \beta, \gamma > 0$.

3.3.14 Sigmoidal Beverton-Holt

The sigmoidal Beverton-Holt recruitment (Myers et al. 1995) is implemented as

$$R(SSB_{y-a_R,s}, y, \log N_{1,y-1,s}) = \frac{\alpha SSB^{\gamma}_{y-a_R,s}}{1 + \beta SSB^{\gamma}_{y-a_R,s}}$$

where $\alpha, \beta, \gamma > 0$.

3.3.15 Spline models

Besides the common parametric models above, four spline models have been implemented. The splines use transformed Gaussian densities functions as basis functions for a given set of knots (see Albertsen and Trijoulet 2020 for details). Below, σ denotes a spline with such basis functions, σ_I denotes a spline where the basis functions are integrated, σ_{I-} denotes a spline where the basis functions are integrated and parameters force the spline to be monotonically non-increasing, and σ_{II-} denotes Monotonically non-decreasing negative spline with a double integrated spline basis. All splines have a location parameter.

3.3.15.1 Compensatory spline (CMP) The compensatory spline is implemented as

$$R(SSB_{y-a_R,s}, y, \log N_{1,y-1,s}) = SSB_{y-a_R,s} \cdot \sigma_{I-}(SSB_{y-a_R,s})$$

This spline is similar to the spline proposed by Cadigan (2012).

3.3.15.2 Smooth spline The smooth spline is implemented as

$$R(SSB_{y-a_R,s}, y, \log N_{1,y-1,s}) = SSB_{y-a_R,s} \cdot \sigma_{I}(SSB_{y-a_R,s})$$

3.3.15.3 General spline The general spline is implemented as

$$R(SSB_{y-a_R,s}, y, \log N_{1,y-1,s}) = SSB_{y-a_R,s} \cdot \sigma(SSB_{y-a_R,s})$$

3.3.15.4 Convex compensatory spline (CC) The convex compensatory spline is implemented as

$$R(SSB_{y-a_R,s}, y, \log N_{1,y-1,s}) = SSB_{y-a_R,s} \cdot \sigma_{II-}(SSB_{y-a_R,s})$$

3.3.16 Depensatory extensions

Besides the standard models above, the SAM models include four types of depensatory extensions. The types are denoted Type A, B, C, and D for convenience.

3.3.16.1 Type A depensatory models The first type of depensatory extensions are of the form (Barrowman et al. 2003 and references therein)

$$R_A(S) = R(S^{\delta}),$$

where $R(S)$ is a compensatory stock-recruitment relationship and $\delta > 0$ is a parameter. For $\delta < 1$ the model is depensatory; for $\delta = 1$, the compensatory model is obtained; and for $\delta > 1$, the model is over-compensatory. The sigmoidal Beverton-Holt model has this form, but currently no other models of this type has been made available in the user interface.

3.3.16.2 Type B depensatory models The second type of depensatory extensions are of the form (Barrowman et al. 2003)

$$R_B(S) = R(S)\frac{S}{S+\delta},$$

where $R(S)$ is a compensatory stock-recruitment relationship and $\delta > 0$ is a parameter. In the SAM model, Type B depensatory extensions are available for the Ricker, Beverton-Holt, logistic hockey stick, hockey stick, bent hyperbola, compensatory power function, Shepherd, Hassel/Deriso, CMO spline, and CC spline models.

3.3.16.3 Type C depensatory models The third type of depensatory extensions are of the form

$$R_C(S) = \frac{R(S)}{1+\exp\left(-\lambda(S-\delta)\right)},$$

where $R(S)$ is a compensatory stock-recruitment relationship and $\delta, \lambda > 0$ is a parameter. Ricker, Beverton-Holt, CMP spline, and CC spline.

3.3.16.4 Type D depensatory models The fourth type of depensatory extensions are of the form (Hilborn et al. 2014)

$$R_D(S) = R\left(S \cdot \left(1 - \frac{1}{2}\exp\left(S/\delta\right)\right)\right),$$

where $R(S)$ is a compensatory stock-recruitment relationship and $\delta > 0$ is a parameter. Currently, no extensions of this type has been made available in the user interface.

4 Biological input

The SAM model takes natural mortality, maturity, catch-mean-weight, stock-mean-weight, landing fraction, landing-mean-weight, and discard-mean-weight as input. By default, these inputs are assumed known without error. However, for natural mortality, maturity, catch-mean-weight, and stock-mean-weight, it is possible to fit a Gaussian Markov Random Field (GMRF) with measurement error to the input data. In this case, the fitted values are used throughout the model. For mortality and weights, the GMRF is fitted on log-scale and the log-input is assumed to follow a normal distribution. For maturity, the GMRF is fitted on logit-scale and observations are assumed to follow a beta distribution. In all four cases, the GMRF has correlation along cohorts and along years. Optionally, an additional correlation parameter can be added for the plus group.

5 Observations

Both the single- and multi-stock SAM models allow several data types to inform the assessment. In the multi-stock SAM, observations can either be included specific to a single stock or as part of stock mixture observations. In the single-stock SAM, only the former is possible.

5.1 Catch

Catches in SAM can be modeled by a multivariate normal on log-scale, or a multivariate additive logistic normal for age composition and a log-normal for total catch (see Albertsen, Nielsen, and Thygesen 2017). Predicted catch is calculated by

$$\log C_{a,y,f,s} = \log N_{a,y,s} - \left(\int_0^{t_{f,0}} F_{a,y,f,s} \cdot S_{a,y,f,s}(t) + M_{a,y,s} dt\right) + \log \int_{t_{f,0}}^{t_{f,1}} F_{a,y,f,s} \cdot S_{a,y,f,s}(t) \cdot \exp(-\sum_g F_{a,y,g,s} \cdot S_{a,y,g,s}(t) - M_{a,y,s}) dt,$$

where the first term, $N_{a,y,f,s}$, is the abundance at the beginning of the year, the second term is the survival until the start of the fleet, and the third term is the catch while the fleet is active. In the formula, $t_{f,0}$ denotes the time of year the fleet starts, and $t_{f,1}$ is the time of year the fleet ends.

In assessments where there is only one fleet which is active throughout the year, and there is no modeled seasonality, the formula above reduces to

$$\log C_{a,y,1,s} = \log\left(\frac{F_{a,y,1,s}}{F_{a,y,1,s} + M_{a,y,s}}(1 - \exp(-F_{a,y,1,s} - M_{a,y,s}))N_{a,y,s}\right)$$

Across ages, catch can be independent or correlated with either an irregular AR(1) structure or unstructured correlation matrix (Berg and Nielsen 2016) and different prediction-variance relations can be used (Breivik, Nielsen, and Berg 2021). Further, the covariance can be scaled by input weights. Finally, data corresponding to the sum of catch fleets can be included.

5.2 Surveys

Survey indices per age can be modeled by a multivariate normal on log-scale, or a multivariate additive logistic normal for age composition and a log-normal for total catch. Predicted survey indices are calculated by

$$\log I_{a,y,i,s} = \log Q_{a,i,s} + \gamma_{a,i,s} \log N_{a,y,s} - \left(\int_0^{t_{i,0}} F_{a,y,f,s} \cdot S_{a,y,f,s}(t) dt + M_{a,y,s} \right),$$

where $Q_{a,i,s}, \gamma_{a,i,s} > 0$. By default, $\gamma_{a,i,s}$ is fixed to one. In assessments where there is one catch fleet and no modeled seasonality, the formula reduces to

$$\log I_{a,y,i,s} = \log \left(Q_{a,i,s} \exp(-(F_{a,y,1,s} + M_{a,y,s}) \cdot t_{i,0}) N_{a,y,s}^{\gamma_{a,i,s}} \right)$$

Similar to catch, surveys can be independent or correlated with either an irregular AR(1) structure or unstructured correlation matrix across ages. Further, the covariance can be scaled by input weights and different prediction-variance relations can be used.

Besides the age-wise abundance surveys, surveys can be included that are assumed to be proportional to spawning stock biomass (SSB), catch, fishable stock biomass (FSB), landings, total stock biomass (TSB), total N, or average F. Each of these are modeled by a univariate log-normal distribution.

5.3 Tagging-recapture

Tagging-recapture data can be modeled by a negative binomial distribution. The predicted number of recaptures is modeled by

$$R_{a,y,s} = \rho_{a,y,s} \eta_{a,y,s} \frac{r_{a,y,s}}{N_{a,y,s}}$$

where $\rho_{a,y,s}$ is a post-release survival parameter, typically shared between several ages and years, $\eta_{a,y,s}$ is the number of captured fish screened for tags, and $r_{a,y,s}$ is the number of tagged fish of the same year class.

5.4 Seasonal proportions

Besides catch fleets limited to part of the year, seasonality can be informed through seasonal composition data. Seasonal compositions can be modeled using a Dirichlet distribution or an additive logistic normal. The covariance of the additive logistic normal can have the same parameterizations as catch and survey data. The predicted seasonal composition is calculated from the catch equation above. For catch in numbers, the predicted log-proportion of catch in season i by fleet f from stock s is

$$
\begin{aligned}
\log C^{(i)}_{a,y,f,s} = \log N_{a,y,s} \\
&- \left(\int_0^{t_{f,i,0}} F_{a,y,f,s} \cdot S_{a,y,f,s}(t) + M_{a,y,s} dt \right) \\
&+ \log \int_{t_{f,i,0}}^{t_{f,i,1}} F_{a,y,f,s} \cdot S_{a,y,f,s}(t) \cdot \exp(-\sum_g F_{a,y,g,s} \cdot S_{a,y,g,s}(t) - M_{a,y,s}) dt \\
&- \log C_{a,y,f,s},
\end{aligned}
$$

where $t_{f,i,0}$ is the time of year the season starts, and $t_{f,i,1}$ is the time of year the season ends. In this equation, the first term is the abundance at the beginning of the year, the second term is the survival until the beginning of the season, the third term is the catch during the season, and the fourth term normalizes by the full year catch. Besides catch in numbers, the proportions can be given for landings in numbers, catch in weight, and catch in numbers. Incorporating time-varying landing fractions, catch weights and landing weights is a subject for future research. However, if seasonality is incorporated through time-restricted fleets, each can be given different input data. Finally, seasonal proportions can be given for a specific age or across all ages and for a specific fleet or across all fleets.

5.5 Stock mixture observations (only multi-stock)

In the multi-stock SAM, mixed-stock catch and surveys can be included. For catch fleets or surveys that cover a mixture of stocks, observations are predicted as the sum of stock-wise predictions. Weights can be given in the sum to let fleets cover anywhere between 0 and 100% of a stock. For mixed-stock observations, the stock-wise covariance matrices can either be combined as a weighted average, using the stock coverage proportions, or using a Taylor approximation. The former is typically more stable and resembles the covariance structure if the stocks were assessed as one combined stock. For composition data (e.g., seasonal proportions), the un-normalized quantity (such as catch per season) is summed across stocks before normalizing to proportions.

5.6 Stock composition proportions (only multi-stock)

Similar to the seasonal proportions, stock composition proportions can be modeled using a Dirichlet or additive logistic normal distribution. Stock compositions are predicted similarly to seasonal proportions, but per stock instead of per season. Again, the composition data can be related to catch in numbers, landings in numbers, catch in weight, or landings in weight. Further, the data correspond to any part of the year, one specific or all fleets, and one specific or all ages.

5.7 Area proportions (only multi-stock)

Similar to the seasonal and stock proportions, area composition proportions can be modeled using a Dirichlet or additive logistic normal distribution. Area compositions are predicted similarly to seasonal and stock proportions, but per area instead of per season or stock. To calculate catch per area for each stock, parameters are included to estimate the proportion of catch that is taken per area. For areas where the catch of a stock is known to be negligible, the parameter can be fixed to 0%. Again, the composition data can be related to catch in numbers, landings in numbers, catch in weight, or landings in weight. Further, the data correspond to any part of the year, one specific or all fleets, and one specific or all ages.

5.8 Individual stock composition samples (only multi-stock)

To inform stock compositions in the model, individual level mixed-stock samples can be included. Currently, genotype data is supported, but support for phenotype, otolith shape, otolith micro chemistry, and vertebrae count data is planned and would follow the same general approach.

The data included must consist of a baseline with known stock origin. For example actively spawning individuals, where the stock origin can be assigned without prior analysis. Further, mixed-stock samples of (a priori) unknown origin from one of the modeled fleets (i.e., catch or a survey) should be included. Baseline samples are used to inform the distribution of observations given the stock origin, $P(X_i \mid S_i = s)$. For genotype data, the number of each possible allele at each locus is counted, and the counts are assumed to follow Dirichlet-multinomial distributions. In turn, the likelihood contribution of individuals of unknown origin is calculated via

$$P(X_i) = \sum_s P(X_i \mid S_i = s) P(S_i = s).$$

Here, the stock-wise data likelihoods are weighted by the probability of coming from each stock. The stock-origin probabilities are calculated from the relative contributions to the mixed-stock fleet the sample originates from. For example, for an individual sampled from a commercial catch fleet, $P(S_i = s)$ would be the catch from fleet s divided by the total catch. Samples can be included either with or without a known age. Finally, random effects can be included to account for intra-trip correlation as well spatio-temporal-age correlations.

Currently, alleles are assumed independent, both within a locus and between loci. That is, linkage equilibrium is assumed. Further, allele frequencies are assumed to be constant over time. However, the Dirichlet-multinomial distribution can account for un-modeled sub-population effects within the baseline stocks (e.g., Tvedebrink, Eriksen, and Morling 2015). Finally, it is possible to include a conversion matrix between assessed stocks and genetic stocks. For example, the conversion matrix in a model for North Sea cod could include Dogger, Viking, and Celtic cod in the genetic baseline. Here, genetic Dogger cod could include both an assessed Northwestern and Southern stock, genetic Viking cod would match the assessed Viking stock, while Celtic cod would not be included in the assessment, but could still contribute to the mixed samples.

6 Sharing parameters between stocks (only multi-stock)

To test assumptions about inter-stock similarities, and to reduce the number of parameters, the multi-stock SAM has an option to share parameters between stocks. In practice, this is done by forcing parameters with the same configuration keys to be equal, and can be done for any subset of the configuration.

7 Summarizing SSB and $\bar{F}$ across stocks (only multi-stock)

To summarize fishing mortality rates across stocks, full-year-combined-stock-equivalent fishing ($\tilde{F}_{a,y}$) and natural mortality ($\tilde{M}_{a,y}$) rates are calculated. The full-year, combined-stock rates are calculating by solving the equations

$$\frac{\tilde{F}_{a,y}}{\tilde{F}_{a,y}+\tilde{M}_{a,y}}\left(1-\exp(-\tilde{F}_{a,y}-\tilde{M}_{a,y})\right)\sum_s N_{a,y,s}=\sum_s C_{a,y,f,s}=u_0$$

and

$$\exp(-\tilde{F}_{a,y}-\tilde{M}_{a,y})\sum_s N_{a,y,s}=\sum_s \exp(-\sum_f F_{a,y,f,s}-M_{a,y,s})\sum_s N_{a,y,s}=v_0.$$

That is, $\tilde{F}_{a,y}$ and $\tilde{M}_{a,y}$ are defined to give the same catch and survival over a full year. The equations are solved by

$$\tilde{F}_{a,y}=\frac{\log v\cdot u}{v-1}$$

and

$$\tilde{M}_{a,y}=\frac{-(u+v-1)\cdot\log v}{v-1}$$

where $v=v_0/\sum_s N_{a,y,s}$ and $u=u_0/\sum_s N_{a,y,s}$. In turn, average fishing mortality is calculated by a simple average similar to single-stock models.

For SSB, the total SSB is calculated as the sum over stocks,

$$S\tilde{S}B_y=\sum_s SSB_{y,s}.$$

8 Other features

Both packages includes functionality for extracting several outputs and derived values in plots and tables. Further, functions are available to forecast, calculate reference points (Albertsen and Trijoulet 2020; Trijoulet et al. 2022), and calculate one-step-ahead quantile residuals (Thygesen et al. 2017). While the SAM models and packages are continuously developed as research evolves, a series of system tests ensures backwards compatibility and consistency with previous model results.

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21.3 Preparation of catch data in InterCatch for Division 6.a cod

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Introduction

This working document was written for the West of Scotland cod benchmark in 2020. Most of the text remains relevant for the WKCOD 2022–23 benchmark meeting. An additional section describing more recent changes to the data preparation is included at the end. Not all tables and figures have been updated since the 2020 benchmark.

A data call was issued in October 2019, requesting national data on landings, discards, sample information and effort (disaggregated by quarter and métier) for 2002 to 2018 to be uploaded into InterCatch (IC). The request covered a long time period to allow for the development of a time series of fleet-based catch-at-age data which could potentially be modelled separately in a stock assessment. In addition to age compositions, length compositions were also requested, to potentially get a handle on landings and discards compositions from countries without age sampling and also to inform the potential estimation of a discard ogive. (In the event, neither of these tasks have been accomplished due to issues with IC which resulted in a severe shortage of time for catch data processing).

Data in Intercatch

Total official landings by country are shown in Figure 1. The major exploiters of the Division 6a cod are UK (Scotland), France and Ireland and in some more recent years, Norway. These nations all responded to the data call as requested for 2009 onwards (there is actually no obligation under the DCMAP to submit data from earlier years) and for UK(Scotland) and Ireland for 2003 onwards. No Faroese data for any year or Norwegian data pre 2011 were uploaded by national data submitters and for these year's officially reported landings were used as ICES estimated landings and were uploaded to IC by the stock co-ordinator. Figure 2 shows total landings (L) and discards (D) data availability in IC by country. Due to a lack of Irish samples, 2002 was not considered any further and the commercial data remain unchanged for that year.) The values for 'logbook registered discards' submitted by Ireland are all zero while the 'BMS landings' submitted for 2018 are only 35kg.

Age composition data for landings and discards were provided by UK (Scotland) and Ireland for the main metiers over the time series (the exceptions being: 2006 for Ireland when there was no sampling and occasional years with no sampling of the Scottish Nephrops trawl landings which are in any case, very small). Although France have provided discard estimates for 2009 onwards, no landings or discards age compositions have been provided. All three of these countries (Ireland, UK (Scotland) and France) submitted length composition data (both landings and discards) to IC. Had there been less issues with the use of IC (relating to the area-misreporting data – see next para), further exploration of these length composition data would have taken place and the size composition of the French catches compared to those from the Irish and Scottish fisheries.

The revised estimates of area-misreporting were also uploaded to IC. At first glance, IC appears to have the ability to deal with area-misreported landings by being able to transfer specified landings from one area (stock) to another. IC input files were duly created which reallocated landings data from both the North Sea and Division 5b to Division 6a. However, once these area-misreported landings were uploaded into IC it appeared to be impossible to create discards and age compositions for the unsampled fleets (i.e. IC no longer functioned appropriately). It was not clear why this was the case and the IC developer could provide no fix or explanation. The only solution (in most years) was to use a single area from which to re-allocate the landings (and re-upload the data to IC). The area accounting for the majority of the misreported landings was used and this was typically the North Sea (or in some years Division 5b). Taking this approach results in the correct quantity of landings being reallocated to Division 6a, but potentially some of those landings being removed from an incorrect stock/area. (The area-misreported Division 6a landings are only a very small fraction of the total North Sea cod landings and therefore in practice this is likely to have little impact on the North Sea cod data).

Total catch by category imported into IC is given in Table 1. Table 2 and table 3 show imported landings (including area-misreporting) and imported discards by metier. Figure 3 shows landings by metier and country. It is clear that both the majority of landings and discards can be attributed to the OTB_DEF>=120 metier which is the large mesh trawl fishery targeting demersal fish. (OTB=Otter Trawl Bottom, DEF=Demersal Fishery, >=120 = dominant mesh size). Figure 4 shows total ICES estimated landings by reported and area-misreported components, with the misreported component becoming more important in recent years.

Sampling Coverage

Sampling coverage of the reported landings is shown in Figure 5. The proportion of reported landings (excluding area-misreported landings) which have an estimate of discards associated with them ranges from ~60 % to almost 100 %. Coverage improves when estimates are available for the French fleets from 2009 onwards. The proportion of reported landings which have age composition data associated with them ranges from ~55% to ~95%. The years with poorest age composition coverage are those where the French landings represent a relatively high proportion of the total (25–35 %).

Actually, considering this further, the area-misreported landings probably ought to be included as a sampled fleet given that samples from those trips are included in both the estimation of Scottish landings and discards age compositions. It is just the excess (estimated area-misreported) landings that have not been included when the data have been processed at the national level.

Figure 6 shows the proportion of discards imported to IC which have age compositions associated with them. Typically between 90 and 100 % of imported discards have sampled age compositions (depending on the level of French discards which are unsampled for ages).

Catch Estimation

The catch estimation in IC involved two stages: (i) allocating discard ratios to fleets for which only landings have been imported and (ii) age composition allocation by catch category (for unsampled catches). Age samples were allocated for landings and discards separately. BMS landings were combined with discards for the purpose of age composition estimation.

Discard ratios

Discards were automatically matched to landings by country, area, metier and season (year or quarter) in IC. The resulting discard-landings ratios were then used to estimate discards for landings from fleets without discard estimates. The proportions discarded by fleet and country (imported data) are shown in Figure 7. Due to the mix of both quarterly and annual data submitted for each year, strata for allocating discard rates were independent of season. With the exception of how the area-misreported landings are dealt with, the approach follows that agreed at earlier benchmarks (ICES, 2012). The strata were as follows (by year):

i) based on the analysis conducted in WD 4(Area-misreporting), the area-misreported landings are assumed to have the same discard proportion as the Scottish large mesh demersal target fleet (OTB_DEF>=120_0_0_all).

ii) other large mesh demersal target fleets were allocated a discard-landings ratio on the basis of the weighted average of all available ratios from large mesh demersal target fleets (weighted average of Scottish, Irish and French when available)

iii) small mesh fleets were allocated discard ratio on the basis of all available ratios from small mesh fleets (usually only Scottish Nephrops fleet)

iv) Longline fleets are allocated discard proportions from other longline fleets (and when not available are allocated zero discard rate as observed discard rates appear very low in comparison with other fleets).

v) all other fleets are given a weighted average of all available discard proportions

Weighting scheme used: Landings CATON

Age compositions

The allocation of age compositions to un-sampled landings and discards follows the same stratification as described for the allocation of discard ratios. The exception being the longline fleets which were included in the 'other fleets' category as there were no age composition data provided.

Data Export

Following the catch estimation process within IC, three separate IC extractions (for each year) were carried out to obtain the required stock assessment input data: i) total catch numbers-at-age and catch weights-at-age, ii) landings numbers-at-age and weights-at-age, and iii) discard numbers-at-age and weights-at-age.

Total catches exported from IC (including raised discards estimates are given in Table 4). The resulting age compositions and mean weights at age are shown in Figures 8–10. Figures 11 and 12 compare the new estimates of catch numbers- and weights-at-age with those previously used.

Updates since 2020

Since the 2020 benchmark, VMS data have been unavailable for use in the estimation of area-misreported landings. Instead, the assessment WG has had to resort to the use of estimates provided by Marine Scotland Compliance. These estimates have not been available until immediately prior to the WG meeting and after the start of WGNSSK where N Sea cod is assessed. So as not to impact the N Sea cod data (after the assessment has been run), the misreported component of the 6a catch (Scottish OTB_DEF landings and discards) were therefore adjusted outside of Intercatch without using the Intercatch misreporting feature. This will therefore result in a small amount of double accounting when adding 6a cod and N Sea cod catch data from Intercatch for the years 2019 to 2021.

Table 1. Total landings and discards imported into InterCatch (including area-misreported landings).

	Discards	Landings	Logbook Registered Discard	BMS landing
2003	47.2	1292.3	NA	0
2004	60.9	572.8	NA	0
2005	43.1	516.1	NA	0
2006	298.7	504	NA	0
2007	1054.7	514.7	NA	0
2008	481.3	561.3	0	0
2009	746.8	284.3	NA	0
2010	717.6	358.1	NA	0
2011	1739.7	341	NA	0
2012	1362.7	226.6	NA	0
2013	1225.6	265.8	NA	0
2014	1261	394.4	0	0
2015	1093.3	528.2	NA	0
2016	715.3	608.6	0	NA
2017	1410.7	675.4	0	NA
2018	691.5	990.4	NA	0.035

Table 2. Total imported landings by metier.

	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
GNS_DEF_120-219_0_0_all	13	1	6	9	14	5	1	3	3	0	0	0	0	0	0	0
LLS_FIF_0_0_0_all	1	0	0	4	0	0	0	0	0	1	22	10	54	3	14	0
MIS_MIS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MIS_MIS_0_0_0	4	2	1	1	0	0	0	0	0	0	0	0	0	0	0	0
MIS_MIS_0_0_0_HC	56	22	23	34	49	0	0	0	0	0	1	2	1	0	0	2
OTB_CRU_70-99_0_0_all	125	51	29	25	43	32	9	5	8	9	6	5	6	8	9	3
OTB_DEF_>=120_0_0	3	0	0	0	0	0	0	36	22	3	3	3	10	57	99	101
OTB_DEF_>=120_0_0_all	766	348	304	315	256	305	154	230	231	192	219	360	436	456	507	824
OTB_DEF_100-119_0_0	96	57	83	71	64	75	44	10	23	3	1	3	4	11	11	4
OTB_DEF_100-119_0_0_all	124	35	29	18	67	46	26	48	41	17	13	11	16	26	18	12
OTB_DWS_>=120_0_0_all	0	0	0	0	0	0	0	2	2	0	0	0	0	17	12	6
OTB_DWS_100-119_0_0_all	12	9	9	5	7	6	19	2	1	0	0	0	0	0	0	1
OTM_DEF_100-119_0_0_all	42	32	20	7	4	3	5	0	0	0	0	0	0	0	0	0
OTT_DEF_100-119_0_0	47	16	12	10	9	15	6	0	2	0	0	0	0	3	3	0
SSC_DEF_100-119_0_0_all	1	0	0	0	0	8	0	0	0	1	0	0	1	2	0	0
TBB_DEF_70-99_0_0_all	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
OTB_DEF_70-99_0_0_all	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
GNS_DEF_all_0_0_all	0	0	0	0	0	0	0	0	0	0	0	0	0	26	0	0
LLS_DEF	0	0	0	6	0	0	0	0	0	0	0	0	0	0	1	33
TBB_DEF_>=120_0_0_all	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C-Allgears	0	0	0	0	0	67	18	20	8	0	0	0	0	0	0	0
OTB_MCD_70-99_0_0_all	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
OTB_MOL_70-99_0_0_all	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FPO_CRU_0_0_0_all	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LLS_DEF_0_0_0_all	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
OTB_CRU_100-119_0_0_all	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
OTB_SPF_32-69_0_0_all	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
PTM_SPF_32-69_0_0_all	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
OTB_DEF	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4

Table 3. Total imported discards by metier.

	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
GNS_DEF_120-219_0_0_all	NA	NA	NA	NA	NA	NA	0	NA	23	NA	NA	NA	NA	0	0	NA
LLS_FIF_0_0_0_all	NA	NA	NA	NA	NA	NA	NA	NA	NA	0	NA	NA	NA	0	0	NA
MIS_MIS	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
MIS_MIS_0_0_0	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0	NA
MIS_MIS_0_0_0_HC	0	0	0	0	NA	NA	NA	NA	NA	NA	NA	NA	NA	0	0	NA
OTB_CRU_70-99_0_0_all	12	25	30	83	169	10	105	172	177	305	380	147	226	275	234	72
OTB_DEF_>=120_0_0	NA	NA	NA	NA	NA	NA	NA	8	5	25	13	29	40	32	31	25
OTB_DEF_>=120_0_0_all	14	31	7	216	882	455	592	537	1533	1005	802	1079	792	392	1138	588
OTB_DEF_100-119_0_0	NA	NA	NA	NA	NA	NA	47	0	1	17	0	4	32	0	0	0
OTB_DEF_100-119_0_0_all	21	5	7	NA	4	16	1	1	1	12	21	0	1	15	8	4
OTB_DWS_>=120_0_0_all	NA	NA	NA	NA	NA	NA	NA	NA	0	NA	0	NA	NA	0	0	NA
OTB_DWS_100-119_0_0_all	0	0	NA	NA	NA	NA	NA	NA	0	0	NA	NA	NA	0	0	NA
OTM_DEF_100-119_0_0_all	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0
OTT_DEF_100-119_0_0	NA	NA	NA	NA	NA	NA	2	NA	NA	NA	0	1	1	0	0	NA
SSC_DEF_100-119_0_0_all	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0	0	NA
TBB_DEF_70-99_0_0_all	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0	NA	NA
OTB_DEF_70-99_0_0_all	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
GNS_DEF_all_0_0_all	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0	NA	NA
LLS_DEF	NA	NA	NA	NA	NA	NA	NA	NA	0	NA	NA	1	2	1	1	2
TBB_DEF_>=120_0_0_all	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
C-Allgears	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
OTB_MCD_70-99_0_0_all	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
OTB_MOL_70-99_0_0_all	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	9	NA	NA	NA	NA	NA
FPO_CRU_0_0_0_all	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0	NA
LLS_DEF_0_0_0_all	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0	NA
OTB_CRU_100-119_0_0_all	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0	NA
OTB_SPF_32-69_0_0_all	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0	NA
PTM_SPF_32-69_0_0_all	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0	NA
OTB_DEF	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

Table 4. Total catch, landings & discards in tonnes (after allocation of discards in IC).

	catch	landings	discards	bms
2003	1352.7	1292.3	60.4	NA
2004	650.7	572.8	77.9	NA
2005	570.4	516.1	54.3	NA
2006	965.2	504.1	461.0	NA
2007	2165.6	514.7	1650.9	NA
2008	1598.1	561.3	1036.8	NA
2009	1571.7	284.3	1287.4	NA
2010	1932.8	358.1	1574.7	NA
2011	4207.6	341.0	3866.5	NA
2012	2140.8	226.6	1914.2	NA
2013	2136.2	265.8	1870.4	NA
2014	3763.6	394.4	3369.2	NA
2015	3026.5	528.2	2498.2	NA
2016	2108.0	608.6	1499.4	NA
2017	4194.8	675.4	3519.4	NA
2018	3419.0	990.4	2428.6	0.035

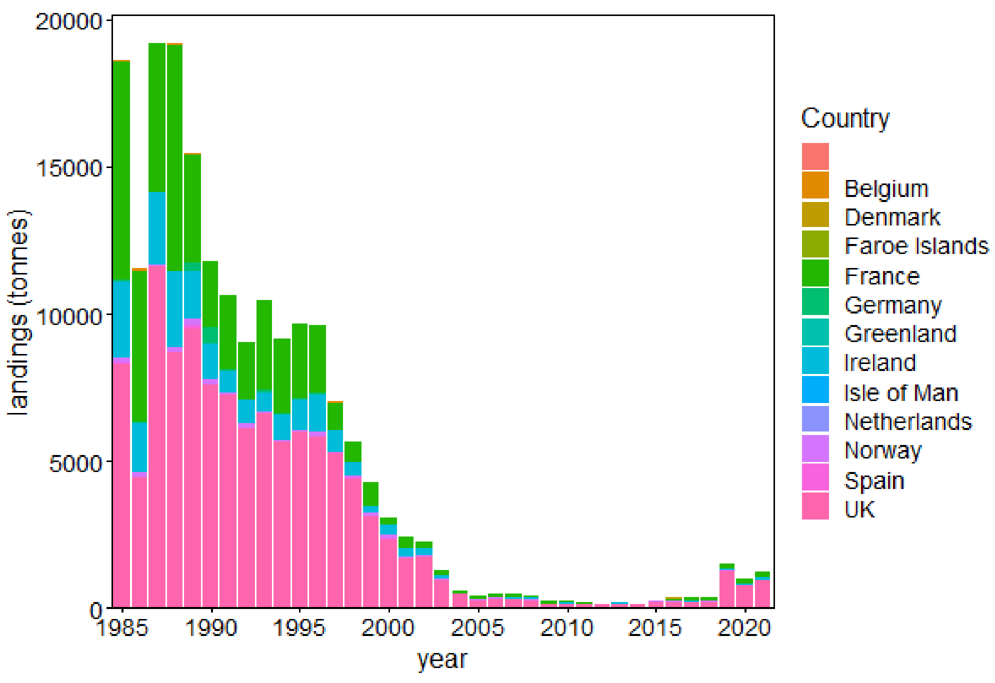

Figure 1. Official landings of Division 6a cod by country.

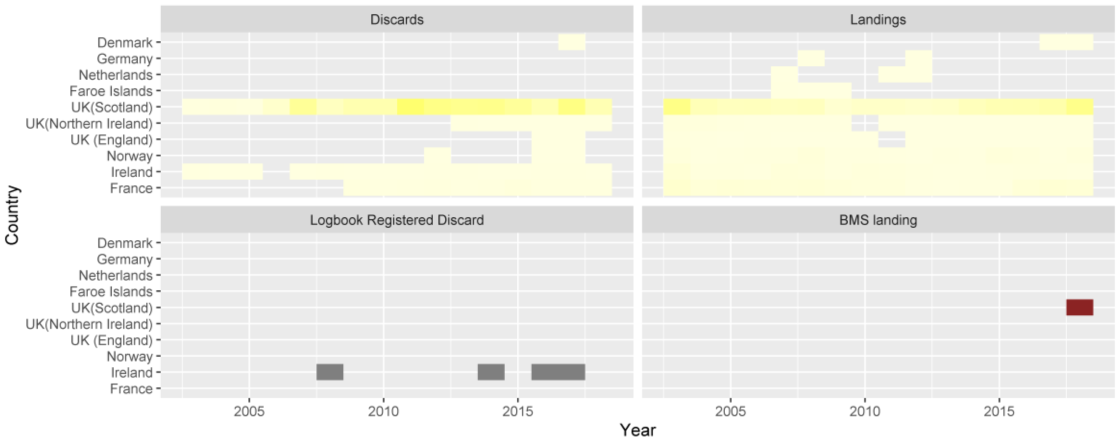

Figure 2. Catch imported to InterCatch by catch category and country (darker yellow shading represents larger quantities).

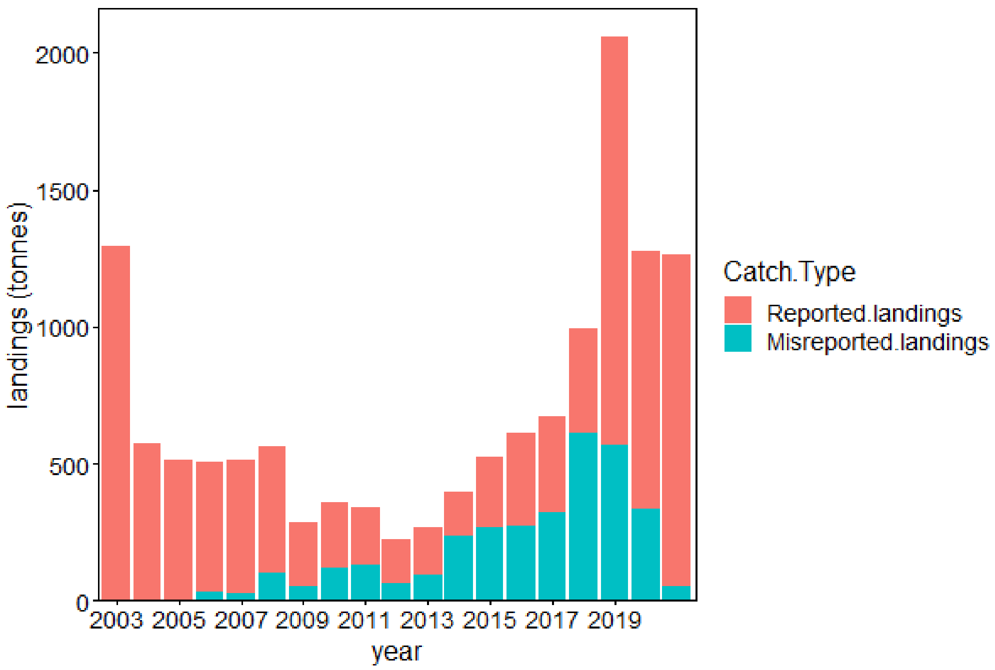

Figure 3. Total estimated landings by reporting category.

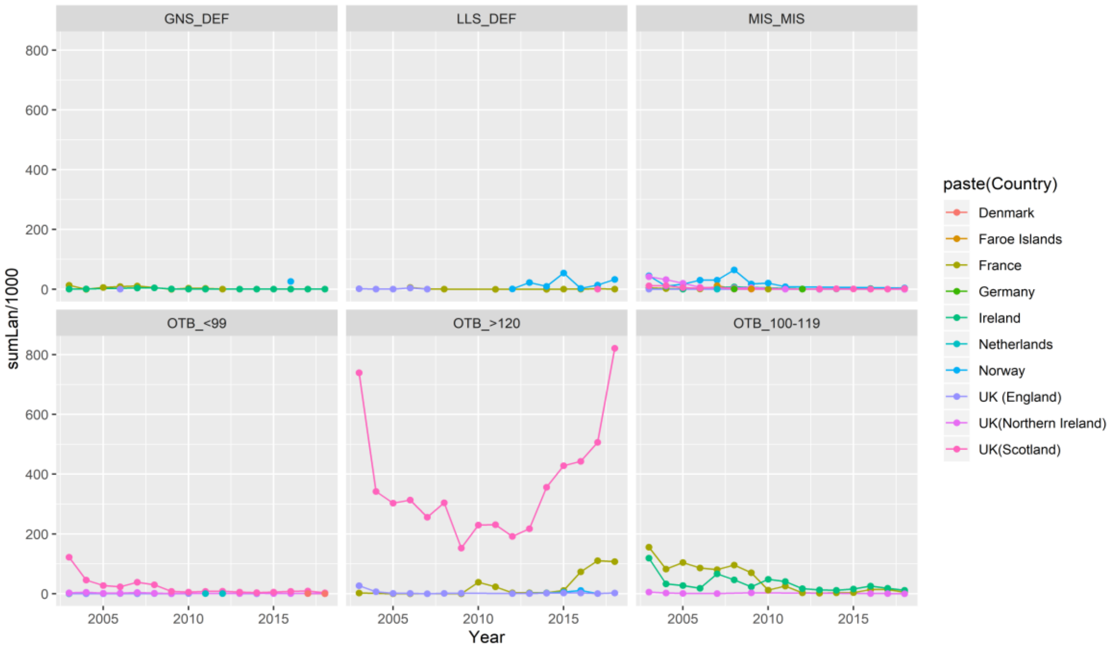

Figure 4. Imported landings by metier and country.

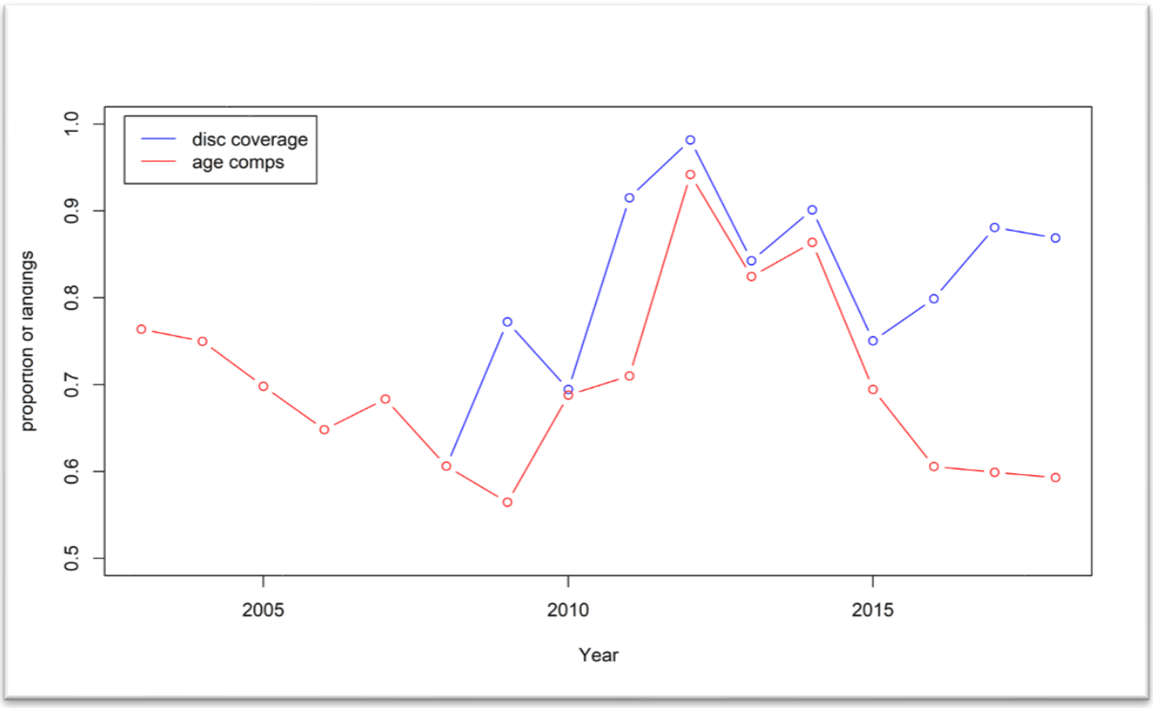

Figure 5. Proportion of reported landings in InterCatch (excluding area-misreported landings) for which i) an estimate of discards is available (blue) and ii) age composition data are available.

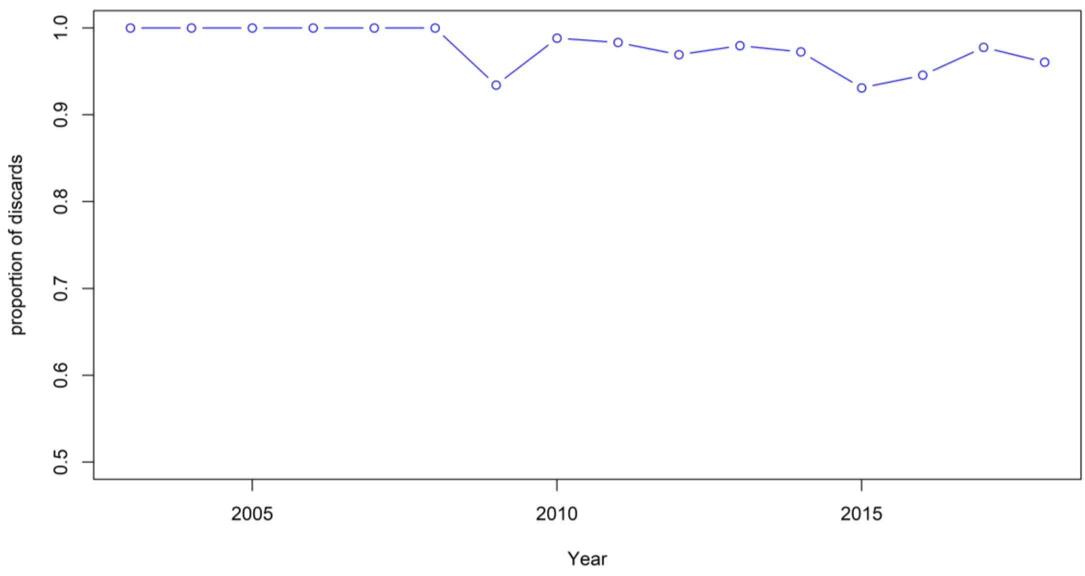

Figure 6. Proportion of imported discards with associated age composition data.

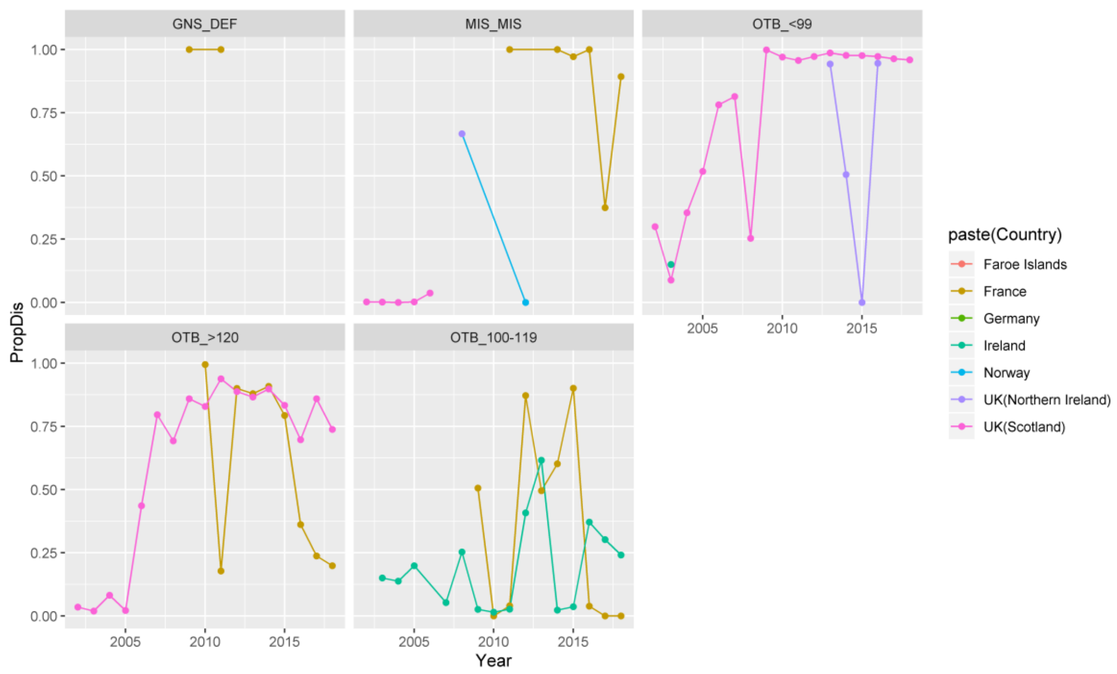

Figure 7. Discard rate by metier and country (data imported into InterCatch).

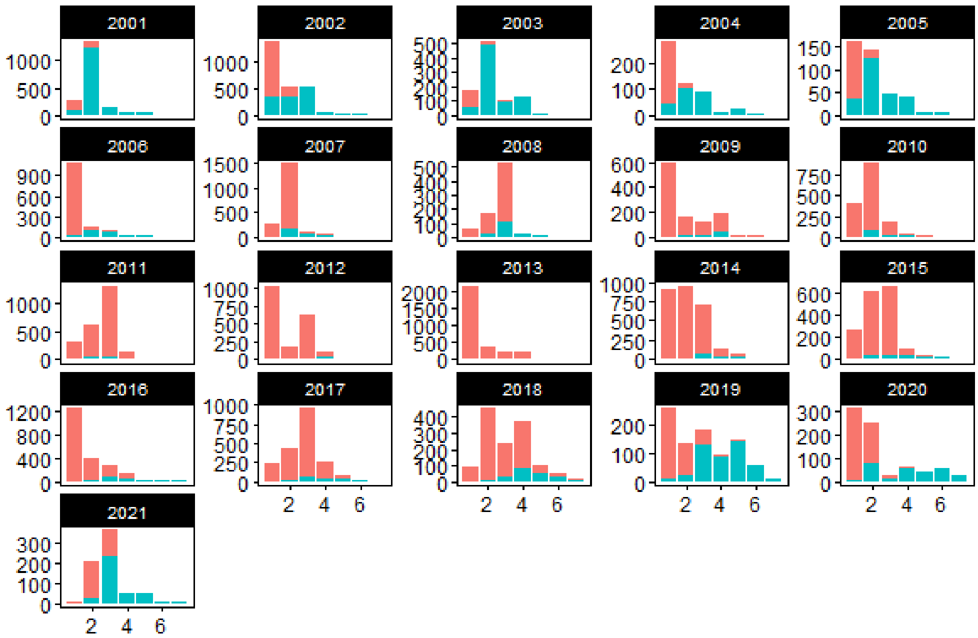

Figure 8. Landings and discards numbers at age. Red =discards, blue = landings.

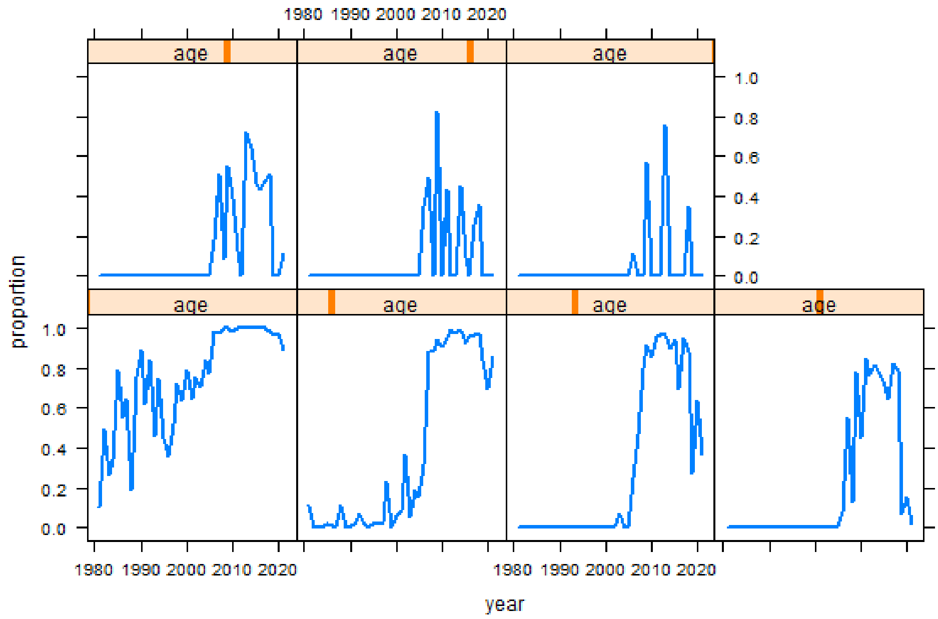

Figure 9. Proportion discarded at age.

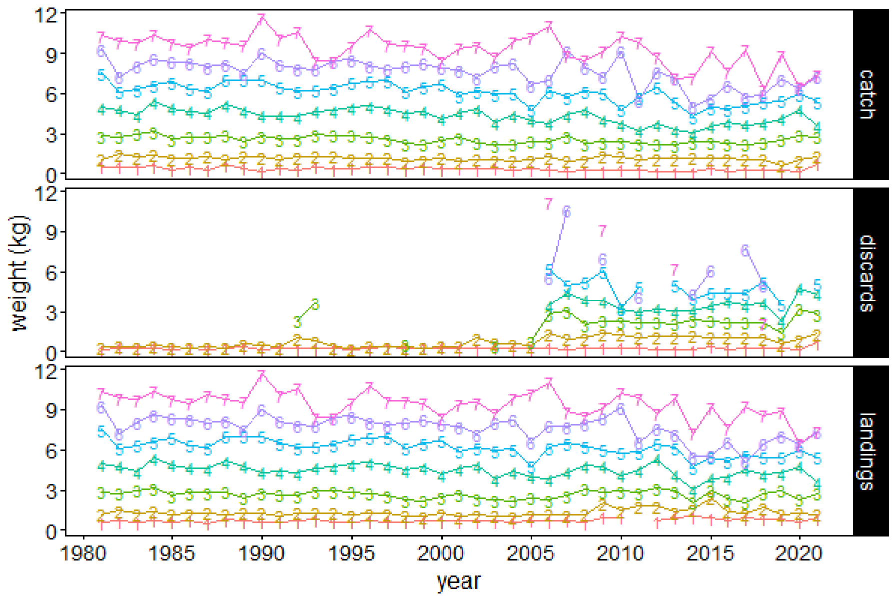

Figure 10. Mean weights at age in the landings and discards.

Figure 11. Comparison between log catch numbers-at-age used at WGCSE2019 and those estimated for WKDEM 2020.

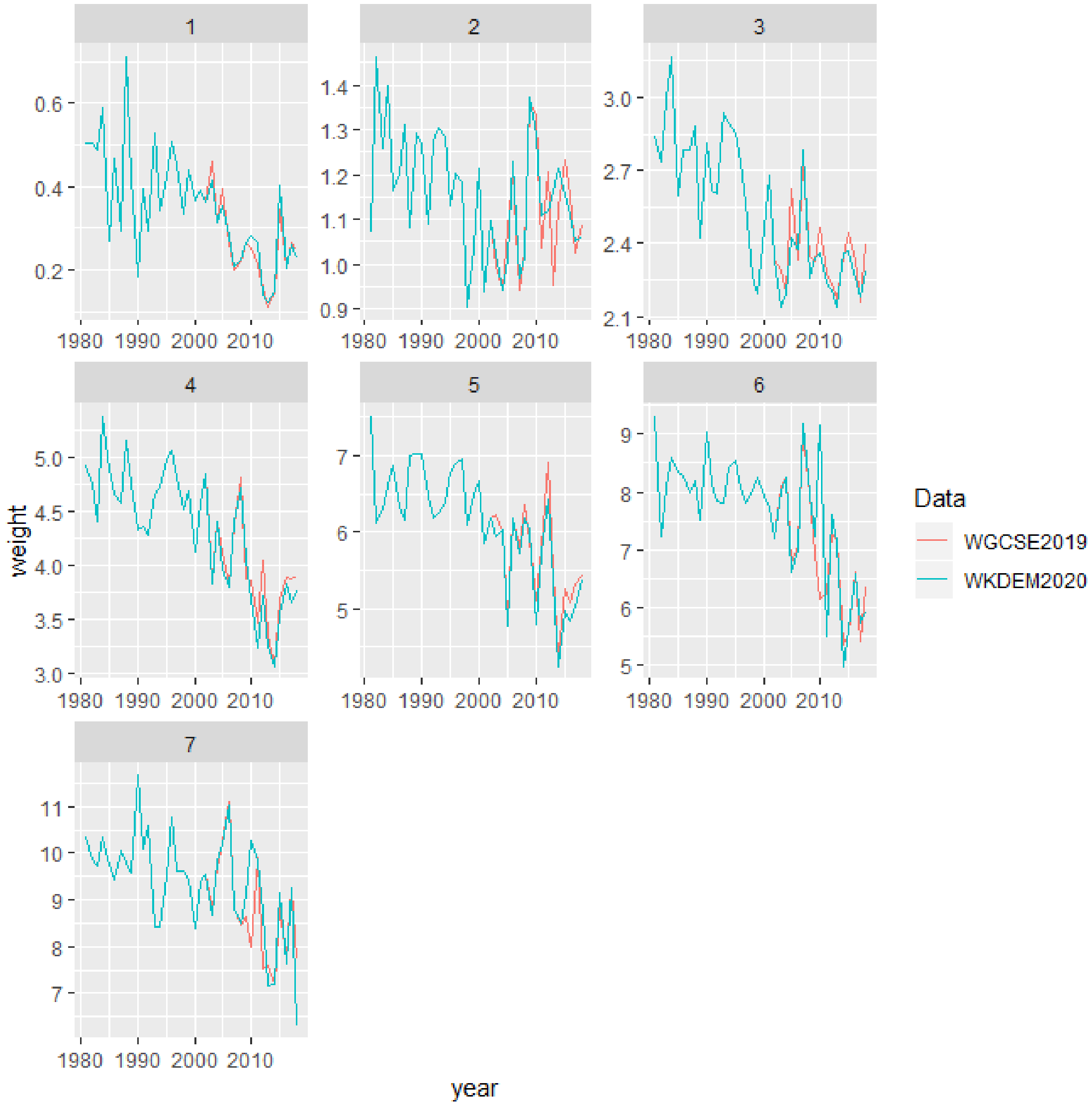

Figure 12. Comparison between catch weights-at-age used at WGCSE2019 and those estimated for WKDEM 2020.

21.4 WD 3 Summary of InterCatch data for North Sea cod

Nicola D. Walker and many others

Introduction

Based on the conclusions of the ICES Workshops on Stock Identification of North Sea Cod (WKNSCodID; ICES 2020) and West of Scotland Sea Cod (WK6aCodID; ICES 2022) the data call for WKCOD 2023 requested national landings data disaggregated by year, quarter, cod area and ICES rectangle, to consider a substock approach to stock assessment. Given no discards or age data were requested, the idea is to investigate the possibility to use the new disaggregated landings to portion the existing catch data for Northern Shelf cod into substocks based on cod area. The proposed Northern Shelf cod stock consists of the North Sea cod stock and West of Scotland cod stock. This document describes the raising procedures for the North Sea stock, which have been in place since 2015 (ICES, 2015).

Catch data for 2002–2021

InterCatch was used for estimation of landings age composition, as well as the estimation of both discards numbers and age composition. Each year, data co-ordinators input data for their nation into InterCatch, disaggregated by area (4, 3.a.20 and 7.d), quarter and métier. The data from Norway excludes Norwegian coastal cod. Tables 1–2 and Figure 1 summarise the data that have been imported into InterCatch while Table 3 indicates the level of discard ratio coverage of the landings, together with the age coverage of both the landings and observed discards. Allocations of discard ratios and age compositions for unsampled strata are then performed to obtain the data required for the assessment.

The approach used for discard ratio allocations is to do it by area (4, 3.a.20 and 7.d) and treat FDF métiers separately (note, FDF métiers were not available prior to 2009 and there have been very few FDF métiers since termination of the cod specific FDF scheme at the end of 2016), giving six broad categories (only three prior to 2009 and from 2017). Annual discards are first matched to quarterly landings. Then, within each of these six categories, ignoring country and season, where métiers have adequate samples these are pooled and allocated to unsampled records within that métier; this is done only for the most important métiers (those with greater than 1% of the landings in Subarea 4, 2.5% in Subdivision 3.a.20, and 5% in Division 7.d). At the end of this process, any remaining métiers are allocated an all-samples pooled discard ratio for the given area. Because no discard sampling was available for area 7.d in 2002–3, and only minimal age-sampling, areas 4 and 7.d were combined in these years. Table 4 shows the volumes and proportions of discards that were either imported to InterCatch or raised.

A similar approach is used for allocating age compositions, except that there are 12 broad categories (only six prior to 2009 and from 2017) because discards are treated separately to landings. Since 2017, there has been no sampling of discards in 7.d, so discard age allocations were based on Subarea 4. Table 5 shows the volumes and proportions of landings, discards and BMS landings either input with age distributions or with age distributions estimated following the allocation scheme.

The final estimates of landings, discards (including BMS landings) and catches for 2002–2021 are shown in the total columns of Table 4 while Figures 2–3 show the catches (split into landings and discards) and mean weights that form the basis of the assessment.

The InterCatch raising procedure is a laborious one for NS cod, each year taking anything from 1.5 to 4 hours to complete (depending on number of strata and difficulties encountered). Furthermore, it is currently not possible to save the discard ratio allocations (although age allocations can be saved) – this, combined with the length of time for raising, makes simple sensitivity testing difficult to achieve in InterCatch.

Changes to management

Since the benchmark in 2015 (ICES, 2015) there have been several changes to management that may affect catches of North Sea cod and the subsequent raising of catch data (see Stock Annex for details of the below measures):

- The Scottish Conservation Credits scheme was suspended on 20 November 2016.
- The cod specific FDF scheme was terminated at the end of 2016. While some FDF métiers still report catches of North Sea cod, it is no longer possible to allocate discard ratios and ages separately as there has been no sampling of these métiers.
- The days-at-sea regulation, which was part of the cod recovery plan (EC 1342/2008), was discontinued in 2017 (EC 2094/2016).
- Cod is under the EU landing obligation, and Norway and UK national legislation regulating discards. The landing obligation introduced two new catch categories to InterCatch: BMS landing and Logbook Registered Discard. So far, all logbook registered discards uploaded to InterCatch have been zero. BMS landings uploaded to InterCatch are currently negligible (Table 1) and are raised with discards as unwanted catch.

References

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ICES. 2020. Workshop on Stock Identification of North Sea Cod (WKNSCodID). ICES Scientific Reports. 2:89. 82 pp. http://doi.org/10.17895/ices.pub.7499

ICES. 2022. Workshop in Stock Identification of West of Scotland Sea Cod (WK6aCodID; outputs from 2021 meeting). ICES Scientific Reports. 4:5. 24 pp. http://doi.org/10.17895/ices.pub.10031

Table 21.1: Imported landings, discards and BMS landings by area.

	27.4				27.3.a.20				27.7.d				Total			
Year	Landings	Discards	BMS	%Discards	Landings	Discards	BMS	%Discards	Landings	Discards	BMS	%Discards	Landings	Discards	BMS	%Discards
2002	42193	3184		7.0	6854	3041		30.7	3139			0.0	52187	6224		10.7
2003	24083	1682		6.5	3979	816		17.0	2131			0.0	30194	2498		7.6
2004	22529	2454		9.8	3914	2295		37.0	1014	19		1.8	27457	4767		14.8
2005	22855	3078		11.9	3998	2809		41.3	1259	33		2.6	28113	5920		17.4
2006	21078	3681		14.9	3258	3884		54.4	1479	34		2.2	25815	7599		22.7
2007	19056	13496		41.5	3020	3467		53.4	2147	93		4.2	24223	17056		41.3
2008	21657	13252		38.0	3393	1623		32.4	1629	250		13.3	26679	15125		36.2
2009	27634	7742		21.9	3794	2614		40.8	1887	3701		66.2	33315	14057		29.7
2010	30980	7496		19.5	4057	1660		29.0	1708	279		14.0	36746	9435		20.4
2011	26675	4782		15.2	3956	1656		29.5	1319	375		22.1	31950	6813		17.6
2012	26627	4523		14.5	4327	1561		26.5	1120	80		6.7	32074	6164		16.1
2013	25315	6329		20.0	4154	1310		24.0	916	97		9.6	30386	7737		20.3
2014	28550	5170		15.3	4687	1701		26.6	1436	526		26.8	34673	7398		17.6
2015	31244	7587		19.5	4563	2315		33.7	1398	16		1.1	37205	9918		21.0
2016	33035	8514	10	20.5	4774	1318	0.00	21.6	421	56		11.8	38230	9888	10	20.6
2017	33109	6781	16	17.0	4715	663	0.00	12.3	170	5	0.00	3.0	37994	7449	16	16.4
2018	34444	5387	26	13.6	5484	785	0.49	12.5	84	0		0.0	40012	6172	26	13.4
2019	28558	2463	30	8.0	3478	288	0.00	7.7	36	0		0.1	32072	2751	30	8.0
2020	17192	1800	21	9.6	2299	887	0.00	27.8	32	0	0.03	0.1	19523	2687	21	12.2
2021	12737	2040	2	13.8	2017	469	0.00	18.9	37	0	0.00	1.0	14791	2509	2	14.5

Table 21.2: Imported landings and discards (including BMS landings from 2016) by country. Countries reporting < 1 tonne are excluded.

Year	Belgium	Denmark	Faroe Islands	France	Germany	Netherlands	Norway	Sweden	UK (England)	UK(Scotland)
Imported landings										
2002	2673	15049		4919	2095	4114	3639	1336	3222	15140
2003	1538	8050		2555	1985	2070	3324	749	2319	7604
2004	1673	9292		1143	2216	1574	2418	721	1980	6440
2005	1774	9674		1520	2649	1509	2160	795	1452	6579
2006	1389	7919		1506	2551	1469	1903	681	1759	6637
2007	1086	5932		2508	1974	1529	2405	758	1627	6403
2008	1037	6635	16	2144	1792	1916	3681	804	1691	6963
2009	943	7788	44	3281	2439	2650	3756	837	2125	9452
2010	741	9318	32	2026	2927	2670	3963	822	1855	12393
2011	712	8285		1704	2283	2005	3746	796	1488	10930
2012	905	8287		1322	2462	1873	3939	991	1222	11072
2013	1124	7839		1013	1989	1140	3617	860	815	11988
2014	1324	9190		1865	2341	1300	4055	969	967	12663
2015	1302	9647		1693	2221	1389	4921	994	1414	13625
2016	1145	10494		666	2177	1392	5186	1014	757	15398
2017	712	10082		484	2381	655	5145	947	397	17191
2018	825	10008		602	1596	556	5347	948	351	19780
2019	726	7911		462	864	738	4683	702	213	15771
2020	696	5038		275	779	591	2425	579	167	8974
2021	536	3718		292	798	615	1726	636	160	6309
Imported discards (including BMS)										
2002		3867			76			293	492	1496
2003		1144			32			67	197	1058
2004	116	1930			318			837	297	1270
2005	253	3106			71			1191	156	1143
2006	705	4259			33			583	376	1644
2007	273	4355			25			273	214	11916
2008	1502	1588	13		39			420	495	11068
2009	246	2955	20	3663	17			282	130	6744
2010	108	1915		259	69			170	246	6669
2011	12	1722		43	290	242		158	397	3949
2012	11	1570		68	29	162		285	525	3513
2013	407	1290		90	10	128		440	89	5282
2014	104	1186		438	52	54		782	236	4546
2015	59	2102		4	9	170		531	81	6960
2016	214	1486		37	4	13	10	259	109	7764
2017	8	798		17	16	11	16	78	30	6493
2018	2	778		20	16	13	6	151	11	5201
2019	26	376		4	5	37		27	37	2268
2020	136	1061		1	5	35		4	4	1464
2021	65	456		2	7	24		96	6	1855

Table 21.3: Proportion of landings (as a percentage) taken in each of the three areas together with discard ratio coverage of the landings, age coverage of the landings and age coverage of the observed discards. Shaded cells indicate where there has been less than 50% coverage.

	Landings proportions (%)			Discard ratio coverage			Landings age coverage			Discards age coverage		
Year	4	3.a.20	7.d	4	3.a.20	7.d	4	3.a.20	7.d	4	3.a.20	7.d
2002	81	13	6.0	50%	73%	0%	64%	83%	0%	88%	69%	0%
2003	80	13	7.1	57%	67%	0%	59%	93%	3%	88%	42%	0%
2004	82	14	3.7	54%	67%	6%	68%	93%	7%	81%	94%	100%
2005	81	14	4.5	58%	55%	5%	75%	91%	4%	81%	82%	100%
2006	82	13	5.7	75%	66%	6%	77%	91%	14%	85%	96%	100%
2007	79	12	8.9	58%	60%	5%	71%	90%	11%	99%	92%	100%
2008	81	13	6.1	65%	59%	10%	73%	89%	16%	95%	100%	100%
2009	83	11	5.7	57%	85%	81%	72%	95%	80%	97%	93%	100%
2010	84	11	4.6	70%	77%	81%	80%	95%	84%	100%	90%	100%
2011	83	12	4.1	75%	83%	74%	72%	95%	74%	93%	90%	100%
2012	83	13	3.5	70%	79%	77%	79%	88%	81%	96%	89%	100%
2013	83	14	3.0	76%	75%	78%	82%	88%	81%	92%	96%	97%
2014	82	14	4.1	69%	75%	83%	78%	90%	84%	99%	100%	100%
2015	84	12	3.8	72%	75%	83%	80%	89%	86%	95%	97%	100%
2016	86	12	1.1	72%	75%	71%	82%	92%	51%	97%	79%	88%
2017	87	12	0.4	74%	84%	57%	82%	69%	37%	100%	100%	0%
2018	86	14	0.2	75%	81%	51%	87%	93%	17%	99%	96%	0%
2019	89	11	0.1	75%	76%	43%	88%	96%	39%	98%	98%	0%
2020	88	12	0.2	72%	49%	44%	73%	92%	0%	98%	100%	0%
2021	86	14	0.2	55%	69%	71%	76%	95%	54%	95%	93%	0%

Table 21.4: The volumes (and associated proportion) of landings, discards and BMS landings that were imported or raised.

	Wanted	Unwanted					Total	Discard
Year	Landings	Imported	Raised	%Raised	BMS	Total	catch	rate
2002	52187	6224	5686	47.7		11911	64098	18.6
2003	30194	2498	1583	38.8		4081	34274	11.9
2004	27457	4767	4035	45.8		8802	36259	24.3
2005	28113	5920	4167	41.3		10087	38200	26.4
2006	25815	7599	4412	36.7		12011	37826	31.8
2007	24223	17056	13394	44.0		30450	54673	55.7
2008	26679	15125	9955	39.7		25080	51759	48.5
2009	33315	14057	6907	32.9		20965	54280	38.6
2010	36746	9435	3054	24.5		12488	49234	25.4
2011	31950	6813	1932	22.1		8745	40695	21.5
2012	32074	6164	2526	29.1		8689	40763	21.3
2013	30386	7737	2588	25.1		10324	40710	25.4
2014	34673	7398	3268	30.6		10666	45339	23.5
2015	37205	9918	2645	21.1		12562	49767	25.2
2016	38230	9888	2417	19.6	10	12315	50544	24.4
2017	37994	7449	1266	14.5	16	8731	46725	18.7
2018	40012	6172	1626	20.8	26	7824	47836	16.4
2019	32072	2751	826	22.9	30	3607	35679	10.1
2020	19523	2687	1992	42.4	21	4701	24224	19.4
2021	14791	2509	1281	33.8	2	3792	18583	20.4

Table 21.5: The volumes (and associated proportion) of landings, discards and BMS landings with age distributions sampled or estimated.

	Landings			Discards				BMS			Total		
Year	Sampled	Estimated	%Estimated	Sampled	Estimated	Raised	%Estimated	Sampled	Estimated	%Estimated	Sampled	Estimated	%Estimated
2002	32859	19328	37.0	4900	1324	5686	58.9				37759	26338	41.1
2003	17887	12307	40.8	1829	669	1583	55.2				19716	14558	42.5
2004	19063	8394	30.6	4175	593	4035	52.6				23238	13022	35.9
2005	20711	7402	26.3	4810	1110	4167	52.3				25521	12679	33.2
2006	19402	6412	24.8	6885	714	4412	42.7				26287	11539	30.5
2007	16536	7687	31.7	16680	376	13394	45.2				33216	21457	39.2
2008	19164	7515	28.2	14495	630	9955	42.2				33659	18101	35.0
2009	25098	8217	24.7	13644	414	6907	34.9				38742	15538	28.6
2010	30228	6518	17.7	9238	196	3054	26.0				39466	9768	19.8
2011	23815	8135	25.5	6294	519	1932	28.0				30109	10586	26.0
2012	25821	6253	19.5	5798	366	2526	33.3				31619	9144	22.4
2013	25299	5087	16.7	7106	630	2588	31.2				32405	8305	20.4
2014	27838	6835	19.7	7336	62	3268	31.2				35174	10165	22.4
2015	30134	7071	19.0	9467	451	2645	24.6				39601	10166	20.4
2016	31948	6281	16.4	9353	535	2417	24.0	0.0	10.1	100.0	41301	9243	18.3
2017	30785	7209	19.0	7422	28	1266	14.8	0.0	16.1	100.0	38207	8518	18.2
2018	36434	3578	8.9	6104	68	1626	21.7	0.8	25.4	96.9	42539	5297	11.1
2019	28565	3507	10.9	2697	54	826	24.6	29.7	0.3	1.0	31292	4388	12.3
2020	14665	4859	24.9	2645	41	1992	43.5	21.3	0.2	0.9	17331	6893	28.5
2021	11582	3209	21.7	2364	145	1281	37.6	0.0	2.0	100.0	13946	4637	25.0

Figure 21.1: Imported landings and discards (including BMS landings from 2016) by country.

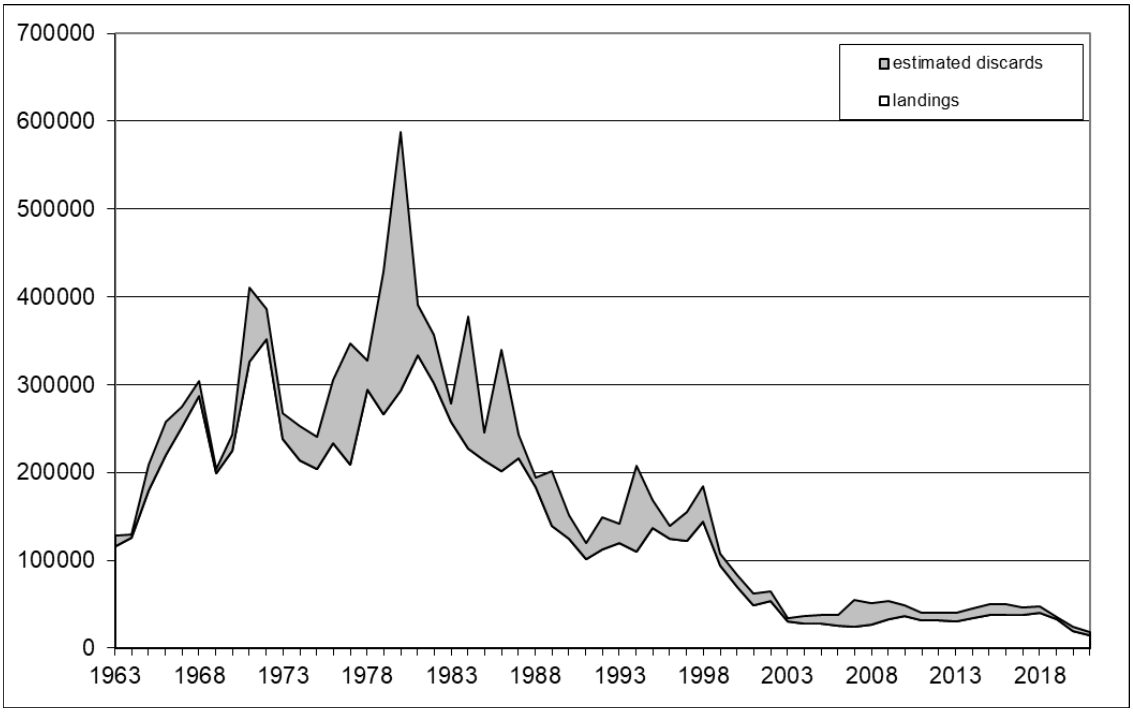


Figure 21.2: Stacked area plot of reported landings and estimated discards (including BMS landings; in tonnes).

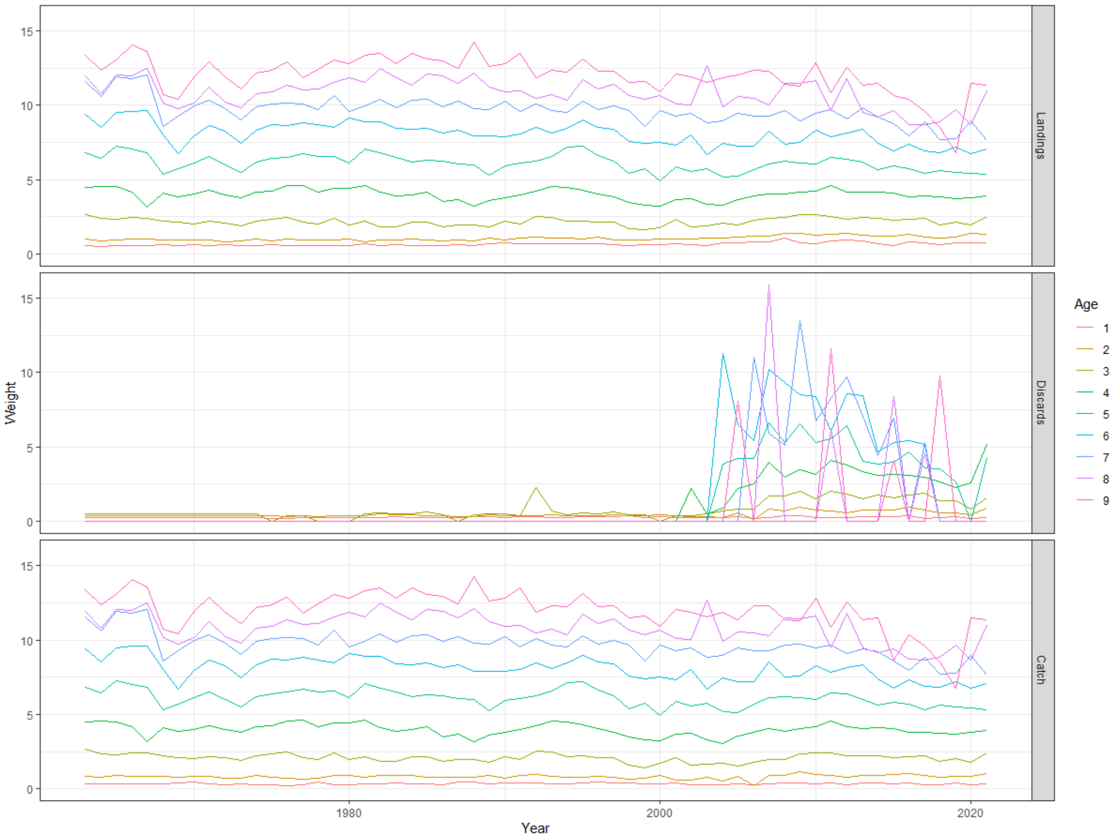


Figure 21.3: Mean weights-at-age in the landings, discards and catch.

21.5 Spatial landings

Summary of commercial landings data for Northern Shelf cod: WKCOD 2023

Alex Holdgate and Helen Dobby

2022-11-10

Contents

1 Summary

Following the recommendations of the two ICES workshops on stock identification for North Sea cod (WKNSCodID, 2020) and West of Scotland Sea cod (WK6aCodID, 2021), the data call for the ICES benchmark of Northern Shelf cod (WKCOD 2023) requested commercial and recreational landings data for cod in ICES subarea 27.4, divisions 27.6a and 27.7d, and subdivision 27.3a.20 split by the proposed sub-stock areas: Northwestern, Southern and Viking with a further split of the Northwestern sub-stock into inshore and offshore components where possible.

This working document considers the commercial landings data only, where comparisons are made between the data received through Accessions in response to the data call and the commercial landings data available in InterCatch for the current stock assessments of North Sea cod (cod.27.47d20) and West of Scotland cod (cod.27.6a).

1.1 Accessions submissions

A general summary of the data submitted to Accessions is given in Table 1. Data were received from eleven ICES Member Countries (Belgium, Denmark, England (UK), France, Germany, Ireland, Netherlands, Northern Ireland (UK), Norway, Scotland (UK) and Sweden), with each submitting a time series of:

- Commercial landings by year, quarter, cod sub-stock area and ICES rectangle
- Recreational landings by year, ICES area, and cod sub-stock area

Data were requested for the period 1995 - 2021. Four countries have submitted data that do not cover the complete time period (Belgium, France, the Netherlands and Northern Ireland). All countries have submitted data by quarter, with only Ireland missing Q4 data in 2008. Data that are available in InterCatch but missing in the Accessions submissions include Belgian data for 2002 - 2005 and Irish data for 2011 - 2013.

Table 1: Descriptive summary of Accessions submissions for WKCOD 2023. The columns 'Missing Quarters' and Missing Years' refer to data that are available in InterCatch but missing in the Accessions submissions

Country	Year Range	Quarters	Missing Quarters	Missing Years
Belgium	2006 - 2021	Y	-	2002 - 2005
Denmark	1995 - 2021	Y	-	-
France	2000 - 2021	Y	-	-
Ireland	1995 - 2021	Y	2008 (Q4)	2011 - 2013
Germany	1995 - 2021	Y	-	-
Netherlands	1997 - 2021	Y	-	-
Norway	1995 - 2021	Y	-	-
Sweden	1995 - 2021	Y	-	-
UK (England)	1995 - 2021	Y	-	-
UK(Northern Ireland)	2000 - 2021	Y	-	-
UK(Scotland)	1995 - 2021	Y	-	-

2 Comparison of commerical landings data: InterCatch vs. Accessions

In the following section, a comparison between Accessions submissions and landings data available in InterCatch is provided for the two current cod stock assessment areas (i.e. West of Scotland & the North Sea) as well as the combined Northern Shelf cod stock assessment area.

2.1 West of Scotland cod (Cod.27.6a)

Figure 1 compares the total landings submitted to InterCatch vs. the total landings submitted to Accessions for the West of Scotland cod stock (i.e. division 27.6a). InterCatch data are available for this stock from 2003 onwards. InterCatch values are generally higher than Accessions submissions for cod in division 27.6a, and this is mostly due to the estimates of area-misreporting that are included in the InterCatch data but not in the Accessions submissions. There are also missing Irish landings (from accessions) in some years and low Norwegian landings in some years, but these both represent a very small amount of the total.

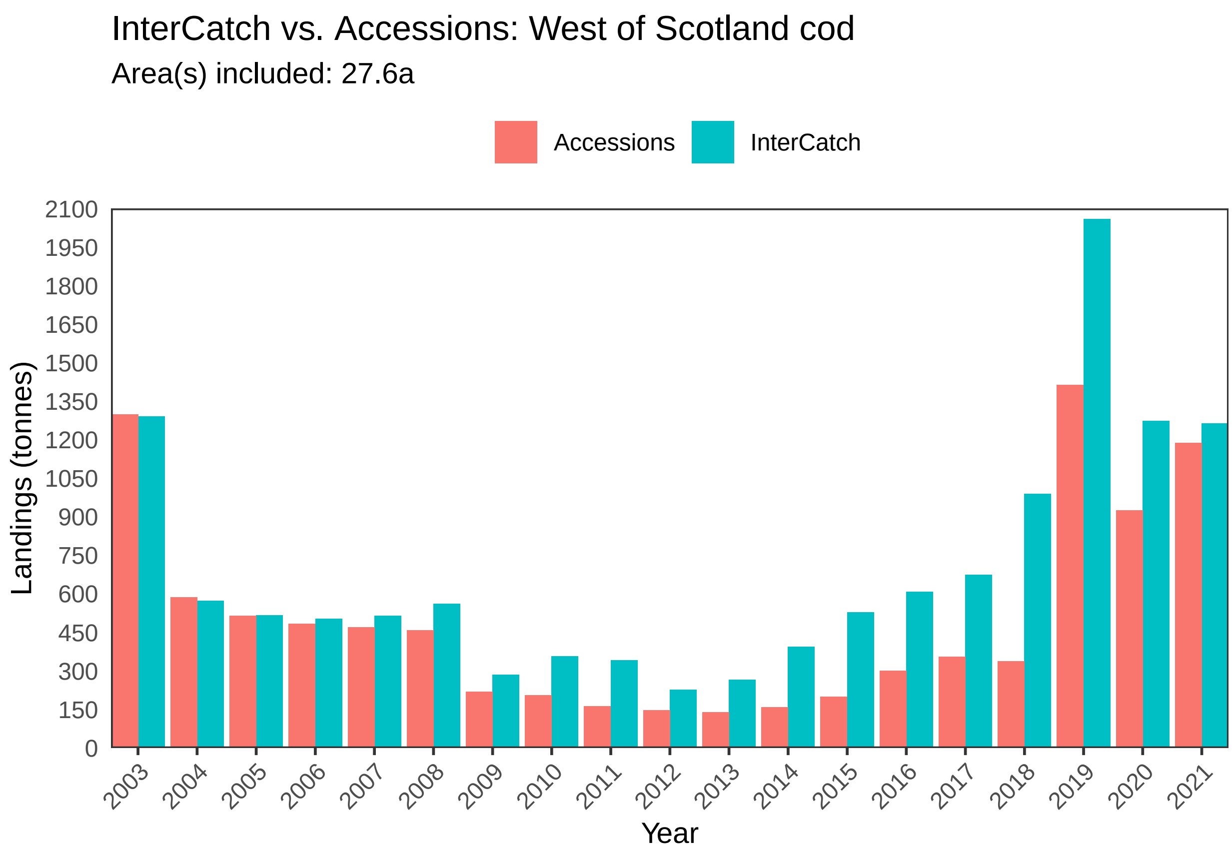


Figure 1: Total landings submitted to InterCatch (blue) vs. Accessions (red) for cod in division 27.6a (West of Scotland)

2.1.1 Area-misreporting of cod in division 27.6a

Since the introduction of legislation making under-reporting of landings more difficult in 2006, area-misreported landings by the Scottish fleet represent a considerable proportion of the total landings for cod.27.6a. Area-misreporting refers to catches taken in division 6a which are reported as taken in division 4a (or sub-area 5). Consequently, the reported landings of 6a are assumed lower than the true landings. During the 2020 benchmark, a more objective approach for estimating area-misreported landings was developed using Vessel Monitoring System (VMS) data linked to logbook data for the period 2006 - 2021.

The InterCatch values for cod.27.6a have been adjusted to include estimates of area-misreporting for the period 2006 - 2018 using the 'misreporting' facility in InterCatch. From 2019 onwards, estimates of area-misreporting have not been received in time for the working group meeting (WGNSSK). To account for this, estimates of area-misreporting have been incorporated into the 'reported' landings data category for these years so as not to affect completed assessments by altering InterCatch files. As a result, the area-misreported landings that have been added to cod.27.6a since 2019 have not been removed from other stocks (including cod.27.47d20) meaning a small amount of double accounting may be present. Table 2 shows that the observed differences between InterCatch and Accessions landings data for cod.27.6a are mostly accounted for by the estimates of area-misreporting.

Table 2: Area-misreporting from the Scottish fleet. The differences between landings submitted to Accessions vs. landings available in InterCatch in tonnes are show in the 'Diff.' column. Estimates of area-misreported landings in tonnes are show in the 'Misreported' column.

Year	InterCatch	Accessions	Diff.	Misreported
2003	872	879	7	–
2004	399	413	14	–
2005	336	335	-1	–
2006	340	318	-22	34
2007	302	272	-30	30
2008	334	232	-102	102
2009	161	107	-54	54
2010	235	116	-119	119
2011	239	109	-130	130
2012	201	136	-64	64
2013	223	130	-93	93
2014	361	128	-234	234
2015	435	165	-270	270
2016	450	179	-271	272
2017	515	197	-318	320
2018	827	213	-614	613
2019	1797	1219	-577	–
2020	1045	715	-330	–
2021	974	925	-50	–

2.2 North Sea cod (Cod.27.47d20)

Figure 2 compares the total landings available in InterCatch vs. the total landings submitted to Accessions for the North Sea area (i.e. omitting division 27.6a and subdivision 27.3a.21 from the Accessions submissions, as these areas are not covered by the current cod.27.47d20 assessment). Accessions data are subset to the period 2002 - 2021 as InterCatch data are available for the North Sea cod stock from 2002 onwards. There is generally good agreement between the InterCatch data and Accessions submissions in the North Sea. For the years 2019 to 2021, no adjustment was made for area-misreporting by the Scottish fleet which likely explains the higher InterCatch landings compared with Accessions data across this period (see section 2.1.1.

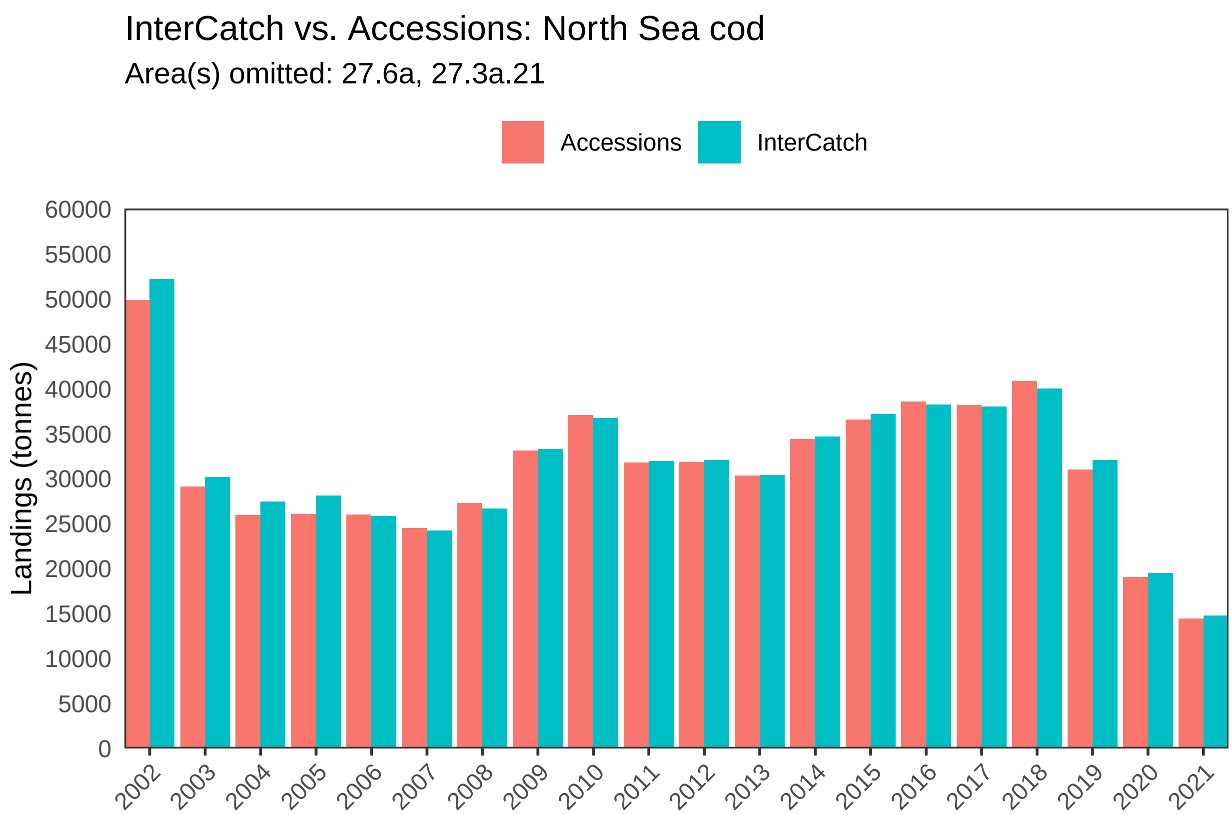


Figure 2: Total landings submitted to InterCatch (blue) vs. Accessions (red) for 2002 - 2021 for cod in the North Sea.

2.3 Northern Shelf cod (Cod.27.47d20 & Cod.27.6a)

Figure 3 compares the total landings submitted to InterCatch vs. the total landings submitted to Accessions for the combined Northern Shelf cod area in the North Sea and West of Scotland area. There appears to be a slight systematic under-representation of Accessions landings for the periods 2002 - 2005 and 2019 to 2021. For the period 2002 - 2005, this is likely due to missing Accessions data from Belgium that is available in InterCatch. For the period 2019 to 2021, this is likely a cumulative affect of lower accessions submissions from several countries (Denmark, the Netherlands and Norway) and the potential double counting of landings from the Scottish fleet which have not been removed from the North Sea (see Table 3).

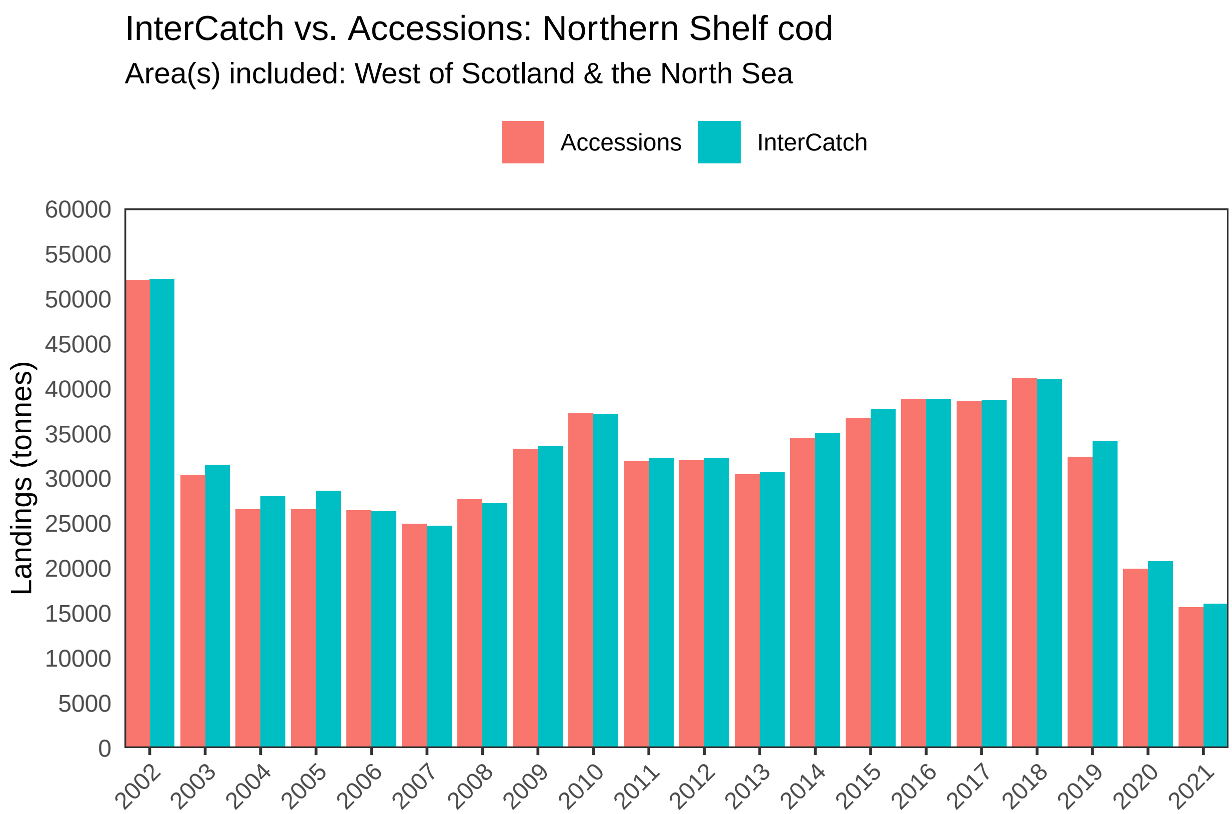


Figure 3: Total landings submitted to InterCatch (blue) vs. Accessions (red) for the Northern Shelf cod meta-population North Sea and West of Scotland

Otherwise there is generally good agreement between the InterCatch and Accessions data for the entire Northern Shelf cod area, with $< 5\%$ difference between the two datasets for almost all years (see Figure 4.

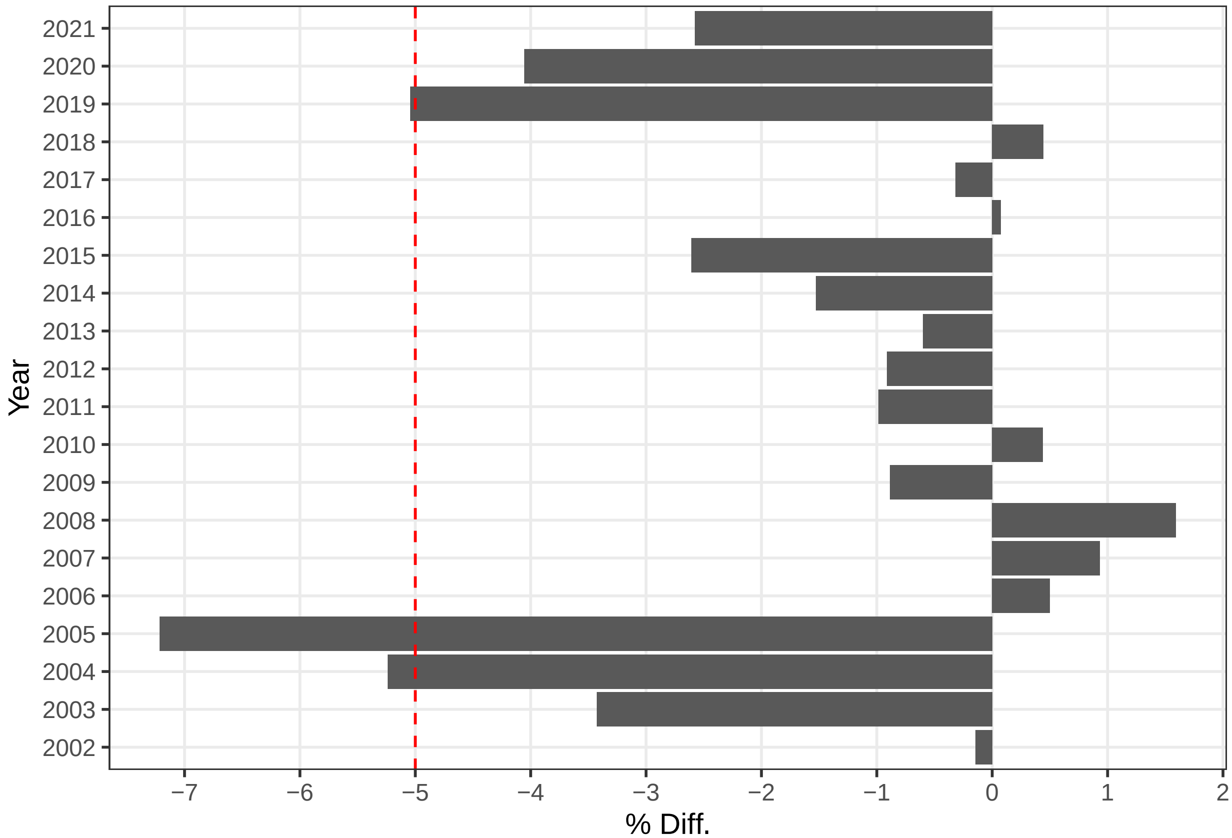


Figure 4: Percentage difference in landings data submitted to Accessions vs. InterCatch for the combined North Sea and West of Scotland area.

2.4 Country comparisons

Table 3 provides a summary of all landings data submitted to Accessions vs. all landings data available in InterCatch for the combined Northern Shelf cod area (i.e. North Sea + West of Scotland) split by country for the period 2002 - 2021. There is generally good agreement for all countries across all years between Accessions submissions and InterCatch data. Data from Spain and the Faroe Islands are available in InterCatch but have no matching Accessions submissions. However, as these amount to minimal landings (<50 tonnes) in a given year across a small number of years (<5) each, they have been omitted from Table 3. Most cases where large differences in percentage terms are observed are due to numerical differences between relatively small landings values (e.g. Northern Ireland).

Table 3: Comparison of Northern Shelf cod landings submitted to Accessions (Acc.) vs. landings available in InterCatch (Inter.) in tonnes by ICES Member Country for the period 2002 - 2021. The rounded differences between the landings submitted to Accessions vs. landings available in InterCatch in percentage terms are shown for each country in 'Diff.'.

	Belgium			Denmark			France			Germany			Ireland			Netherlands			Norway			Sweden			England			N. Ireland			Scotland		
Year	Inter.	Acc.	Diff.	Inter.	Acc.	Diff.	Inter.	Acc.	Diff.	Inter.	Acc.	Diff.	Inter.	Acc.	Diff.	Inter.	Acc.	Diff.	Inter.	Acc.	Diff.	Inter.	Acc.	Diff.	Inter.	Acc.	Diff.	Inter.	Acc.	Diff.	Inter.	Acc.	Diff.
2002	2673.2	–	–	15049.4	14625.0	-3	4918.5	5350.2	9	2094.8	2088.4	0	–	186.6	–	4113.6	4113.1	0	3639.4	4033.5	11	1336.1	1337.6	0	3222.2	3265.6	1	–	189.2	–	15139.6	16922.6	12
2003	1538.3	–	–	8049.8	7807.2	-3	2730.7	2808.1	3	1984.8	2109.1	6	120.3	120.4	0	2069.8	2044.5	-1	3369.4	3618.1	7	748.8	754.7	1	2348.1	2348.1	0	49.9	66.6	33	8476.2	8730.7	3
2004	1673.2	–	–	9292.2	8961.2	-4	1227.1	1272.4	4	2216.1	2316.1	5	33.5	33.2	-1	1574.2	1524.1	-3	2428.5	2627.0	8	720.6	728.3	1	1986.4	1986.4	0	38.9	52.3	34	6839.2	7060.9	3
2005	1774.3	–	–	9674.0	9356.8	-3	1631.3	1481.7	-9	2648.9	2745.4	4	27.9	27.9	0	1508.9	1323.3	-12	2177.2	2288.0	5	795.3	802.4	1	1453.7	1453.5	0	22.9	24.7	8	6914.6	7059.7	2
2006	1389.4	1376.5	-1	7918.6	7704.1	-3	1607.5	1655.6	3	2550.7	2621.3	3	18.2	18.2	0	1469.5	1365.2	-7	1933.4	2085.1	8	681.1	681.1	0	1764.1	1762.2	0	8.5	8.5	-1	6977.8	7172.9	3
2007	1086.4	1086.3	0	5931.8	5834.8	-2	2599.7	2648.0	2	1974.3	1977.7	0	70.4	70.4	0	1528.9	1491.5	-2	2434.9	2539.3	4	757.9	758.7	0	1627.3	1626.3	0	8.7	8.6	-1	6705.1	6927.0	3
2008	1037.3	1039.0	0	6634.5	6617.6	0	2240.4	2328.4	4	1793.1	2123.2	18	58.2	58.2	0	1915.6	1896.4	-1	3745.8	3684.2	-2	804.4	806.5	0	1692.0	1691.3	0	5.2	5.1	-2	7297.1	7424.6	2
2009	943.4	958.9	2	7788.0	7540.6	-3	3351.0	3417.2	2	2439.1	2439.4	0	24.4	13.2	-46	2649.9	2646.8	0	3773.2	3749.7	-1	837.2	838.9	0	2127.0	2126.4	0	9.1	9.1	0	9612.4	9561.9	-1
2010	740.6	711.3	-4	9317.7	9028.5	-3	2079.3	2843.5	37	2926.9	2927.2	0	48.7	13.5	-72	2669.6	2633.1	-1	3984.0	3892.0	-2	821.6	831.0	1	1855.0	1854.8	0	0.1	2.1	3256	12628.3	12529.4	-1
2011	712.4	711.3	0	8285.5	8001.6	-3	1756.3	1749.6	0	2283.1	2283.1	0	41.4	–	–	2005.1	2004.4	0	3754.1	3845.9	2	796.4	853.0	7	1487.9	1487.9	0	0.4	0.4	0	11168.8	11035.6	-1
2012	905.4	902.7	0	8287.4	7989.2	-4	1327.8	1321.5	0	2462.4	2475.3	1	17.8	–	–	1872.7	1953.7	4	3940.5	3939.3	0	990.9	996.4	1	1222.4	1222.1	0	0.4	0.4	-1	11272.6	11204.5	-1
2013	1124.1	1127.1	0	7839.1	7640.6	-3	1017.7	1053.1	3	1988.8	2000.4	1	13.3	–	–	1140.1	1152.0	1	3640.9	3636.5	0	860.5	860.5	0	815.4	831.2	2	0.7	0.7	2	12210.9	12165.5	0
2014	1323.6	1325.3	0	9190.2	8939.1	-3	1870.7	1937.1	4	2341.2	2352.4	0	12.0	11.0	-8	1299.5	1085.8	-16	4066.7	4122.0	1	969.3	969.3	0	967.9	968.4	0	1.6	1.3	-16	13024.9	12819.1	-2
2015	1301.8	1301.6	0	9646.6	9378.3	-3	1707.1	1690.3	-1	2220.5	2234.0	1	16.9	16.6	-1	1388.6	1187.6	-14	4980.5	4724.8	-5	993.9	994.1	0	1416.8	1419.9	0	0.5	0.5	0	14060.2	13802.1	-2
2016	1145.1	1146.3	0	10494.2	10408.2	-1	753.9	753.1	0	2177.1	2188.4	1	27.9	26.3	-6	1391.8	1218.9	-12	5225.8	5227.8	0	1013.8	1013.9	0	759.4	759.7	0	0.9	1.0	2	15848.5	16125.0	2
2017	711.8	712.3	0	10082.4	9783.9	-3	609.9	606.8	0	2380.9	2401.2	1	18.7	17.9	-4	655.3	542.2	-17	5158.6	5201.7	1	947.3	947.3	0	397.8	409.0	3	0.6	0.6	0	17705.7	17922.8	1
2018	824.9	823.6	0	10008.3	9709.0	-3	714.4	701.7	-2	1596.3	1576.1	-1	12.2	11.0	-10	556.1	471.6	-15	5383.8	5302.8	-2	947.8	951.3	0	352.7	370.4	5	0.3	0.4	6	20606.1	21267.7	3
2019	726.4	726.4	0	7910.7	7700.1	-3	607.0	605.1	0	864.1	874.1	1	39.9	39.8	0	738.2	638.7	-13	4730.1	4263.5	-10	702.5	704.1	0	213.5	215.3	1	1.1	1.1	0	17567.6	16641.6	-5
2020	696.1	696.1	0	5037.9	4918.8	-2	413.0	411.1	0	778.7	789.1	1	65.1	64.0	-2	591.4	549.4	-7	2424.6	2062.0	-15	578.9	581.7	0	166.6	167.2	0	2.7	2.7	0	10018.5	9711.3	-3
2021	536.3	537.5	0	3718.3	3618.4	-3	454.9	451.8	-1	798.0	789.3	-1	98.3	96.1	-2	615.5	587.6	-5	1726.2	1501.8	-13	635.6	636.7	0	160.4	163.9	2	2.5	2.3	-6	7283.1	7256.2	0

3 Accessions submissions by sub-stock area

The new SAM modelling framework proposed for WKCOD 2023 requires landings data split proportionally by the different sub-stock areas. It is assumed that the sub-stock components do not mix in quarter 1 (Q1), and so Accessions landings data from Q1 only are used to determine the relative sub-stock proportions over time. A summary of the total landings submitted to Accessions split by the four sub-stock areas is shown in Table 4. Data are available across all years for each of the proposed sub-stock areas, including the inshore/offshore split of the Northwestern sub-stock.

Table 4: Landings and relative proportions submitted to Accessions split by the proposed WKCOD 2023 sub-stock areas (Q1) for the period 1995 - 2021.

	Northwestern inshore		Northwestern offshore		Southern		Viking	
Year	Landings (tonnes)	Proportion (%)	Landings (tonnes)	Proportion (%)	Landings (tonnes)	Proportion (%)	Landings (tonnes)	Proportion (%)
1995	2156.9	1.9	27039.0	23.9	33603.4	29.7	50272.3	44.5
1996	2393.8	2.2	27625.1	25.1	33575.0	30.5	46362.7	42.2
1997	1842.3	1.8	20190.2	19.3	38245.8	36.5	44458.6	42.4
1998	1612.3	1.4	22265.7	19.0	49956.1	42.5	43575.0	37.1
1999	819.5	1.0	13466.6	16.8	32745.1	40.9	33030.4	41.3
2000	1014.3	1.5	10672.1	15.9	24535.1	36.5	31088.2	46.2
2001	708.4	1.5	8455.9	17.9	15271.6	32.3	22809.7	48.3
2002	696.7	1.4	8938.5	18.1	17780.5	36.0	21914.5	44.4
2003	309.1	1.1	4246.1	15.1	10478.6	37.3	13064.1	46.5
2004	128.0	0.5	2906.1	11.9	8539.7	34.8	12947.0	52.8
2005	68.5	0.3	3157.3	12.0	8267.8	31.5	14783.0	56.3
2006	65.5	0.2	3289.2	12.5	8929.1	33.9	14043.1	53.3
2007	76.6	0.3	3435.0	13.8	8533.7	34.3	12828.9	51.6
2008	84.9	0.3	3505.9	12.9	8894.1	32.6	14796.8	54.2
2009	19.4	0.1	4832.7	14.8	10897.8	33.4	16886.5	51.7
2010	8.0	0.0	7002.4	18.9	11092.7	29.9	19007.3	51.2
2011	7.2	0.0	6739.4	21.1	7738.4	24.2	17449.4	54.6
2012	16.9	0.1	6443.5	20.1	6102.7	19.1	19464.4	60.8
2013	20.9	0.1	7189.3	23.6	4465.7	14.6	18810.5	61.7
2014	16.2	0.0	7983.3	23.1	5276.7	15.3	21282.1	61.6
2015	19.6	0.1	9146.3	24.9	5353.8	14.6	22253.3	60.5
2016	26.4	0.1	10422.0	26.8	3229.0	8.3	25240.4	64.9
2017	37.5	0.1	11894.6	30.9	1586.1	4.1	24979.3	64.9
2018	27.9	0.1	17642.3	43.2	1426.8	3.5	21777.0	53.3
2019	89.2	0.3	13924.0	43.1	911.1	2.8	17358.2	53.8
2020	42.9	0.2	6745.3	33.9	799.4	4.0	12300.6	61.8
2021	32.2	0.2	5464.2	35.0	652.0	4.2	9464.3	60.6

3.1 Landings proportions by sub-stock area

Figure 5 shows the change in the relative proportions of landings submitted to Accessions split between the sub-stock areas for the period 1995 - 2021. The relative proportions of both the Northwestern offshore sub-stock and the Viking sub-stock have increased in recent years, whereas the Southern sub-stock proportion has decreased. The Northwestern inshore sub-stock makes up a relatively small proportion of the total landings across all years, and has decreased in recent years.

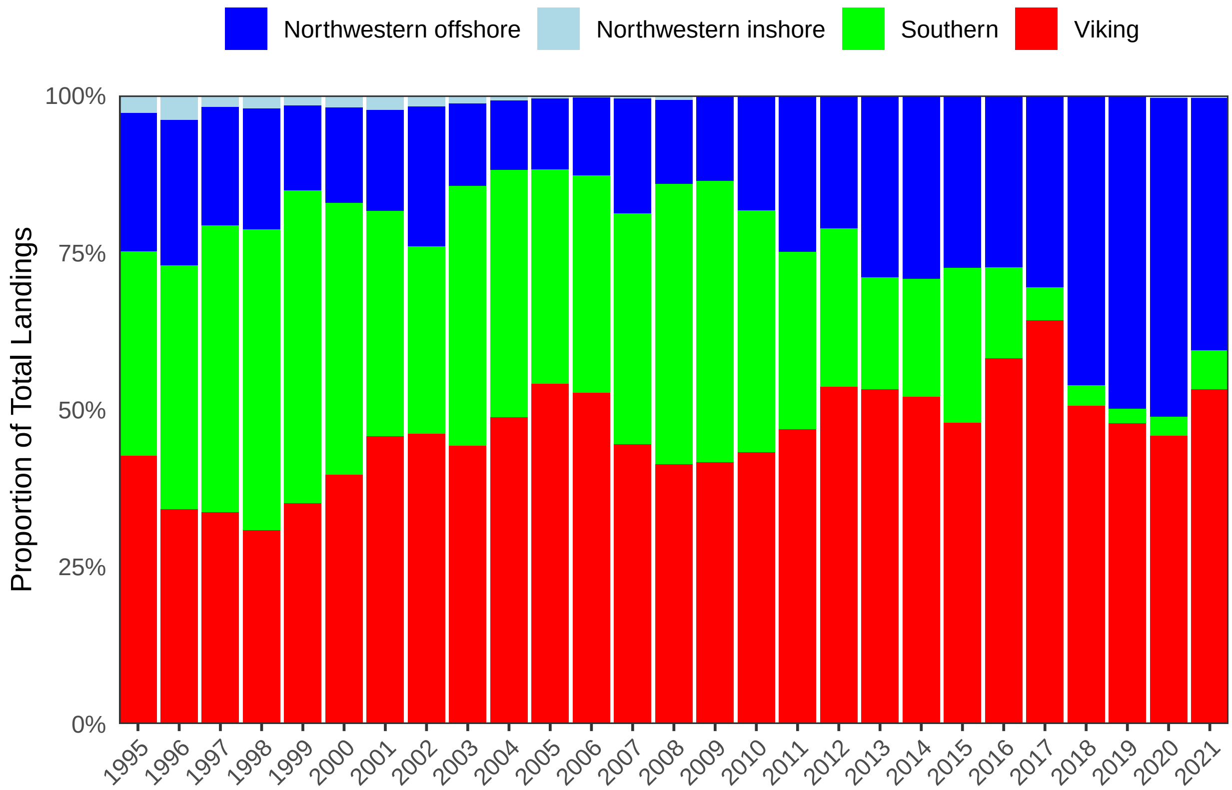


Figure 5: Accessions submissions split proportionally by the different sub-stock areas for the period 1995 - 2021. Landings data taken from Q1 only, where it is assumed sub-stock components do not mix.

4 Conclusions

The authors conclude:

- The landings data submitted to Accessions are consistent with the landings data available in InterCatch for both the West of Scotland and North Sea assessment areas individually, as well as the whole Northern Shelf cod area combined
- The landings data submitted to Accessions are of sufficient quality to be used to split landings proportions across the main sub-stock areas (i.e. Northwestern, Southern and Viking) through time

The authors recommend:

- To use Accessions data starting from 2002, as all countries should have landings by sub-stock area from this point
- That a three sub-stock approach be adopted given the low landings proportions observed for the Northwestern inshore population in recent years
- To discuss the implications of changing landings proportions between the different sub-stock areas over time

21.6 Spilt of historic landings 1963–1994

By Alessandro Orio and Massimiliano Cardinale

Historical North Sea cod (Cod.27.47d20) landings by country and area for the years 1963–1994 were obtained from the ICES landings database (https://www.ices.dk/data/dataset-collections/Pages/Fish-catch-and-stock-assessment.aspx). The historical landings were available for different combinations of countries and areas (Figures 1 and 2).

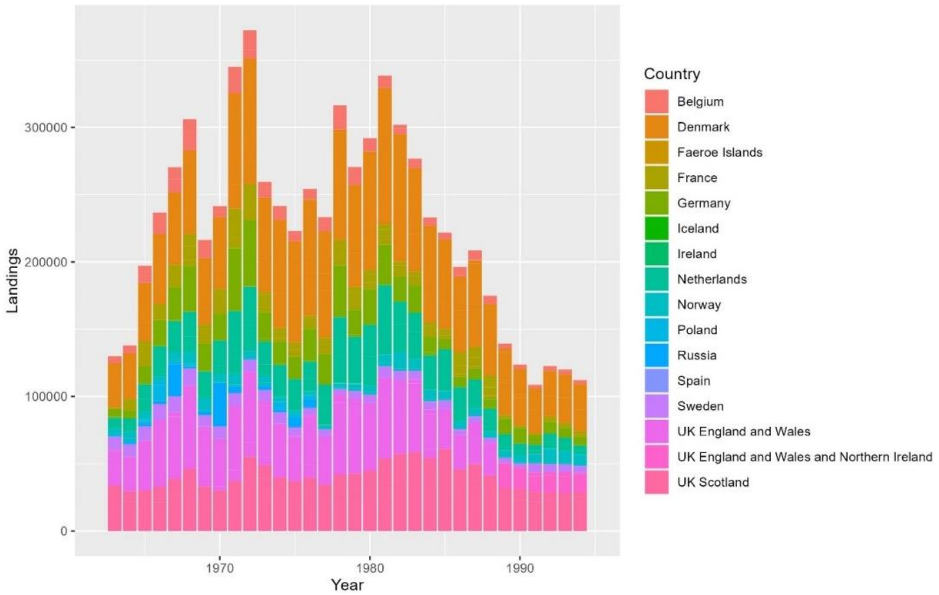


Figure 1. Historical landings by country for North Sea cod (Cod.27.47d20) as reported in the ICES landings database.

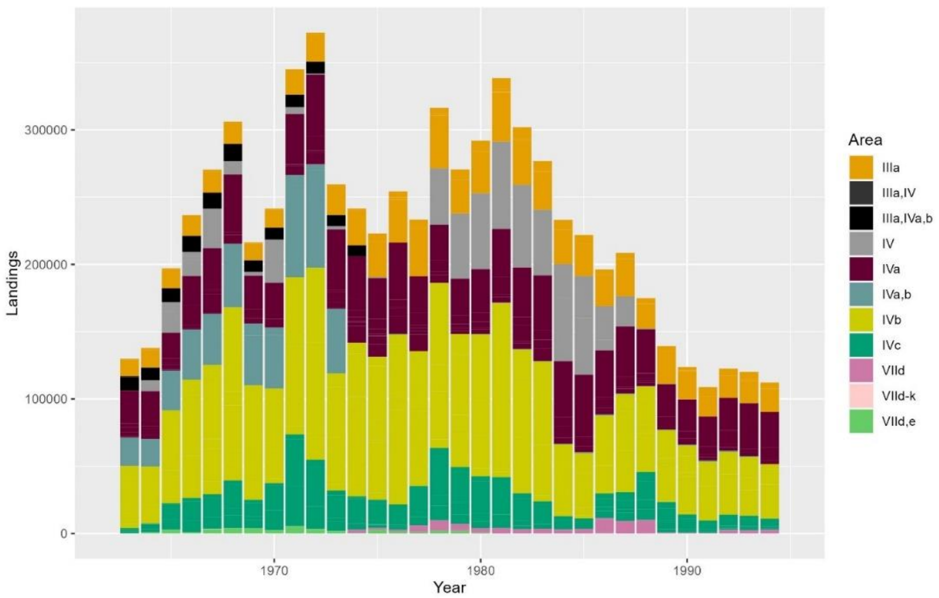


Figure 2. Historical landings by area for North Sea cod (Cod.27.47d20) from 1963 to 1994 as reported in the ICES landings database.

As shown in Figure 2 the spatial resolution of the Historical landings is variable for different years. To obtain the most reliable estimate of the split of the historical landings by the different substocks, assumptions have been made to split the aggregated areas into single ICES divisions.

In the next sections the assumptions made for each country are discussed.

Belgium

Belgian data have been reported by ICES division for all years available except for areas IIIa (i.e split between IIIaN and IIIaS, the latter belonging to Kattegat cod), and VIId,e in some cases (Figure 3). However, due to the lack of data, no assumptions were made to split those landings.

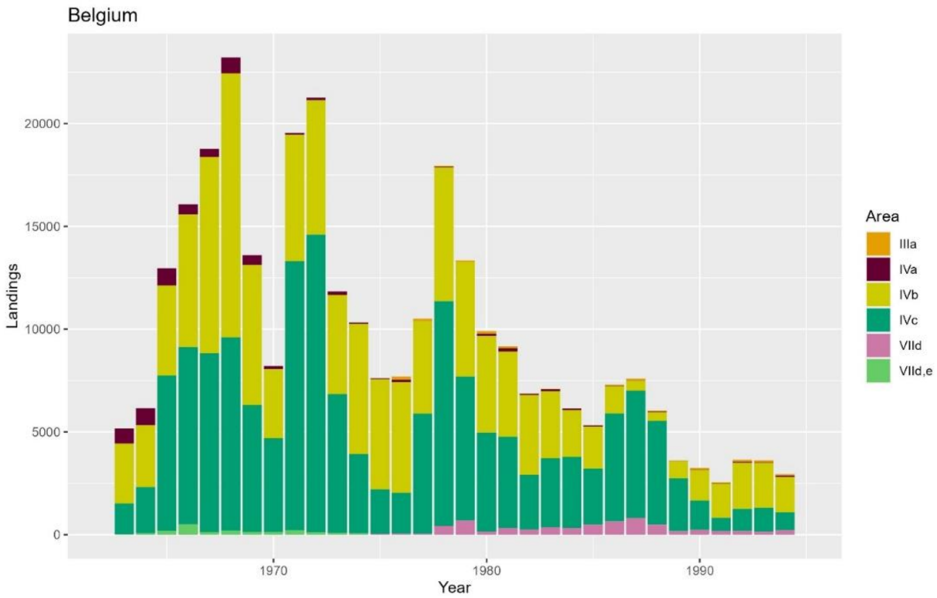


Figure 3. Historical landings by area for North Sea cod (Cod.27.47d20) for Belgium for the period 1963–1994.

Denmark

Danish data have been reported by division for all years available except for areas IIIa, IV, IVa,b and VIId,e in some cases (Figure 4). For area VIId,e, due to the lack of data, no assumptions were made to split those landings.

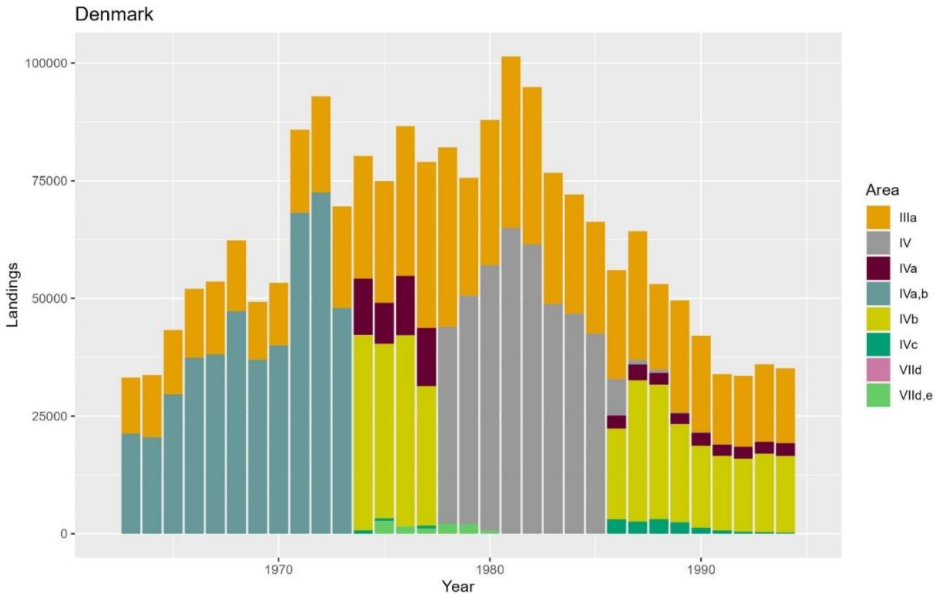


Figure 4. Historical landings by area for North Sea cod (Cod.27.47d20) for Denmark for the period 1963–1994.

In order to split area IIIa, additional information have been requested to Danish experts, which provided spatially disaggregated cod landings for the periods 1950–1981, 1982–1986, 1987–1994 using different sources and assumptions depending on the period (Figure 5).

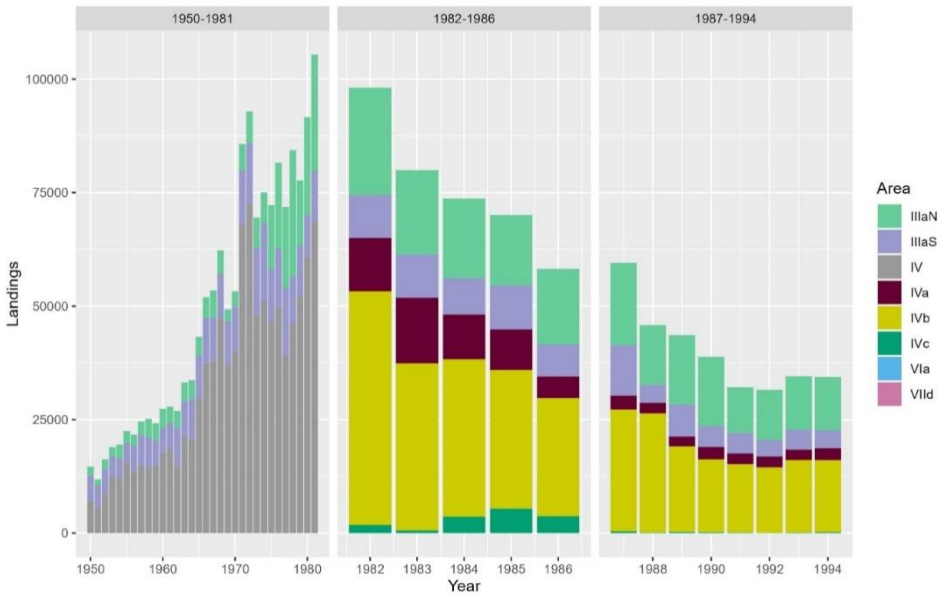


Figure 5. Spatially disaggregated cod landings of Denmark for the period 1950–1981.

To split areas IIIa from 1963 to 1994 the average of the proportion of the different divisions from the spatially disaggregated landings for the same years was used (Figure 6). To split area IV from 1986 to 1994 the average of the proportion of the different divisions for the same years was used (Figure 6). To split area IV from 1982 to 1985 the average of the proportion of the different divisions from the spatially disaggregated landings for the same years was used (Figure 6). To split area IV from 1978 to 1981 the average of the proportion of the different divisions for the two years before (1976–1977) and after (1982–1983) was used (Figure 6). To split area IVa,b from 1963 to 1973 the average of the proportion of the different divisions for the three years after (1974–1976) was used (Figure 6). Landings from area IIIaS (Kattegat) were then removed (Figure 6).

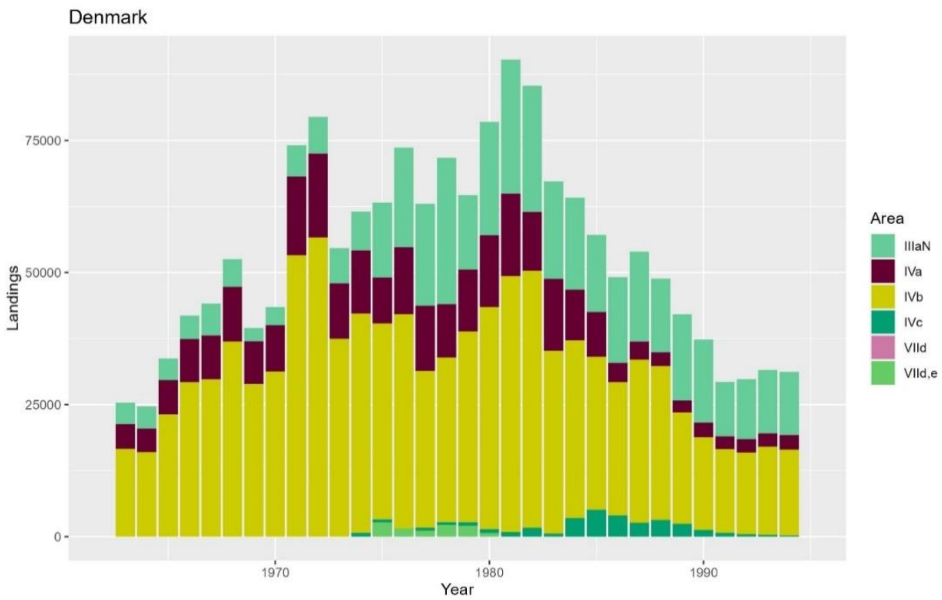


Figure 6. Historical landings by area for North Sea cod (Cod.27.47d20) for Denmark for the period 1963–1994 after assumptions have been made to split areas into divisions.

Faeroe Islands

Faeroese data have been reported by division for all years available except for area IIIa in some cases (Figure 7). For area IIIa, due to the lack of data, no assumptions were made to split those landings.

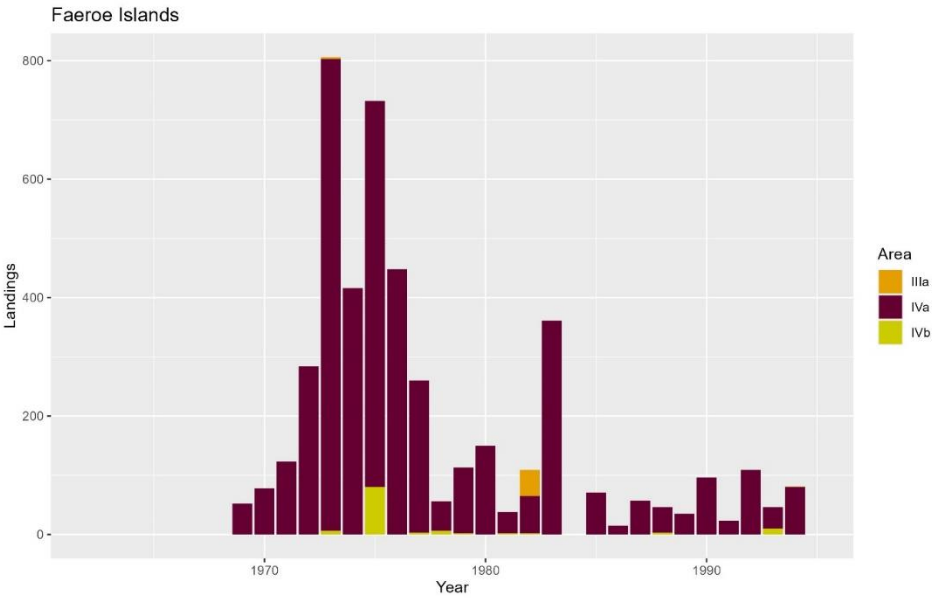


Figure 7. Historical landings by area for North Sea cod (Cod.27.47d20) for Faeroe Islands for the period 1963–1994.

France

French data have been reported by division for all years available except for areas IV and VIId,e in some cases (Figure 8). For area VIId,e, due to the lack of data, no assumptions were made to split those landings.

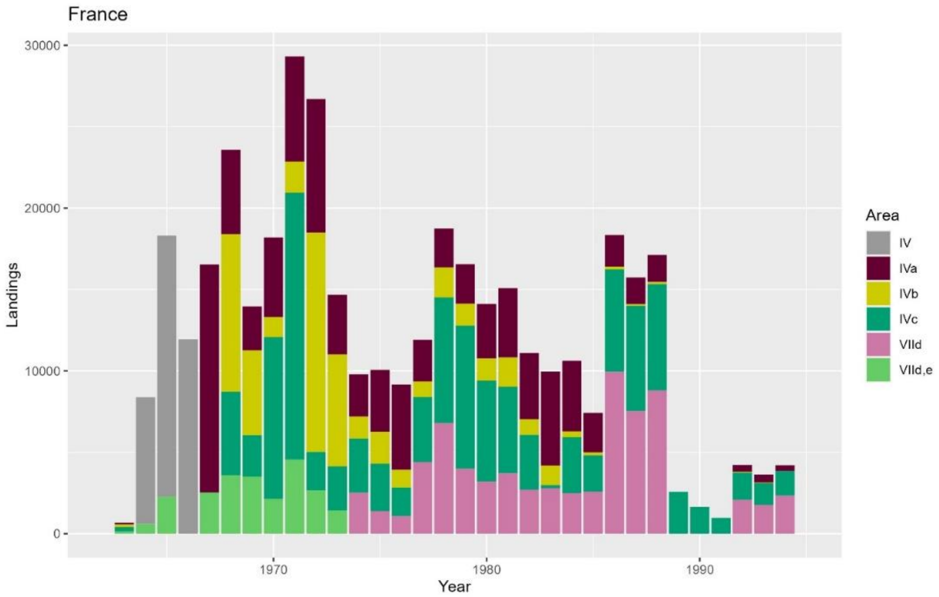


Figure 8. Historical landings by area for North Sea cod (Cod.27.47d20) for France for the period 1963–1994.

To split area IV from 1964 to 1966 the average of the proportion of the different divisions for the year before (1963) and 2 years after (1967–1968) was used (Figure 9).

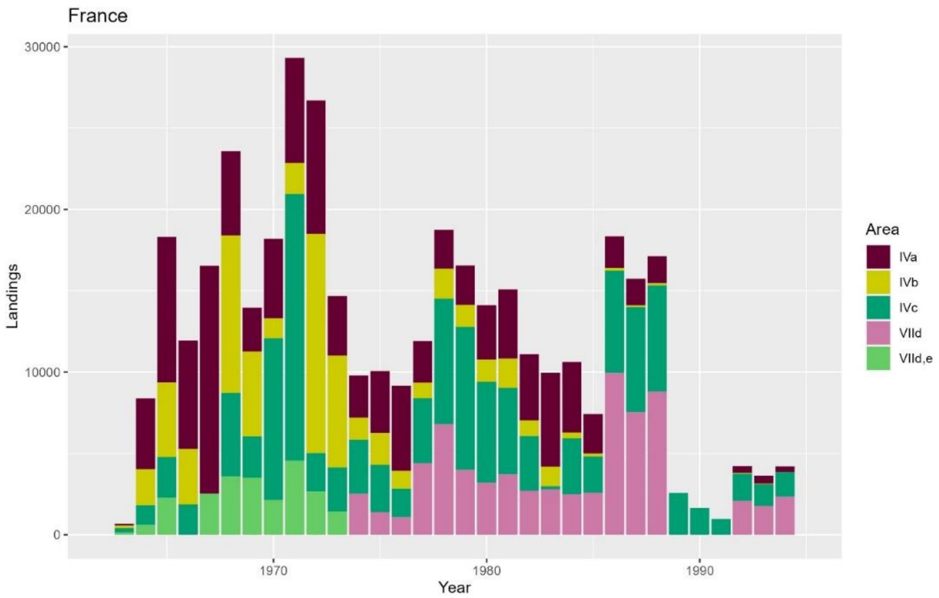


Figure 9. Historical landings by area for North Sea cod (Cod.27.47d20) for France for the period 1963–1994 after assumptions have been made to split areas into divisions.

Germany

German data have been reported by division for all years available except for areas IIIa, IIIa,IV and VIId-k in some cases (Figure 10). For areas IIIa and VIId-k, due to the lack of data, no assumptions were made to split those landings.

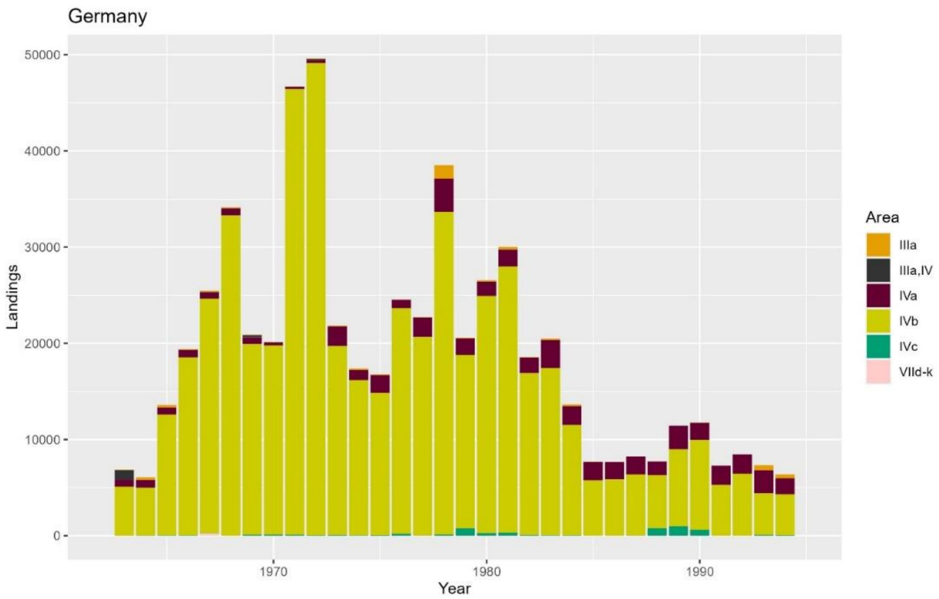


Figure 10. Historical landings by area for North Sea cod (Cod.27.47d20) for Germany for the period 1963–1994.

To split area IIIa,IV from 1963 to 1972 the average of the proportion of the different divisions for the same years was used (Figure 11).

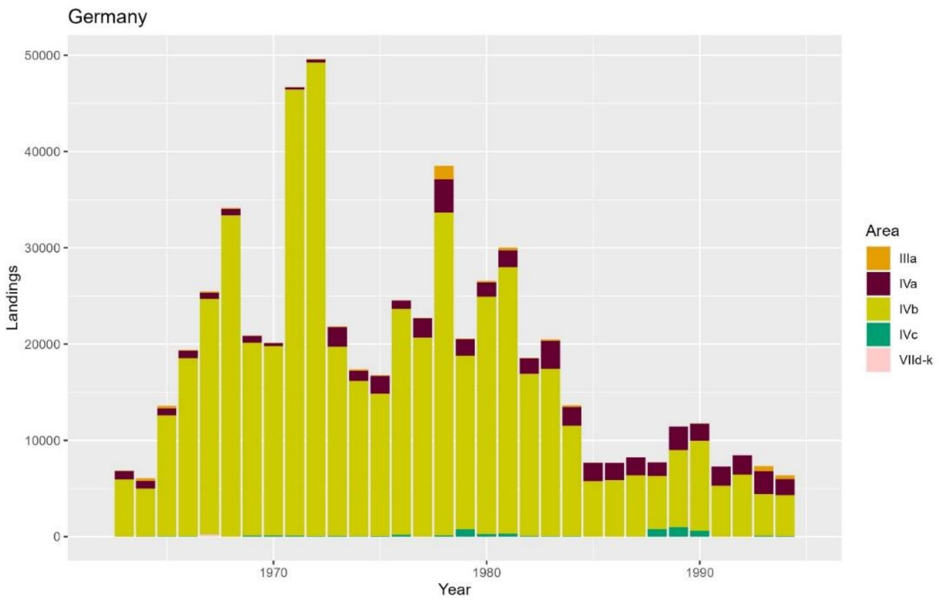


Figure 11. Historical landings by area for North Sea cod (Cod.27.47d20) for Germany for the period 1963–1994 after assumptions have been made to split areas into divisions.

Iceland

Icelandic data have been reported by division for the only year available in the database (Figure 12).

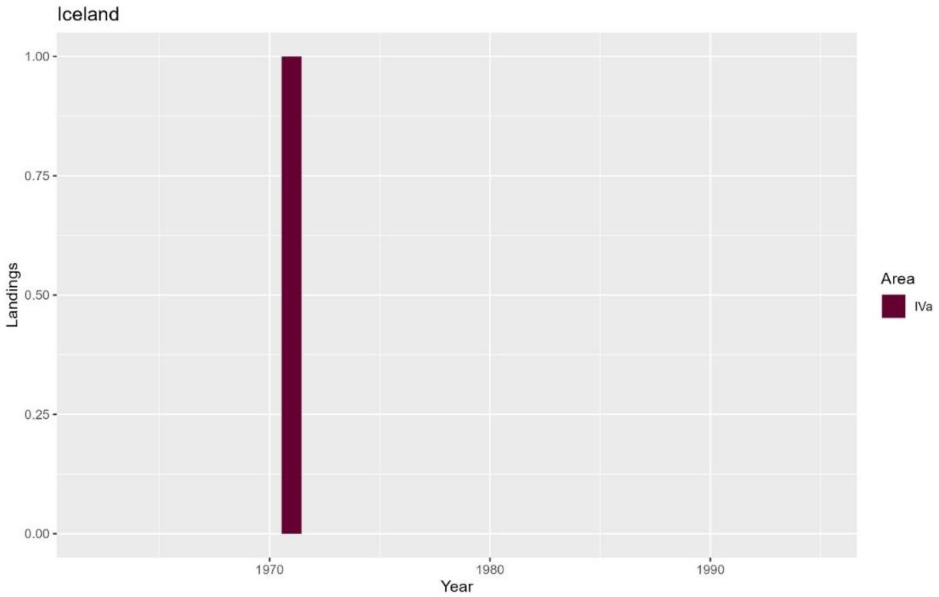


Figure 12. Historical landings by area for North Sea cod (Cod.27.47d20) for Iceland for the period 1963–1994.

Ireland

Irish data have been reported by division for all years available in the database (Figure 13).

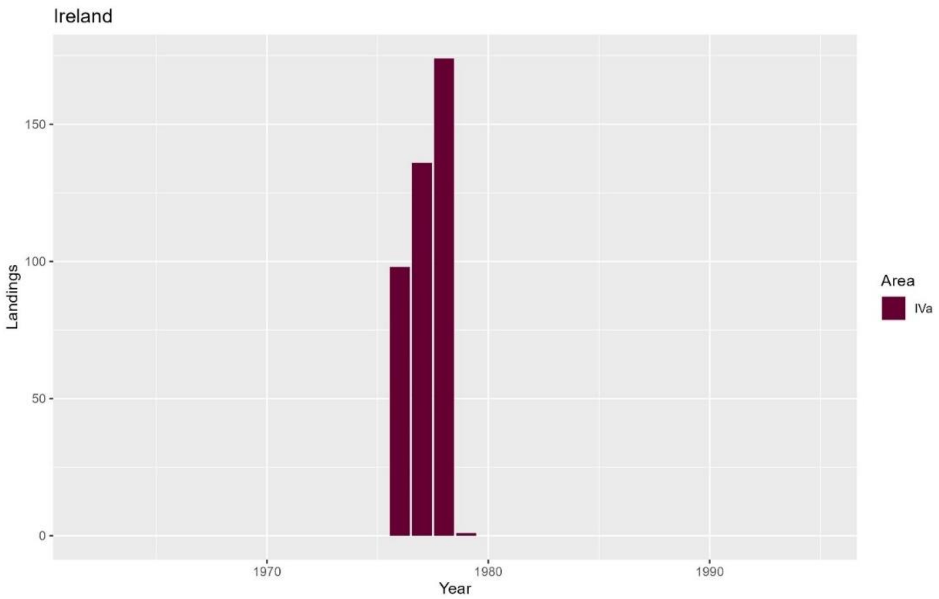


Figure 13. Historical landings by area for North Sea cod (Cod.27.47d20) for Ireland for the period 1963–1994.

Netherlands

Dutch data have been reported by division for all years available except for areas IIIa, IV and VIId-e in some cases (Figure 14). For areas IIIa and VIId,e, due to the lack of data, no assumptions were made to split those landings.

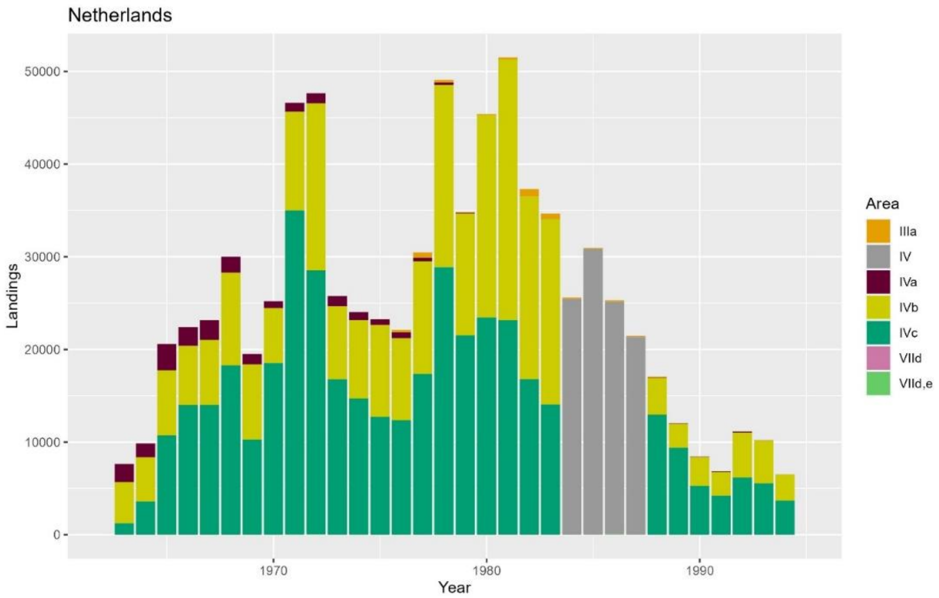


Figure 14. Historical landings by area for North Sea cod (Cod.27.47d20) for Netherlands for the period 1963–1994.

To split area IV from 1984 to 1987 the average of the proportion of the different divisions for the two years before (1982–1983) and after (1988–1989) was used (Figure 15).

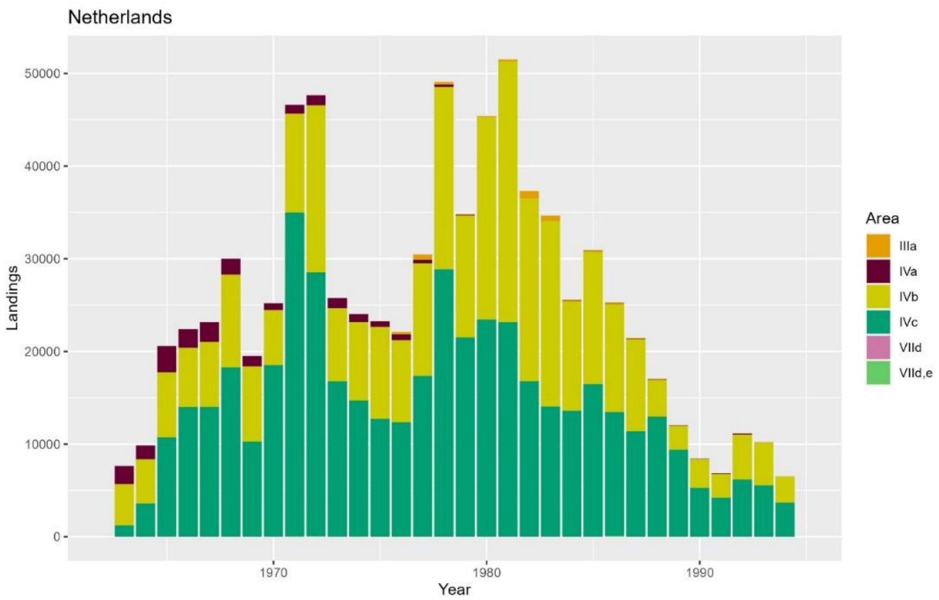


Figure 15. Historical landings by area for North Sea cod (Cod.27.47d20) for Netherlands for the period 1963–1994 after assumptions have been made to split areas into divisions.

Norway

Norwegian data have been reported by division for all years available except for areas IIIa, IV and IVa,b in some cases (Figure 16). For area IIIa, due to the lack of data, no assumptions were made to split those landings.

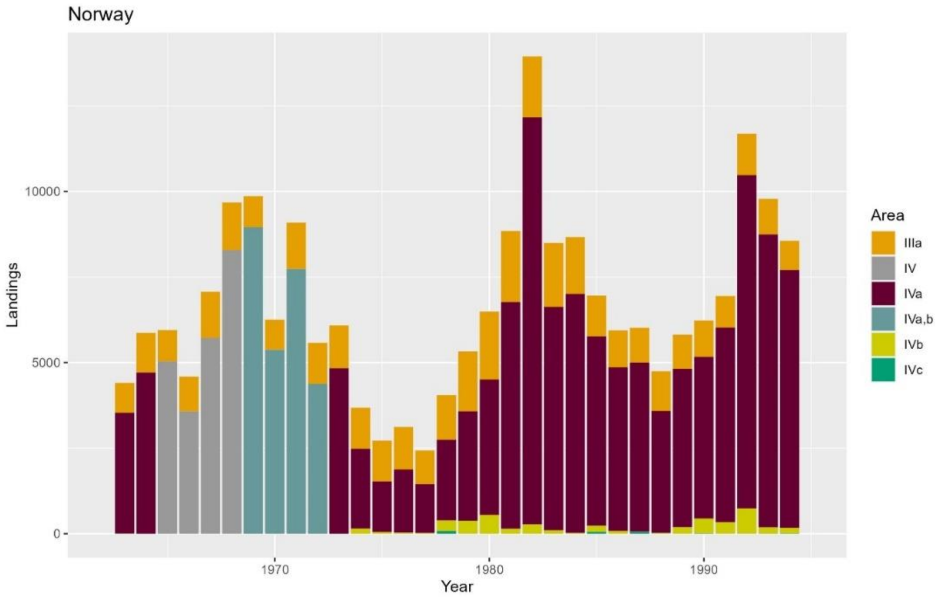


Figure 16. Historical landings by area for North Sea cod (Cod.27.47d20) for Norway for the period 1963–1994.

To split area IVa,b from 1969 to 1972 the average of the proportion of the different divisions for the three years after (1973–1975) was used (Figure 17). To split area IV from 1965 to 1968 the average of the proportion of the different divisions for the two years before (1963–1964) and after (1969–1970) was used (Figure 17).

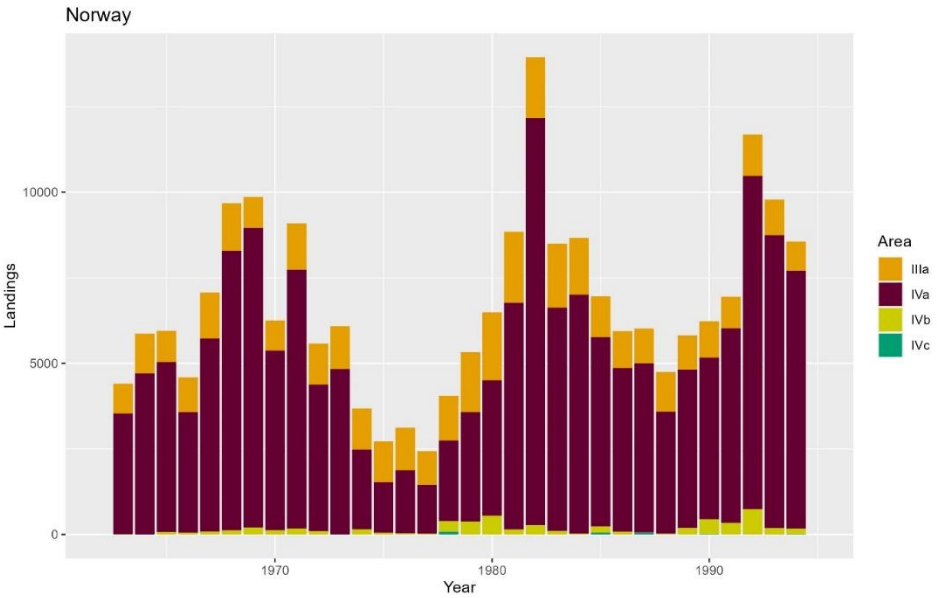


Figure 17. Historical landings by area for North Sea cod (Cod.27.47d20) for Norway for the period 1963–1994 after assumptions have been made to split areas into divisions.

Poland

Polish data have been reported by division for all years available except for areas IIIa and VIId-e in some cases (Figure 18). For areas IIIa and VIId,e, due to the lack of data, no assumptions were made to split those landings.

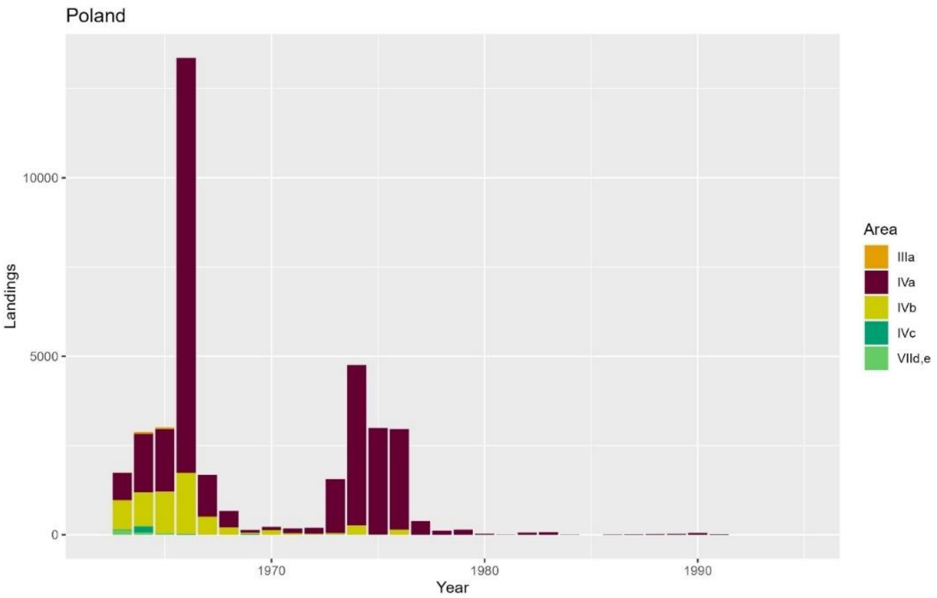


Figure 18. Historical landings by area for North Sea cod (Cod.27.47d20) for Poland for the period 1963–1994.

Russia

Russian data have been reported by division for all years available except for areas IV and VIId-e in some cases (Figure 19). For area VIId,e, due to the lack of data, no assumptions were made to split those landings.

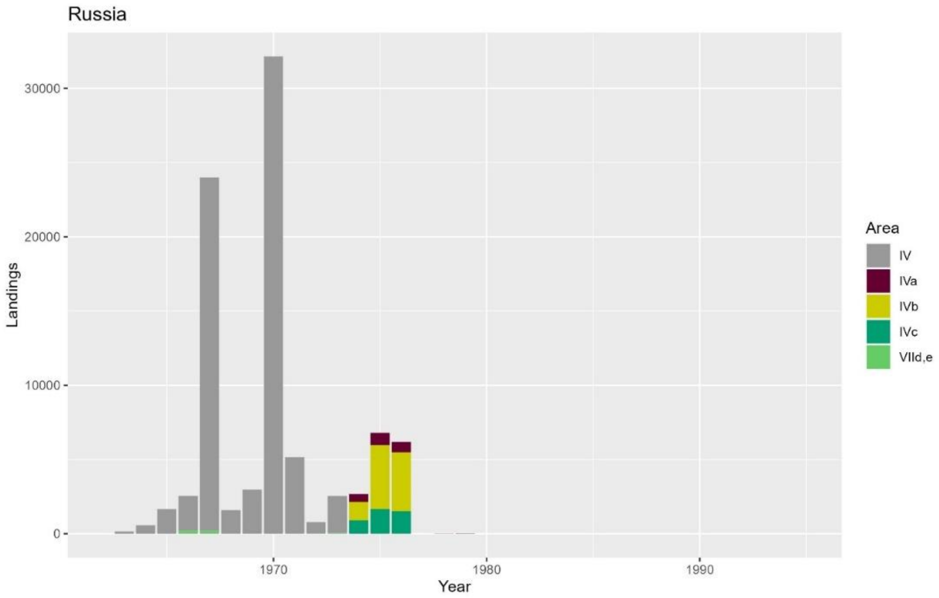


Figure 19. Historical landings by area for North Sea cod (Cod.27.47d20) for Russia for the period 1963–1994.

To split area IV from 1963 to 1973 the average of the proportion of the different divisions for the three years after (1974–1976) was used (Figure 20).

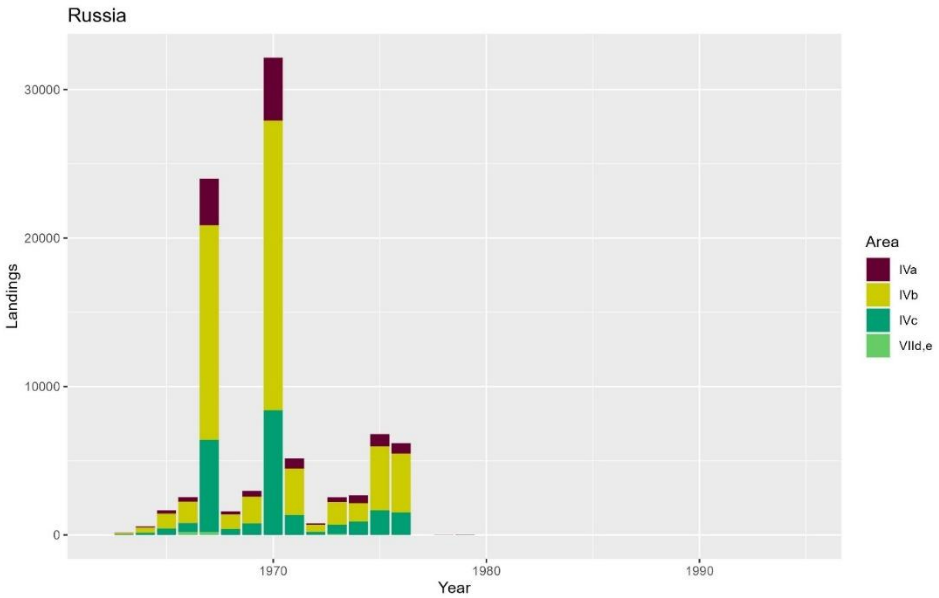


Figure 20. Historical landings by area for North Sea cod (Cod.27.47d20) for Russia for the period 1963–1994 after assumptions have been made to split areas into divisions.

Spain

Spanish data have been reported by division for all years available (Figure 21).

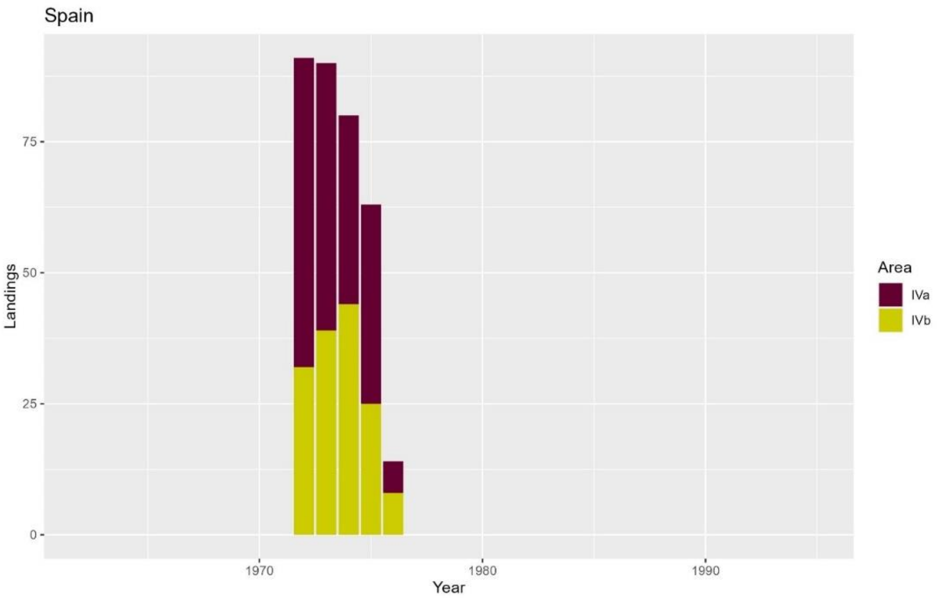


Figure 21. Historical landings by area for North Sea cod (Cod.27.47d20) for Spain for the period 1963–1994.

Sweden

Swedish data have been reported by division for all years available except for areas IIIa, IIIa,IVa,b, IV, and IVa,b in some cases (Figure 22).

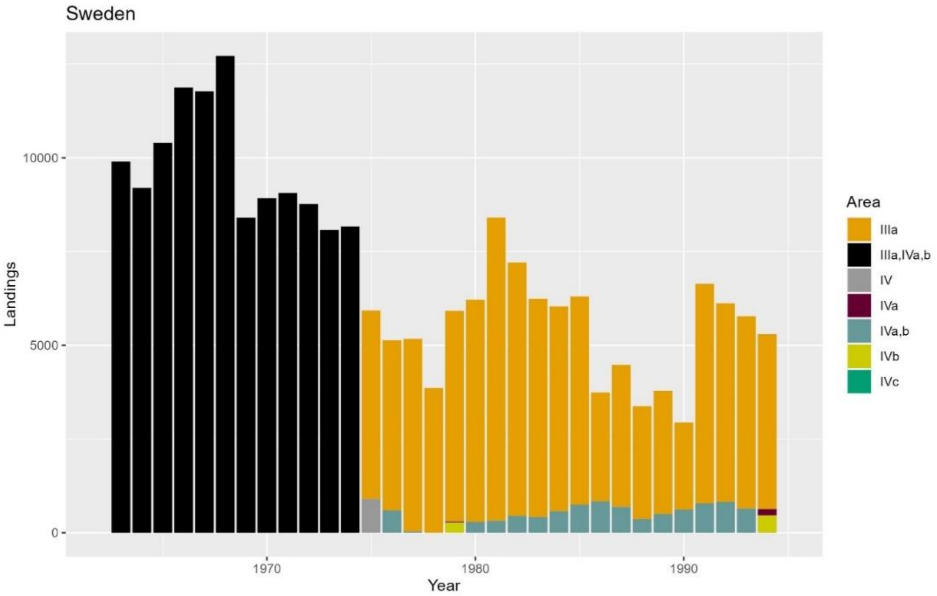


Figure 22. Historical landings by area for North Sea cod (Cod.27.47d20) for Sweden for the period 1963–1994.

In order to split those areas, additional information have been requested to Swedish experts, which provided spatially disaggregated cod landings for the period 1978–2021 (Figure 23).

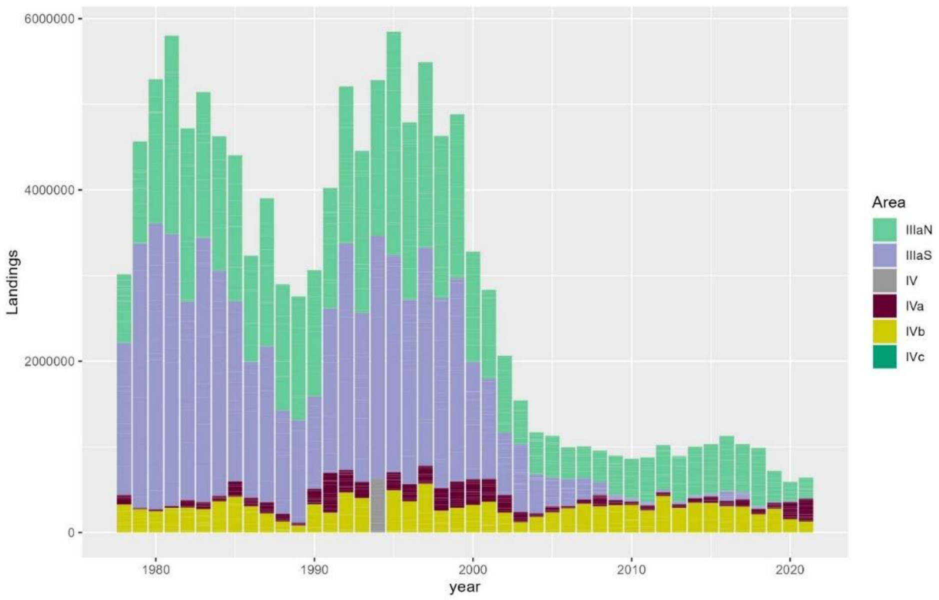


Figure 23. Spatially disaggregated cod landings of Sweden for the period 1978–2021.

To split areas IIIa and IVa,b from 1978 to 1994 the average of the proportion of the different divisions from the spatially disaggregated landings for the same years was used (Figure 24). To split area IIIa from 1975 to 1977 the average of the proportion of the different divisions for the three years after (1978–1980) was used (Figure 24). To split area IVa,b from 1976 to 1977 and area IV in 1975 the average of the proportion of the different divisions for the three years after (1979–1981; 1978 was excluded because ladings reported are only for area IIIa) was used (Figure 24). To split area IIIa,IVa,b from 1963 to 1974 the average of the proportion of the different divisions for the three years after (1975–1977) was used (Figure 24). Landings from area IIIaS (Kattegat) were then removed (Figure 24).

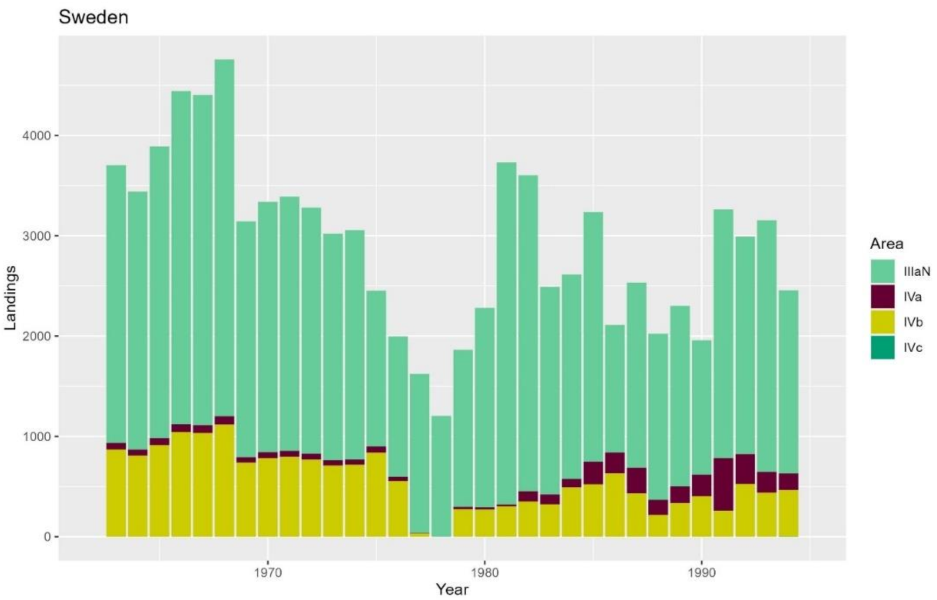


Figure 24. Historical landings by area for North Sea cod (Cod.27.47d20) for Sweden for the period 1963–1994 after assumptions have been made to split areas into divisions.

UK England and Wales

Data for UK England and Wales have been reported by division for all years available except for area IIIa and VIId,e in some cases (Figure 25). For areas IIIa and VIId,e, due to the lack of data, no assumptions were made to split those landings.

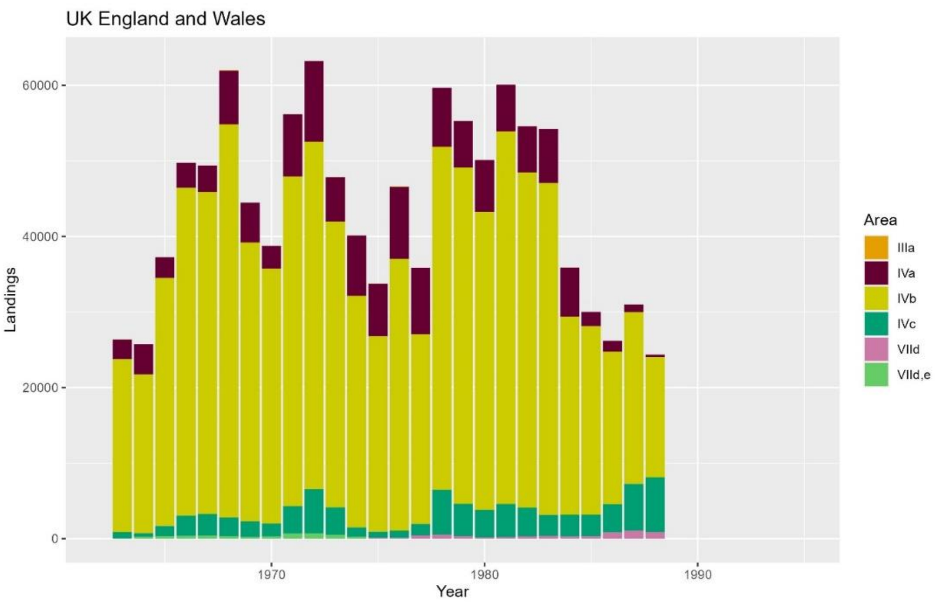


Figure 25. Historical landings by area for North Sea cod (Cod.27.47d20) for UK England and Wales for the period 1963–1994.

UK England and Wales and Northern Ireland

Data for UK England and Wales and Northern Ireland have been reported by division for all years available (Figure 26).

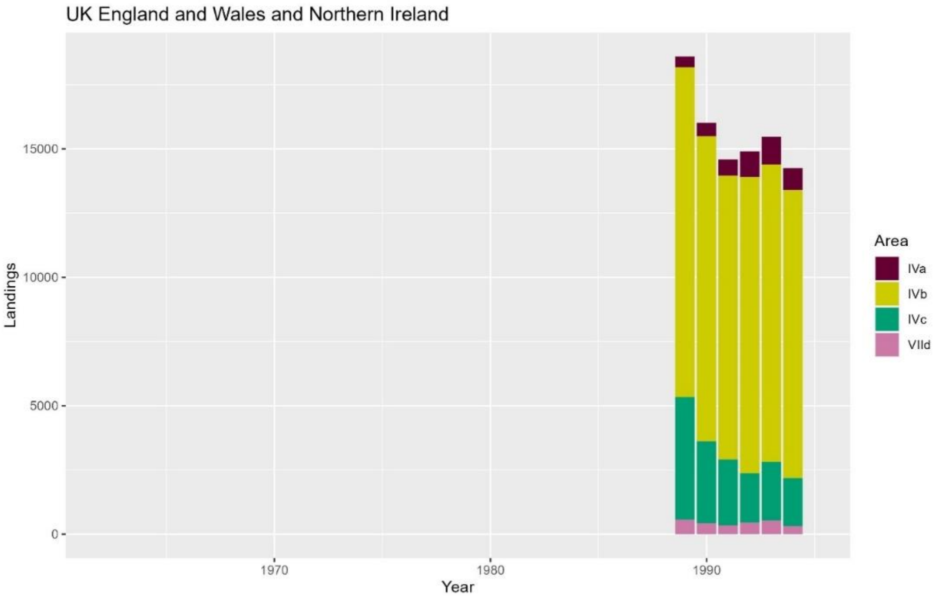


Figure 26. Historical landings by area for North Sea cod (Cod.27.47d20) for UK England and Wales and Northern Ireland for the period 1963–1994.

UK Scotland

Data for UK Scotland have been reported by division for all years available (Figure 27).

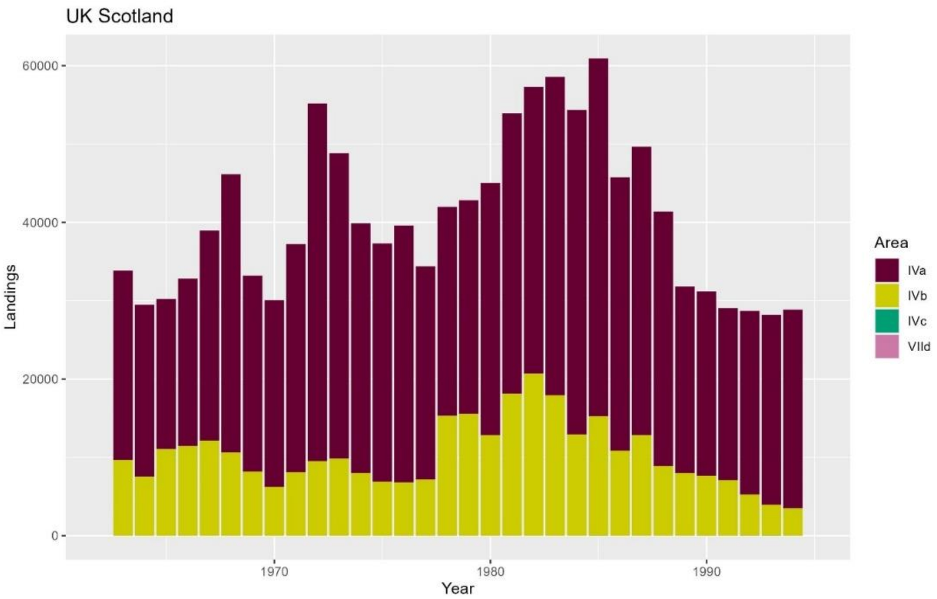


Figure 27. Historical landings by area for North Sea cod (Cod.27.47d20) for UK Scotland for the period 1963–1994.

Split of historical landings by area into substocks

The historical landings split by area after assumptions have been made to split areas into divisions are presented in Figure 28.

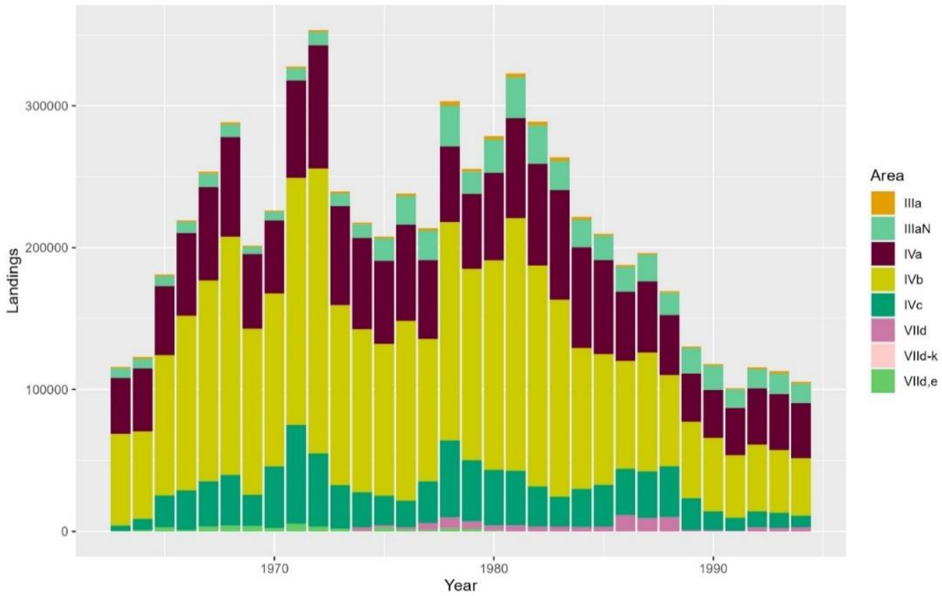


Figure 28. Historical landings by area for North Sea cod (Cod.27.47d20) for the period 1963–1994 after assumptions have been made to split areas into divisions.

Area VIId,e in every year represented always less than 2% of the total landings, area VIId-k less than 0.5% while area IIIa less than 1.5%. Therefore, we decided to keep them in the total landings and consider the potential contamination of cod catches from neighbouring stocks as negligible.

Due to the geographical distribution of the different substocks, all the landings coming from areas IIIa and IIIaN were assumed as Viking substock landings. All the landings coming from areas IVc, VIId, VIId,e and VIId-k were assumed as Southern substock landings.

The proportion of different substocks for areas IVa and IVb for each country were calculated from the Q1 Accessions data (Figure 29).

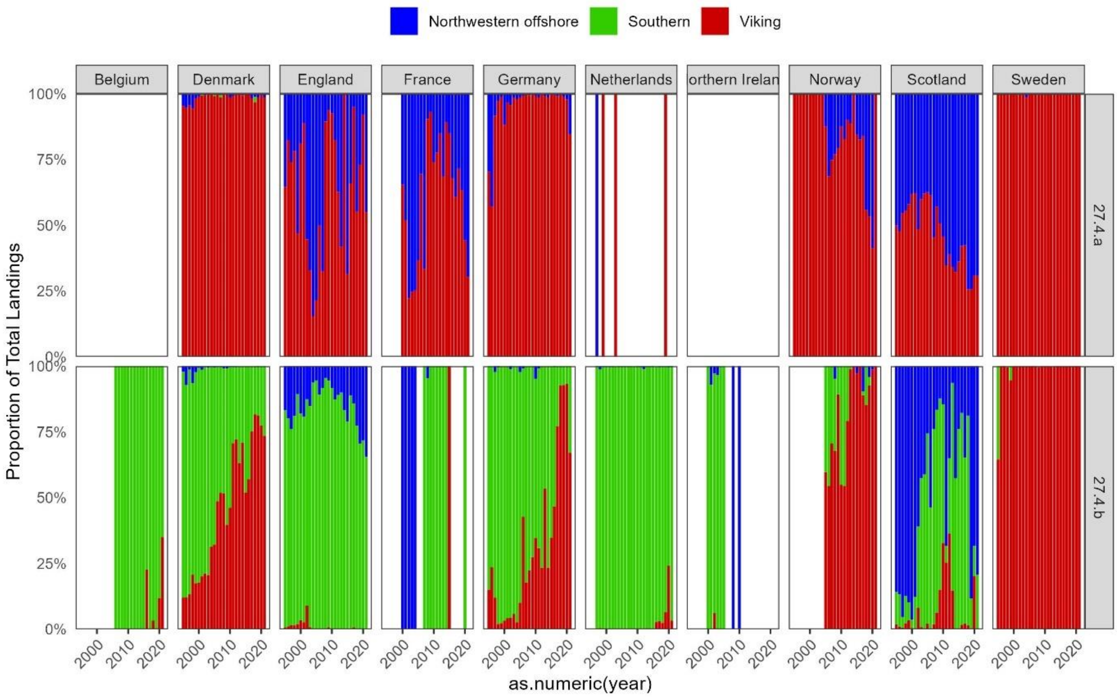


Figure 29. Proportion of cod landings for the different substocks in areas IVa ad IVb for the different countries for the period 1995 to 2021.

For each country the first three years of available accessions data for each area were used to produce average proportion of the different substocks in the different areas and applied to the historical landings.

Some countries in the historical landings do not have accessions data so the following assumptions have been made. For Belgian historical landings in IVa, the Dutch proportions were used. For the Faeroese, Icelandic and Irish historical landings, the Scottish proportions were used. For the Polish historical landings, the German proportions were used. For the Russian historical landings, the Norwegian proportions were used. For the Spanish historical landings, the French proportions were used. The assumptions used for areas IVa and IVb are summarised in Figure 30 while in Figures 31 and 32 the historical landings and the proportion of historical landings split by substocks are shown.

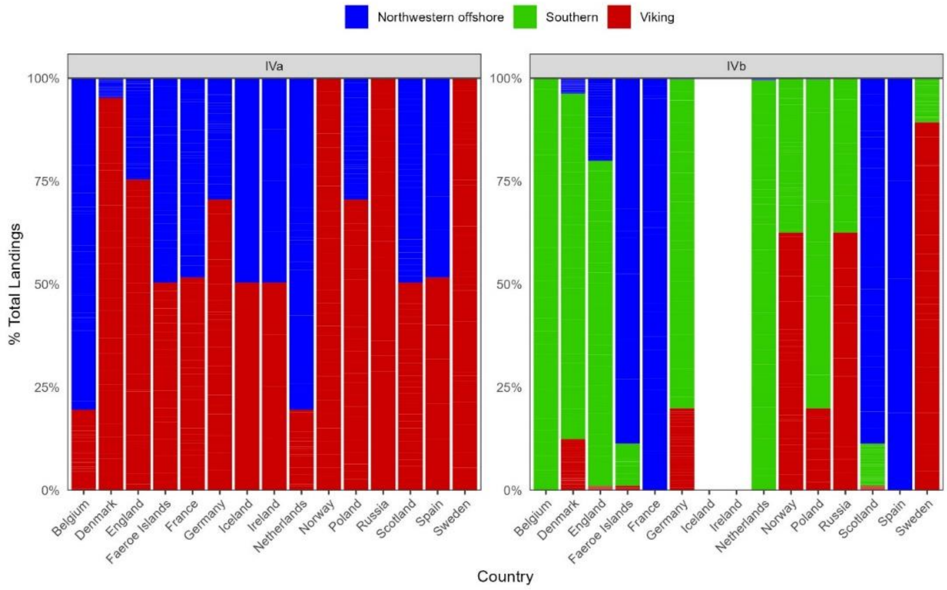


Figure 30. Assumptions used for each country to split historical landings from areas IVa and IVb in different substocks.

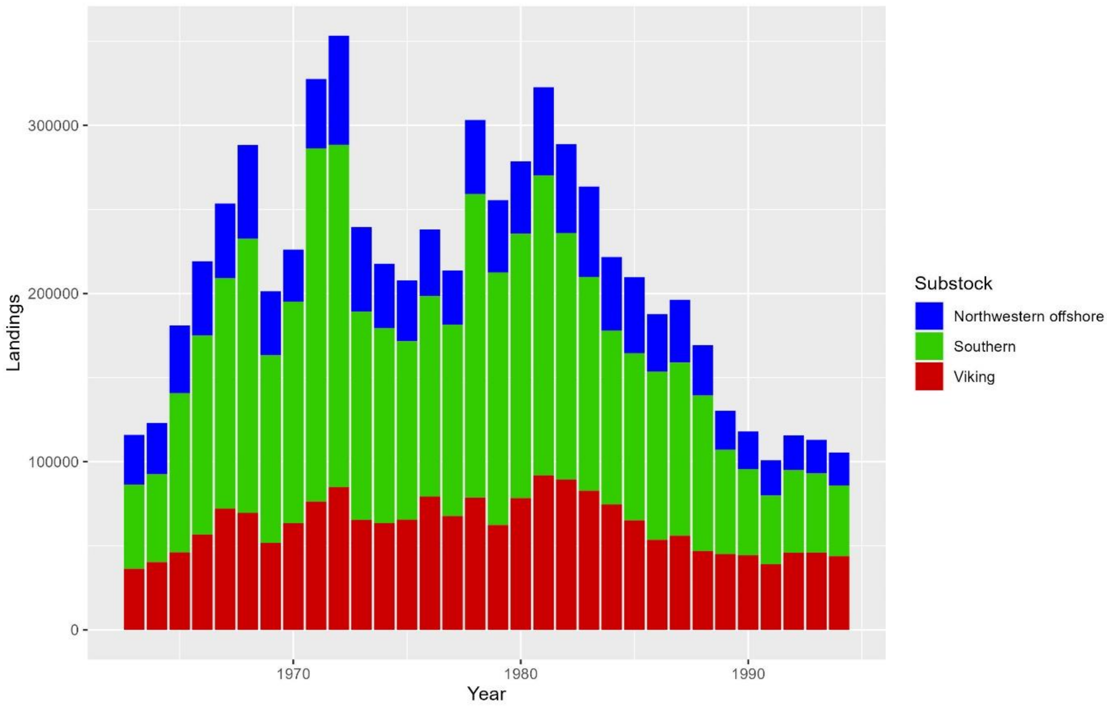


Figure 31. Historical landings of North Sea cod (Cod.27.47d20) split by substock for the period 1963–1994.

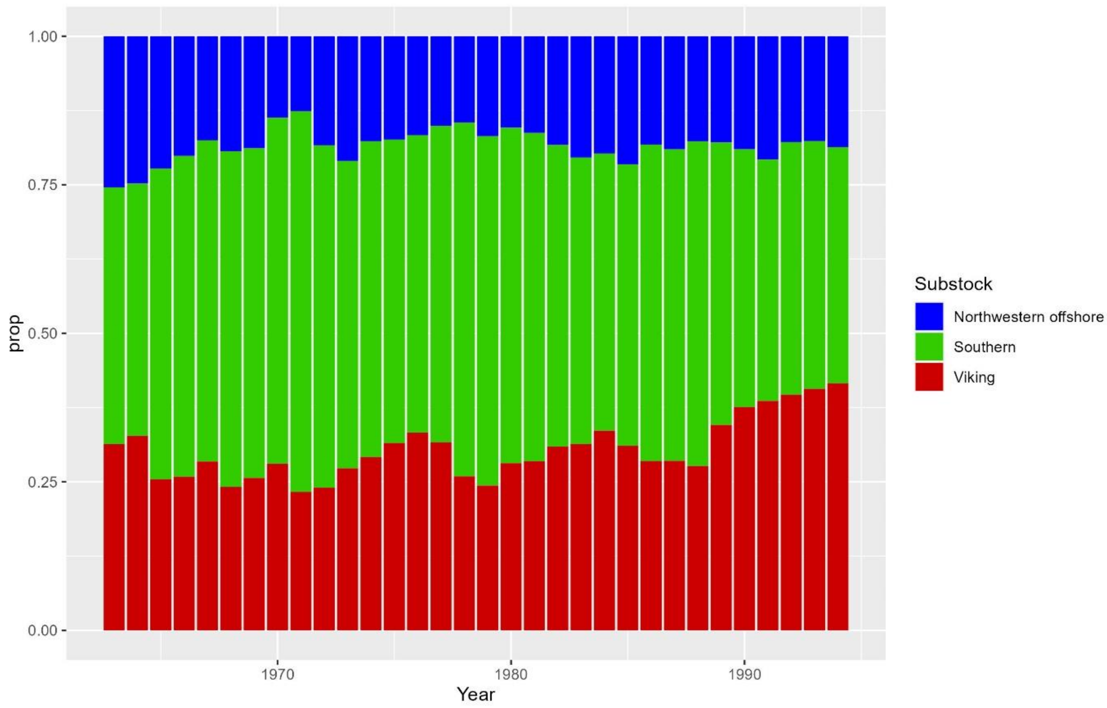


Figure 32. Proportion of historical landings of North Sea cod (Cod.27.47d20) split by substock for the period 1963–1994.

Inclusion of West of Scotland landings in the proportion of historical landings by substock

Historical West of Scotland cod (Cod.27.6a) landings by country and area for the years 1963–1994 were obtained from Scottish experts. The historical landings were available for different combinations of countries and areas (Figure 33).

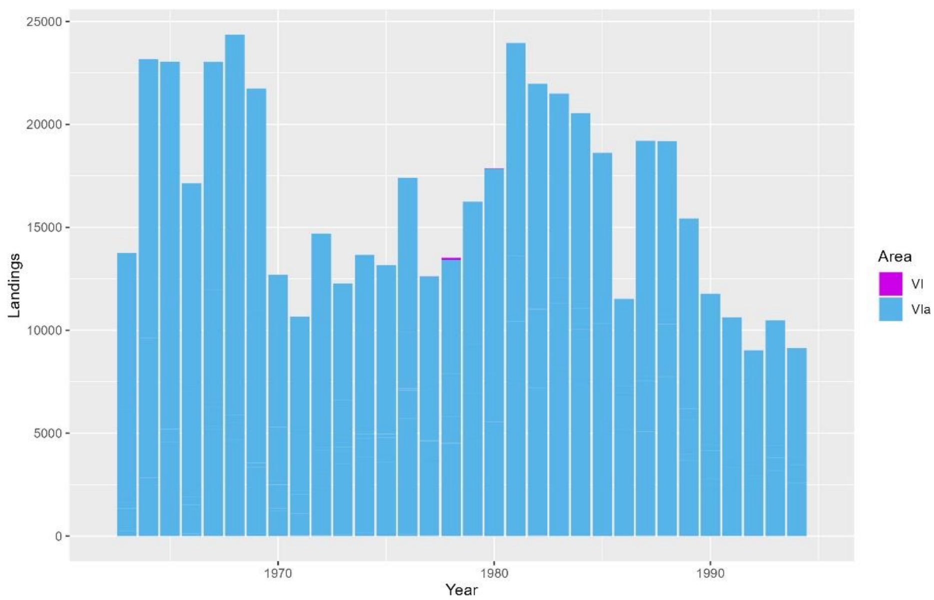


Figure 33. Historical landings by area for West of Scotland cod (Cod.27.6a) for the period 1963–1994.

Area VI in every year represented always a negligible percentage of the total landings. Therefore, we decided to keep area VI in the total landings and consider the potential contamination of cod catches from neighbouring stocks as negligible.

Due to the geographical distribution of the different substocks, all the landings coming from areas VIa and VI were assumed as Northwestern substock landings.

In Figures 34 and 35 the historical landings and the proportion of historical split by substocks are shown for the entire Northern Shelf cod stock area (i.e., North Sea cod and West of Scotland cod).

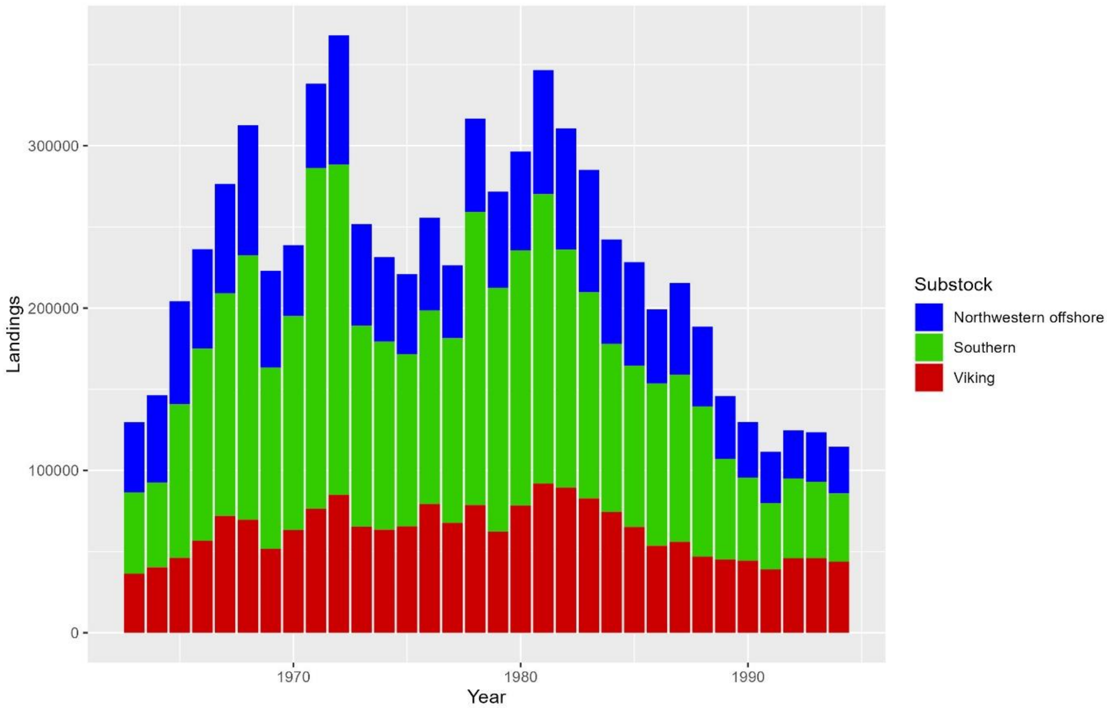


Figure 34. Historical landings of North Sea cod (Cod.27.47d20) and West of Scotland (Cod.27.6a) split by substock for the period 1963–1994.

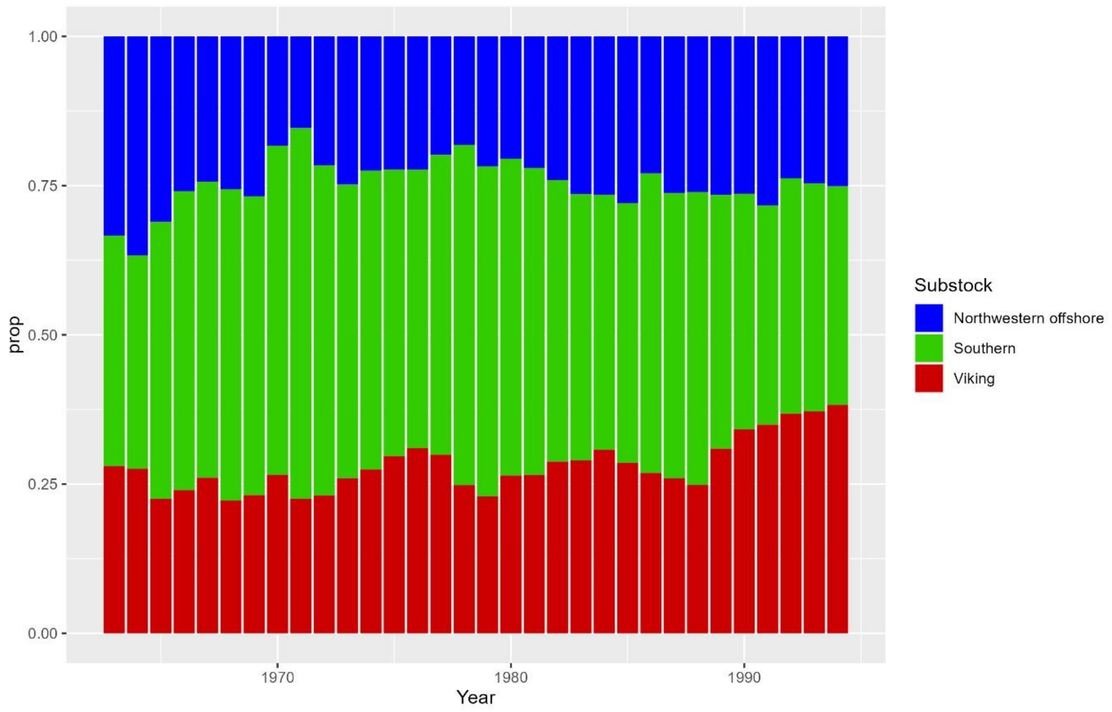


Figure 35. Proportion of historical landings of North Sea cod (Cod.27.47d20) and West of Scotland (Cod.27.6a) split by substock for the period 1963–1994.

Conclusions

The historical landings have been split by substock to produce proportions of landings by substocks.

Several sources of uncertainty need to be considered when using these results.

- The proportion of substocks in the different areas come from Q1 accessions data but are used to split annual landings data.
- The historical landings used include, although in negligible amounts, cod landings from neighbouring stocks.
- Several assumptions have been made to split the historical landings of each country to ICES division.

21.7 Survey index calculations for substocks of Northern Shelf cod

Survey index calculations for sub-stocks of Northern Shelf cod

Nicola Walker, Helen Dobby and Casper Berg

13 November, 2022

Summary

The current advisory units for Northern Shelf cod stocks are North Sea cod in ICES Subarea 4 (North Sea), Division 7.d (English Channel) and Subdivision 20 (Skagerrak), and West of Scotland cod in ICES Division 6.a. The ICES Workshops on Stock Identification of North Sea cod (WKNSCodID, 2020) and West of Scotland Sea cod (WK6aCodID, 2022) concluded (1) genetic populations of Viking and Dogger cod; (2) spatial heterogeneity in the Dogger cod population; and (3) linkages between inshore and offshore sub-populations of cod in 6.a cod with cod in 4.a.

These conclusions have led to the proposal to develop an assessment framework that determines both metapopulation-level stock and sub-stock status. Here we present indices corresponding to three (Viking, Northwestern and Southern) and four (splitting 6.a into inshore and offshore components) sub-stock hypotheses.

Survey data

The survey data sets used are:

- Quarter 1:
  - North Sea International Bottom Trawl Survey (NS-IBTS): covering the North Sea and Skagerrak from 1983.
  - Scottish West Coast Bottom Trawl Survey (SWC-IBTS): covering the West of Scotland for the period 1985-2010.
  - Scottish West Coast Groundfish Survey (SCOWCGFS): covering the West of Scotland from 2011.
- Quarter 3:
  - North Sea International Bottom Trawl Survey (NS-IBTS): covering the North Sea and Skagerrak from 1992.
- Quarter 4:
  - Scottish West Coast Bottom Trawl Survey (SWC-IBTS): covering the West of Scotland for the period 1996-2009.
  - Scottish West Coast Groundfish Survey (SCOWCGFS): covering the West of Scotland from 2011.
  - Irish Groundfish Survey (IE-IGFS): covering the southern portion of 6.a since 2003.

Methods

Indices were calculated using a model-based approach to account for nuisance factors caused by changes or differences in experimental conditions. The methodology is described in Berg and Kristensen (2012) and Berg, Nielsen, and Kristensen (2014) and consists of the following steps:

1. Fit and apply spatial ALK
2. Fit models for catch-at-age
3. Select a grid of haul positions
4. Predict abundance on the grid = abundance maps
5. Sum grid points by whole or sub-stock area = indices

Delta-GAM

Various formulations of the model for producing standardised indices by age for North Sea cod were considered during ICES WKNSEA (2021). These formulations were tested in the SAM assessment model and evaluated according to four criteria: AIC for the survey index models, internal consistency, AIC of the assessment model and degree of retrospective bias in the assessment model in terms of Mohn's rho. Based on these criteria, a high resolution delta-GAM with yearly independent deviations from a fixed spatial field was judged to be most appropriate, and this is the formulation we retain for the subsequent analysis. The exact model formulae are:

```
Positive:Year + s(lon, lat, bs = "ds", k = 120, m = c(1, 0.5)) + s(lon, lat, bs = "ds",
    m = c(1, 0.5), k = 9, by = Year, id = 1) + s(Depth, bs = "ds", m = c(1, 0),
    k = 6) + s(TimeShotHour, bs = "cc", k = 6) + s(Ship, bs = "re") + offset(log(HaulDur))

Presence/absence:Year + s(lon, lat, bs = "ds", k = 80, m = c(1, 0.5)) + s(lon,
    lat, bs = "ds", k = 7, m = c(1, 0.5), by = Year, id = 1) + s(Depth, bs = "ds",
    m = c(1, 0), k = 6) + s(TimeShotHour, bs = "cc", k = 6) + s(Ship, bs = "re") +
    offset(log(HaulDur))
```

Models

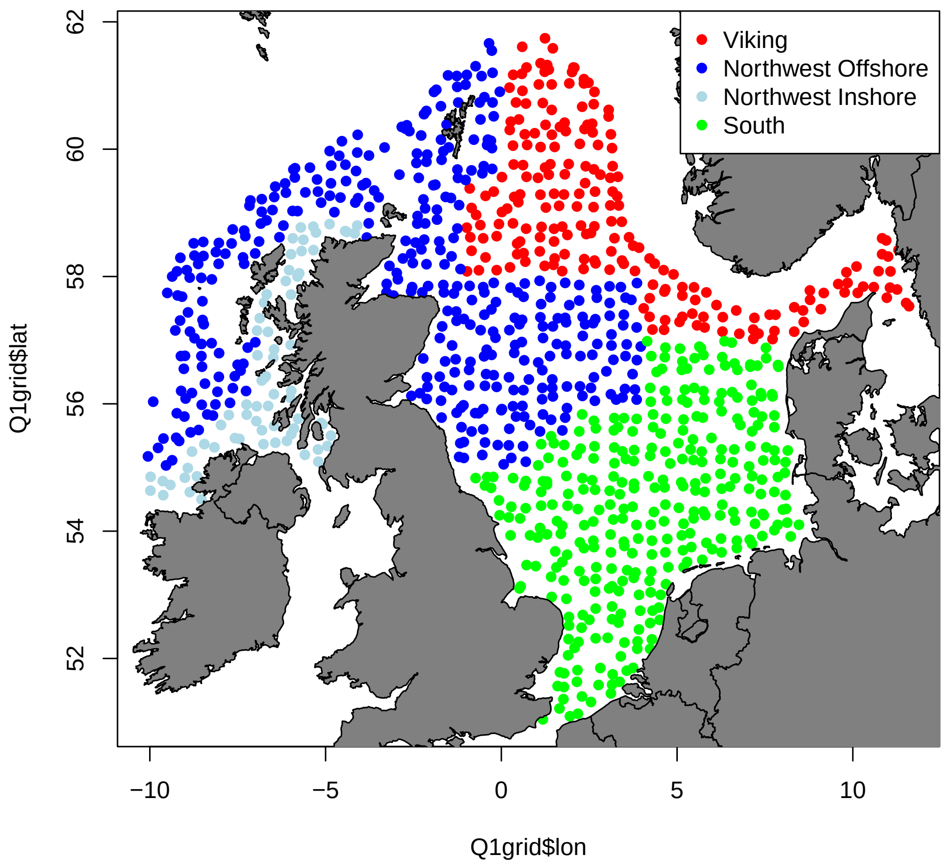
Models were run for each quarter. Given partial areal coverage of the Q3 and Q4 surveys, an additional index combining the Q3 and Q4 data was considered, giving four model runs in total. For the model runs including Q3 and/or Q4 data, a gear effect was included in the formulation to account for use of the Aberdeen Trawl between 1992-1997. A lower resolution formulation had to be used for the Q4 only model. The model runs are summarised as follows:

- Q1 (whole area): Formulation as above; Ages 1-6+
- Q3 (North Sea and Skagerrak only): Includes a gear effect; Ages 0-5+
- Q4 (West of Scotland only): Lower resolution and with a gear effect; Ages 1-4+
- Q3 + Q4 (whole area): Includes a gear effect; Ages 0-5+

For the assessment, it needs to be decided whether to use separate indices per quarter, or to combine Q3 and Q4 for full area coverage.

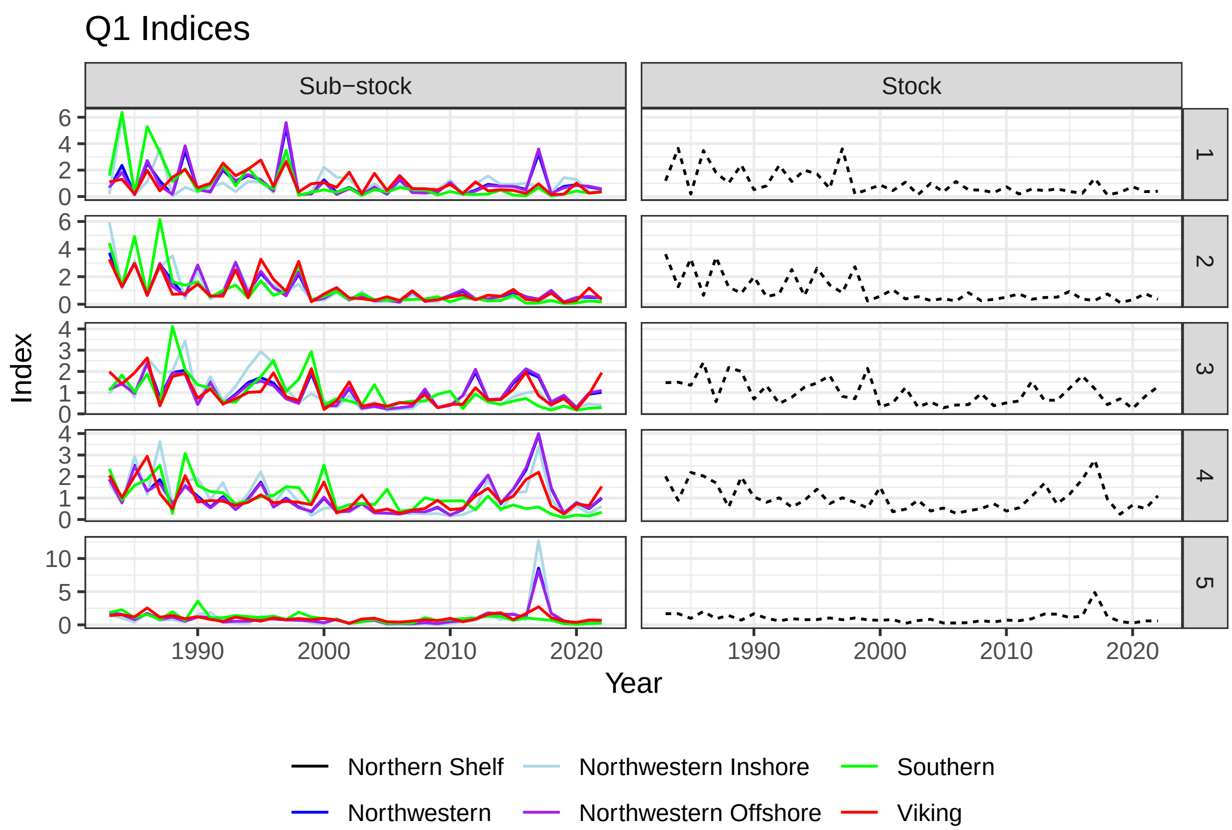
Sub-stocks

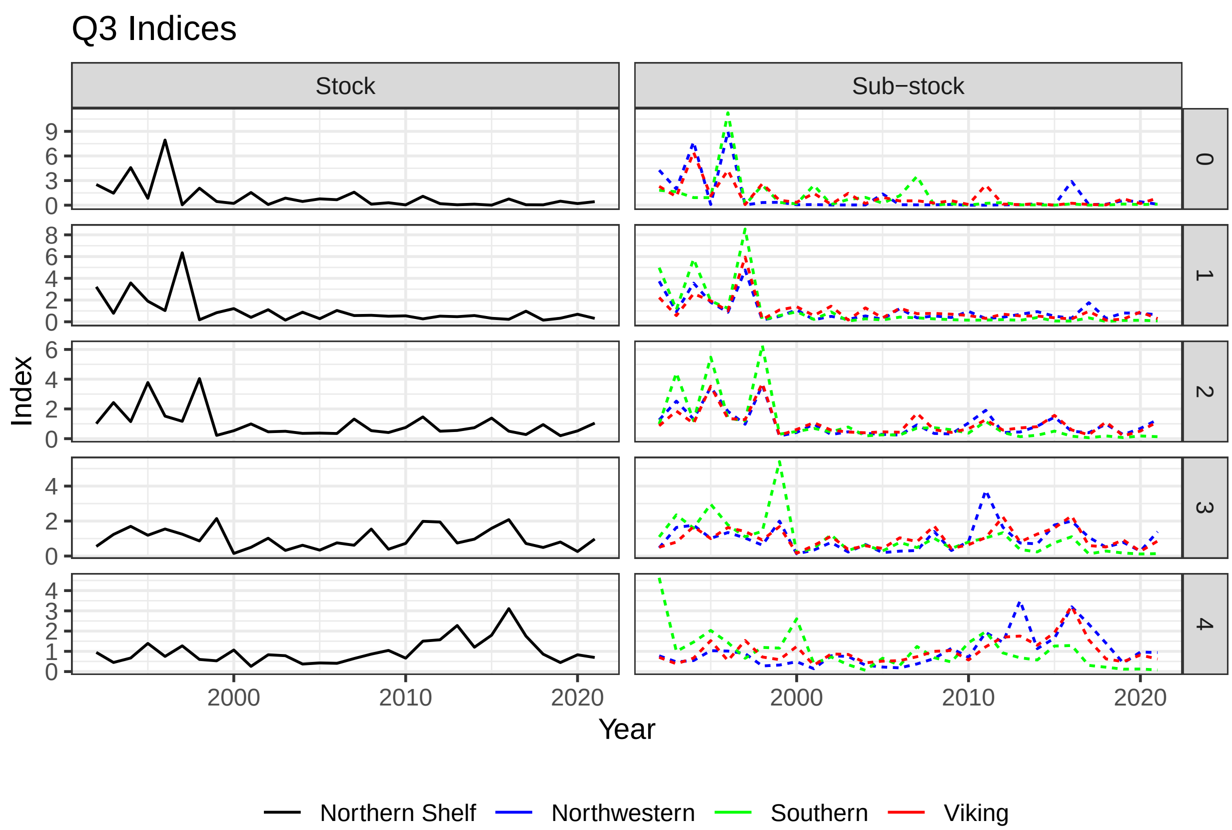
The following plot shows the grid of haul positions. We assume that any mixing during Q1 is small/negligible and that all fish observed during the Q1 surveys can be allocated to sub-stock based on where they were found. Hence indices for Q1 were calculated by summing haul positions by sub-area. We do not make this assumption for fish observed in the Q3 surveys. Hence indices for Q3 and Q4 were obtained by summing all grid points covered by the relevant surveys.

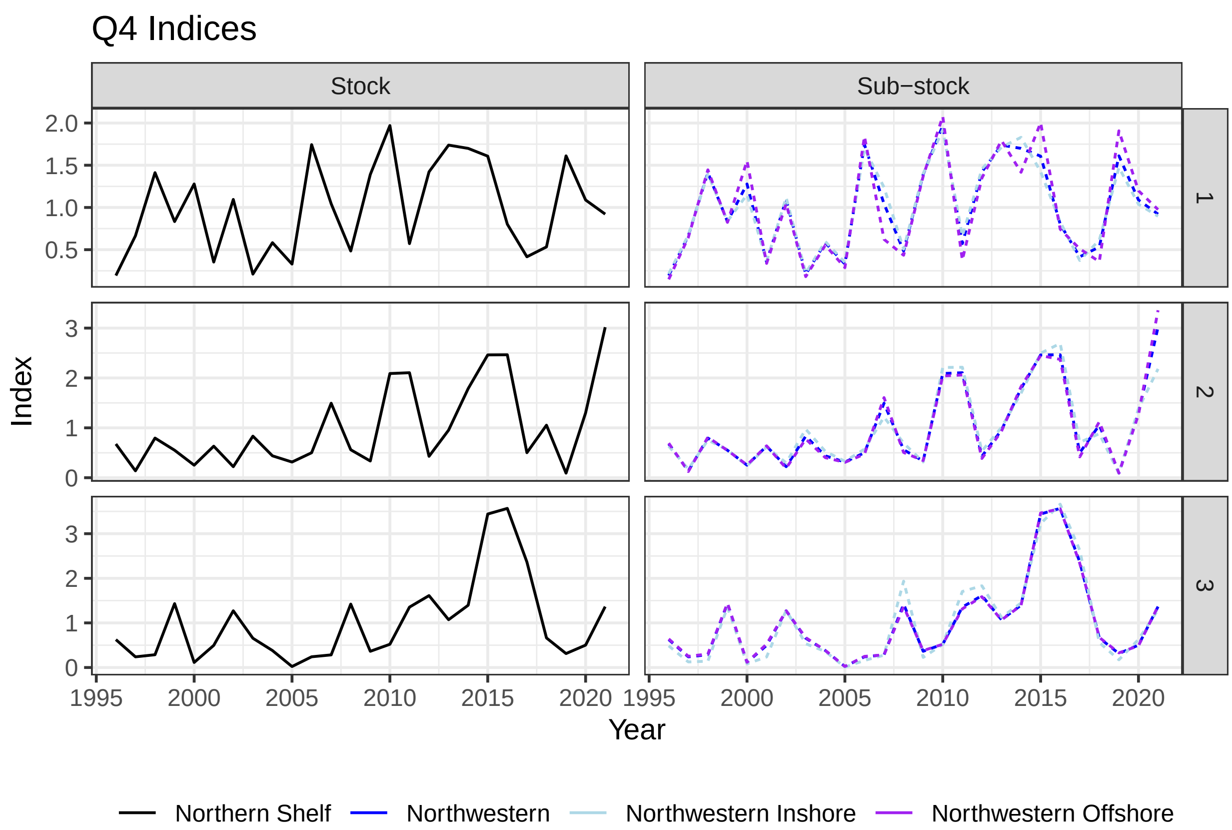


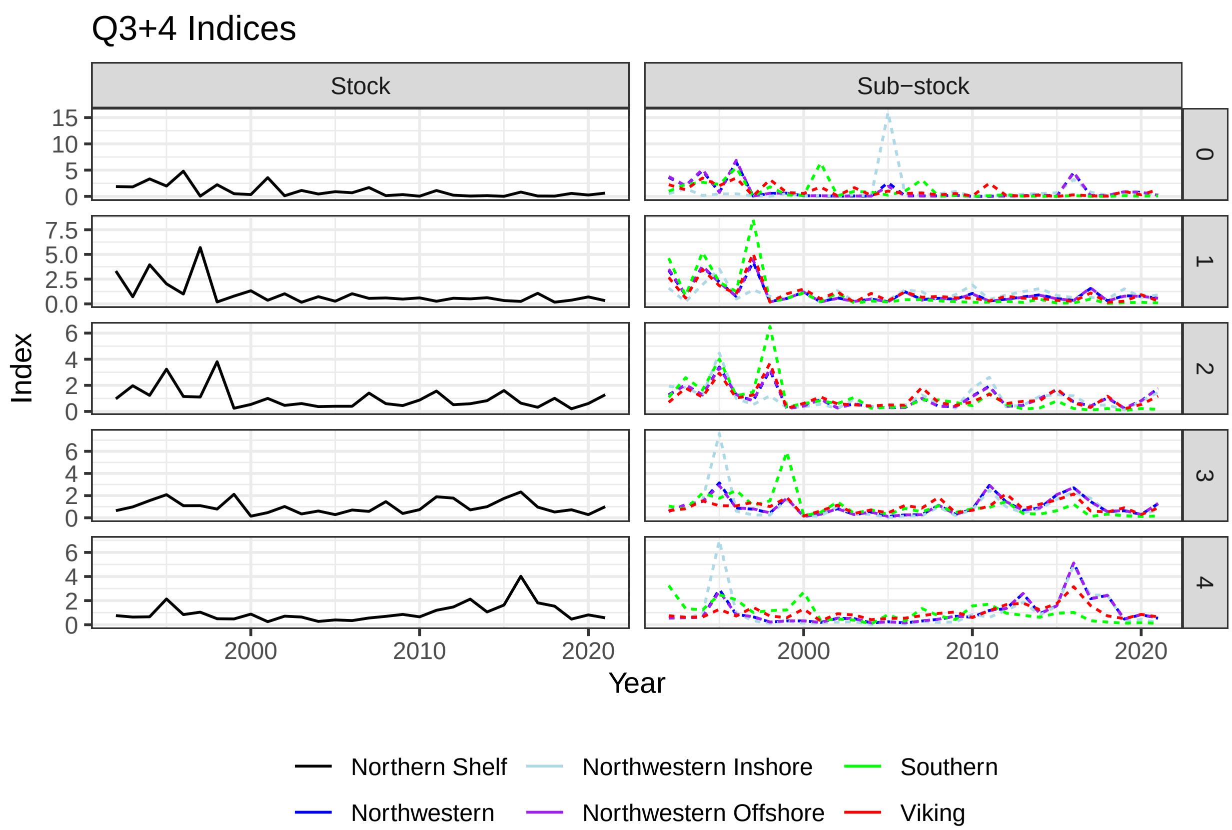
Results

The following plots show the mean standardised indices-at-age corresponding to each of the four models. Solid lines are used to denote the indices that would be used as input to the stock assessment, while dashed lines show either the composite index or substock split, based on mixing assumptions. For the Q1, Q4 and Q3+4 models, the inshore/offshore split in the Northwestern sub-stock is shown with light blue and purple lines respectively. Plus groups are not plotted.


Q1 Indices
Sub−stock
Stock
1
2
3
4
5
Index
Year
1990
2000
2010
2020
Northern Shelf
Northwestern
Northwestern Inshore
Northwestern Offshore
Southern
Viking

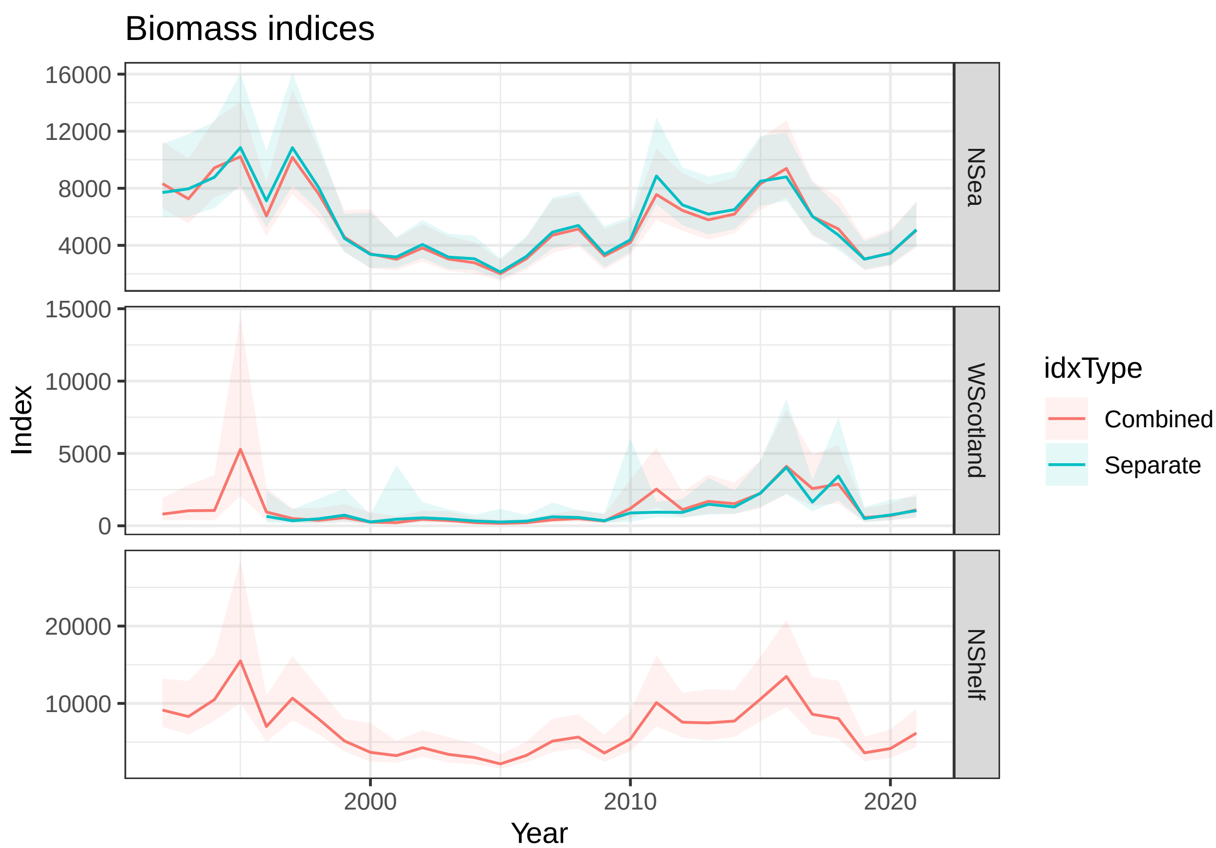

Q3 Indices
Stock
Sub−stock
0
1
2
3
4
Index
Year
2000
2010
2020
Northern Shelf
Northwestern
Southern
Viking


Q4 Indices
Stock
Sub−stock
Index
Year
1
2
3
2.0
1.5
1.0
0.5
0
1
2
3
1995
2000
2005
2010
2015
2020
Northern Shelf
Northwestern
Northwestern Inshore
Northwestern Offshore



Biomass indices

The next plot compares biomass indices calculated using separate models per quarter (Q3 and Q4) to those derived using the combined model (Q3+4). This comparison shows similar trends in the North Sea with slightly less uncertainty in the combined Q3+Q4 index, which lends support to using the combined Q3+4 index. There are larger differences in trends in the West of Scotland which may lend support to using the separate indices for Q3 and Q4; however, these differences may be caused by the lower +group age and model resolution used for Q4. Age 0, where included in the model, was excluded from the biomass plots for the purpose of a fairer comparison.

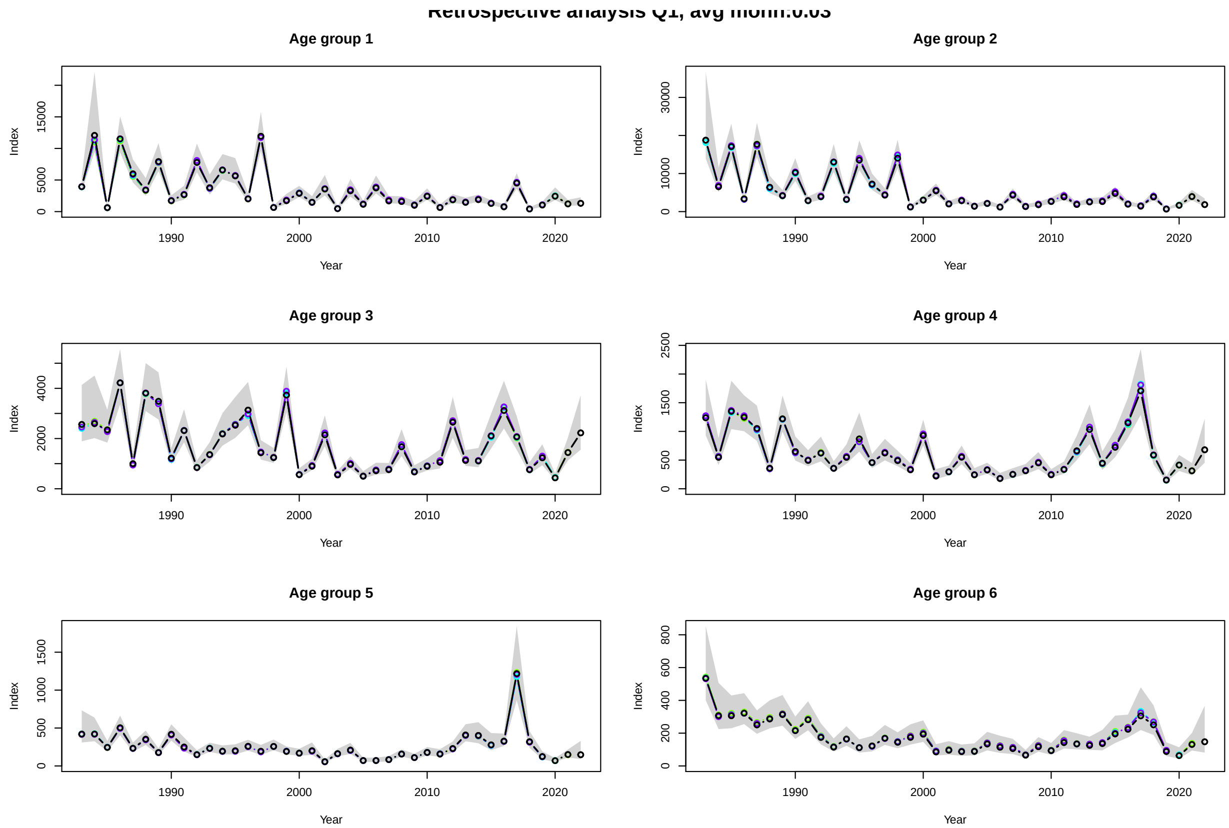


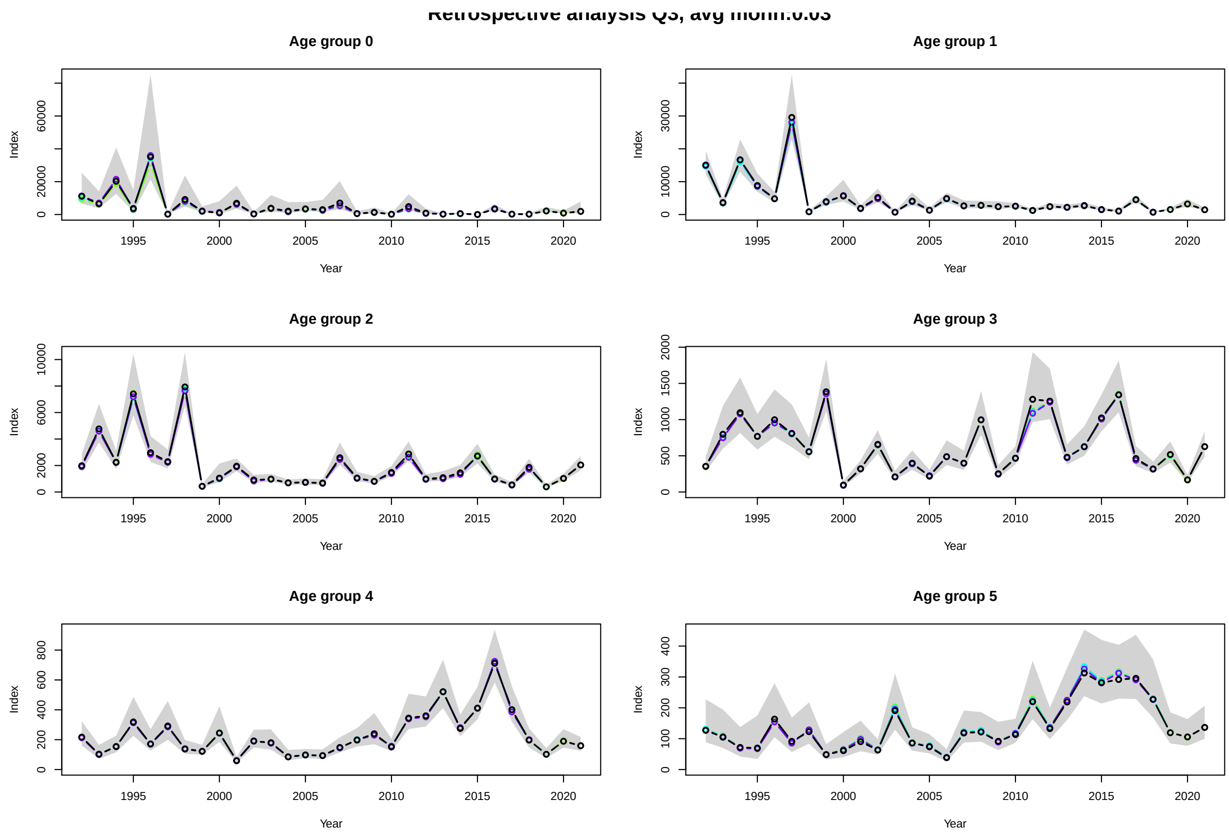
Abundance maps

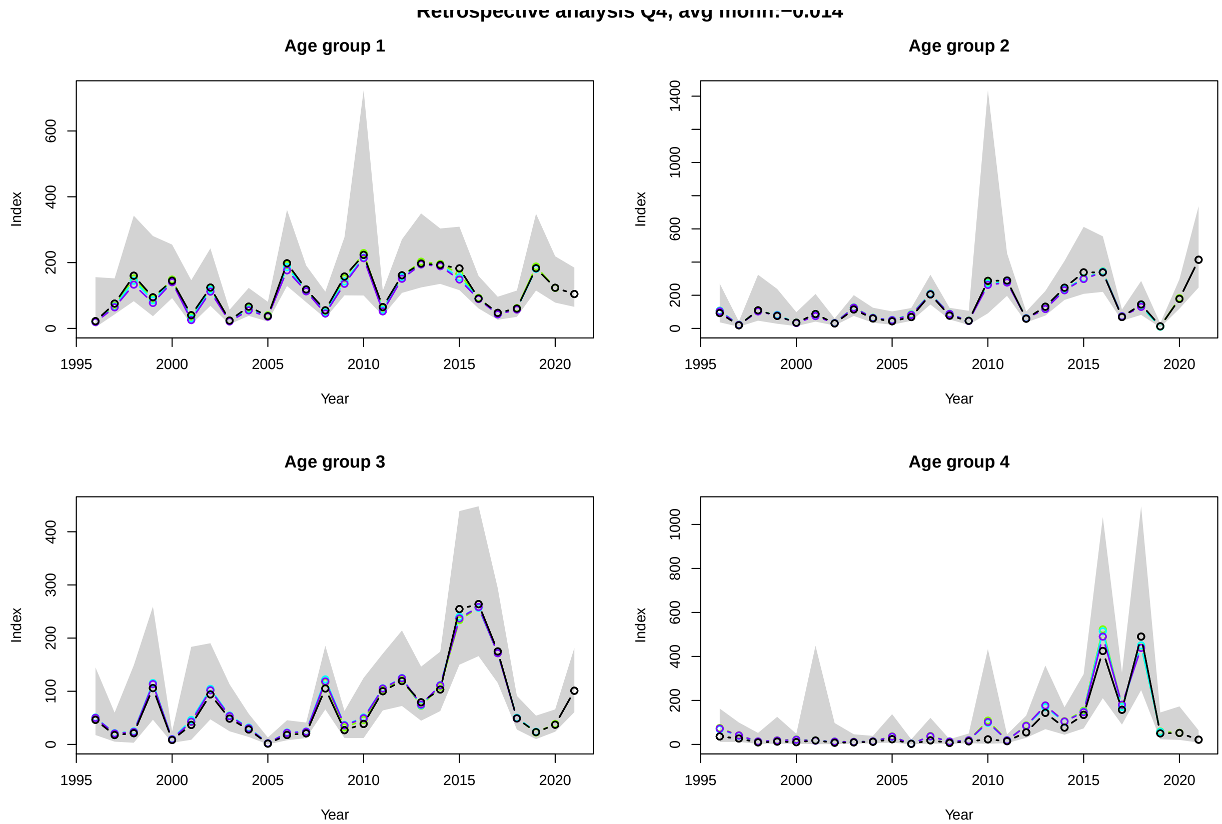
Standardised abundance maps by age for each of the four models are presented along with other detailed model results in Appendix 1. Given age data in Q4 are available only from 1996 and the Q4 model had to be fit to ages 1-4+, results from the Q3+4 model for 1992-1995 and for older and younger ages are to some extent extrapolations from the data.

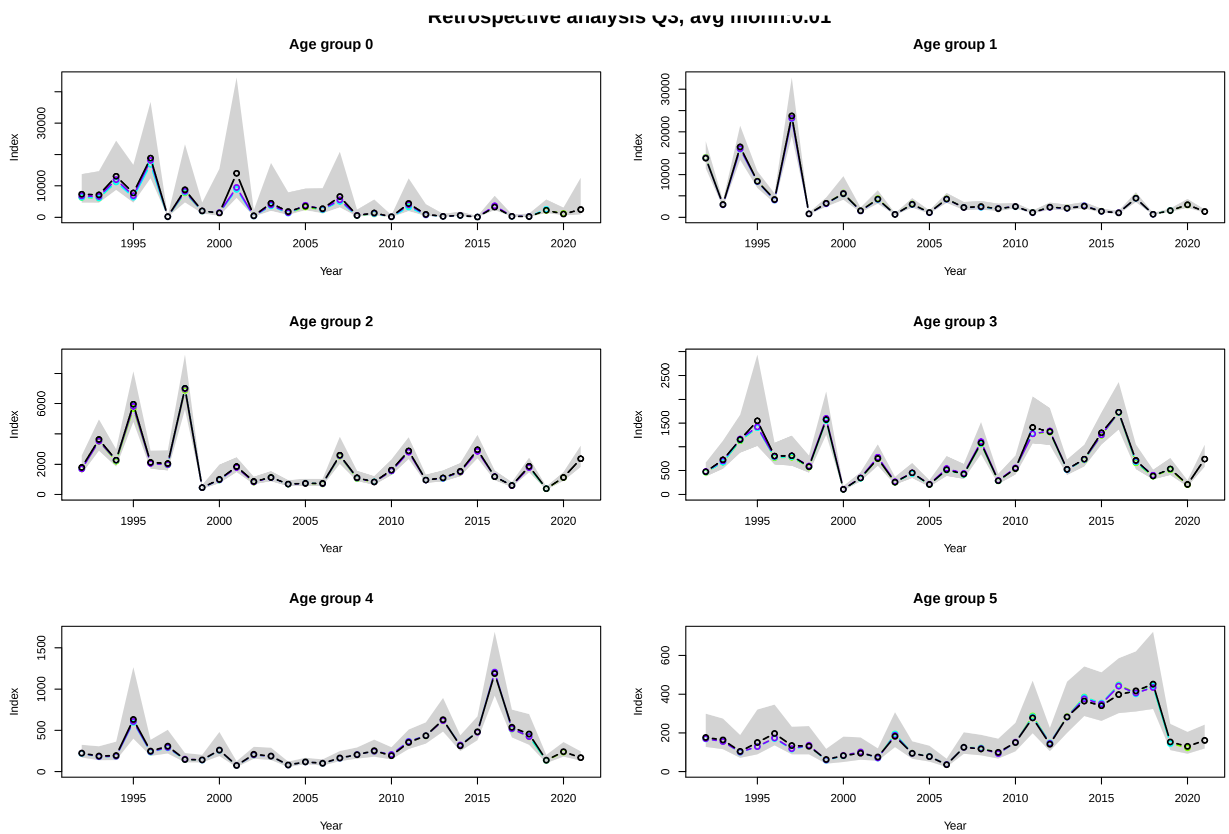
Retrospective analysis

Retrospective analyses with three peels give average Mohn's rho values of 0.03, 0.03, -0.01 and 0.01 for the Q1, Q3, Q4 and Q3+4 models respectively. The higher values for Q1 and Q3 are somewhat driven by the 6+ group and age 0, respectively, which are not included in all models. Taking averages across ages 1-4 gives more consistent Mohn's rho values between models, noting that age 4 is a plus group in the Q4 model.


Retrospective analysis Q1, avg mohn:0.03
Age group 1
Age group 2
Age group 3
Age group 4
Age group 5
Age group 6
Index
Year


Retrospective analysis Q3, avg mohn:0.03
Age group 0
Age group 1
Age group 2
Age group 3
Age group 4
Age group 5
Index
Year





The table below compares Mohn's rho values across ages and models.

	Q1	Q3	Q4	Q34
Age 0	NA	0.22	NA	0.17
Age 1	0.03	0.00	-0.02	0.00
Age 2	0.04	-0.03	-0.07	-0.02
Age 3	0.03	-0.01	0.02	0.01
Age 4	0.01	0.01	0.02	-0.03
Age 5	-0.01	0.00	NA	-0.05
Age 6	0.07	NA	NA	NA
Average	0.03	0.03	-0.01	0.01
Average 1-4	0.03	-0.01	-0.01	-0.01

Internal consistency

The following tables show internal consistencies (in cohort strength) for each of the models both for the whole model area and split to sub-stock.

[1] "Quarter 1"

	Northern Shelf	Viking	Northwestern	Southern	Offshore	Inshore
Age 1 vs 2	0.89	0.76	0.79	0.89	0.81	0.42
Age 2 vs 3	0.83	0.79	0.80	0.88	0.79	0.85
Age 3 vs 4	0.84	0.78	0.84	0.89	0.84	0.74
Age 4 vs 5	0.81	0.76	0.79	0.75	0.81	0.60
Age 5 vs 6	0.67	0.51	0.68	0.72	0.69	0.59
Average	0.81	0.72	0.78	0.82	0.79	0.64

[1] "Quarter 3"

	North Sea	Viking	Northwestern (partial)	Southern
Age 0 vs 1	0.80	0.79	0.79	0.76
Age 1 vs 2	0.86	0.78	0.91	0.91
Age 2 vs 3	0.81	0.81	0.80	0.83
Age 3 vs 4	0.74	0.76	0.63	0.68
Age 4 vs 5	0.77	0.70	0.80	0.44
Average	0.80	0.77	0.78	0.72

[1] "Quarter 4"

	Northwestern (partial)	Offshore (partial)	Inshore
Age 1 vs 2	0.72	0.77	0.67
Age 2 vs 3	0.55	0.55	0.53
Age 3 vs 4	0.71	0.71	0.74
Average	0.66	0.68	0.65

[1] "Quarters 3 + 4"

	Northern Shelf	Viking	Northwestern	Southern	Offshore	Inshore
Age 0 vs 1	0.77	0.76	0.79	0.76	0.80	0.41
Age 1 vs 2	0.85	0.80	0.88	0.88	0.88	0.64
Age 2 vs 3	0.79	0.79	0.76	0.88	0.77	0.58
Age 3 vs 4	0.74	0.75	0.71	0.70	0.71	0.61
Age 4 vs 5	0.77	0.70	0.80	0.57	0.80	0.71
Average	0.78	0.76	0.79	0.76	0.79	0.59

Modelling considerations

In the new SAM modelling framework, data are split only where we have strong evidence that the data can be clearly separated into sub-stocks, based on knowledge about biology, distribution and movement of sub-stocks to infer what data represent. Based on the conclusions of ICES WKNSCodID (2020) and WK6aCodID (2022), we assume that all fish observed during the Q1 surveys can be allocated to sub-stock based on where they were found while the Q3 and Q3+4 indices represent totals for all sub-stocks covered by the relevant surveys.

For the assessment, it needs to be decided whether to use separate indices per quarter, or to combine Q3 and Q4 for full area coverage.

With the SAM modelling assumptions in mind, the below details considerations for the two index options.

Separate Q3 and Q4 indices

- The Q3 index gives partial stock coverage (i.e., does not cover 6.a).
- The Q4 index can only say something about the Northwestern sub-stock. This is again partial coverage (i.e., does not cover the North Sea portion of the Northwestern sub-stock) and assuming no mixing in Q4.
- The new SAM model includes a vulnerability matrix that allows to specify the proportion of sub-stocks covered by each tuning fleet. This may help with the partial stock and sub-stock coverage of the Q3 and Q4 indices; however, this matrix must be specified (it does not estimate well), which may be difficult to do when mixing of sub-stocks is assumed in Q3.
- Keeping the indices separate may contribute to better estimation of fisheries selectivity for sub-stocks within SAM.
- There is a danger that indices for smaller areas (particularly the Q4 indices covering 6.a only) carry disproportionately high influence in the SAM assessment.

Combined Q3 + Q4 indices

- Full stock coverage.
- (Very slightly) less uncertainty in biomass indices.
- There is some extrapolation in 6.a early in the time series and for the youngest and oldest ages. However, this is expected to have a small impact at the stock level (assuming mixing).
- It may not be suitable to combine quarters if we include age 0 in the SAM assessment, due to growth between quarters 3 and 4.

Conclusions

Given the arguments made above, the authors recommend to:

- Proceed with combined Q3 + Q4 indices.
- Continue to feed uncertainty from the indices into the SAM assessment.

References

Berg, C. W., and K. Kristensen. 2012. "Spatial Age-Length Key Modelling Using Continuation Ratio Logits." *Fisheries Research* 129: 119–26.

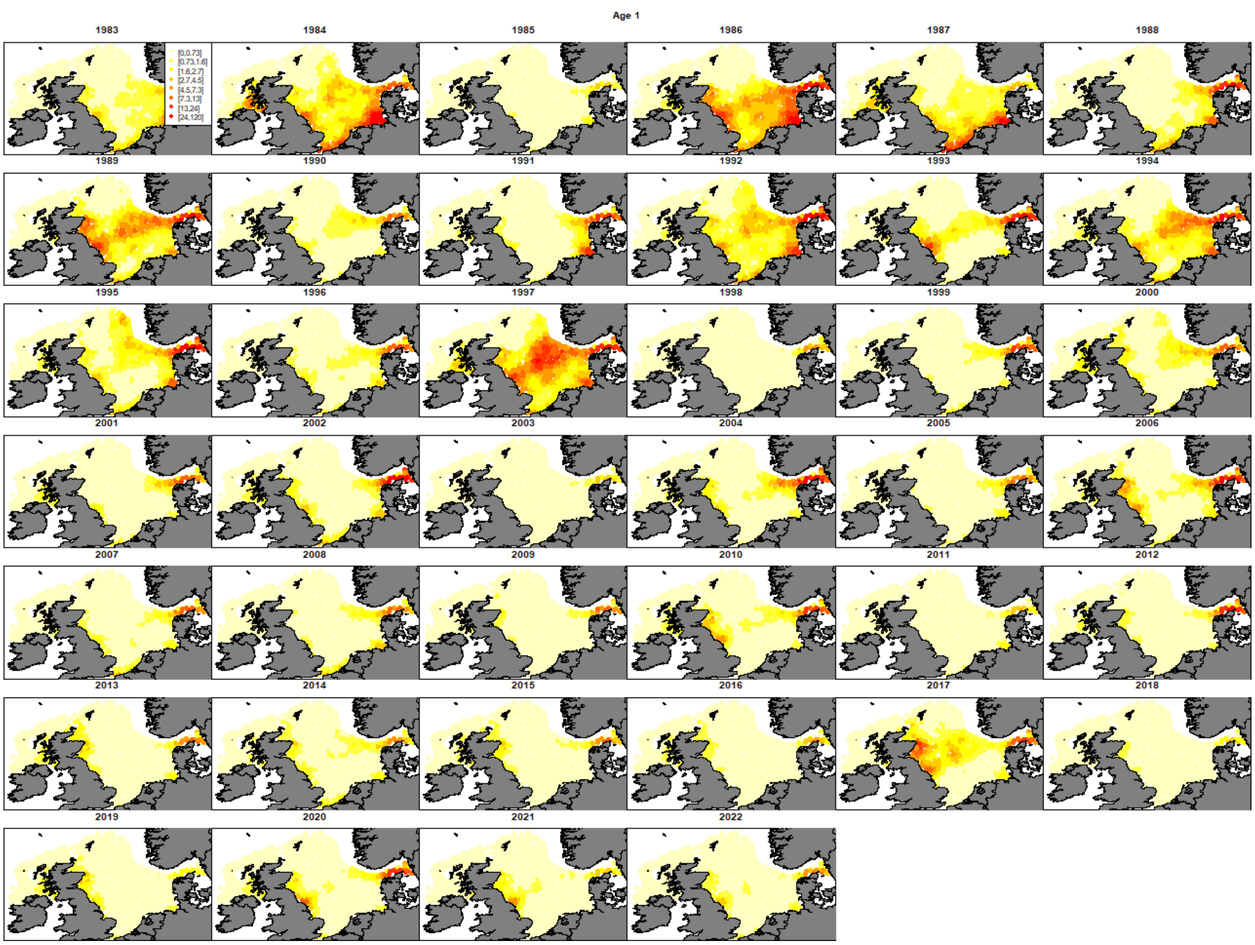
Berg, C. W., A. Nielsen, and K. Kristensen. 2014. "Evaluation of Alternative Age-Based Models for Estimating Relative Abundance from Survey Data in Relation to Assessment Models." *Fisheries Research* 151: 91–99.

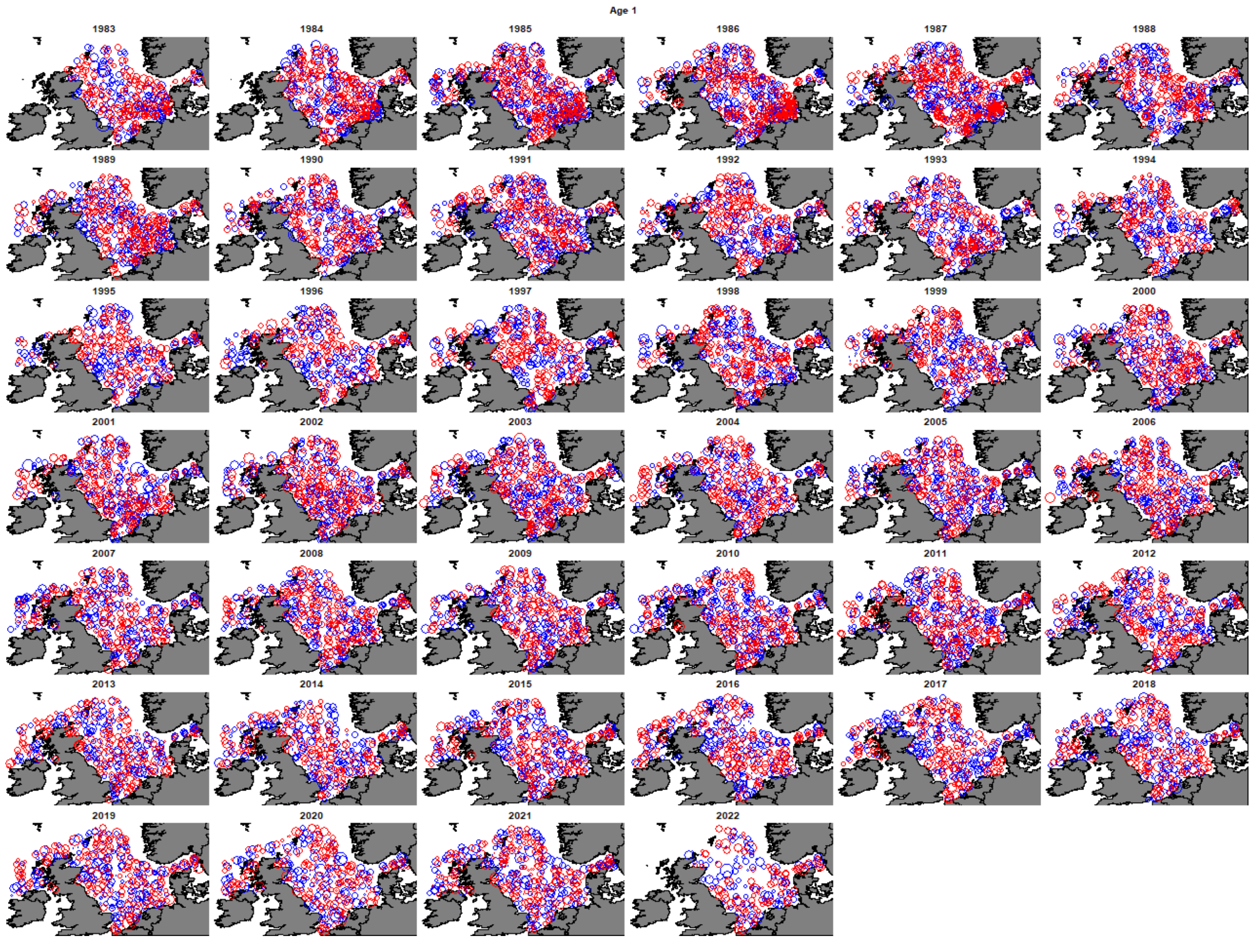
Apendix 1: Detailed model results

The following plots show detailed results for each of the four models. For each age group four figures are shown: Standardised abundance maps, spatial standardised residuals, further residual plots and the estimated effects of bottom depth and time of day.

Quarter 1

Age 1




Age 1
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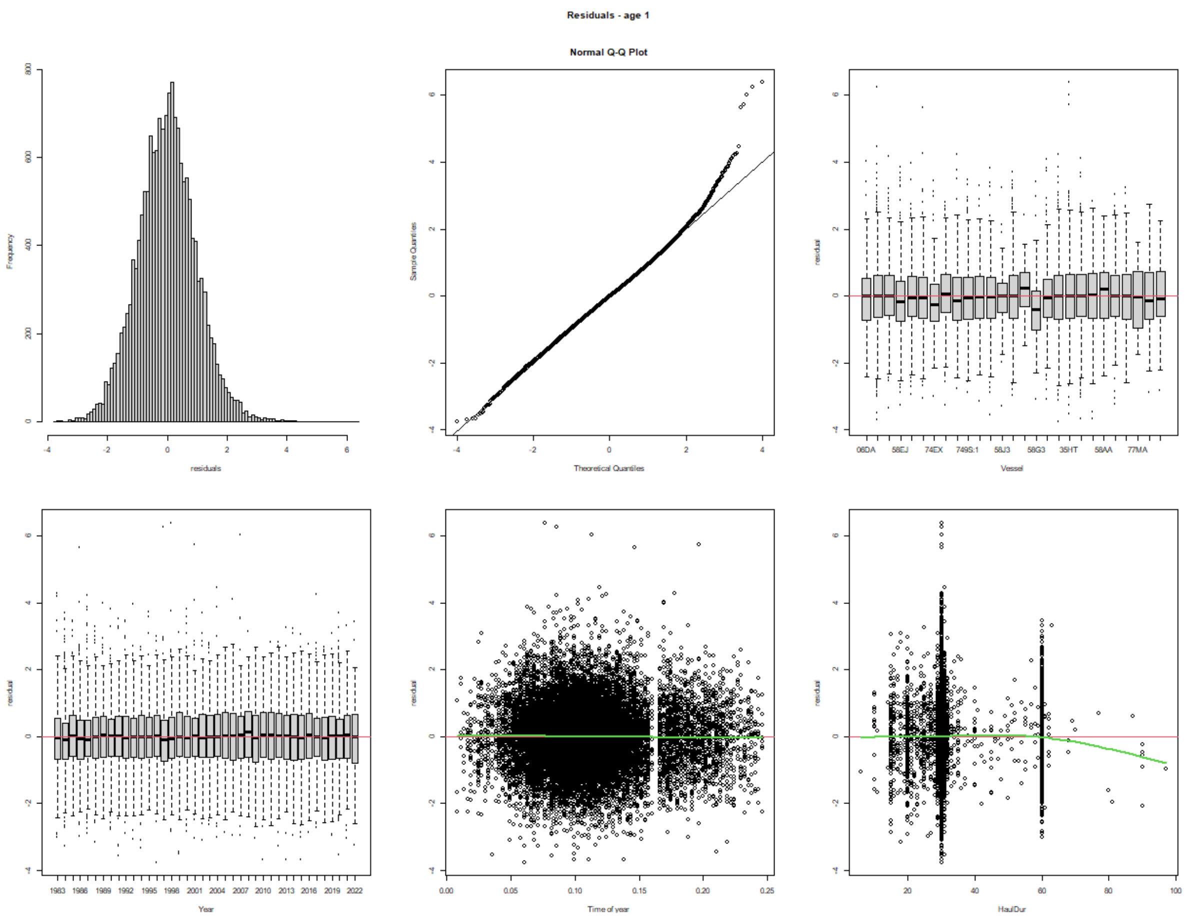
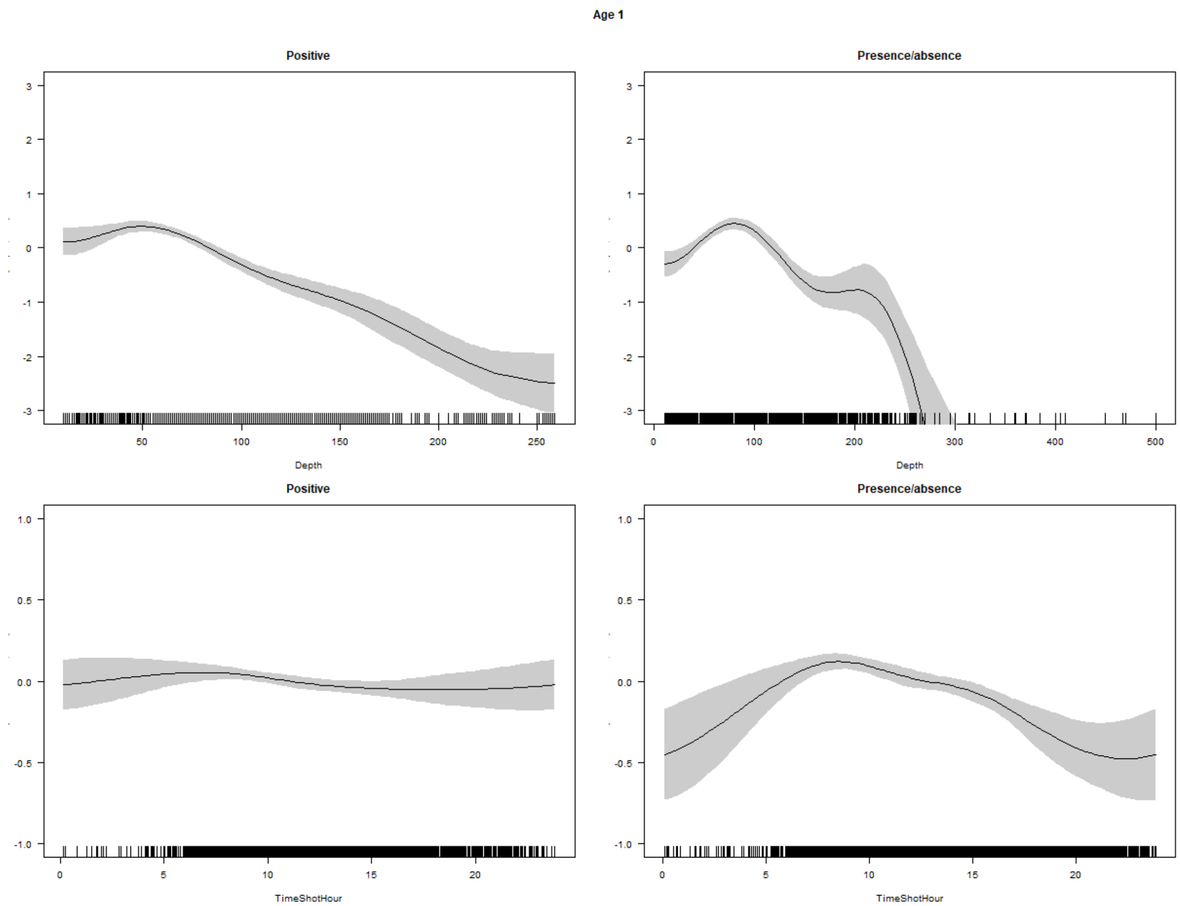
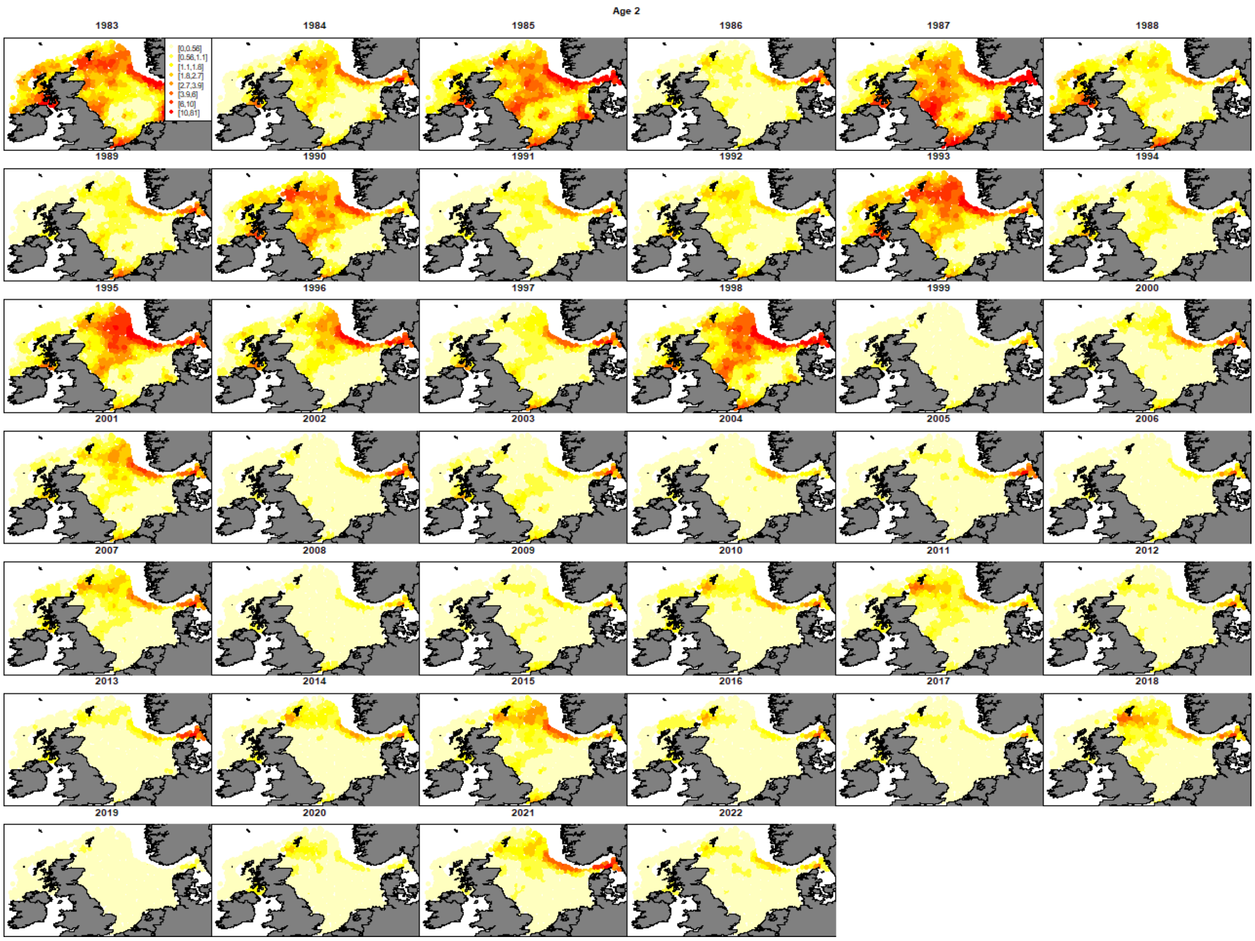

Residuals - age 1
Normal Q-Q Plot
Frequency
residuals
Sample Quantiles
Theoretical Quantiles
residual
Vessel
Year
Time of year
HaulDur


Age 1
Positive
Presence/absence
Depth
Depth
Positive
Presence/absence
TimeShotHour
TimeShotHour

Age 2


Age 2
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2021
2022
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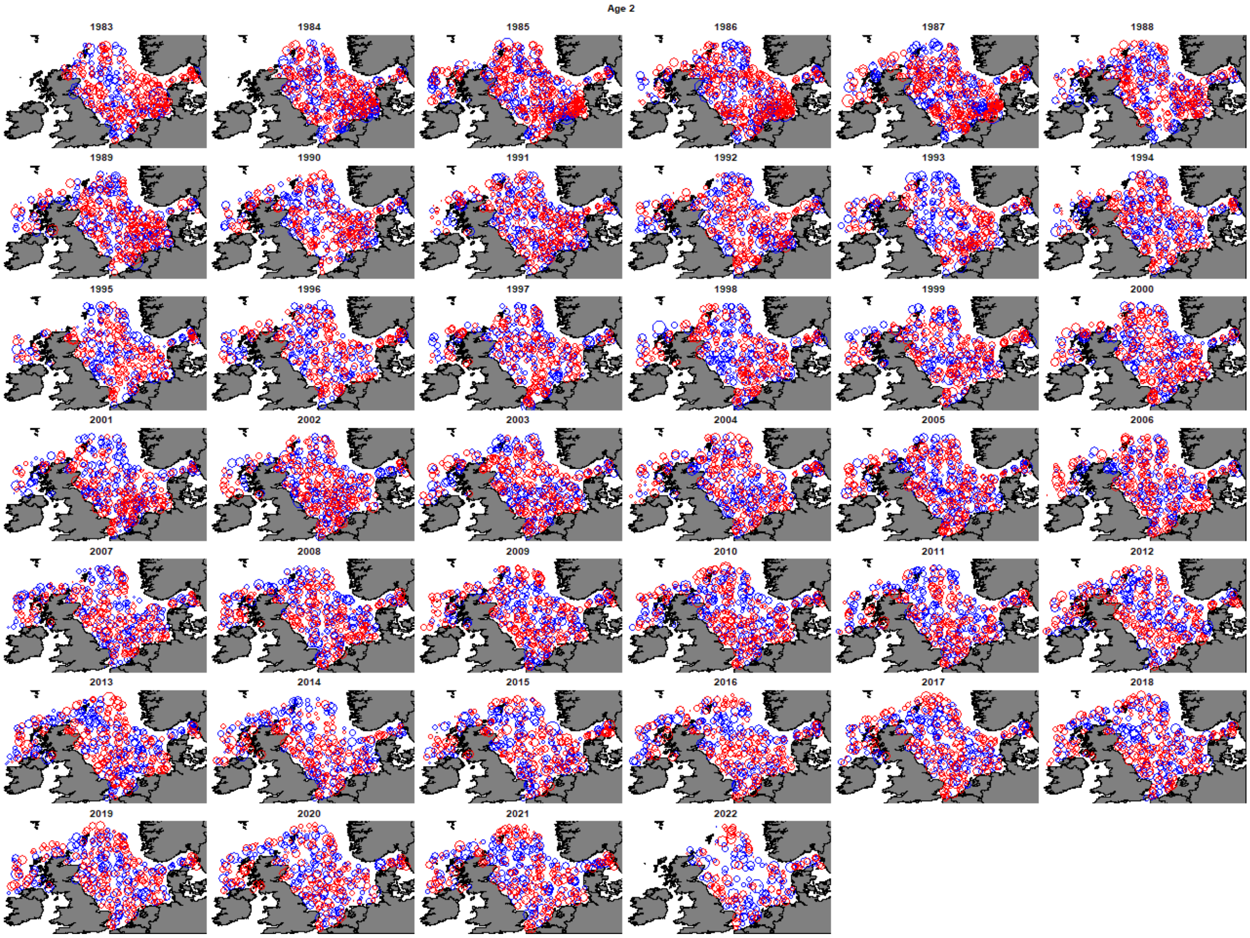
[10,81]


Age 2
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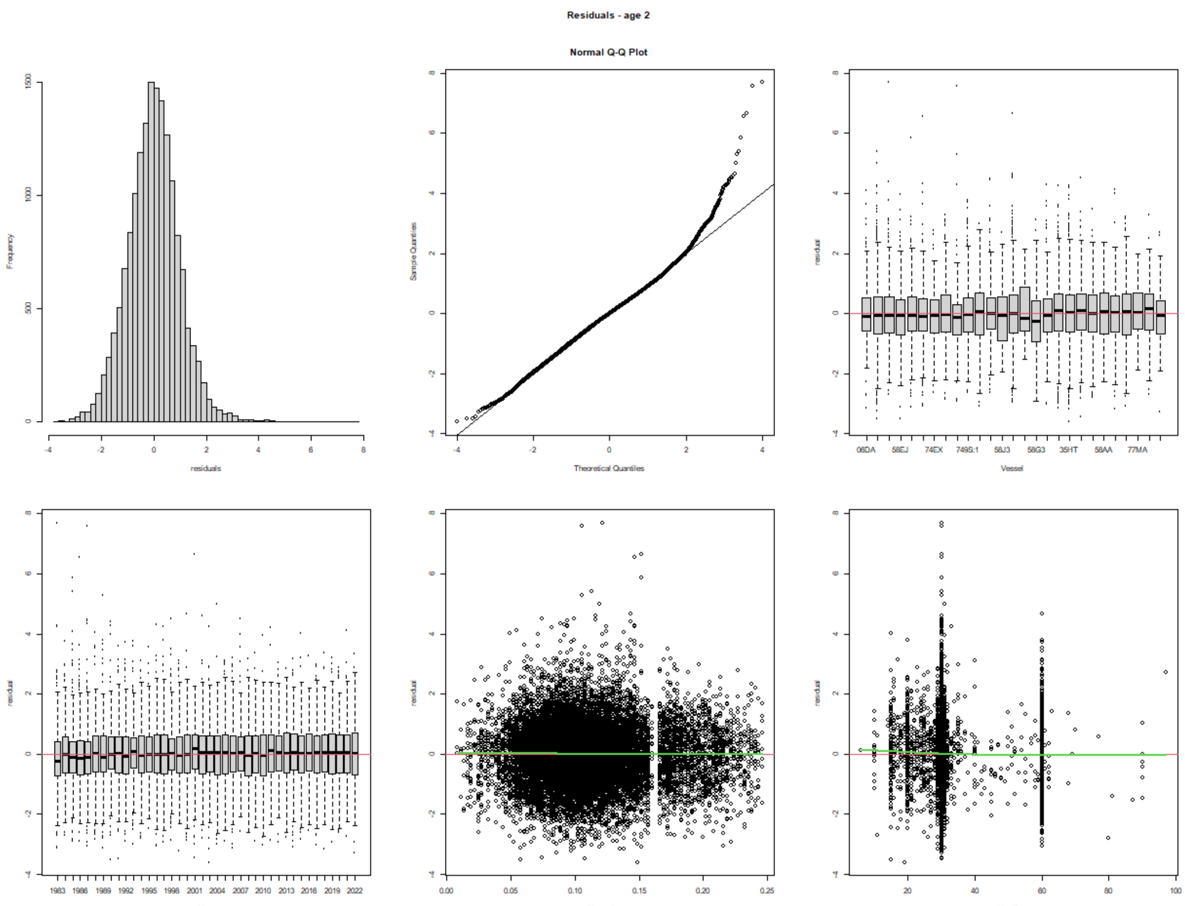
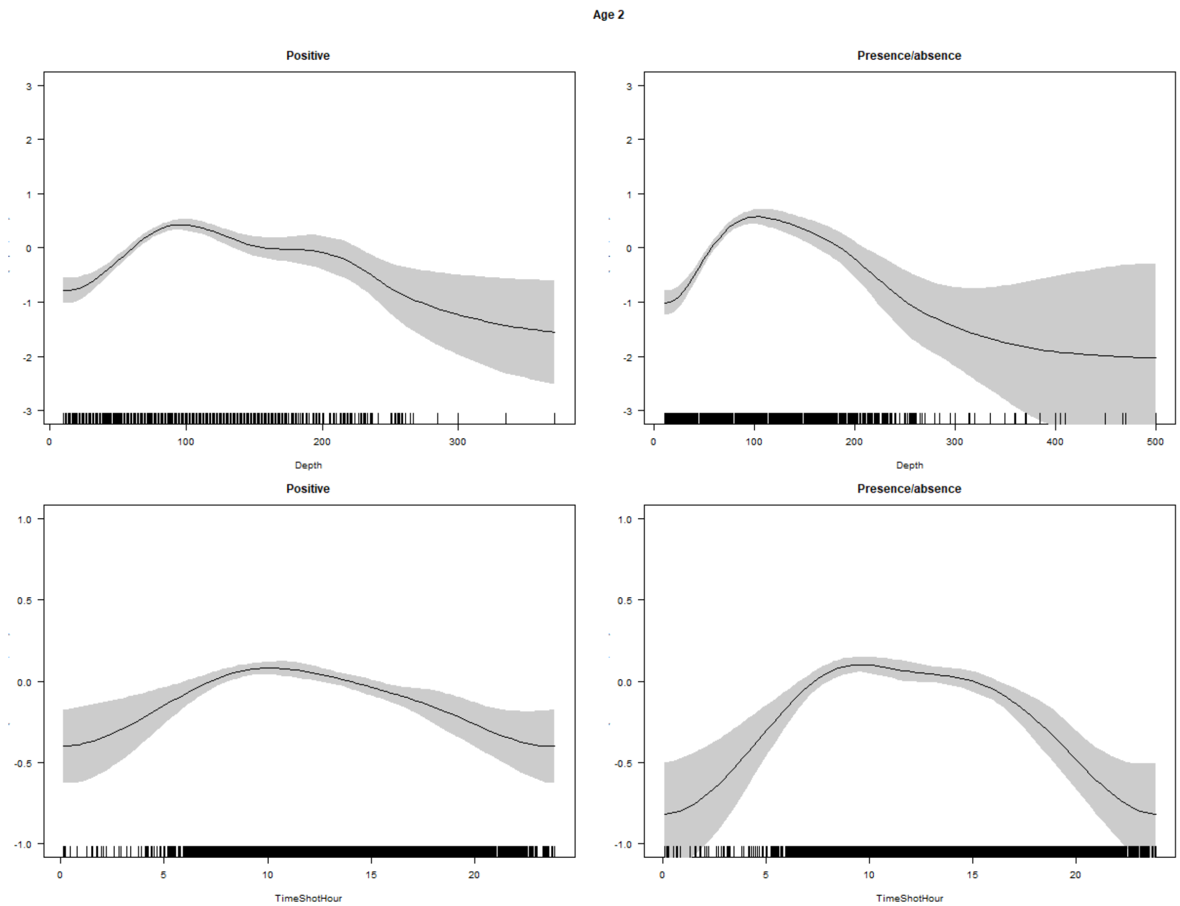
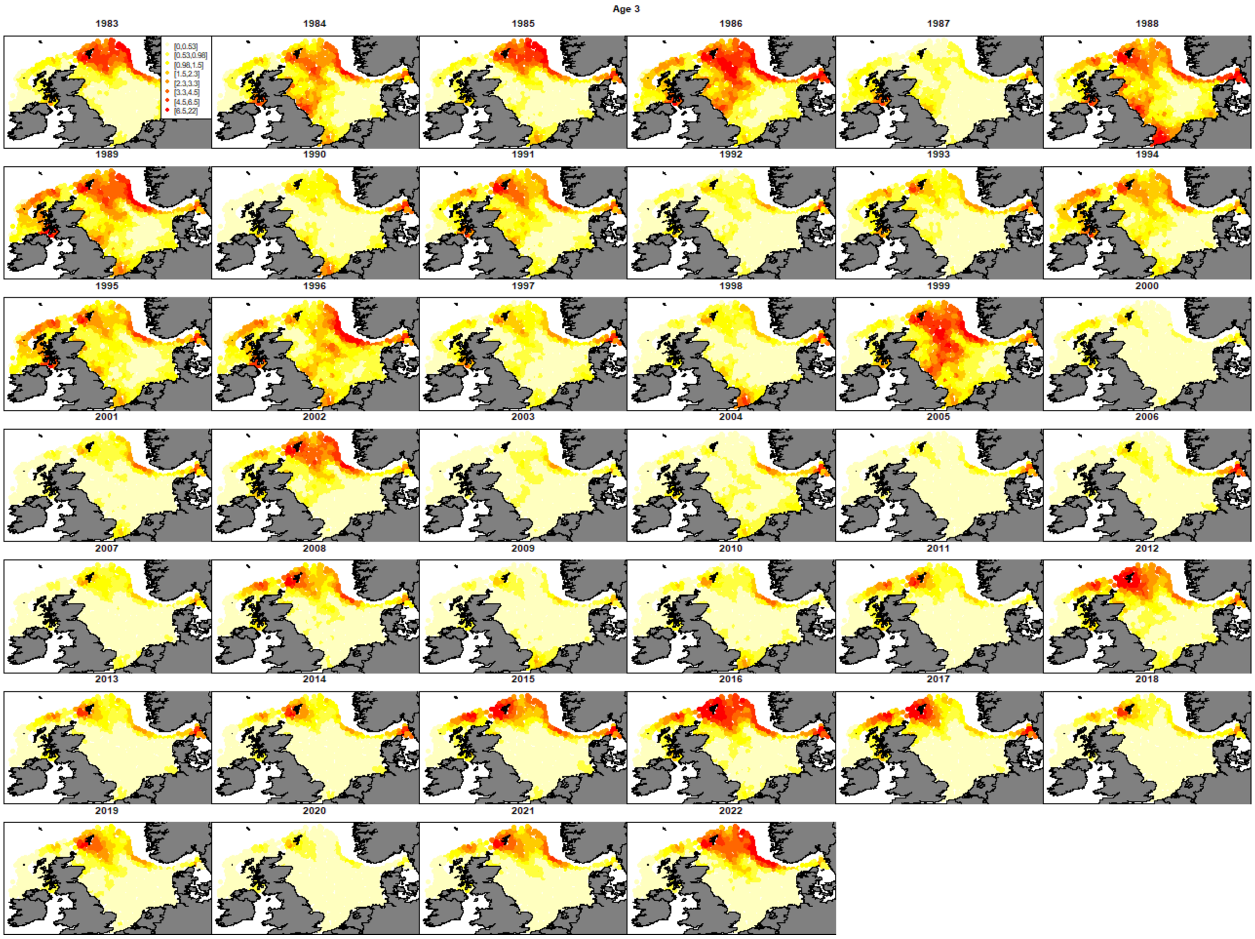

Residuals - age 2
Normal Q-Q Plot
Frequency
residuals
Sample Quantiles
Theoretical Quantiles
residual
Vessel
06DA
58EJ
74EX
749S:1
58J3
58G3
35HT
58AA
77MA
Year
Time of year
HaulDur


Age 2
Positive
Presence/absence
Depth
Depth
Positive
Presence/absence
TimeShotHour
TimeShotHour

Age 3


Age 3
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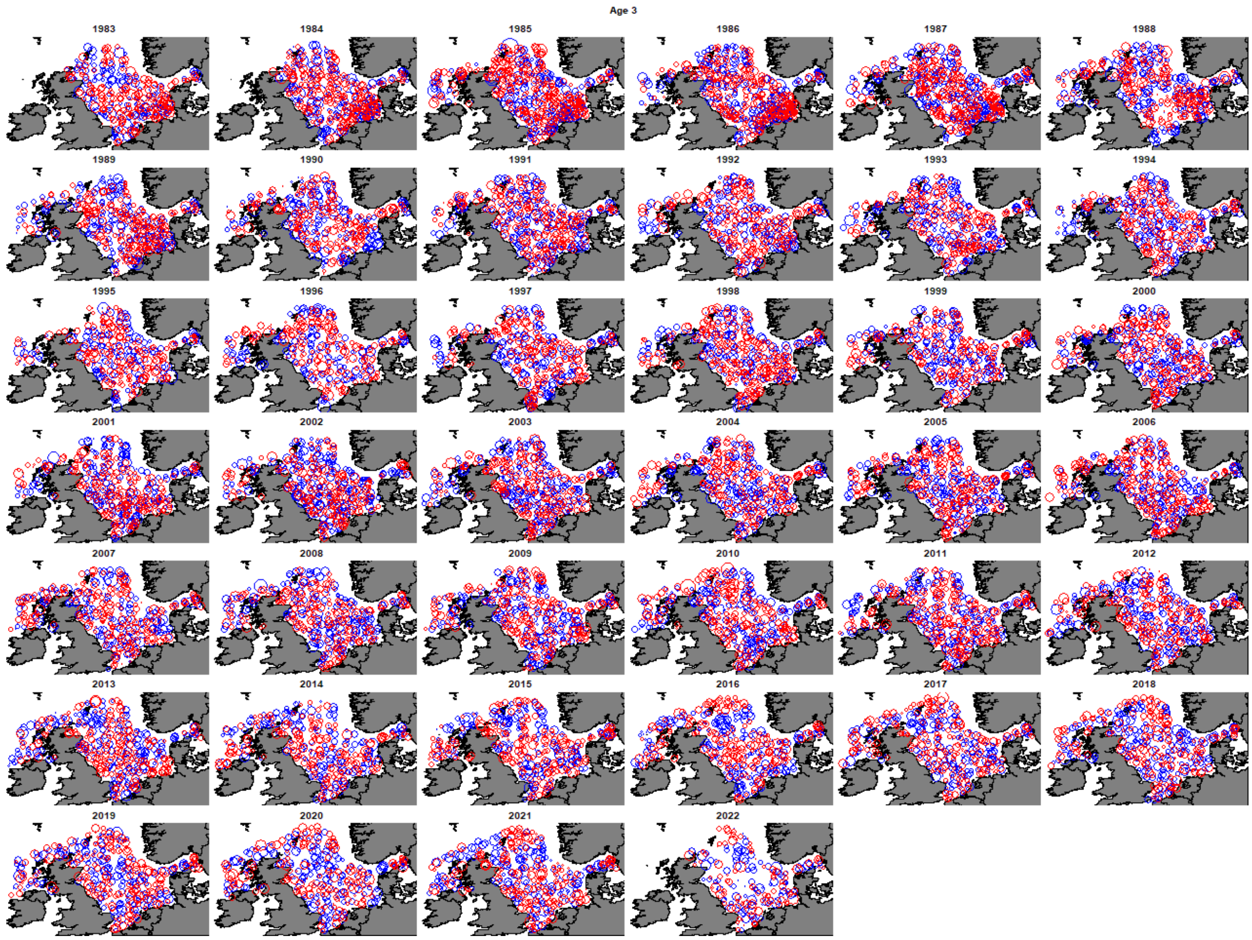
[6.5,22]


Age 3
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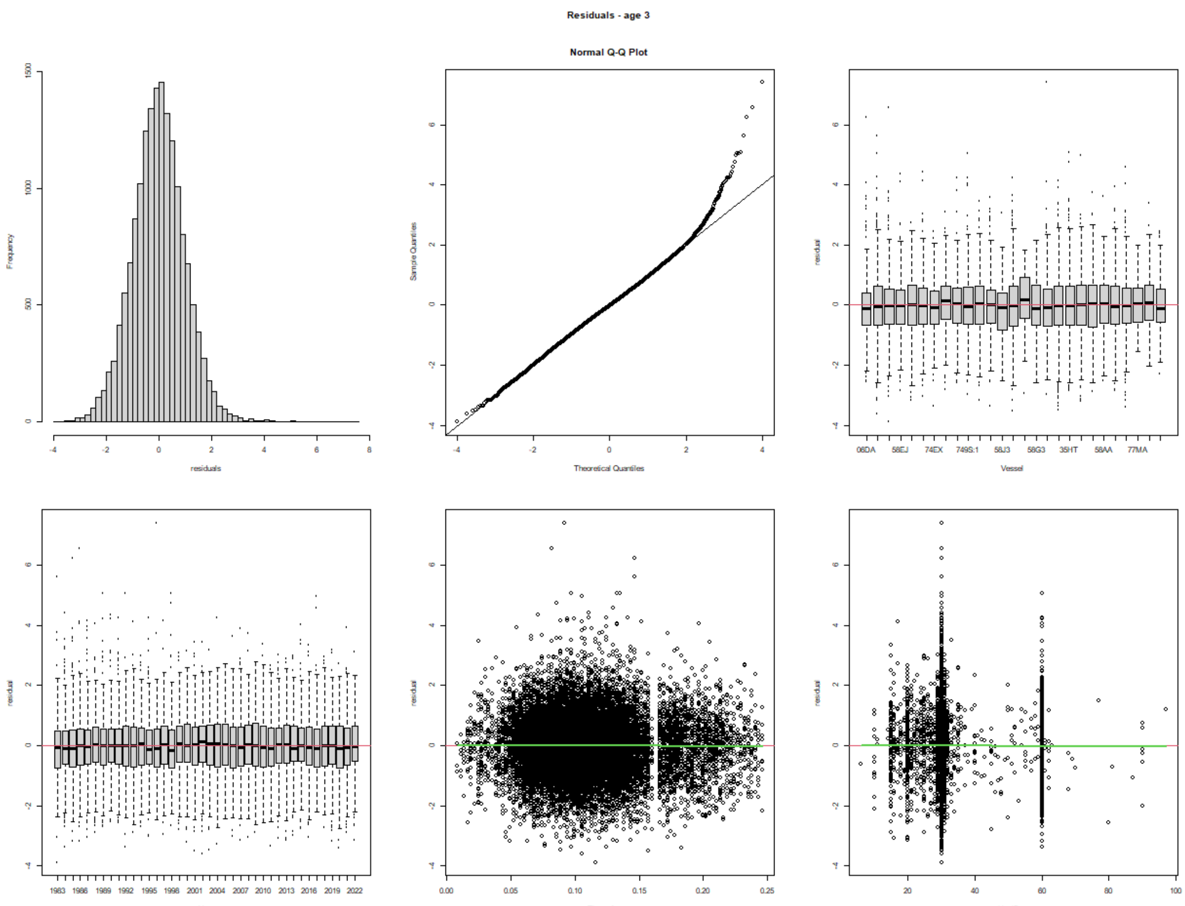
Residuals - age 3
Normal Q-Q Plot
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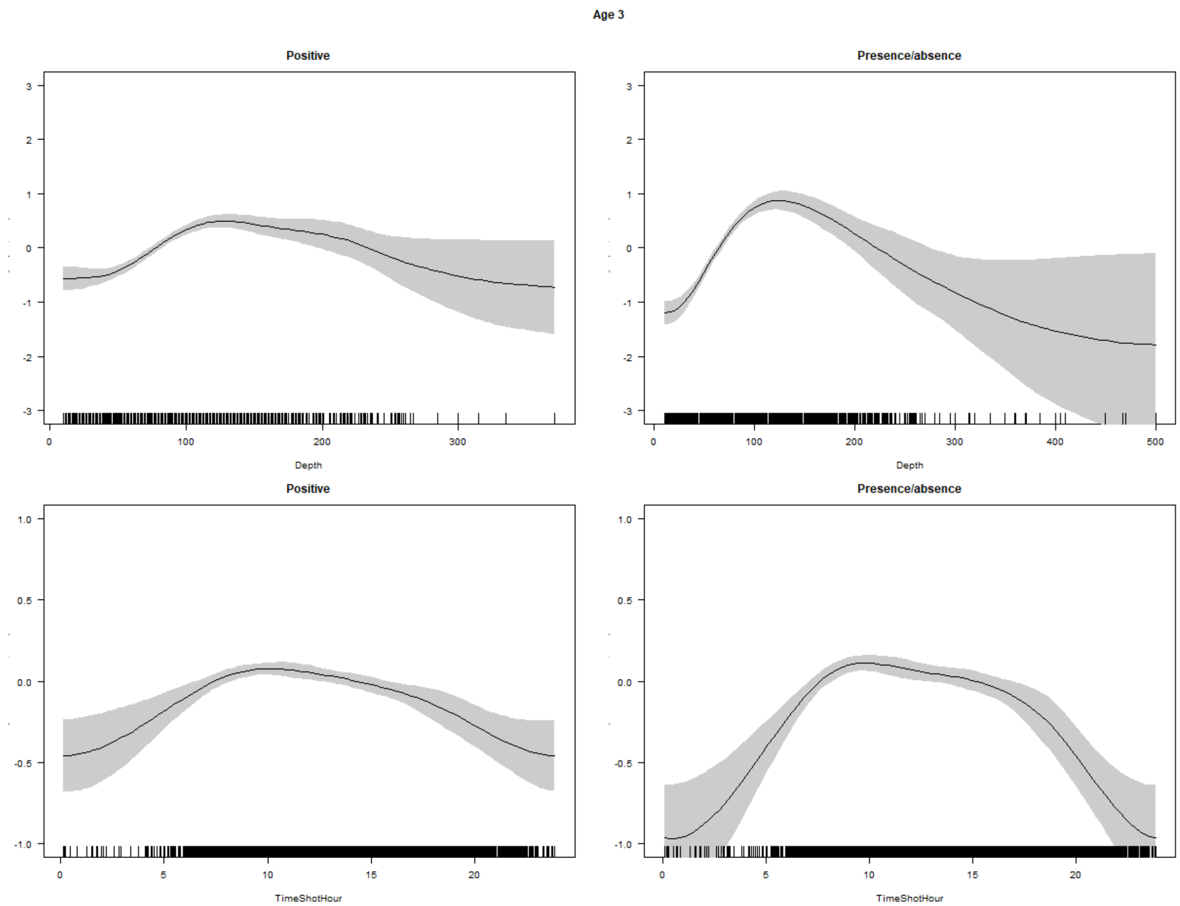
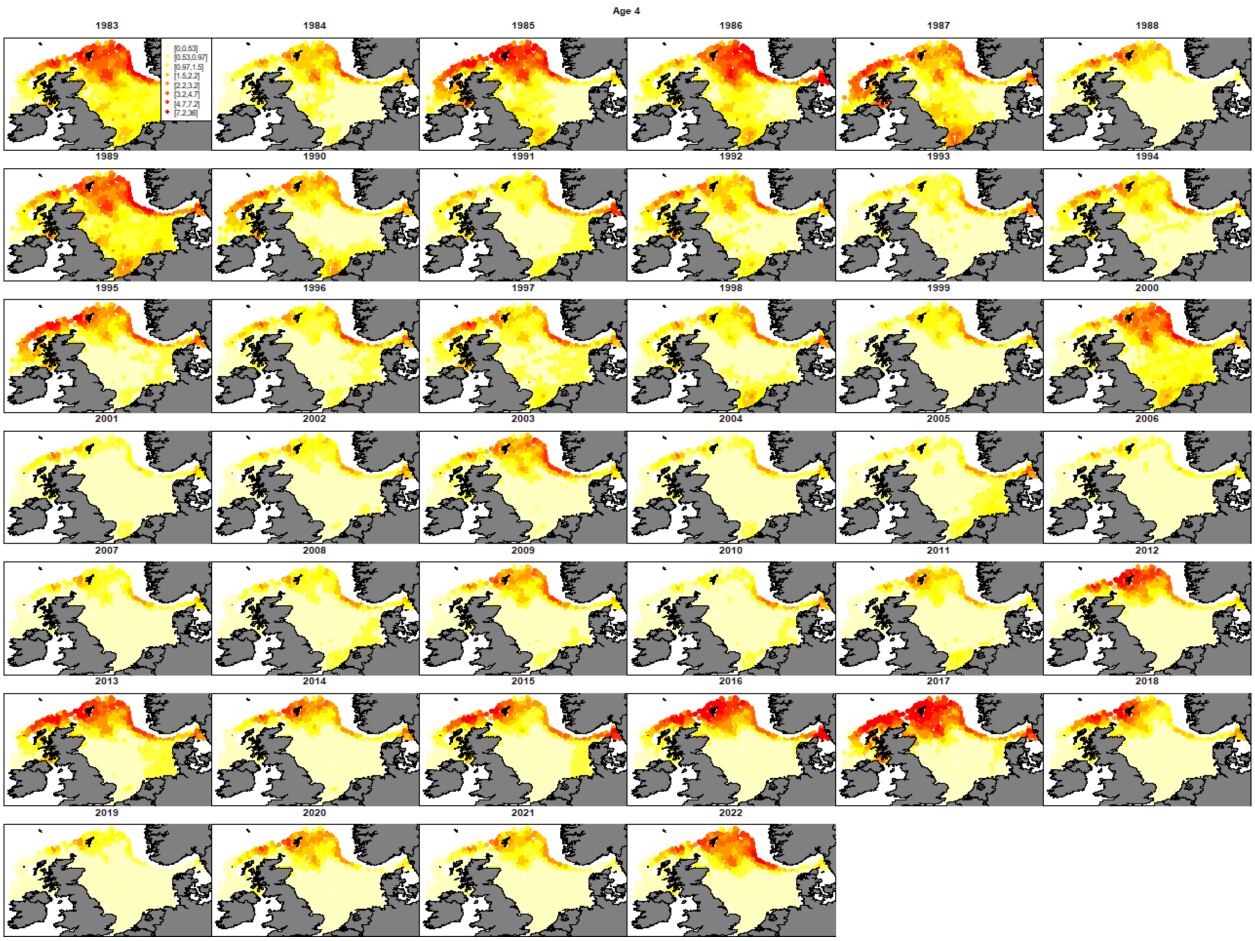
Sample Quantiles
Theoretical Quantiles
residual
Vessel
Year
Time of year
HaulDur


Age 3
Positive
Presence/absence
Depth
Depth
Positive
Presence/absence
TimeShotHour
TimeShotHour

Age 4


Age 4
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1989
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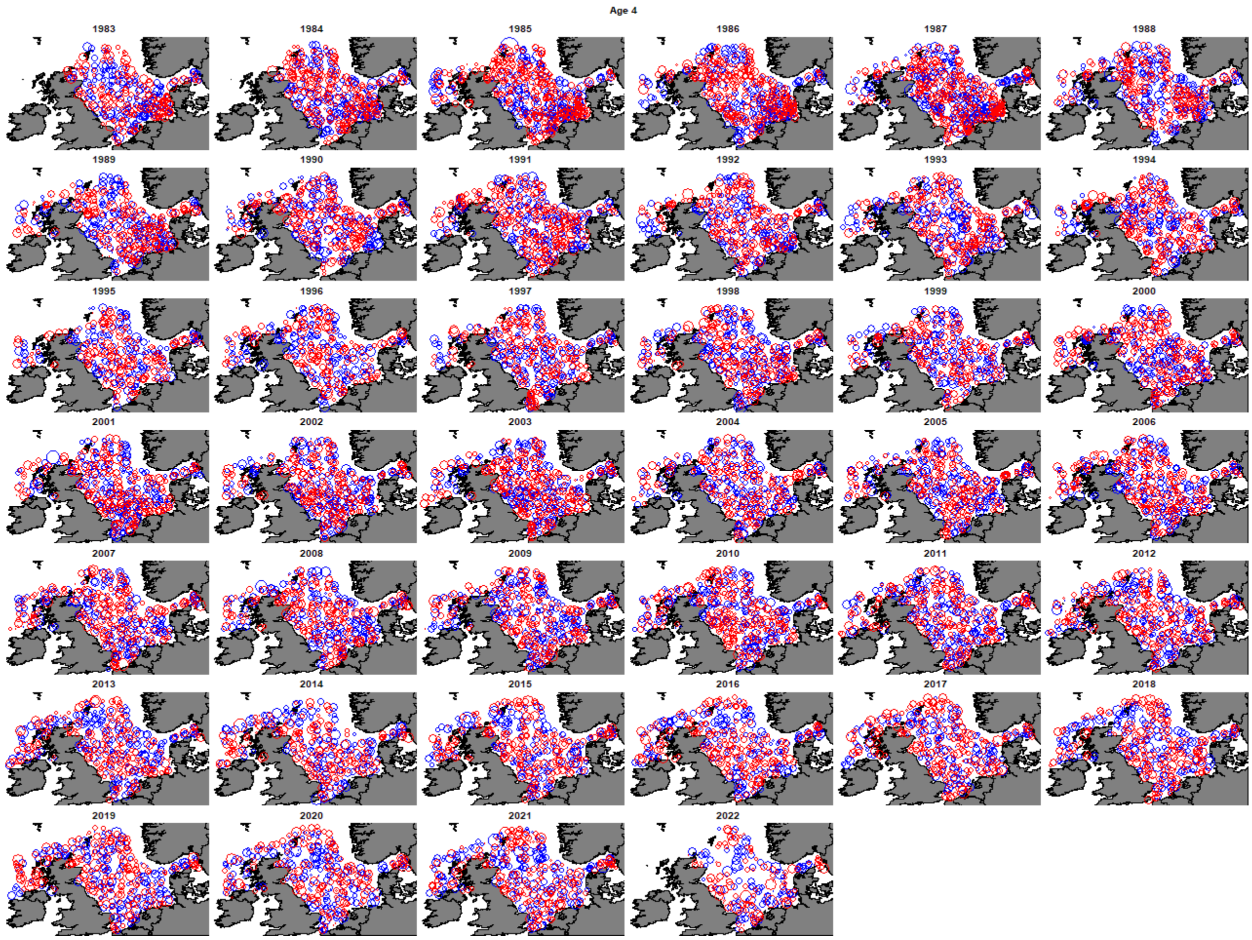
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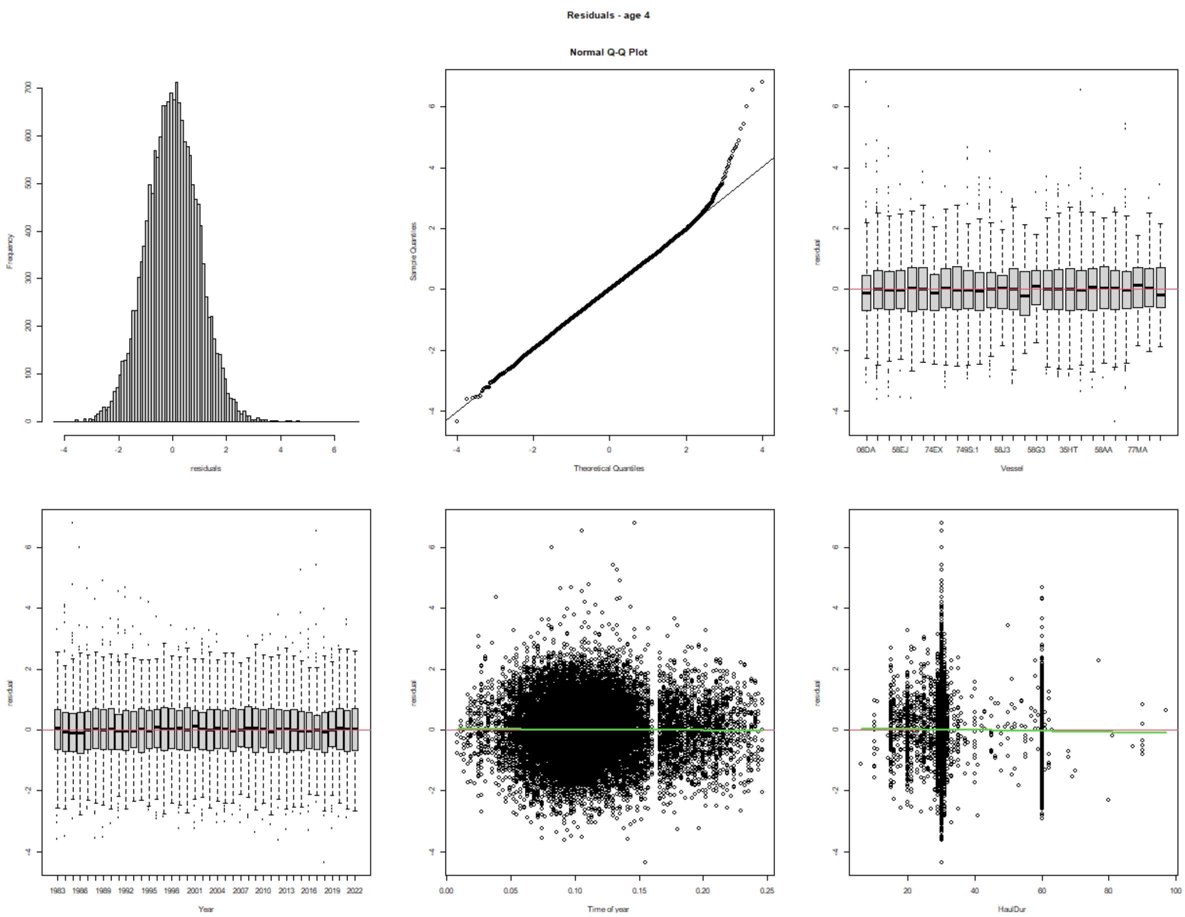
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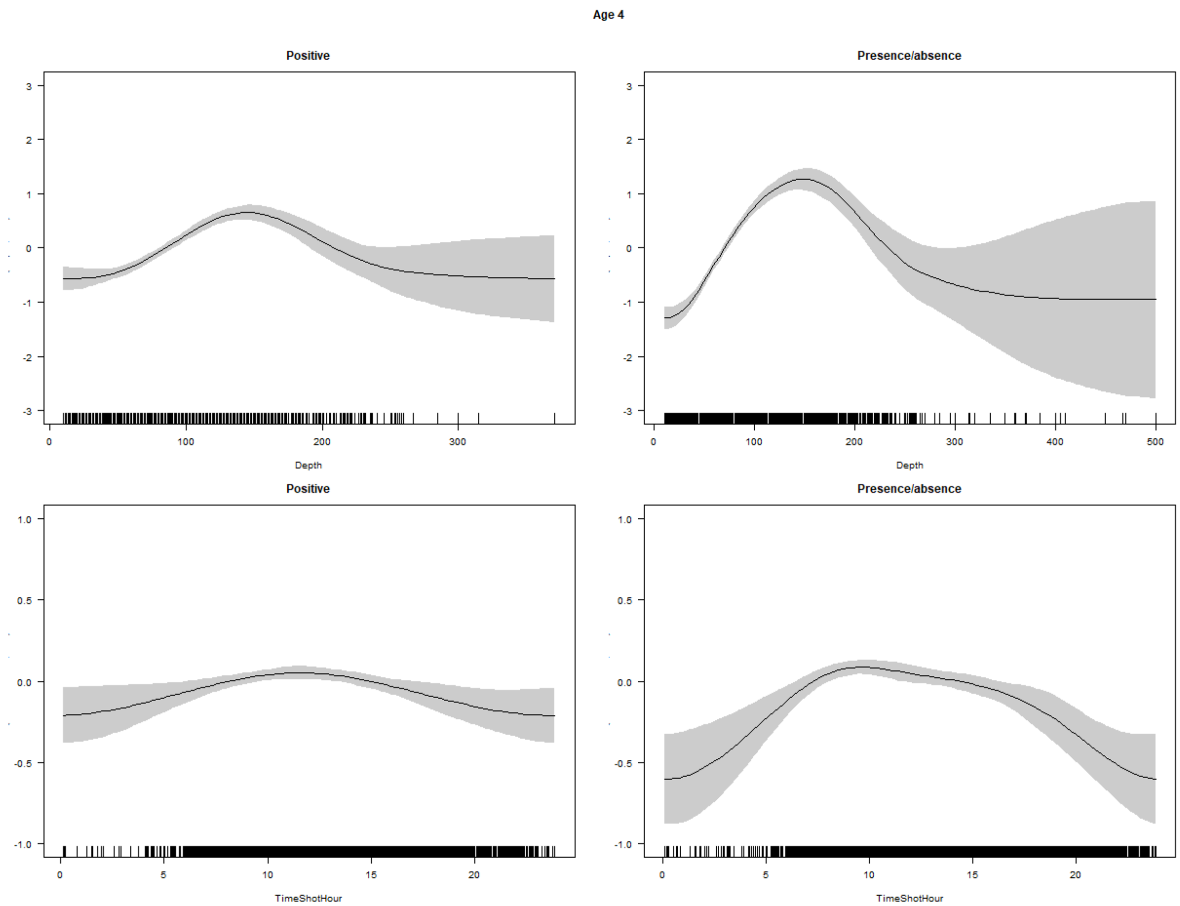
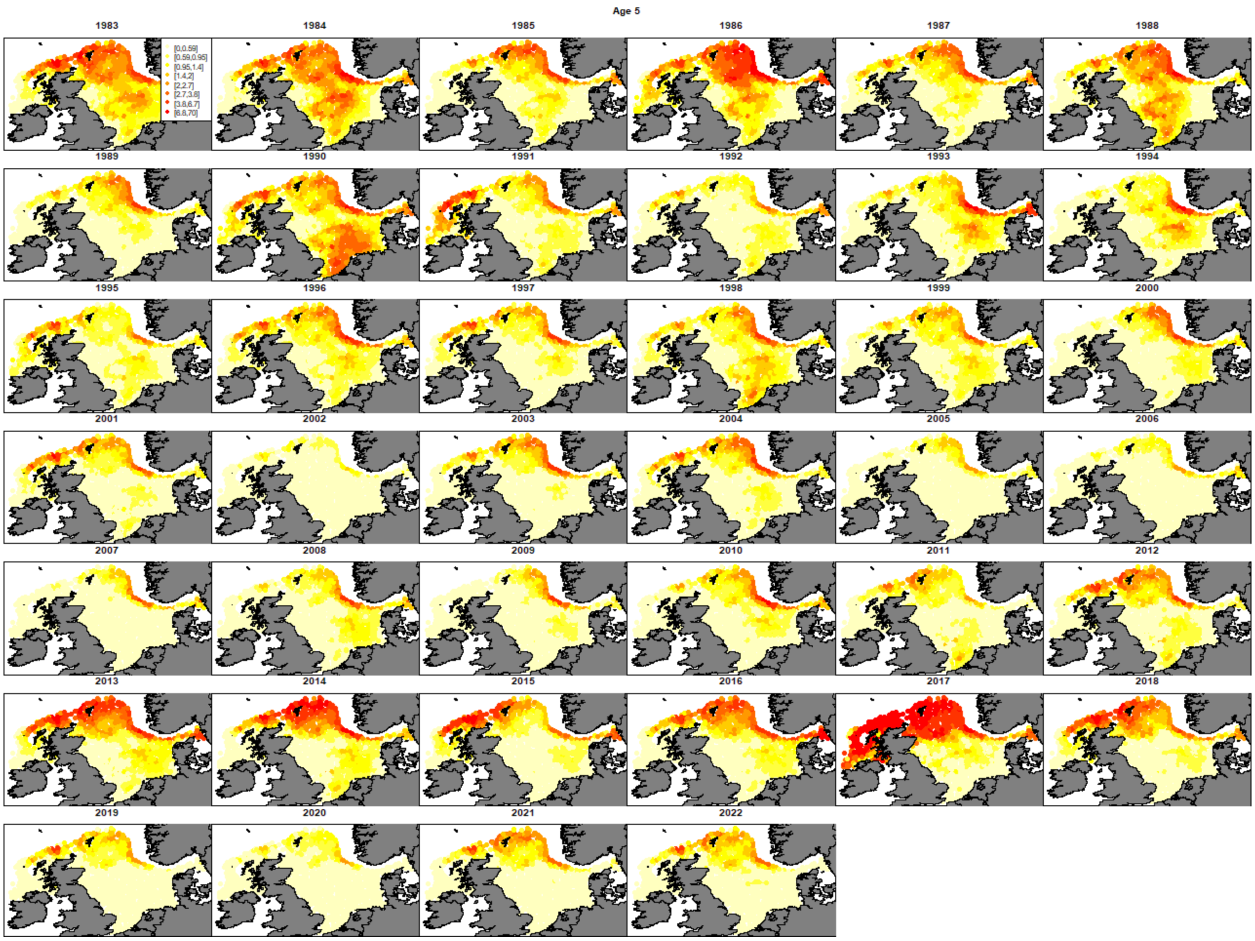
Frequency
residuals
Sample Quantiles
Theoretical Quantiles
residual
Vessel
Year
Time of year
HaulDur



Age 4
Positive
Presence/absence
Depth
Positive
Presence/absence
TimeShotHour

Age 5


Age 5
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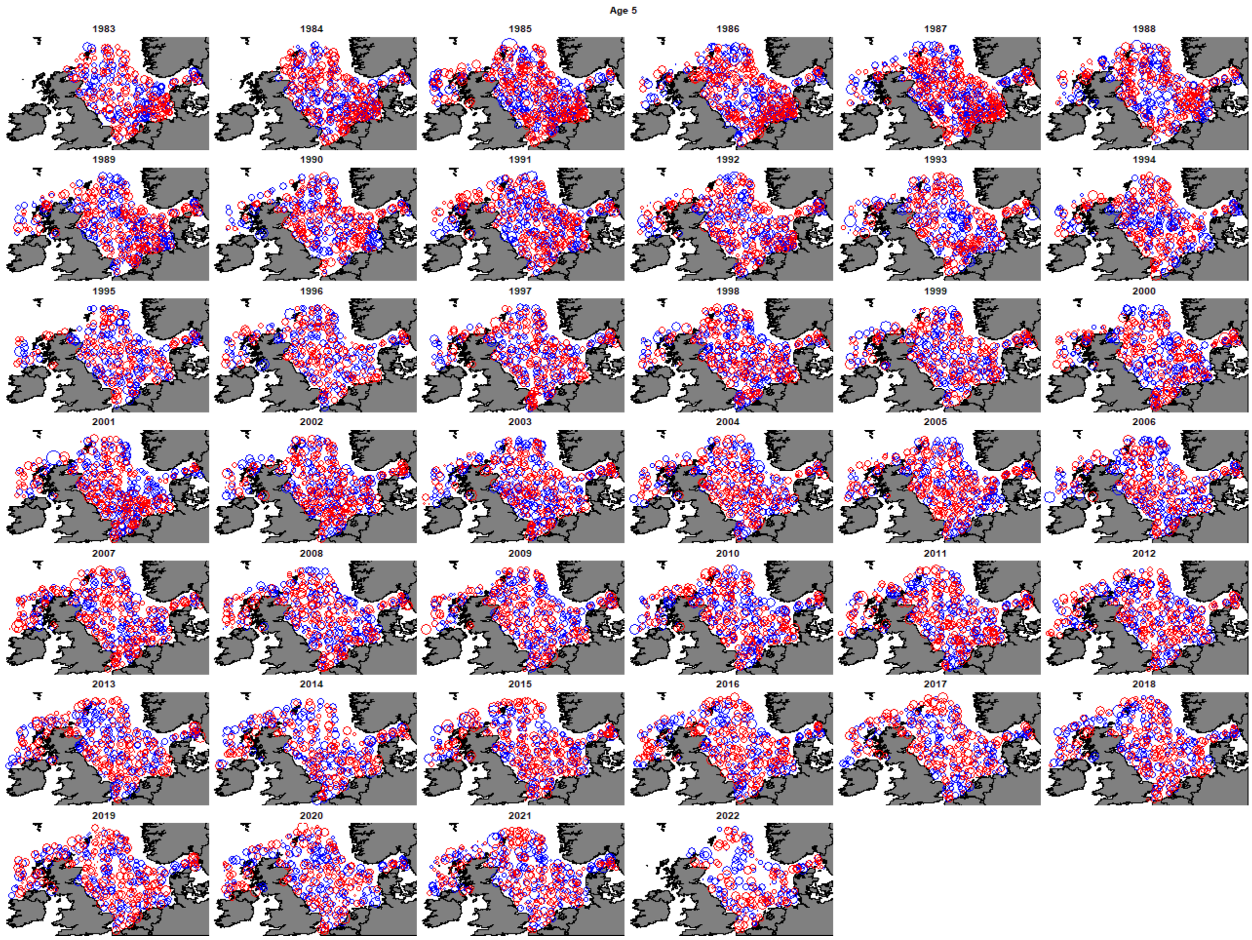
Age 5
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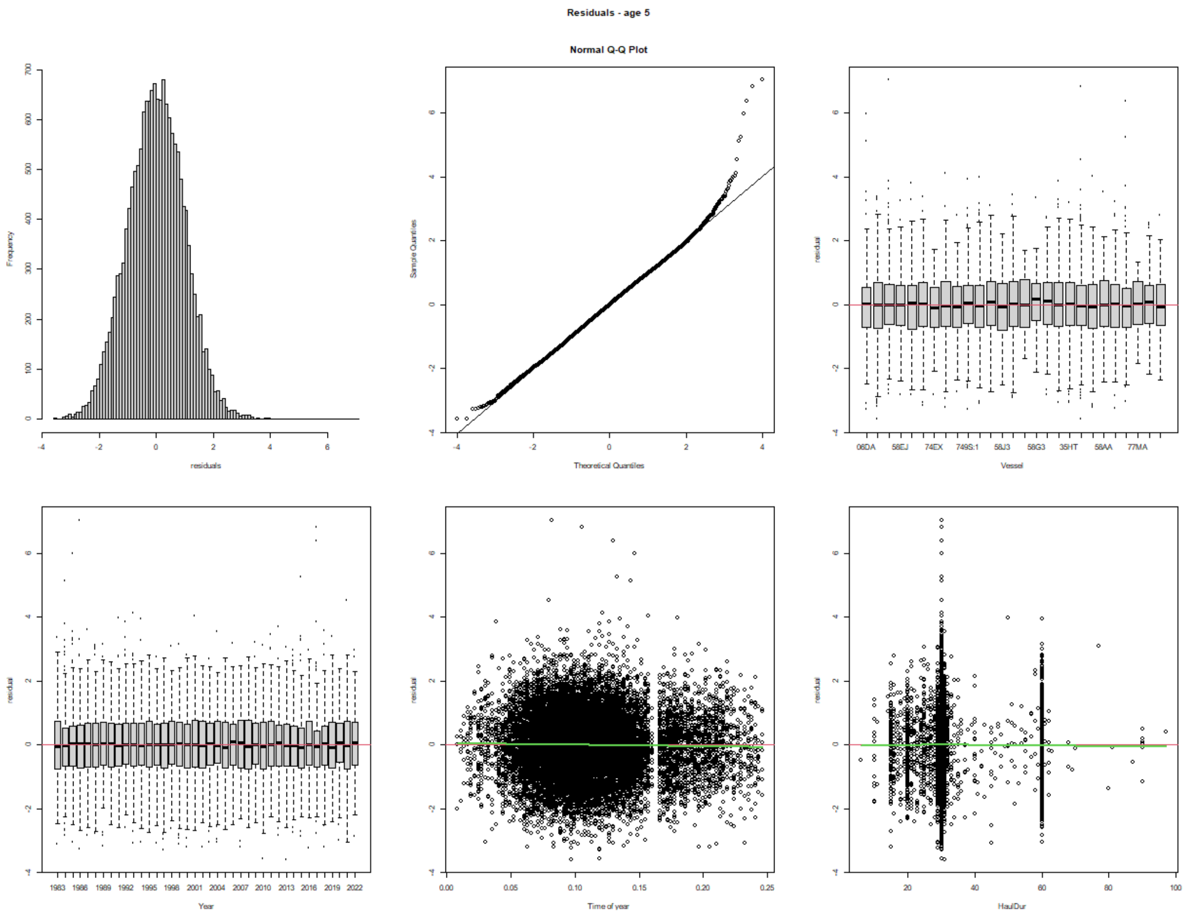
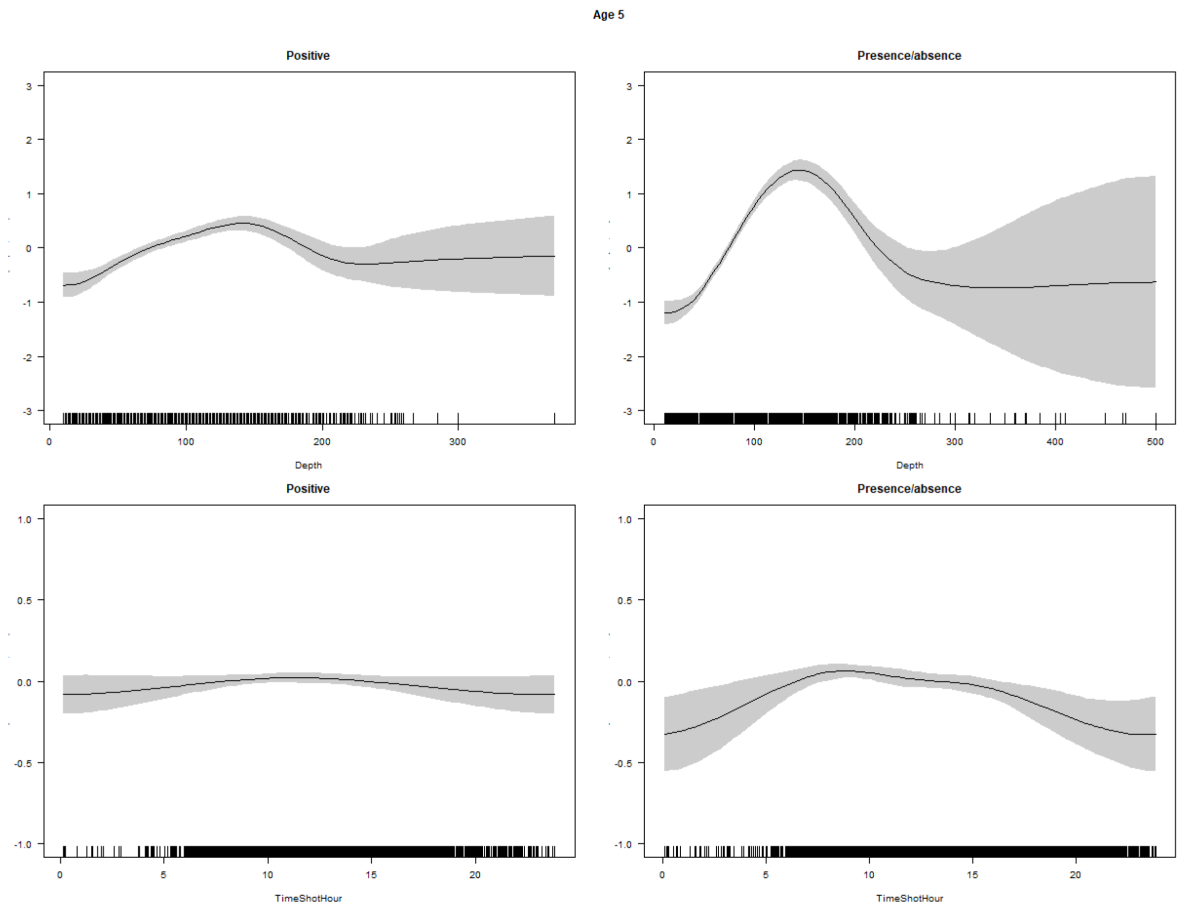
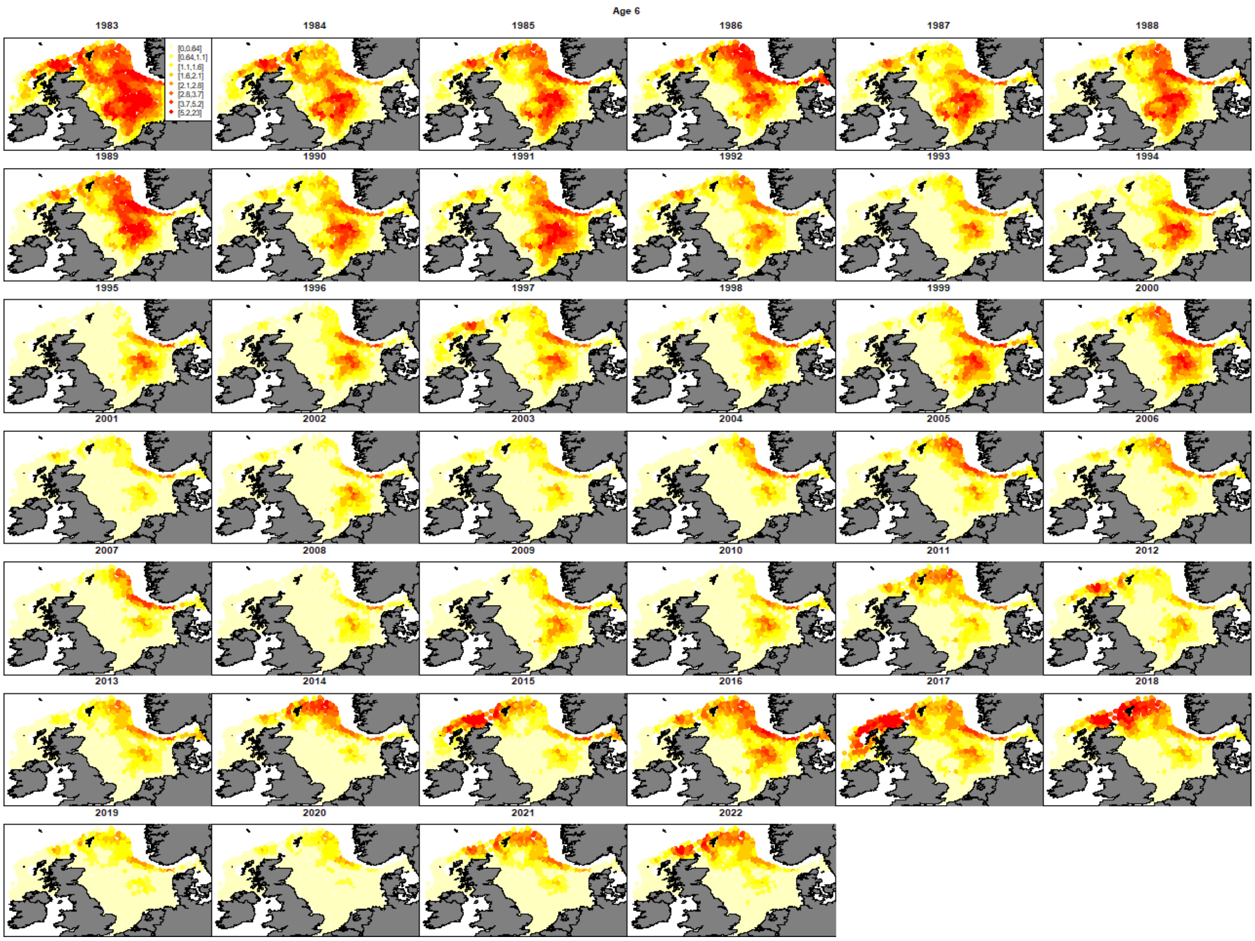

Residuals - age 5
Normal Q-Q Plot
Frequency
residuals
Sample Quantiles
Theoretical Quantiles
residual
Vessel
06DA 58EJ 74EX 749S:1 58J3 58G3 35HT 58AA 77MA
Year
1983 1986 1989 1992 1995 1998 2001 2004 2007 2010 2013 2016 2019 2022
Time of year
HaulDur


Age 5
Positive
Presence/absence
Depth
Depth
Positive
Presence/absence
TimeShotHour
TimeShotHour

Ages 6+


Age 6
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2021
2022
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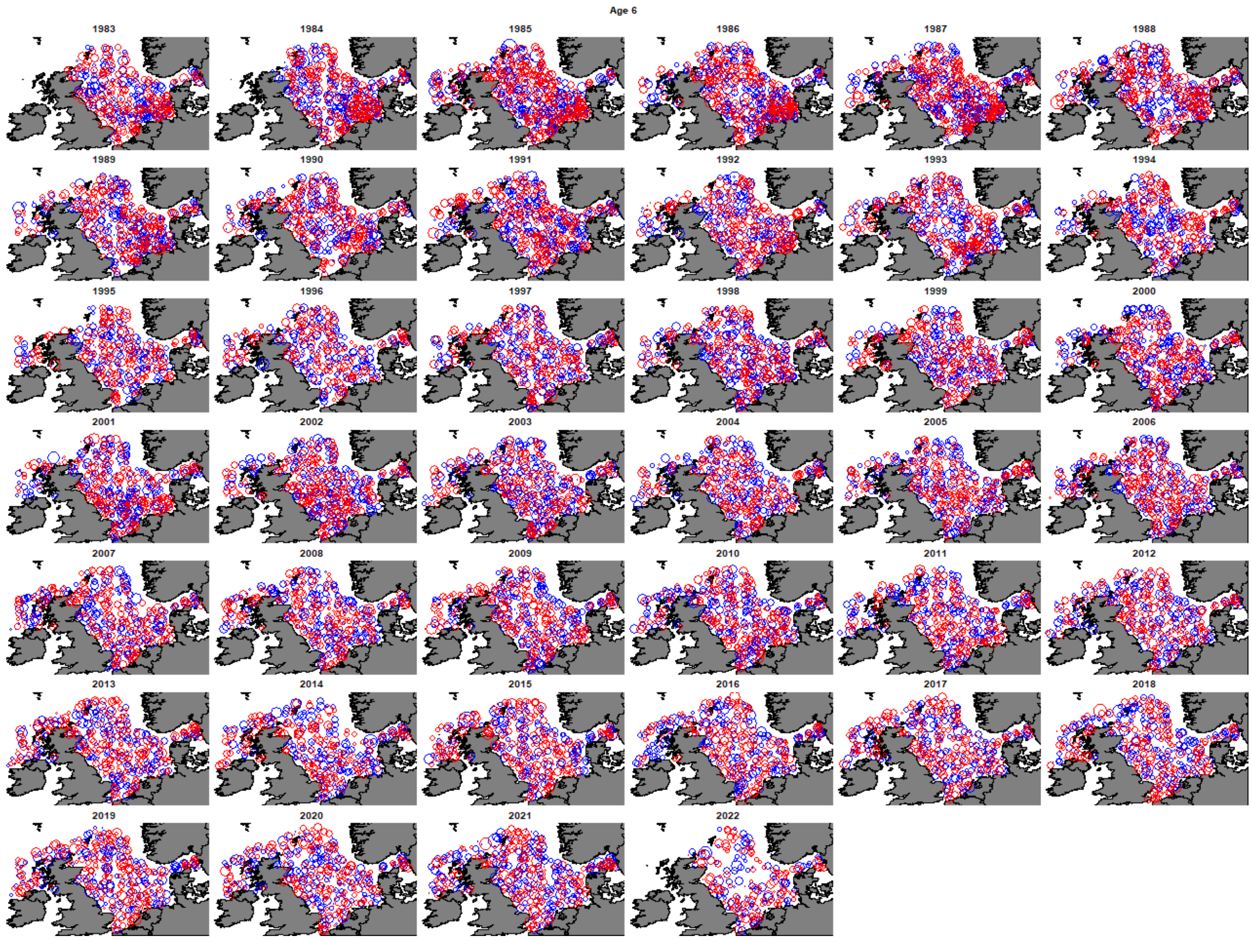
[5.2,23]


Age 6
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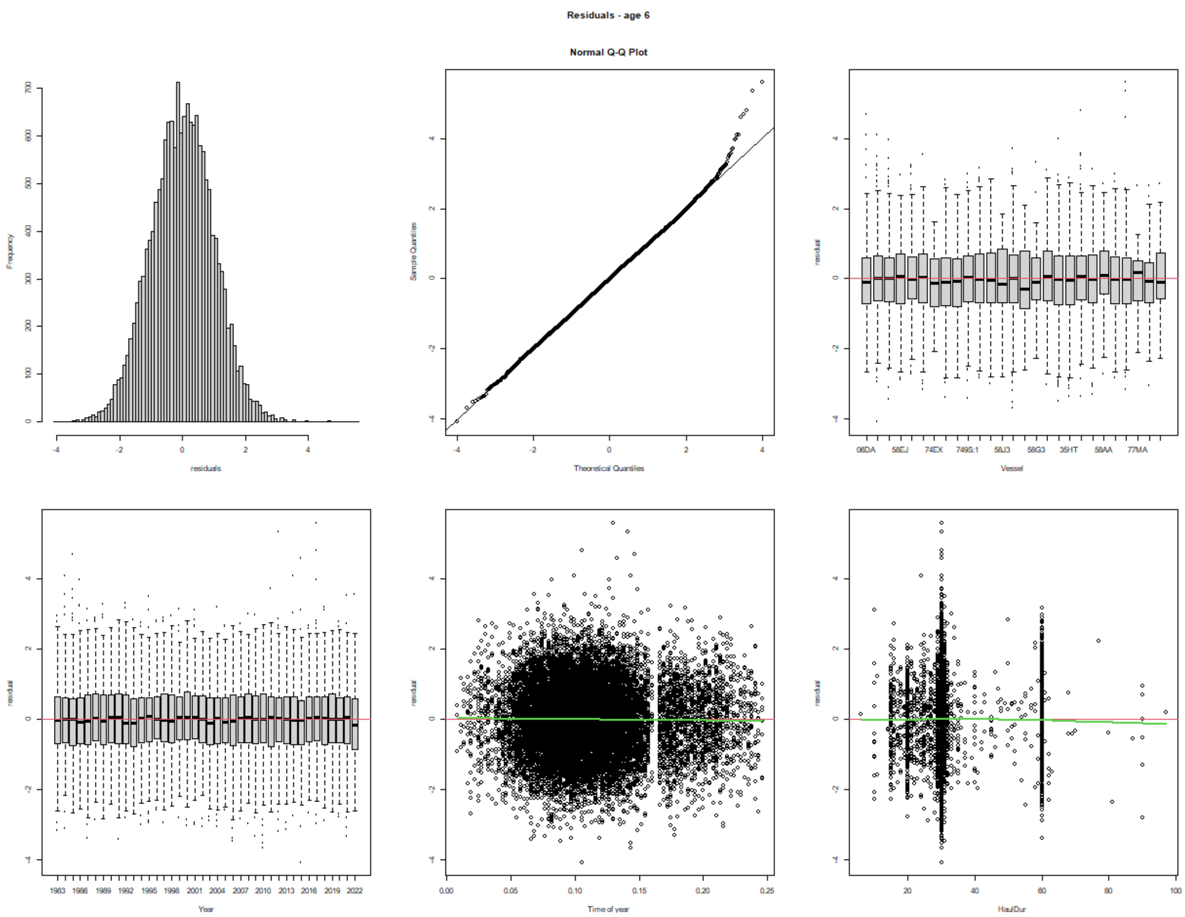
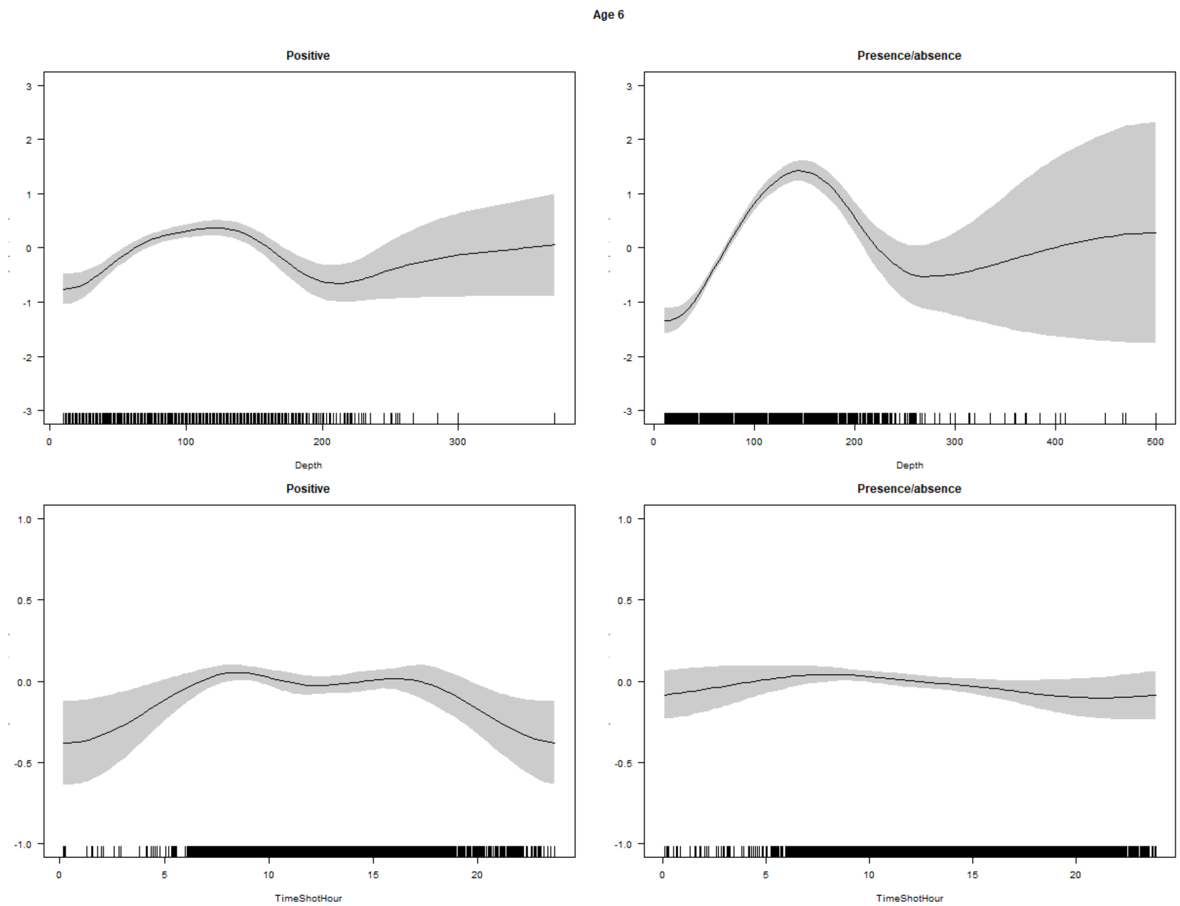
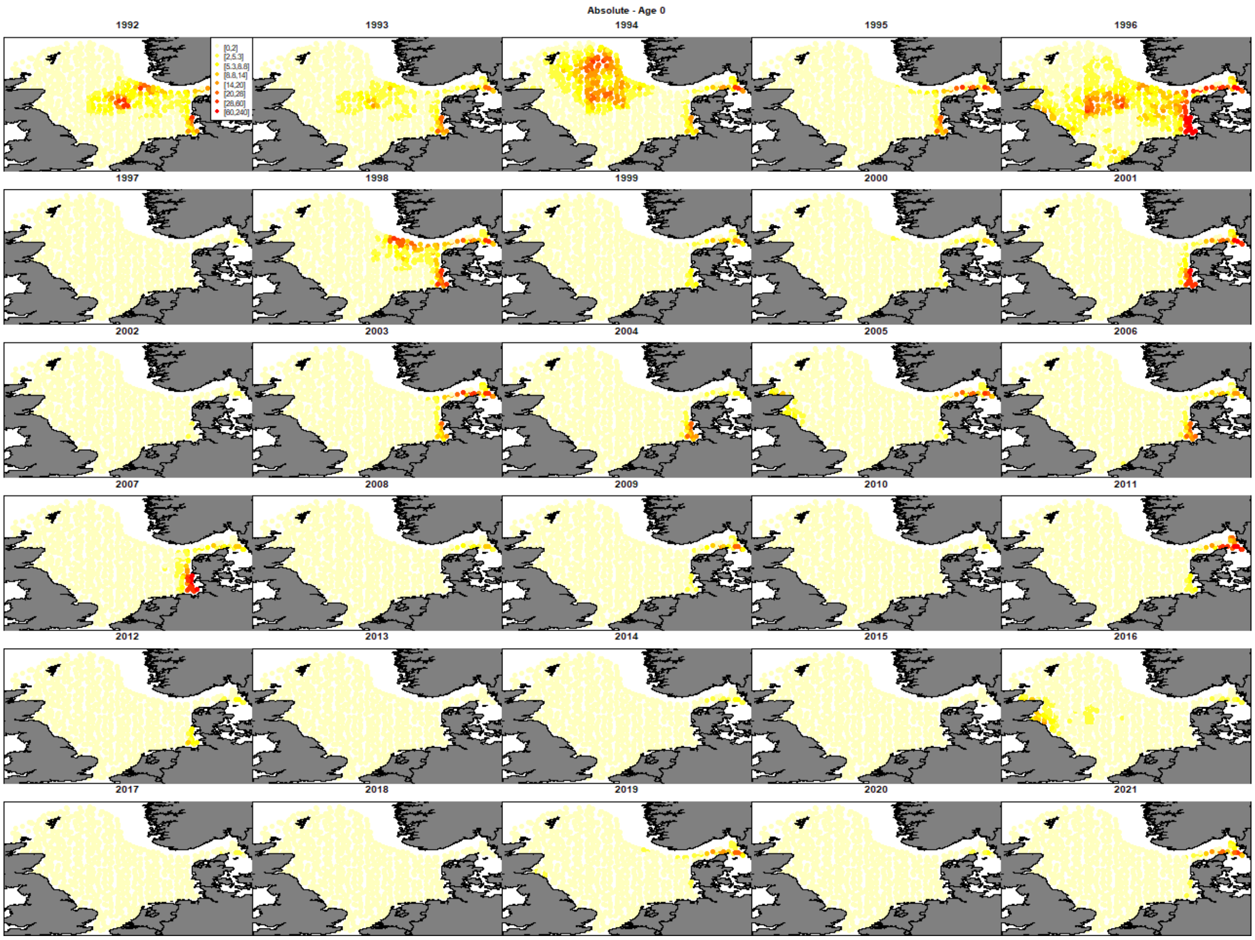
2022

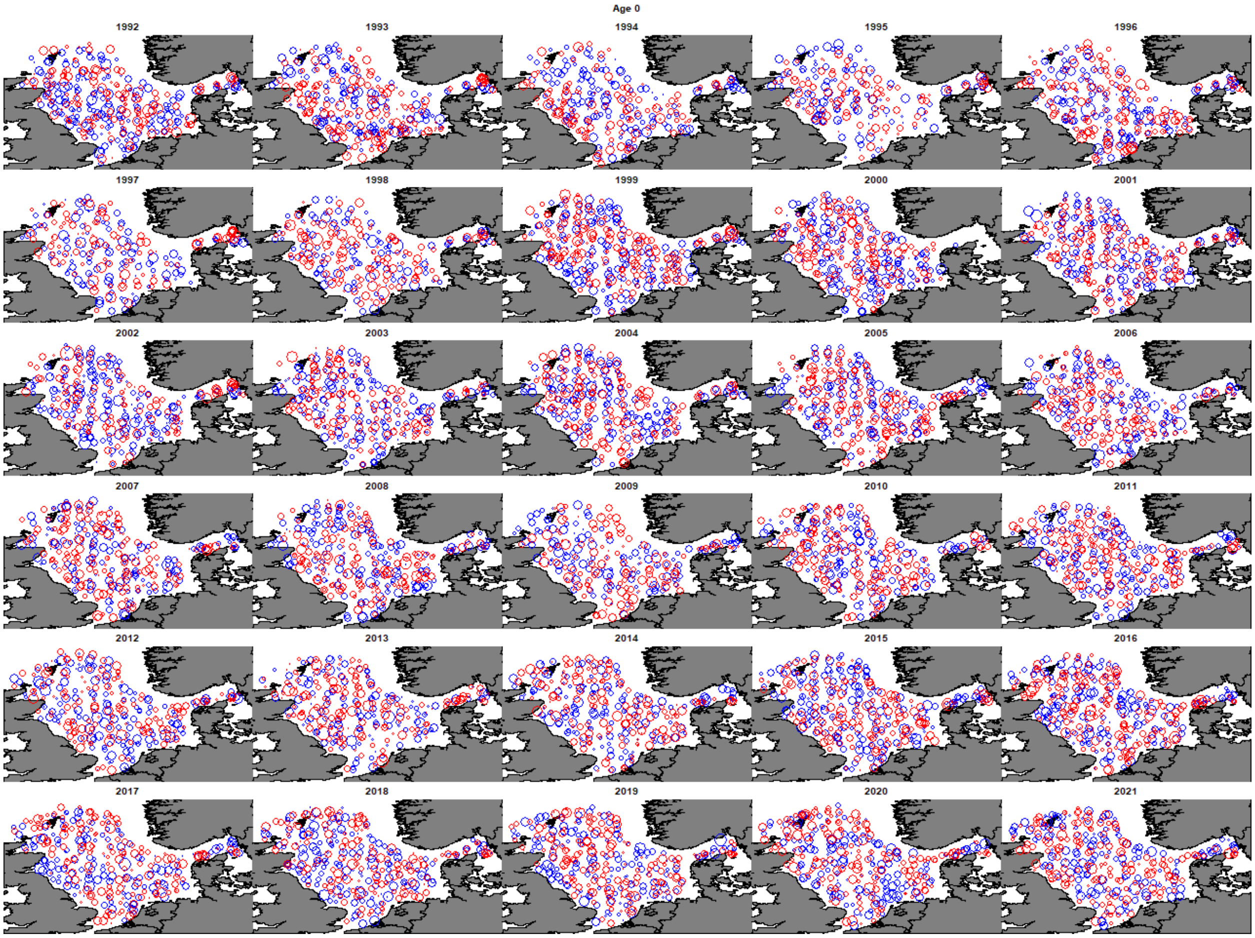

Residuals - age 6
Normal Q-Q Plot
Frequency
residuals
Sample Quantiles
Theoretical Quantiles
residual
Vessel
Year
Time of year
HaulDur


Age 6
Positive
Presence/absence
Depth
Depth
Positive
Presence/absence
TimeShotHour
TimeShotHour

Quarter 3

Age 0




Age 0
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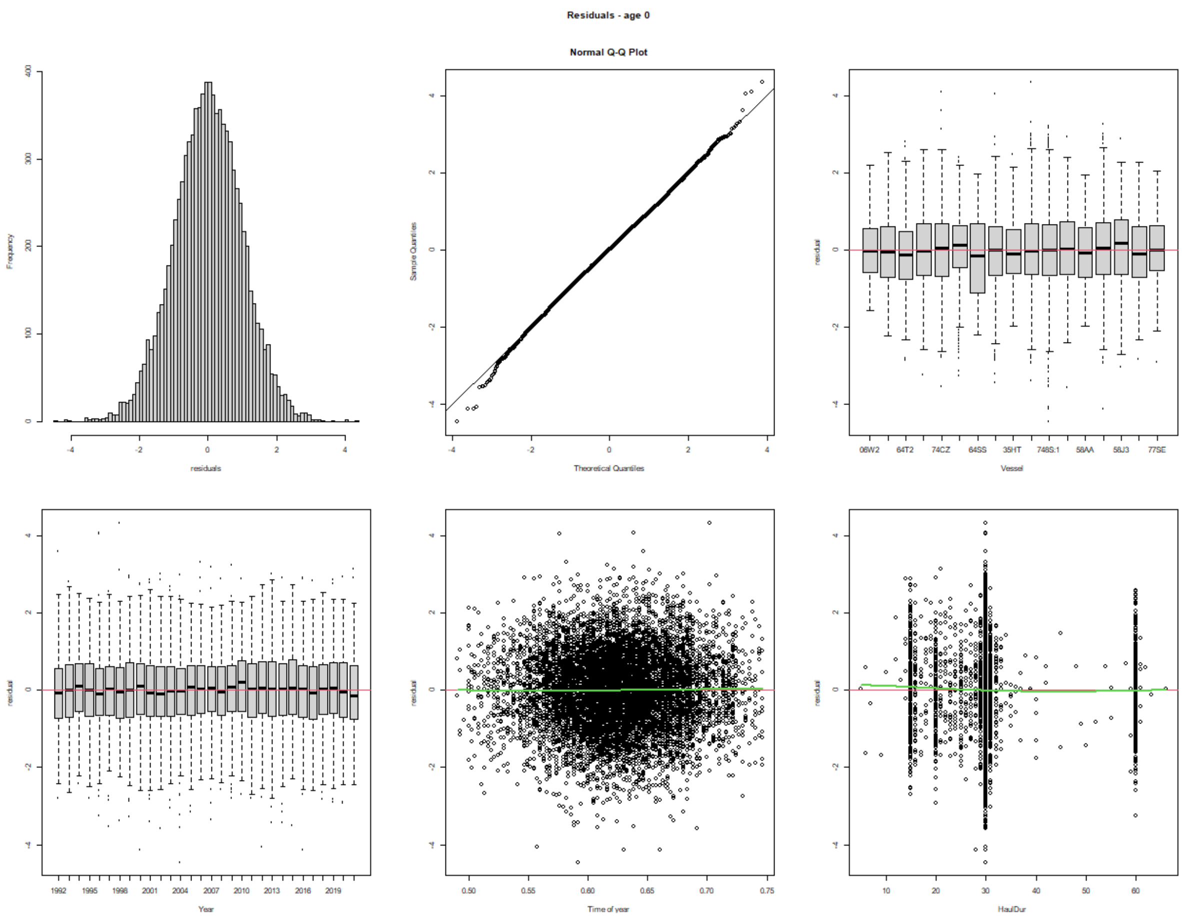
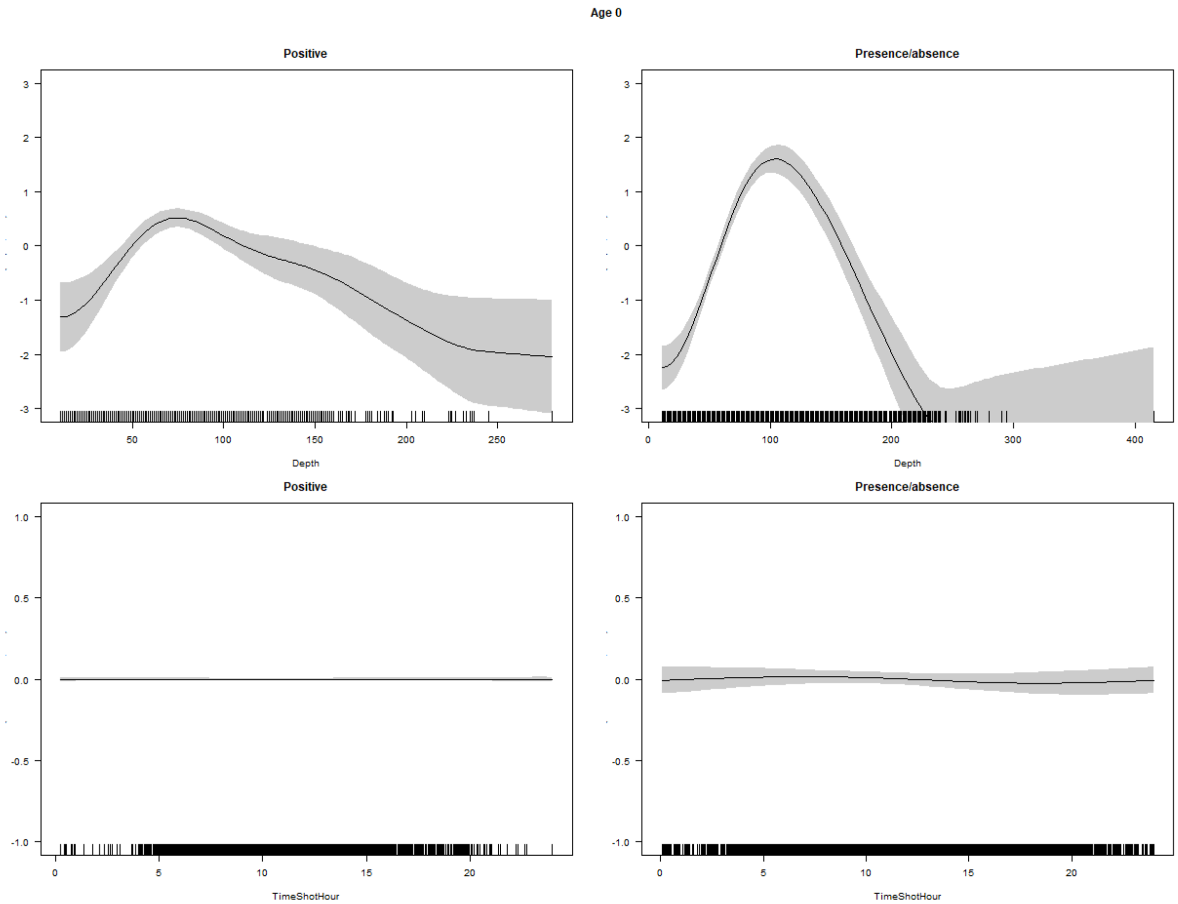
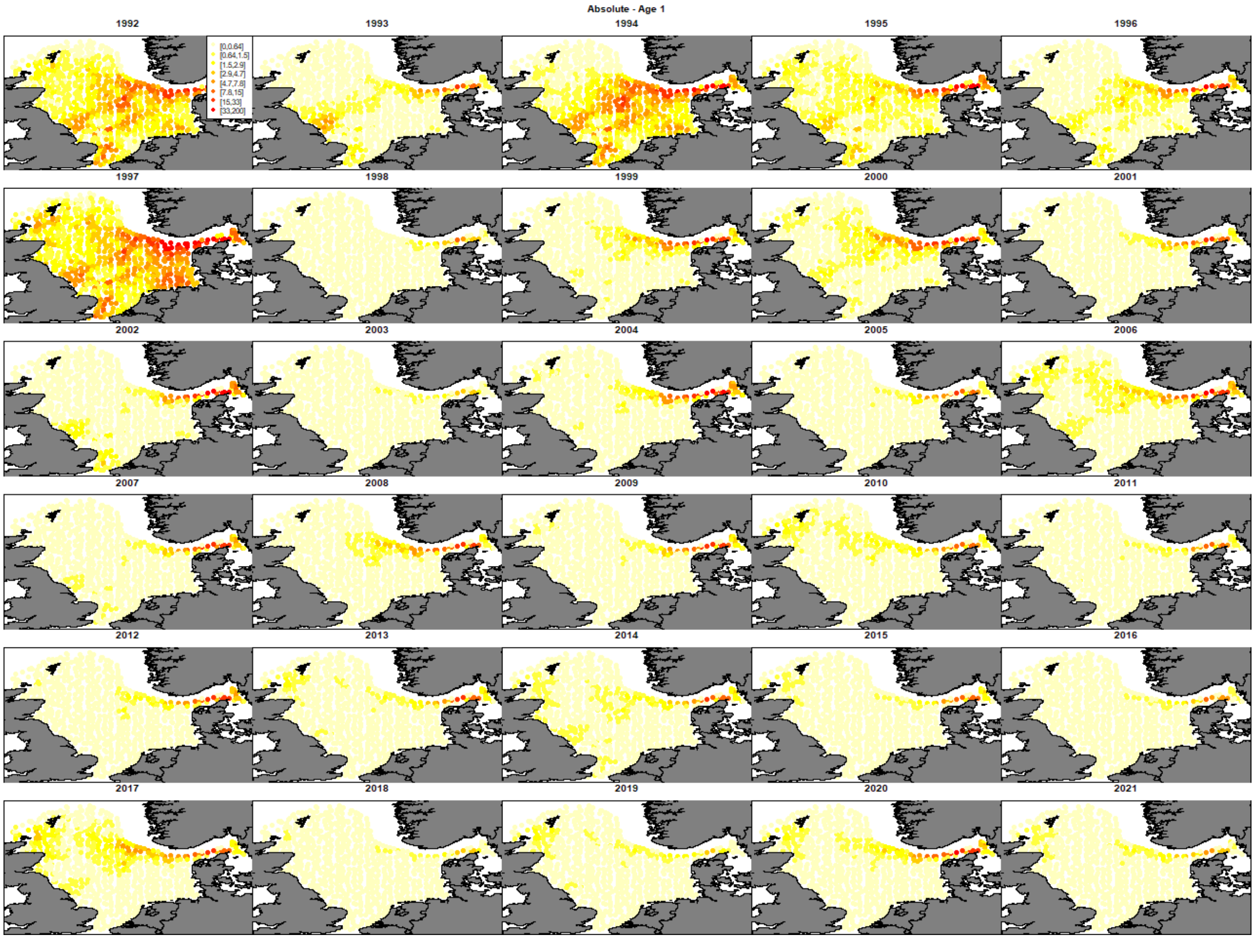

Residuals - age 0
Normal Q-Q Plot
Frequency
residuals
Sample Quantiles
Theoretical Quantiles
residual
Vessel
Year
Time of year
HaulDur


Age 0
Positive
Presence/absence
Depth
Depth
Positive
Presence/absence
TimeShotHour
TimeShotHour

Age 1


Absolute - Age 1
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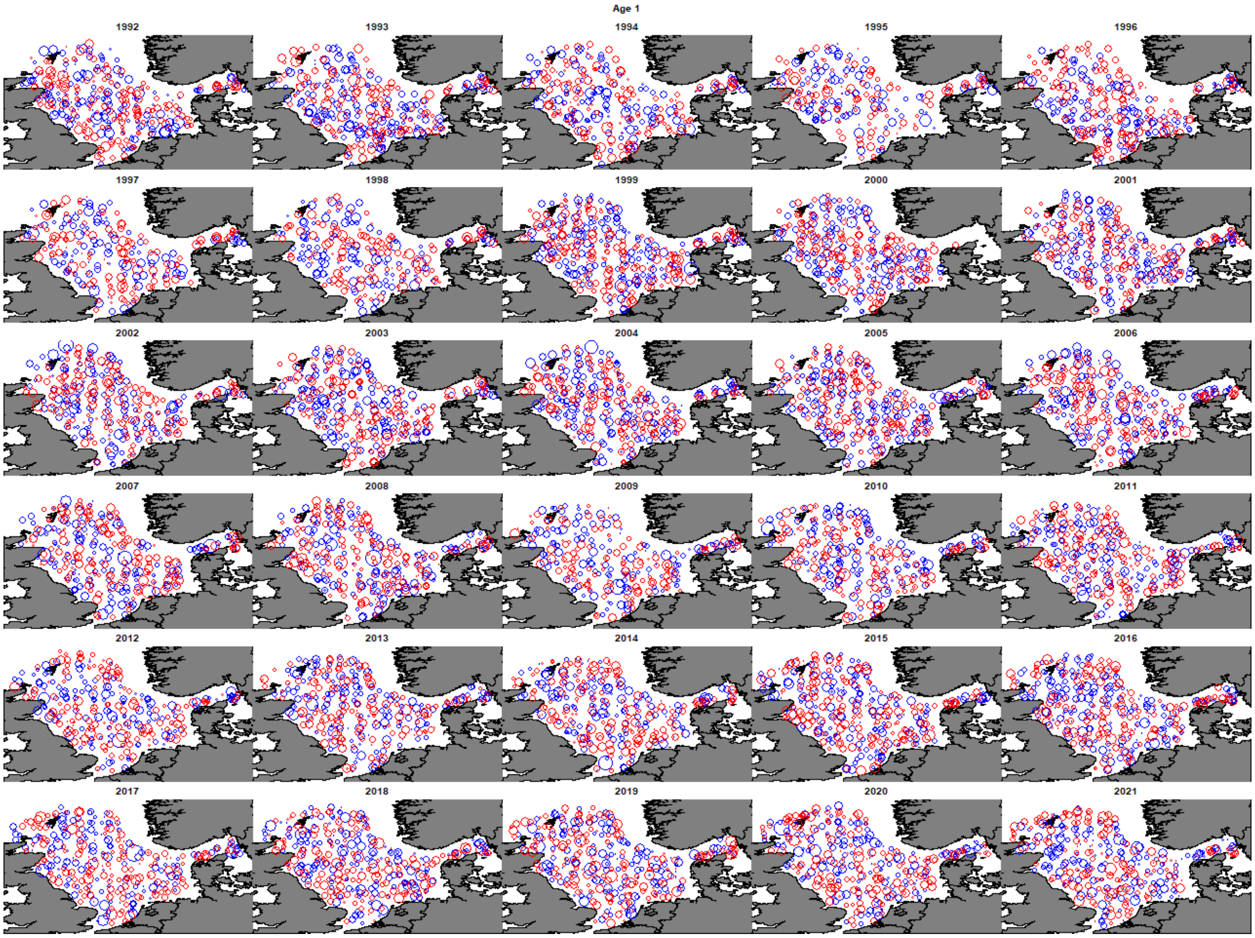
Age 1
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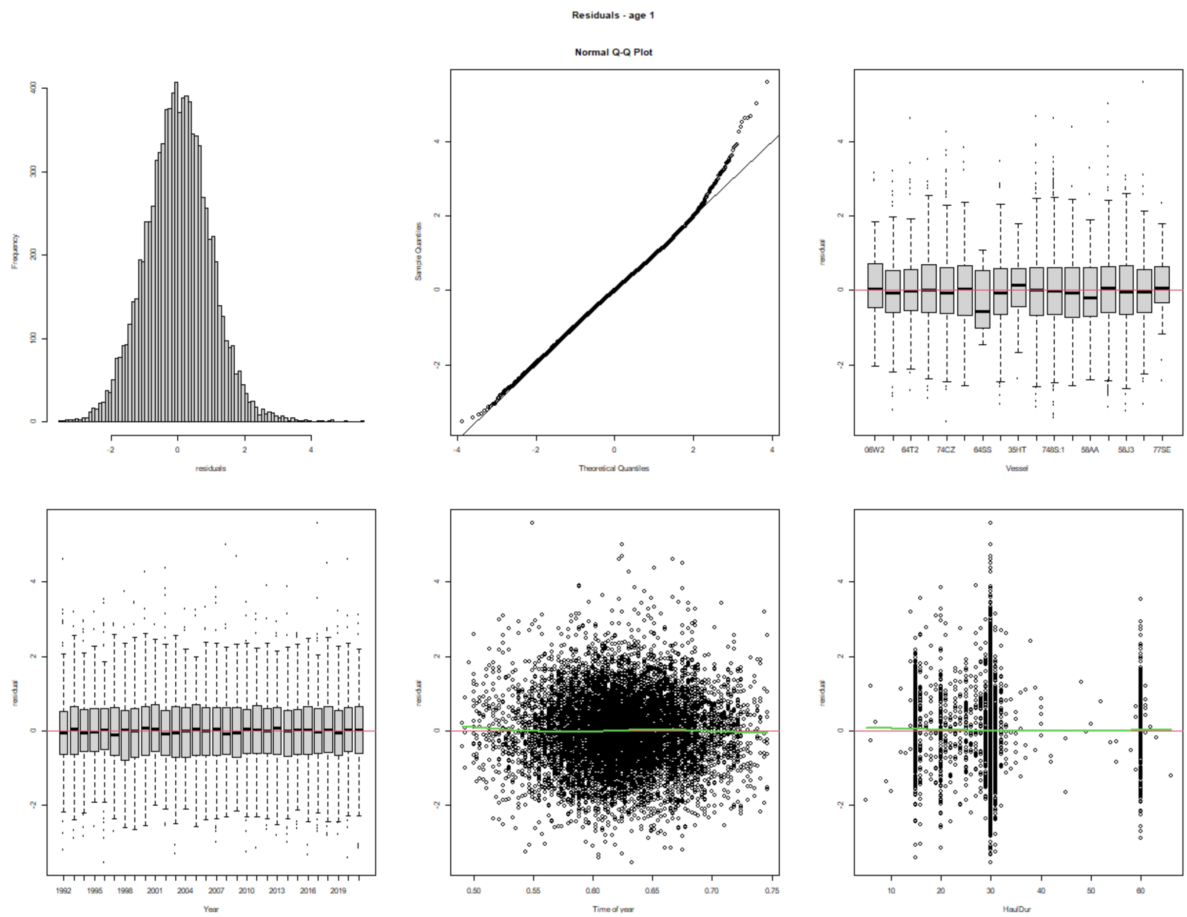
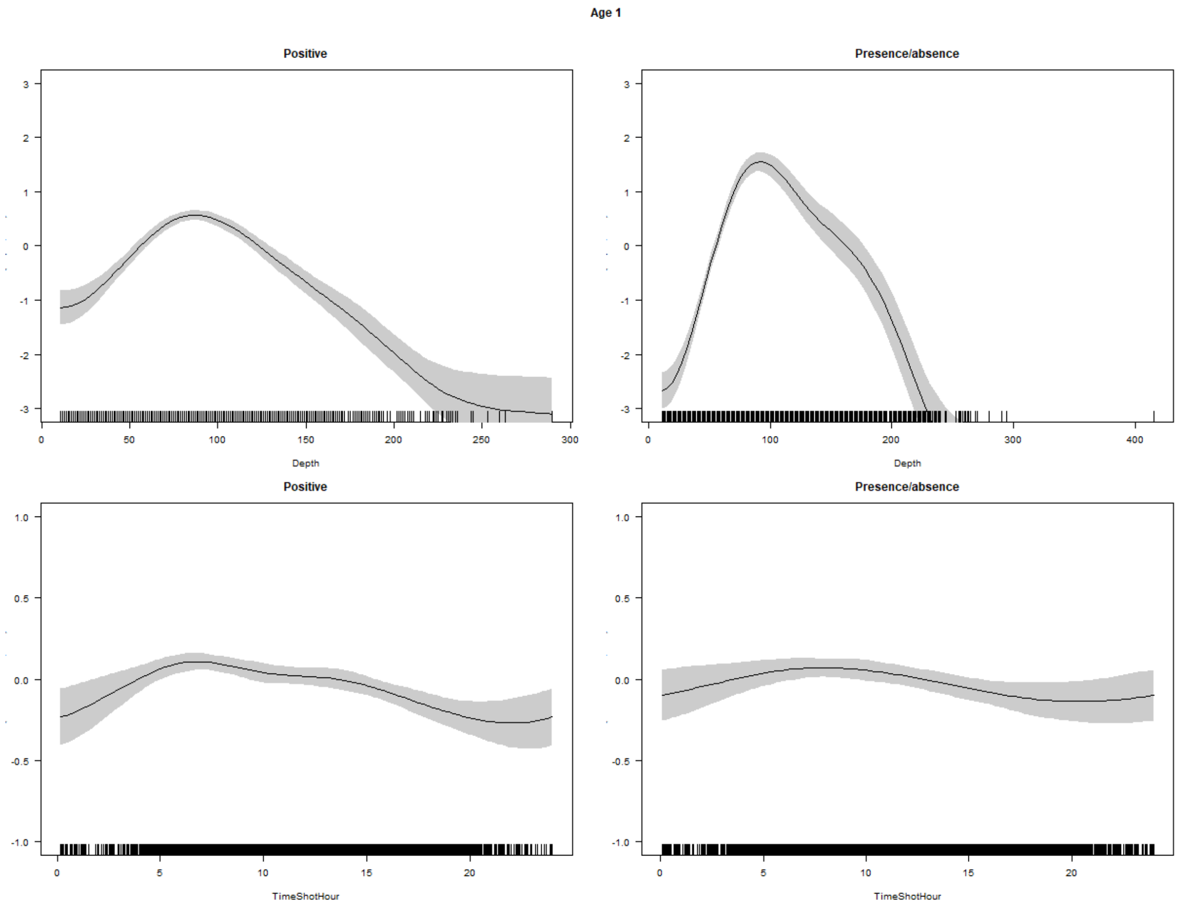
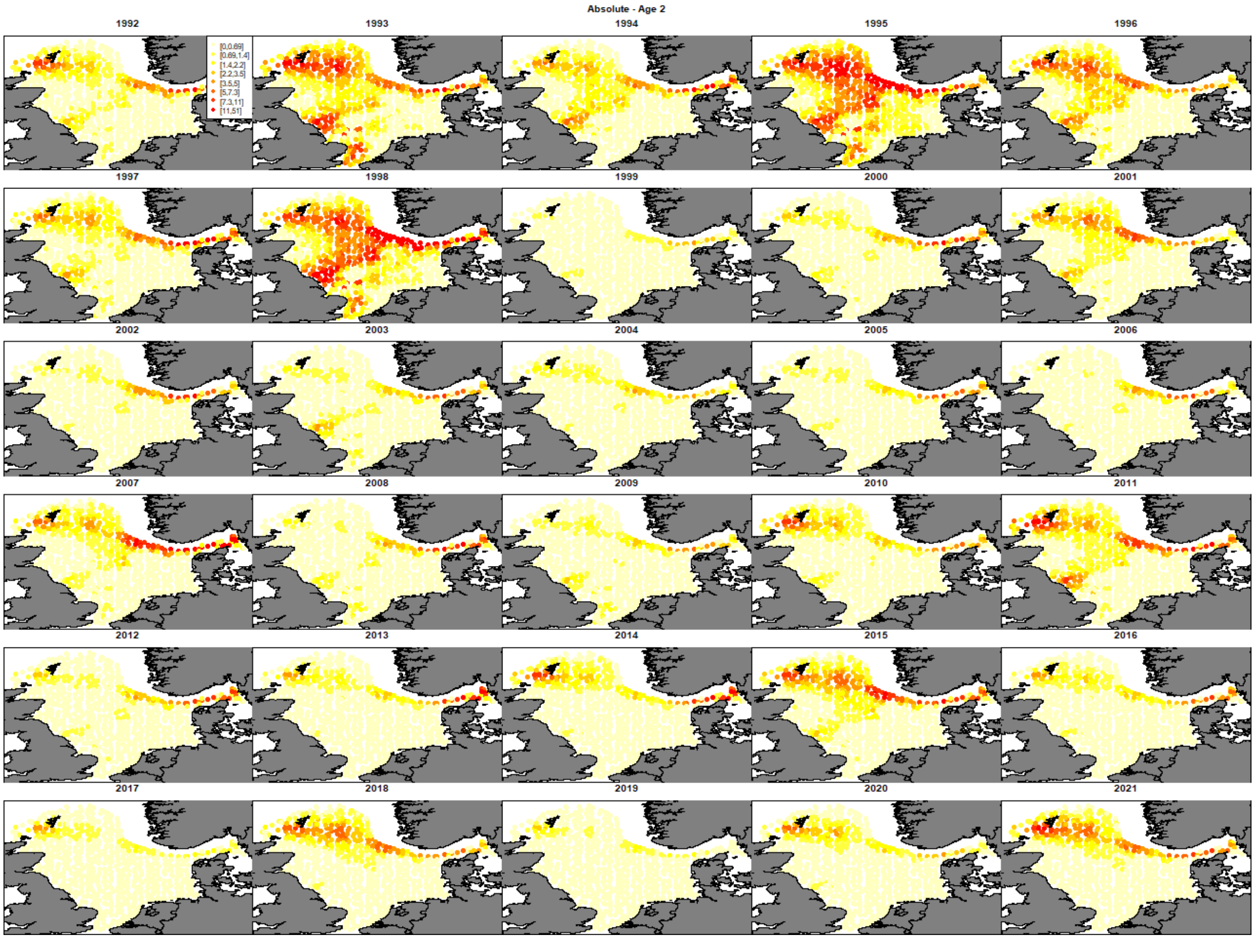

Residuals - age 1
Normal Q-Q Plot
Frequency
residuals
Sample Quantiles
Theoretical Quantiles
residual
Vessel
06W2
64T2
74CZ
64SS
35HT
74SS:1
58AA
58J3
77SE
Year
Time of year
HaulDur


Age 1
Positive
Presence/absence
Depth
Depth
Positive
Presence/absence
TimeShotHour
TimeShotHour

Age 2


Absolute - Age 2
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1993
1994
1995
1996
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[1.4,2.2]
[2.2,3.5]
[3.5,5]
[5,7.3]
[7.3,11]
[11,51]
1997
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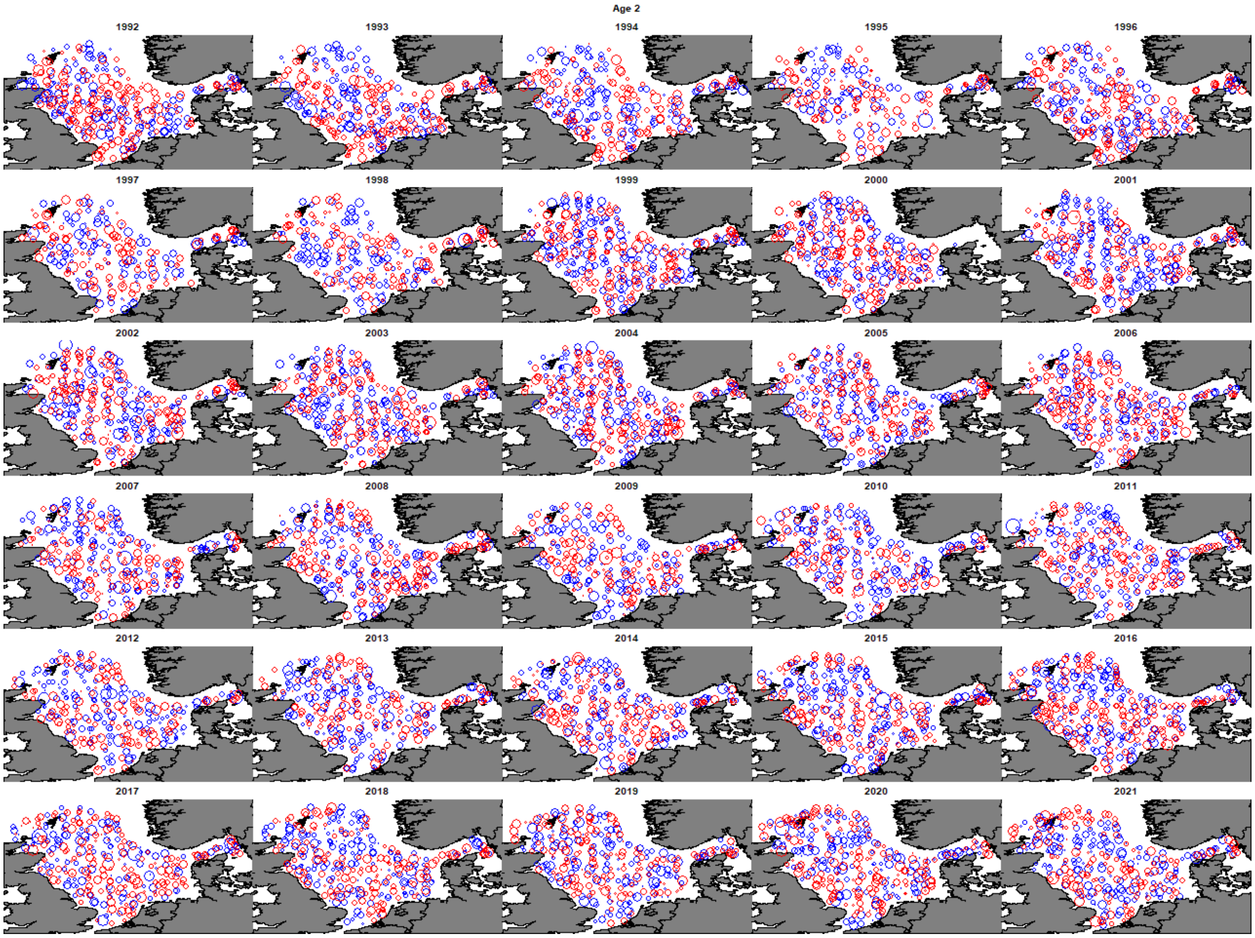
Age 2
1992
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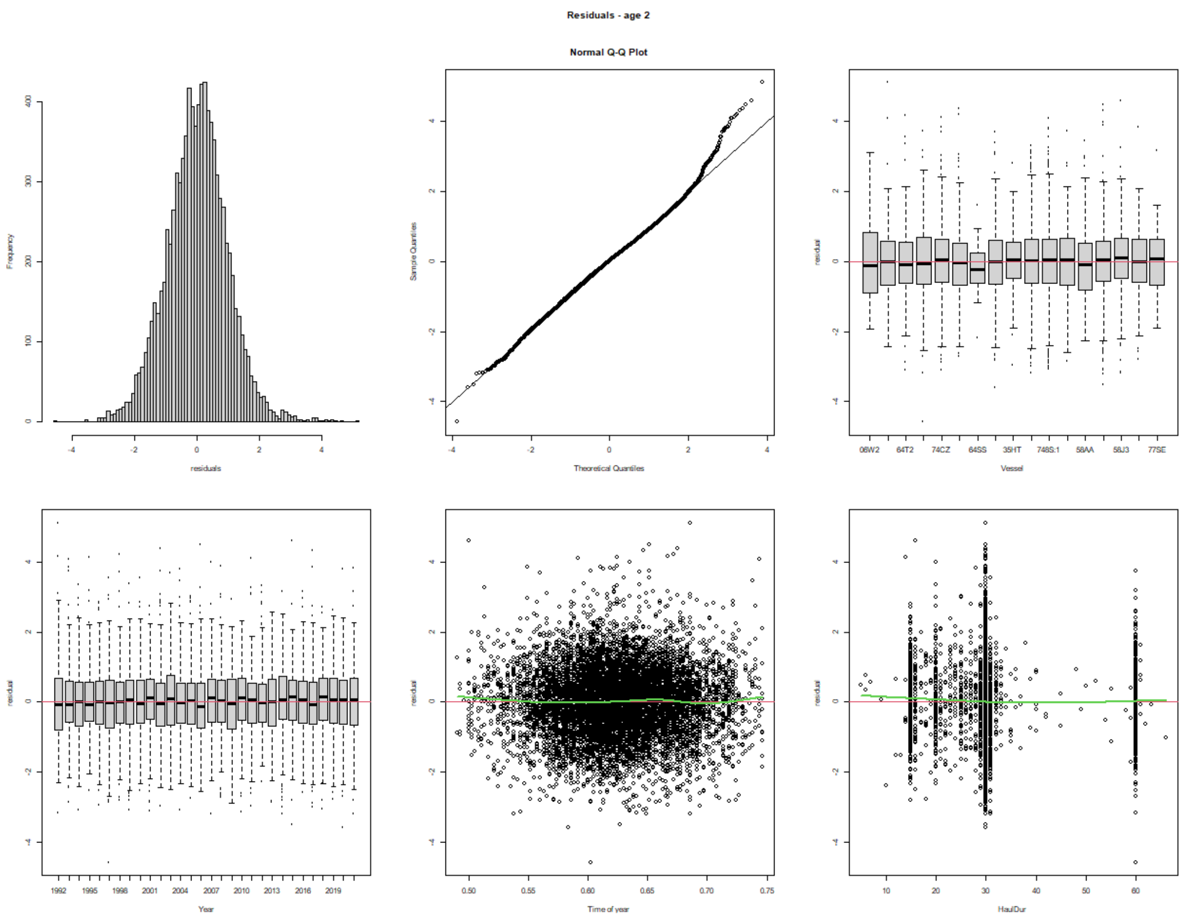
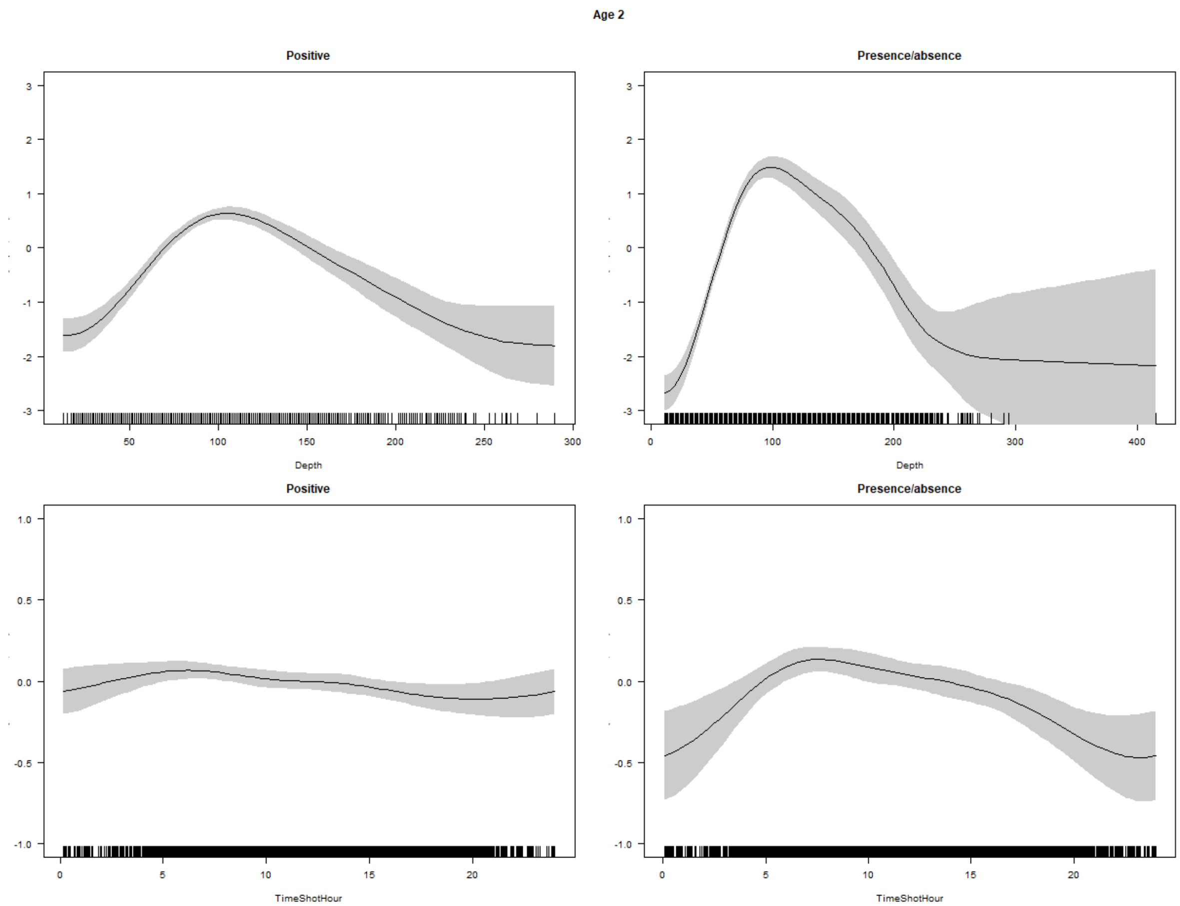
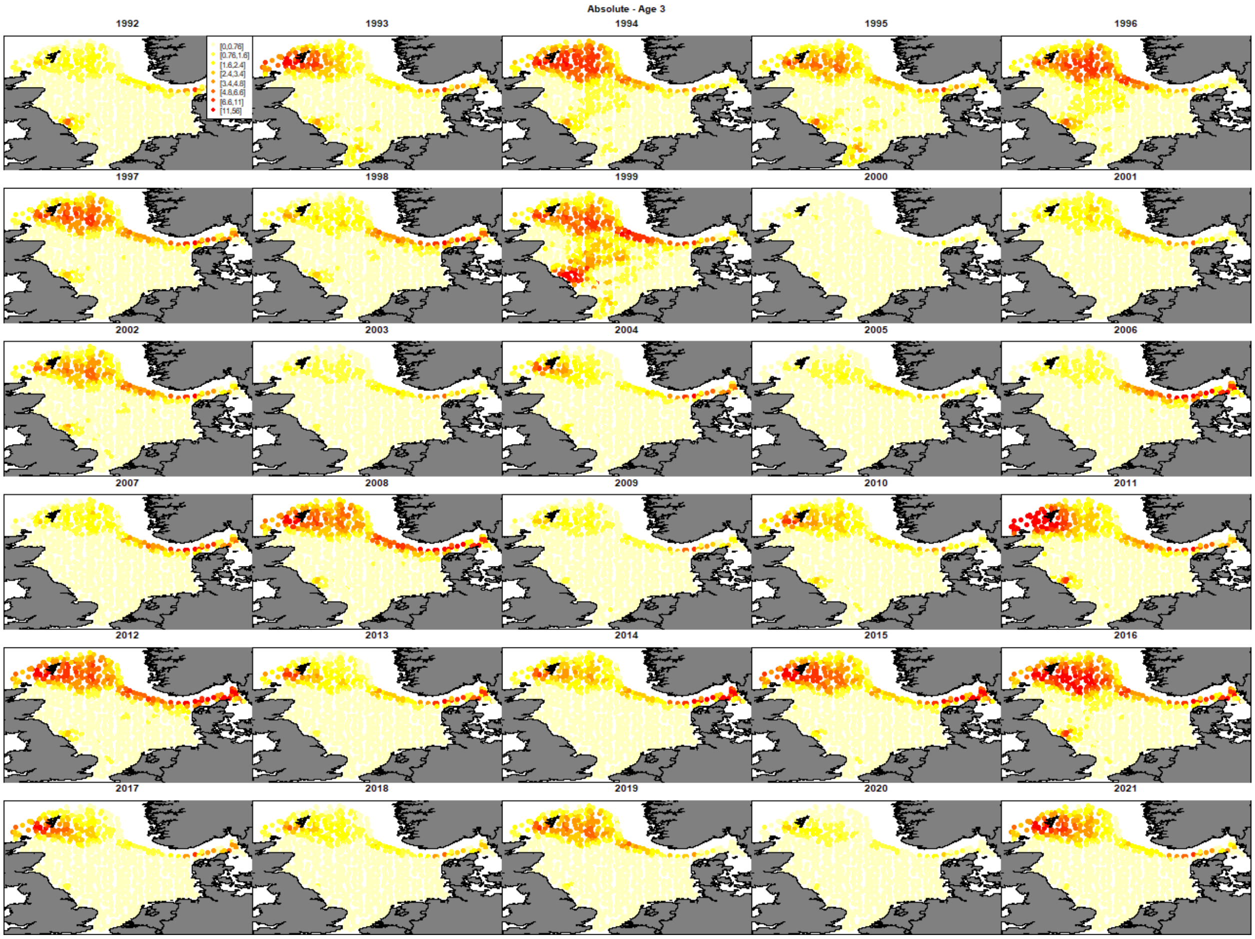

Residuals - age 2
Normal Q-Q Plot
Frequency
residuals
Sample Quantiles
Theoretical Quantiles
residual
Vessel
06W2
64T2
74CZ
64SS
35HT
74SS:1
58AA
58J3
77SE
Year
Time of year
HaulDur


Age 2
Positive
Presence/absence
Depth
Depth
Positive
Presence/absence
TimeShotHour
TimeShotHour

Age 3


Absolute - Age 3
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2021
[0,0.76]
[0.76,1.6]
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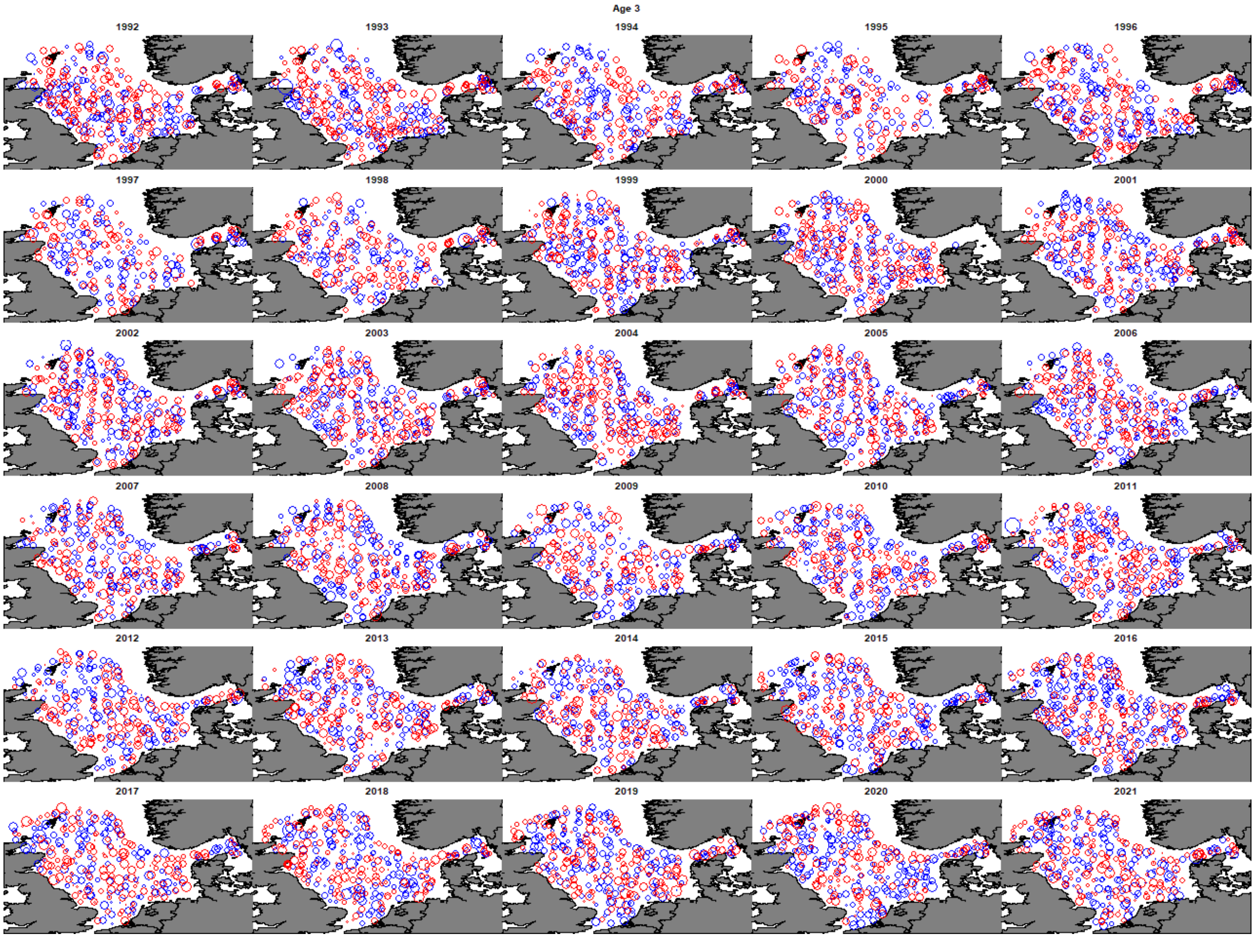
[2.4,3.4]
[3.4,4.8]
[4.8,6.6]
[6.6,11]
[11,56]


Age 3
1992
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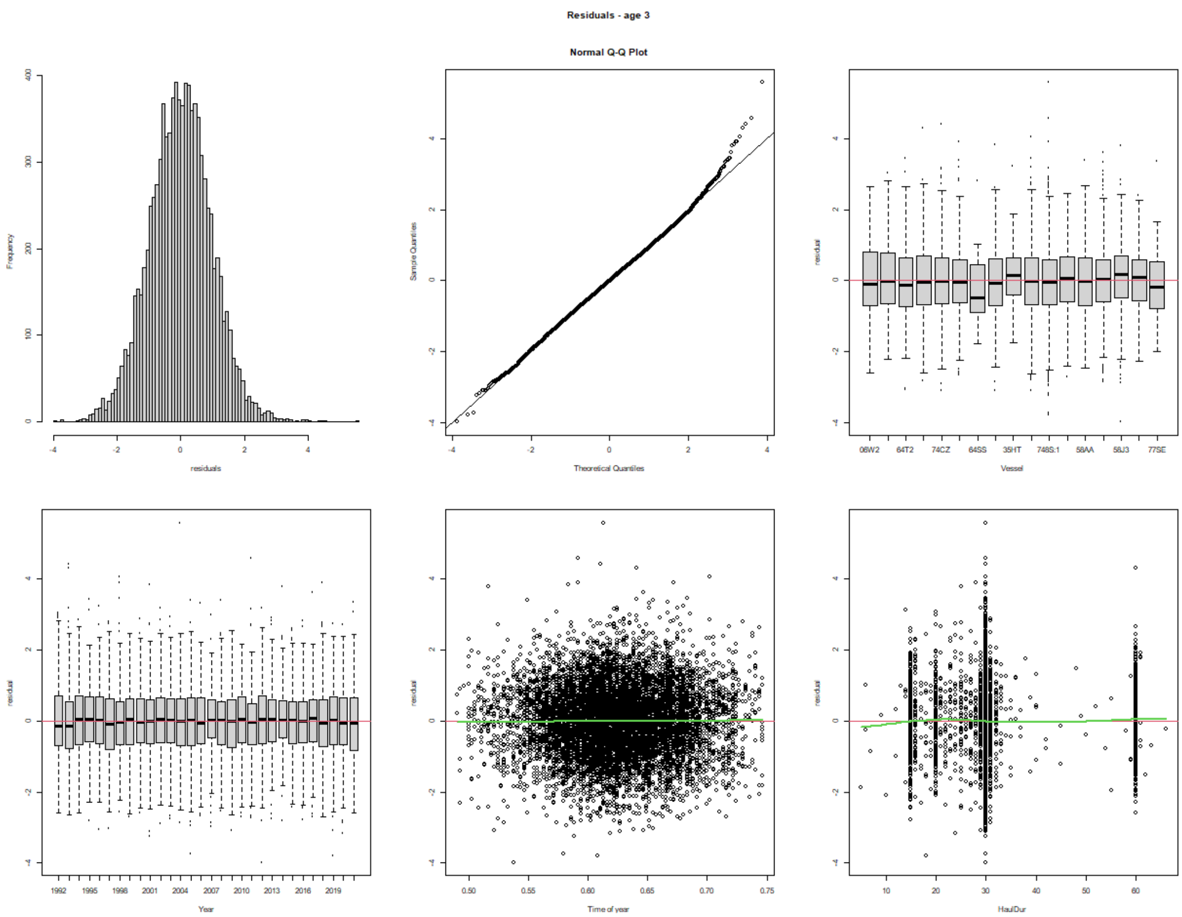
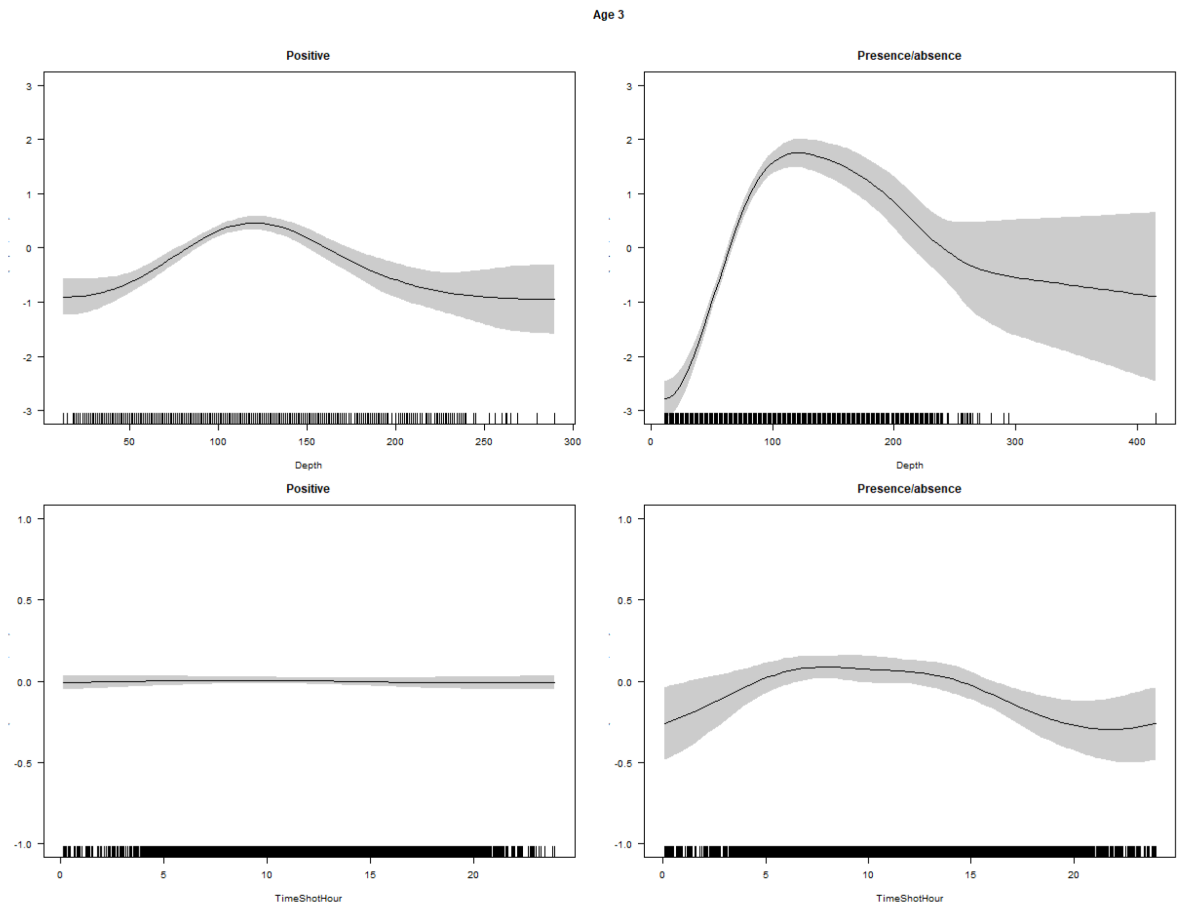
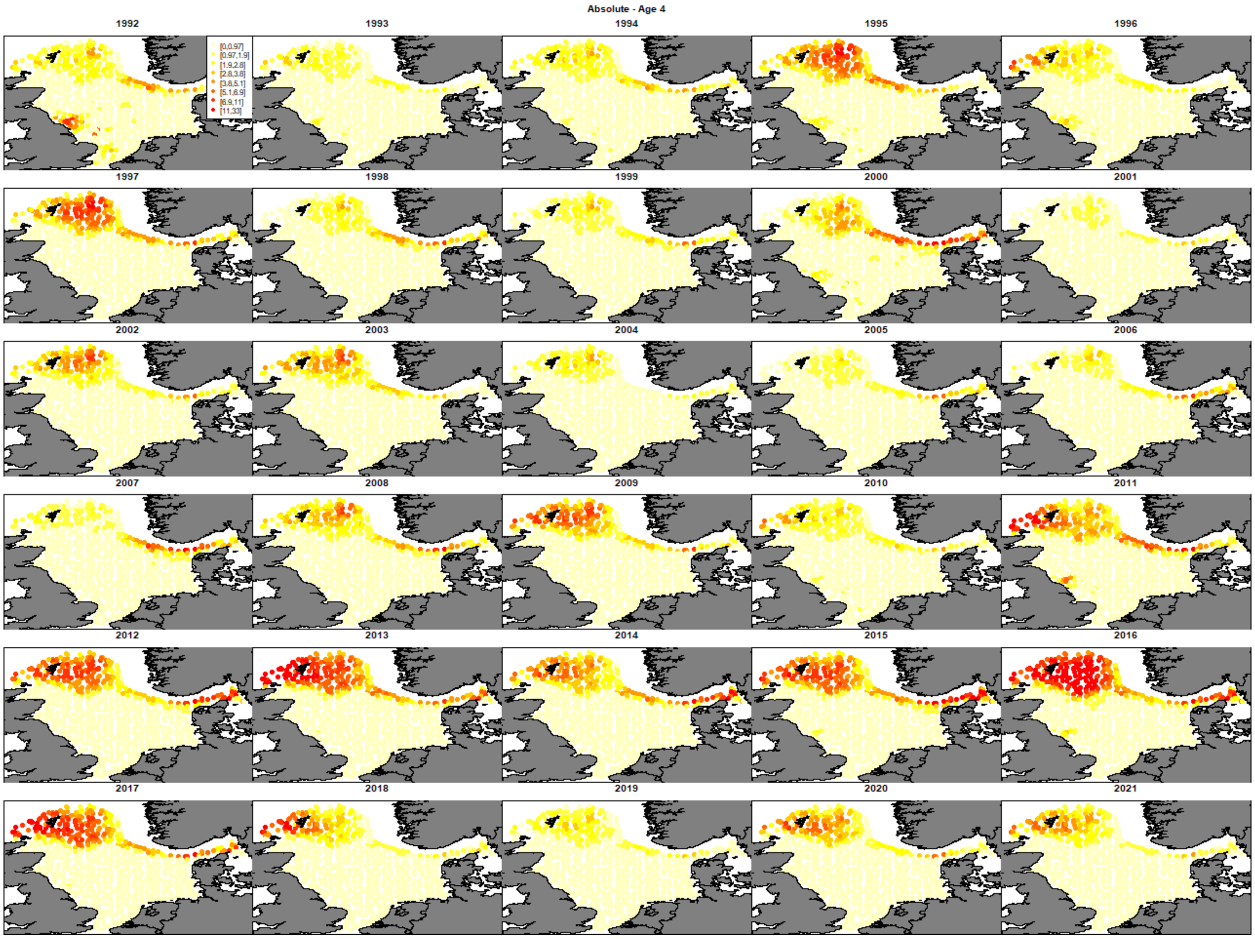

Residuals - age 3
Normal Q-Q Plot
Frequency
residuals
Sample Quantiles
Theoretical Quantiles
residual
Vessel
Year
Time of year
HaulDur


Age 3
Positive
Presence/absence
Depth
Positive
Presence/absence
TimeShotHour

Age 4


Absolute - Age 4
1992
1993
1994
1995
1996
[0,0.97]
[0.97,1.9]
[1.9,2.8]
[2.8,3.8]
[3.8,5.1]
[5.1,6.9]
[6.9,11]
[11,33]
1997
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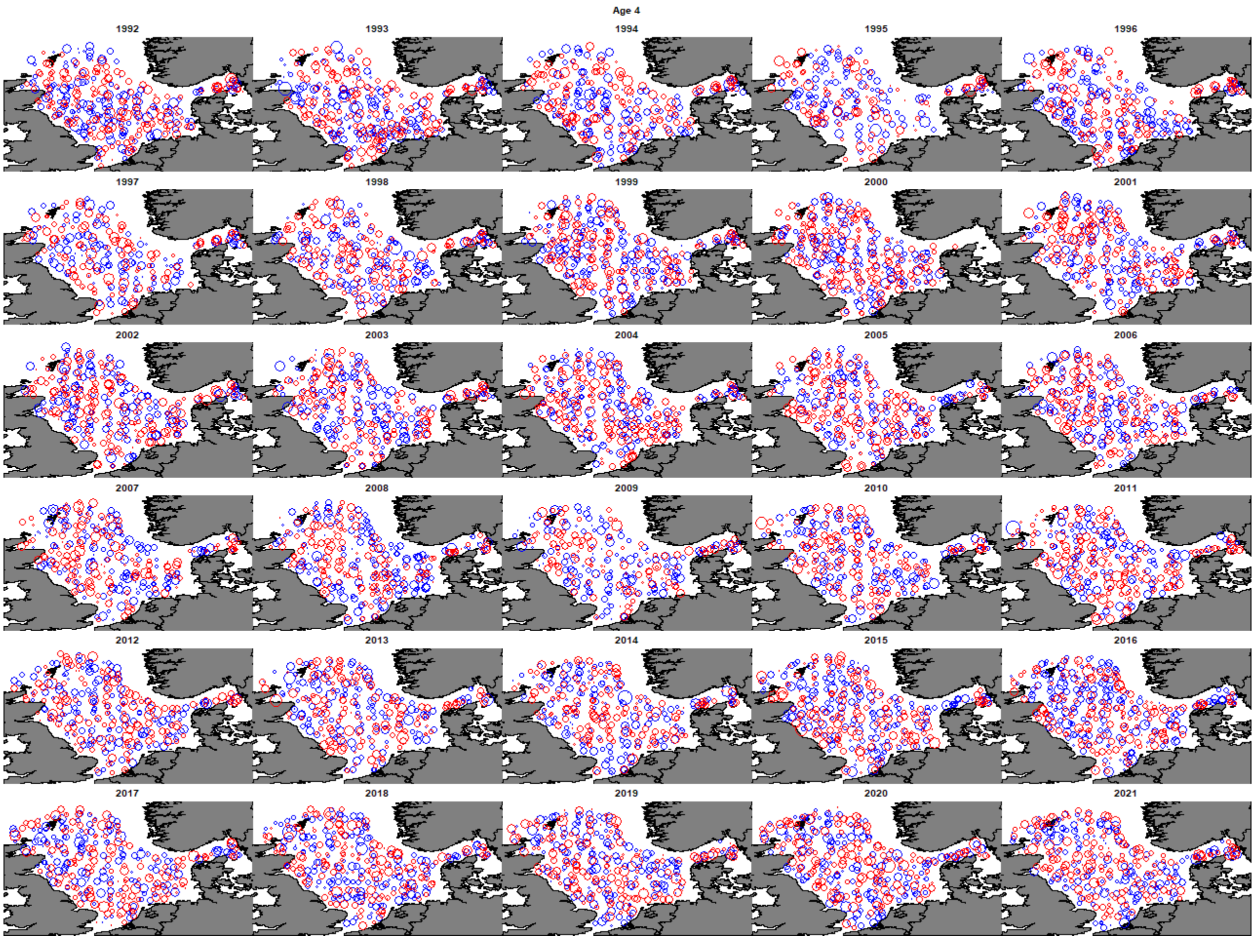
Age 4
1992
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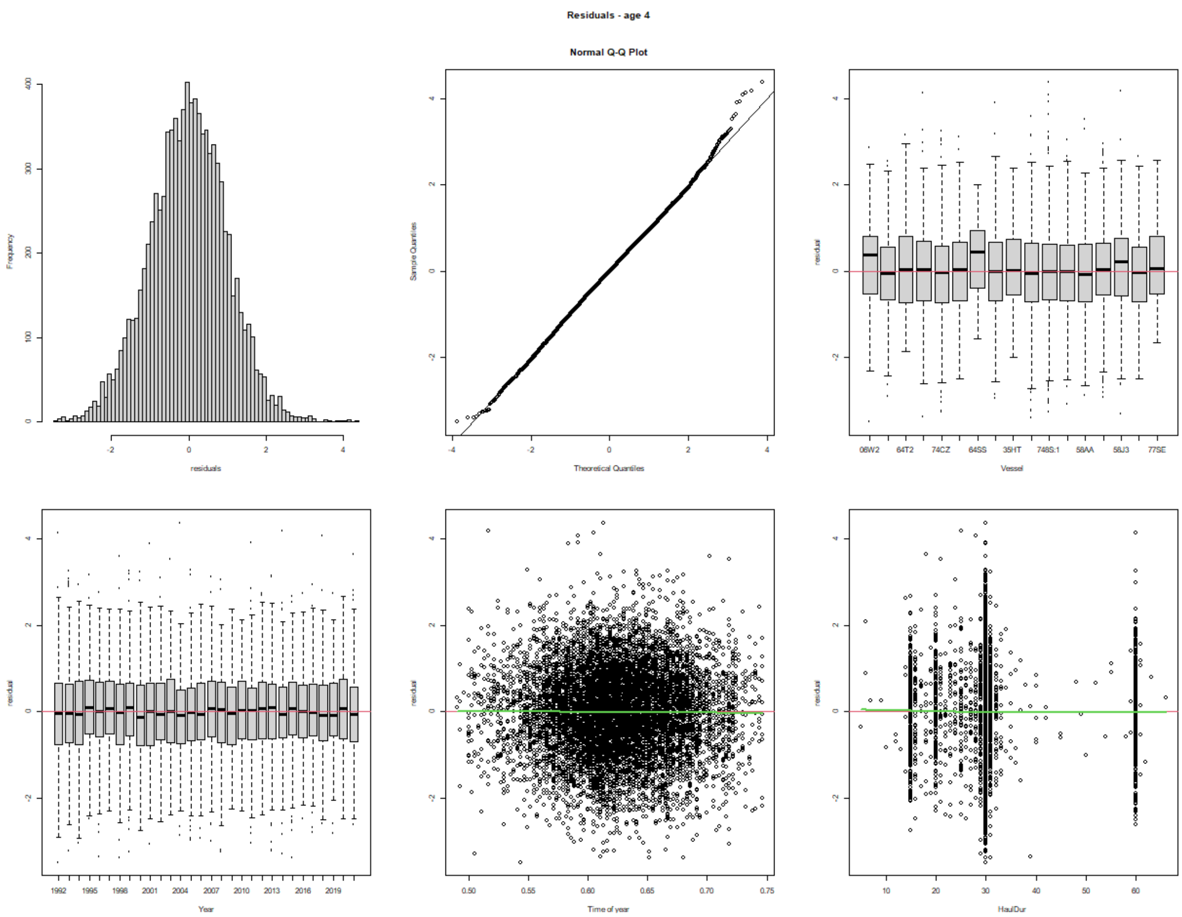
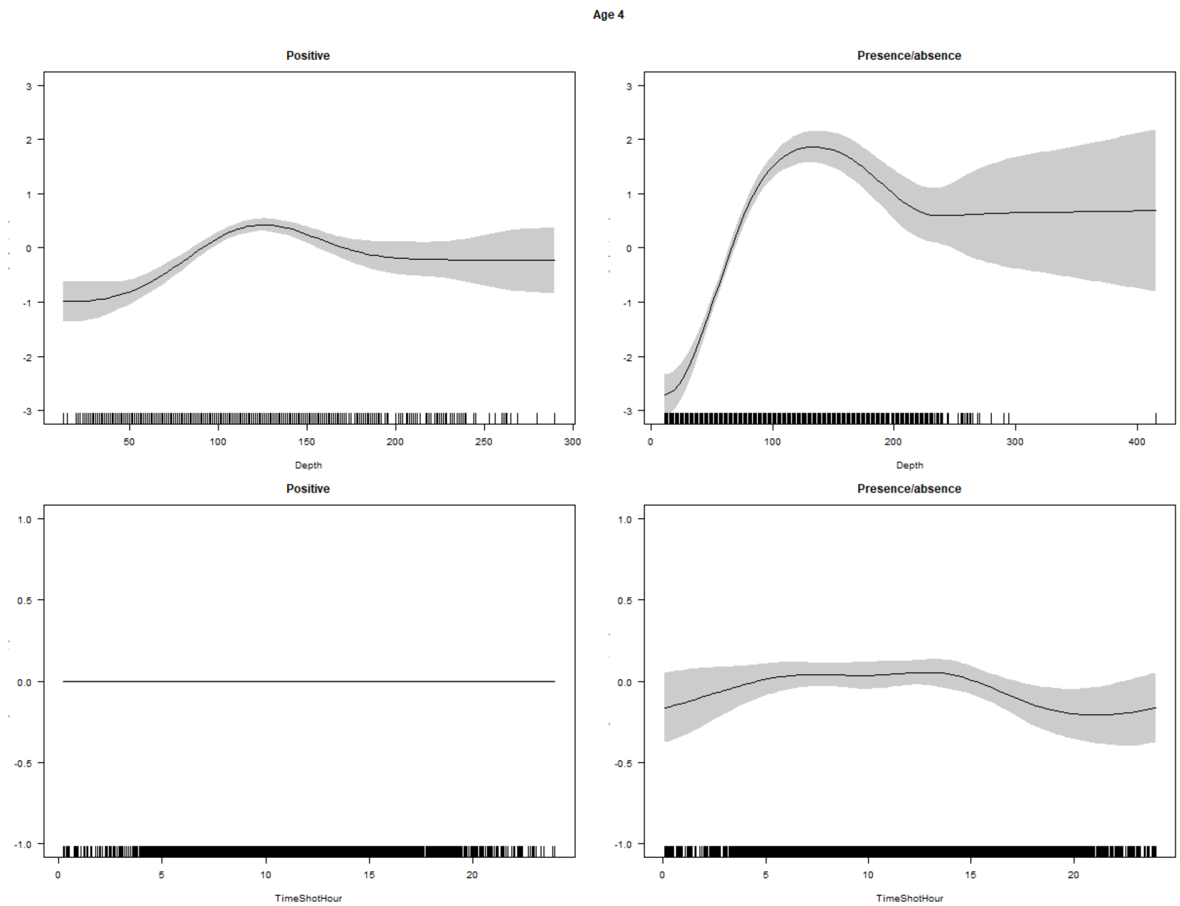
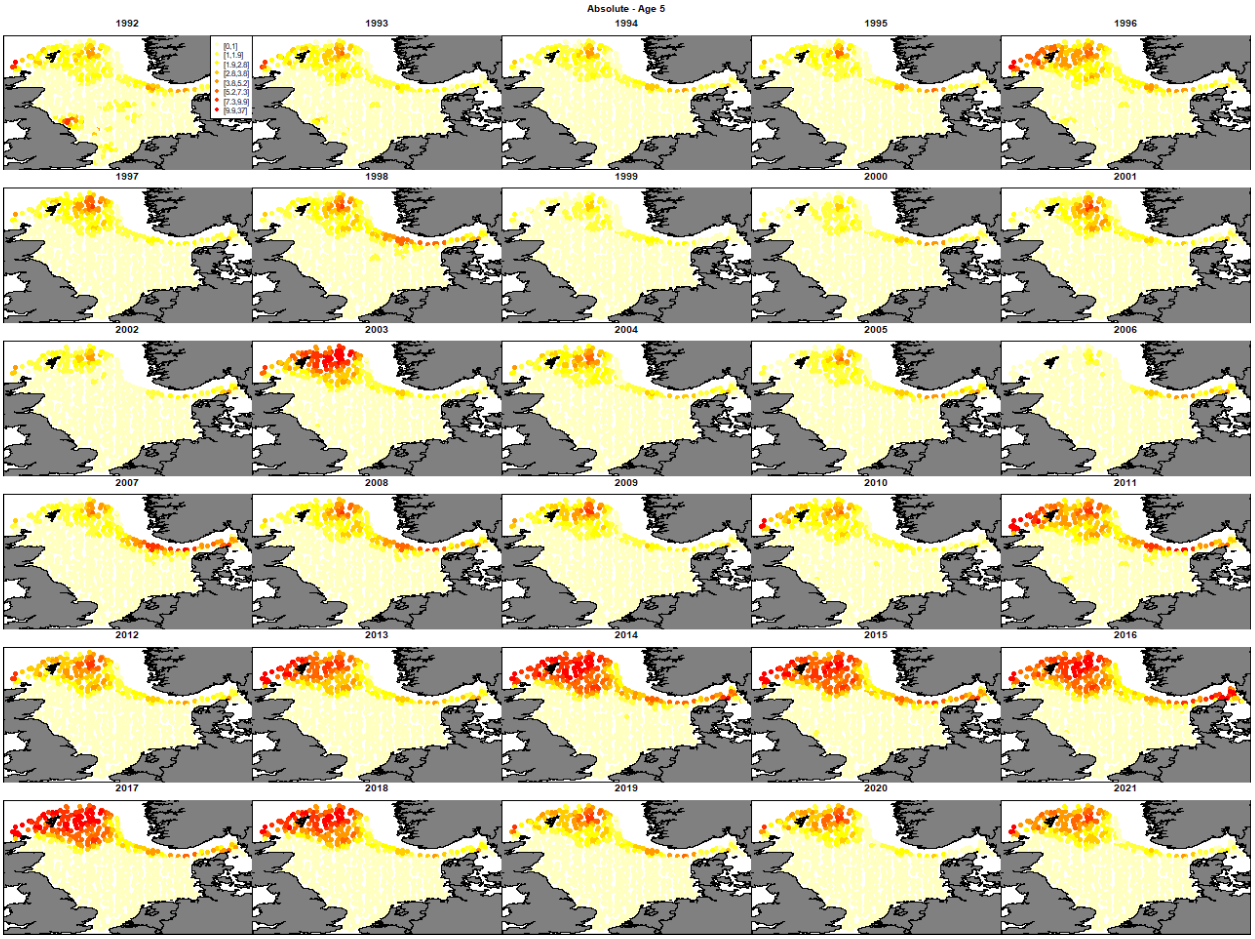

Residuals - age 4
Normal Q-Q Plot
Frequency
residuals
Sample Quantiles
Theoretical Quantiles
residual
Vessel
Year
Time of year
HaulDur



Age 4
Positive
Presence/absence
Depth
Depth
Positive
Presence/absence
TimeShotHour
TimeShotHour

Ages 5+


Absolute - Age 5
1992
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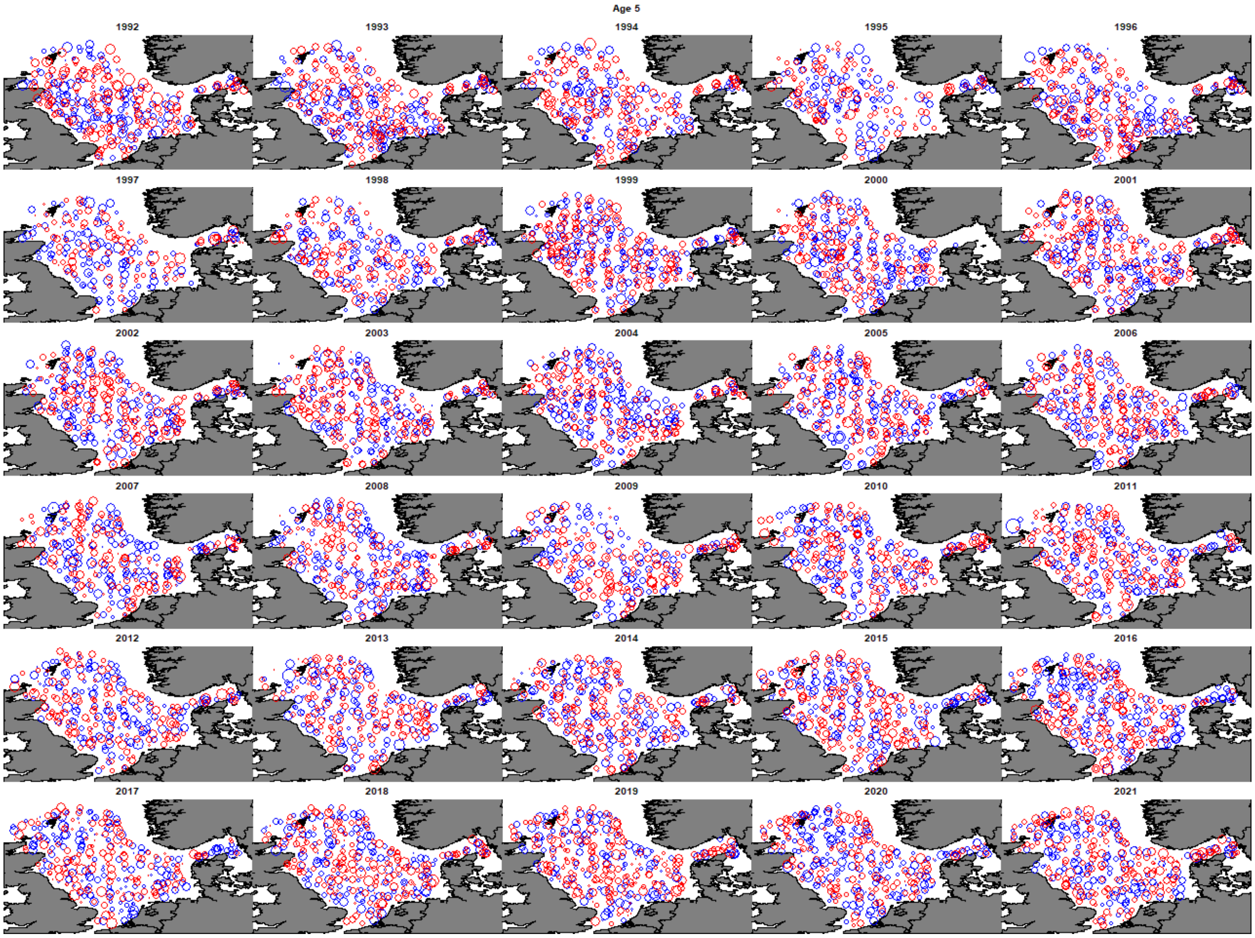
2018
2019
2020
2021
[0,1]
[1,1.9]
[1.9,2.8]
[2.8,3.8]
[3.8,5.2]
[5.2,7.3]
[7.3,9.9]
[9.9,37]


Age 5
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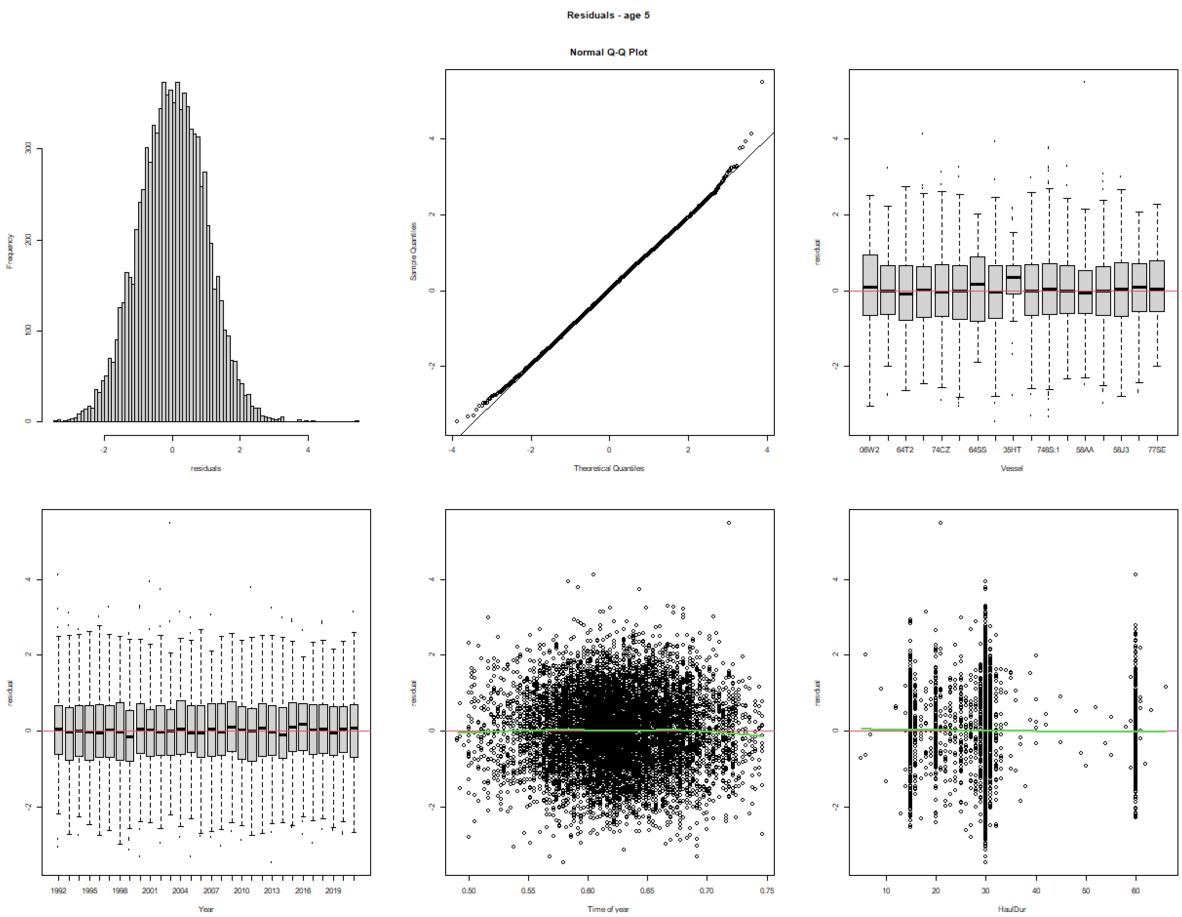
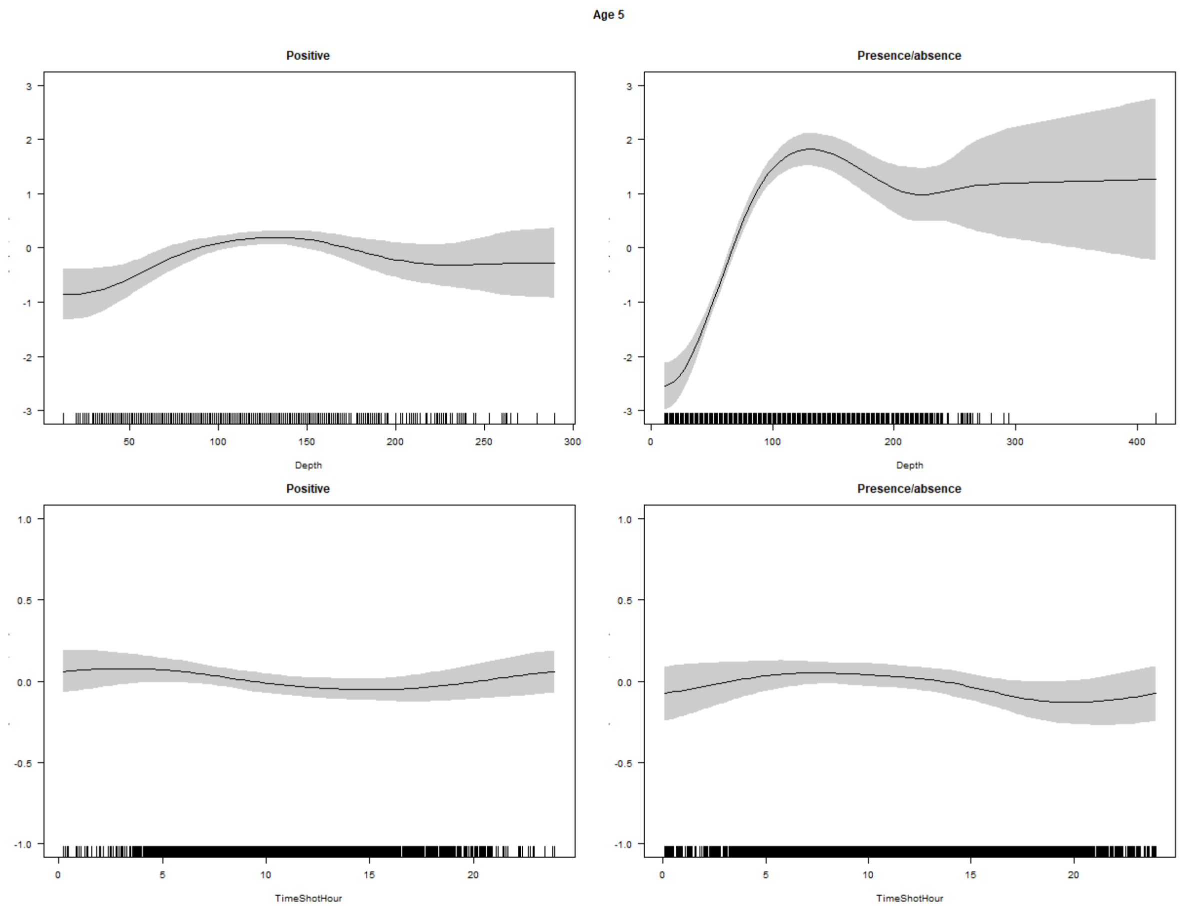
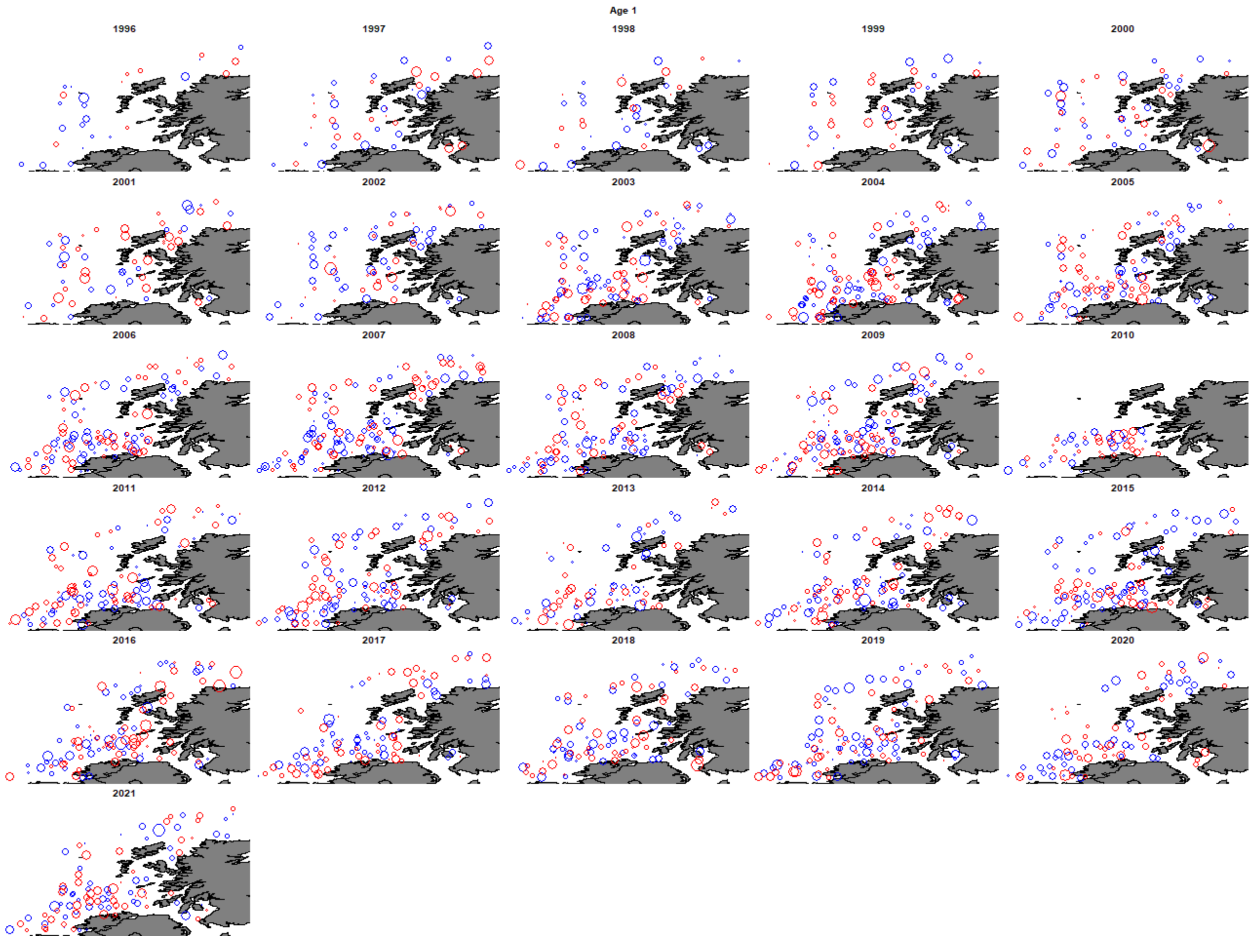

Residuals - age 5
Normal Q-Q Plot
Frequency
residuals
Sample Quantiles
Theoretical Quantiles
residual
Vessel
Year
Time of year
HaulDur


Age 5
Positive
Presence/absence
Depth
Depth
Positive
Presence/absence
TimeShotHour
TimeShotHour

Quarter 4

Age 1


Age 1
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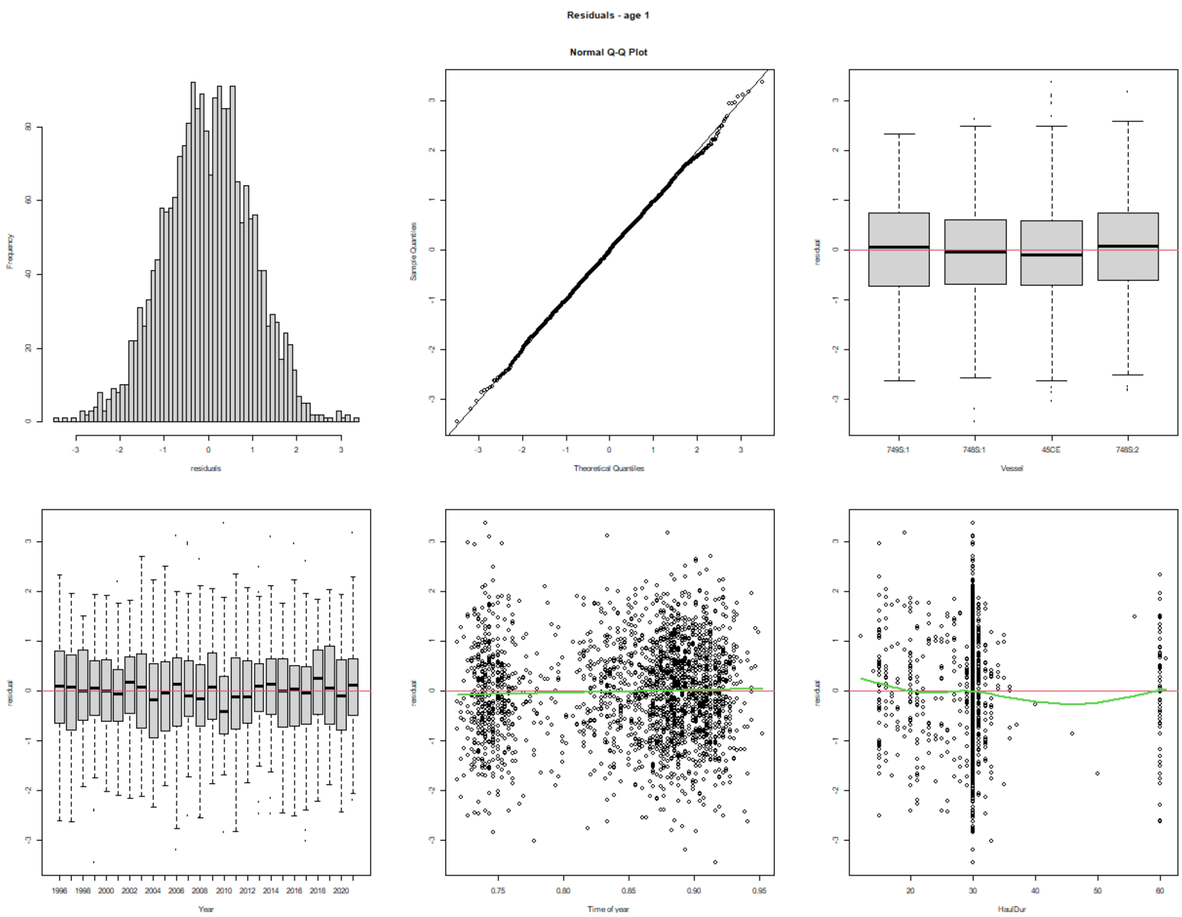
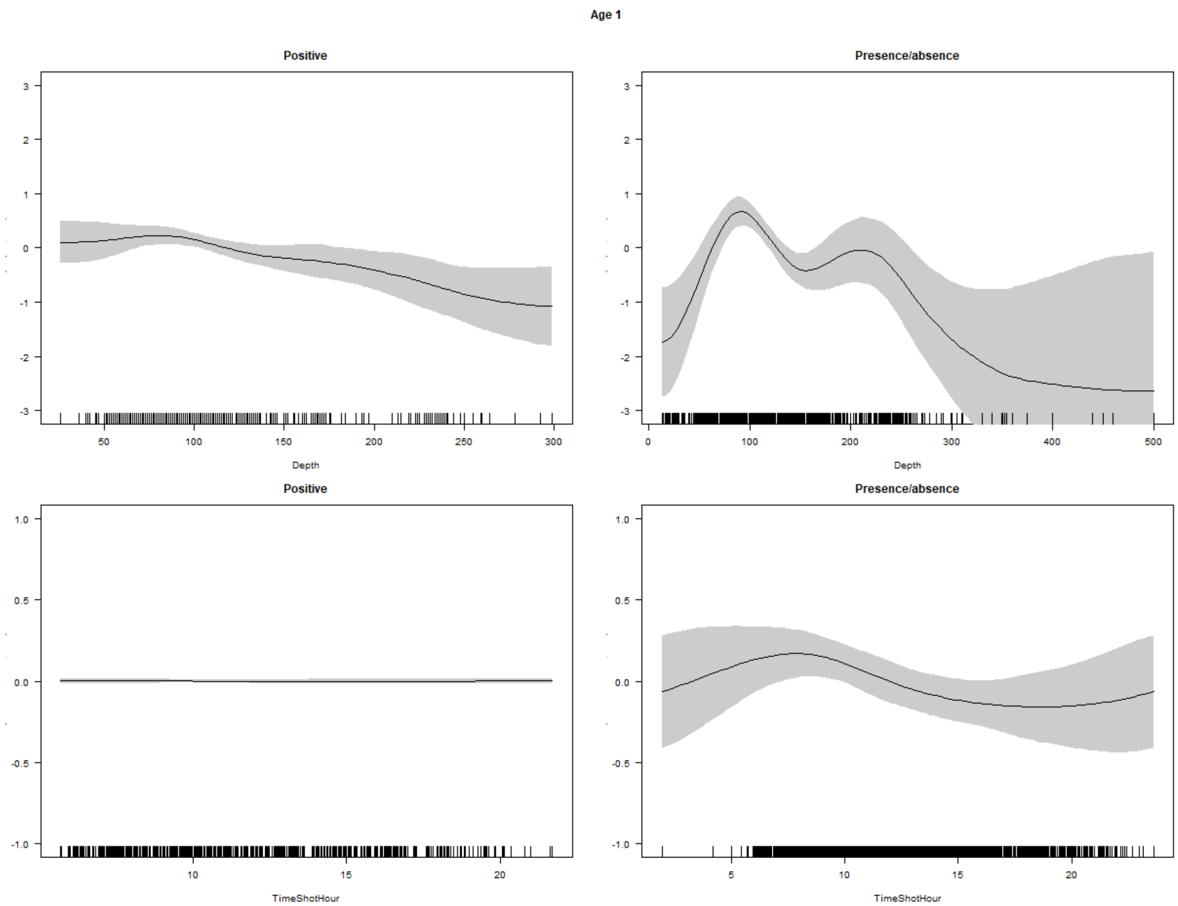
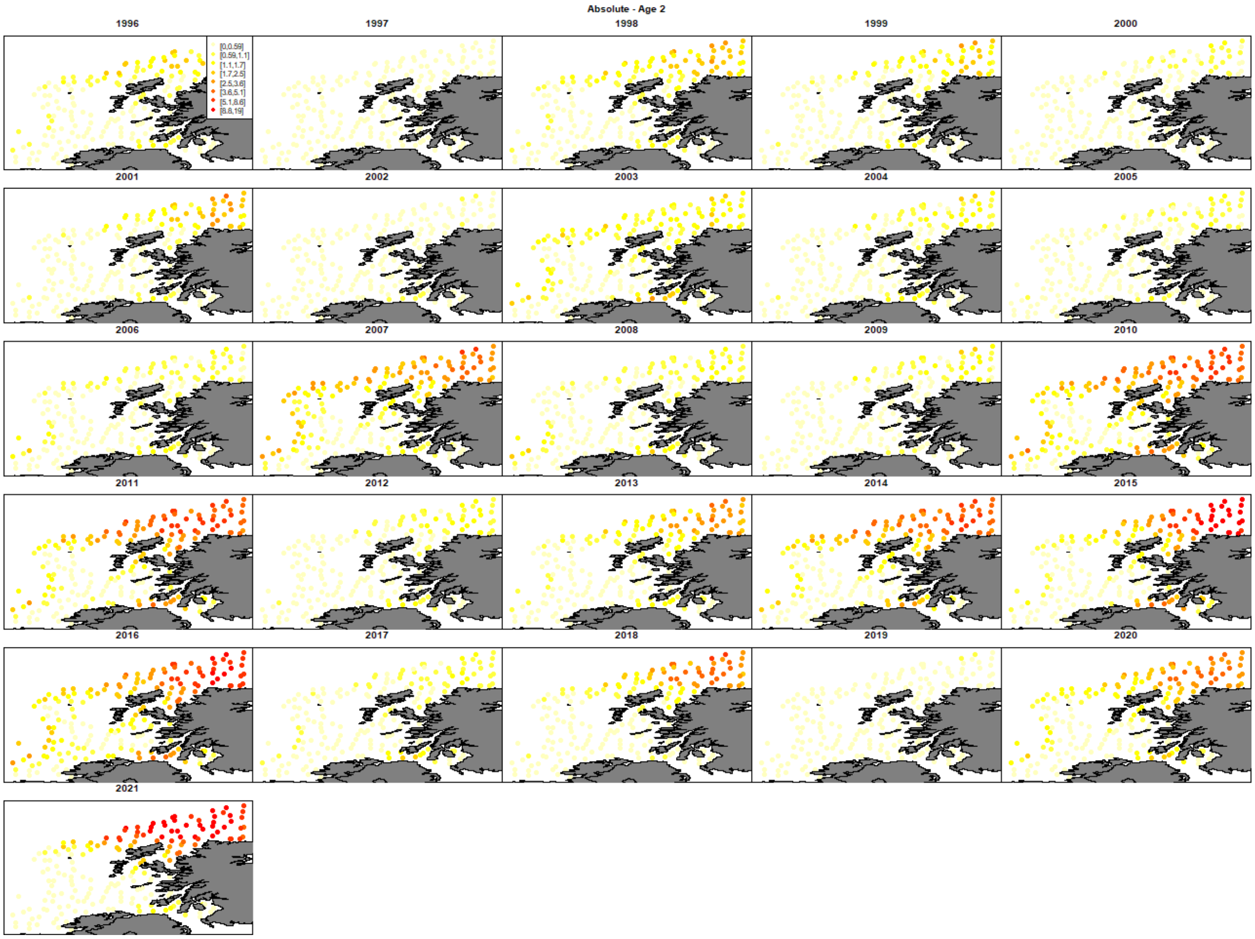

Residuals - age 1
Normal Q-Q Plot
Frequency
residuals
Sample Quantiles
Theoretical Quantiles
residual
749S:1
748S:1
45CE
748S:2
Vessel
Year
Time of year
HaulDur


Age 1
Positive
Presence/absence
Depth
Positive
Presence/absence
TimeShotHour

Age 2


Absolute - Age 2
1996
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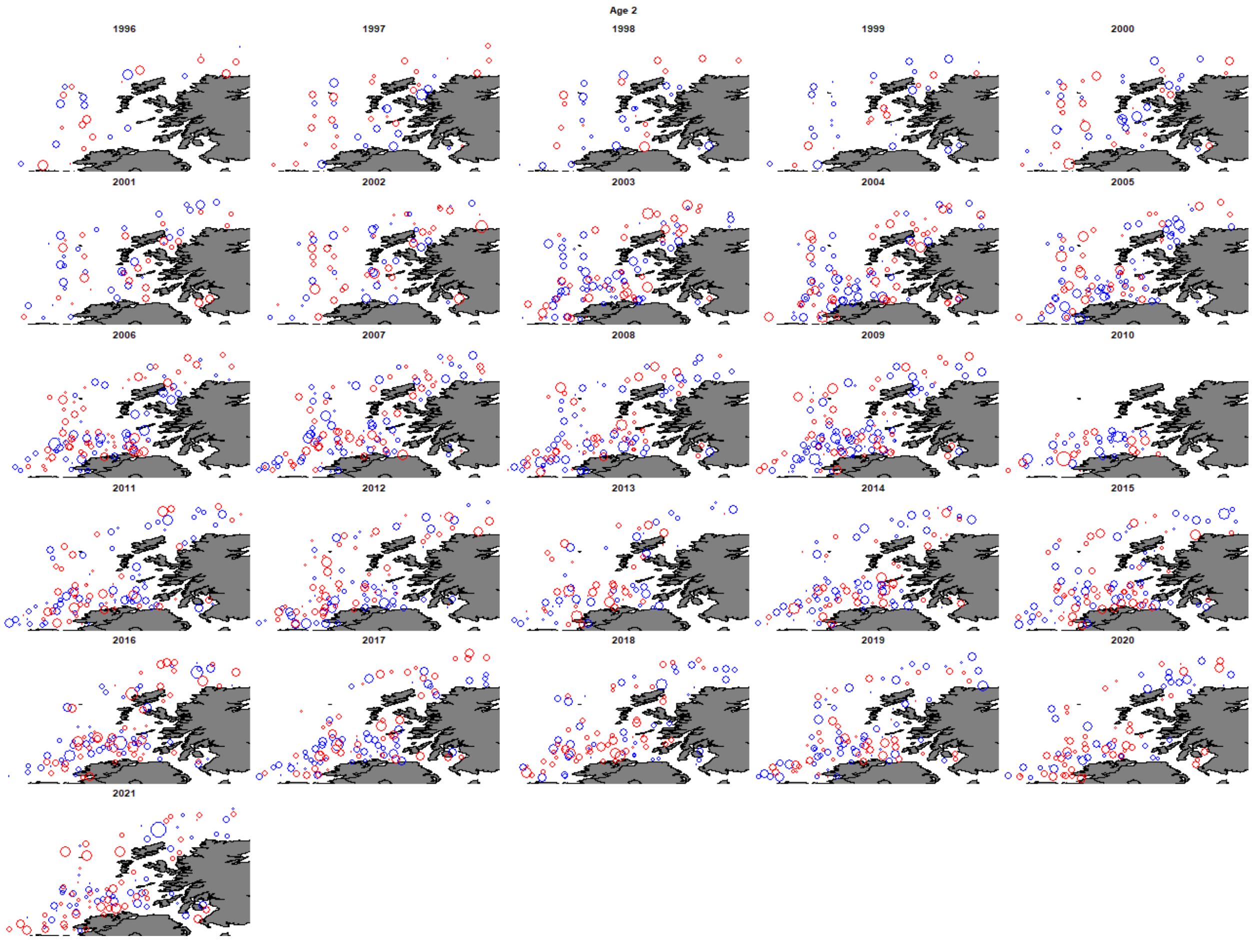
2020
2021
[0,0.59]
[0.59,1.1]
[1.1,1.7]
[1.7,2.5]
[2.5,3.6]
[3.6,5.1]
[5.1,8.6]
[8.8,19]


Age 2
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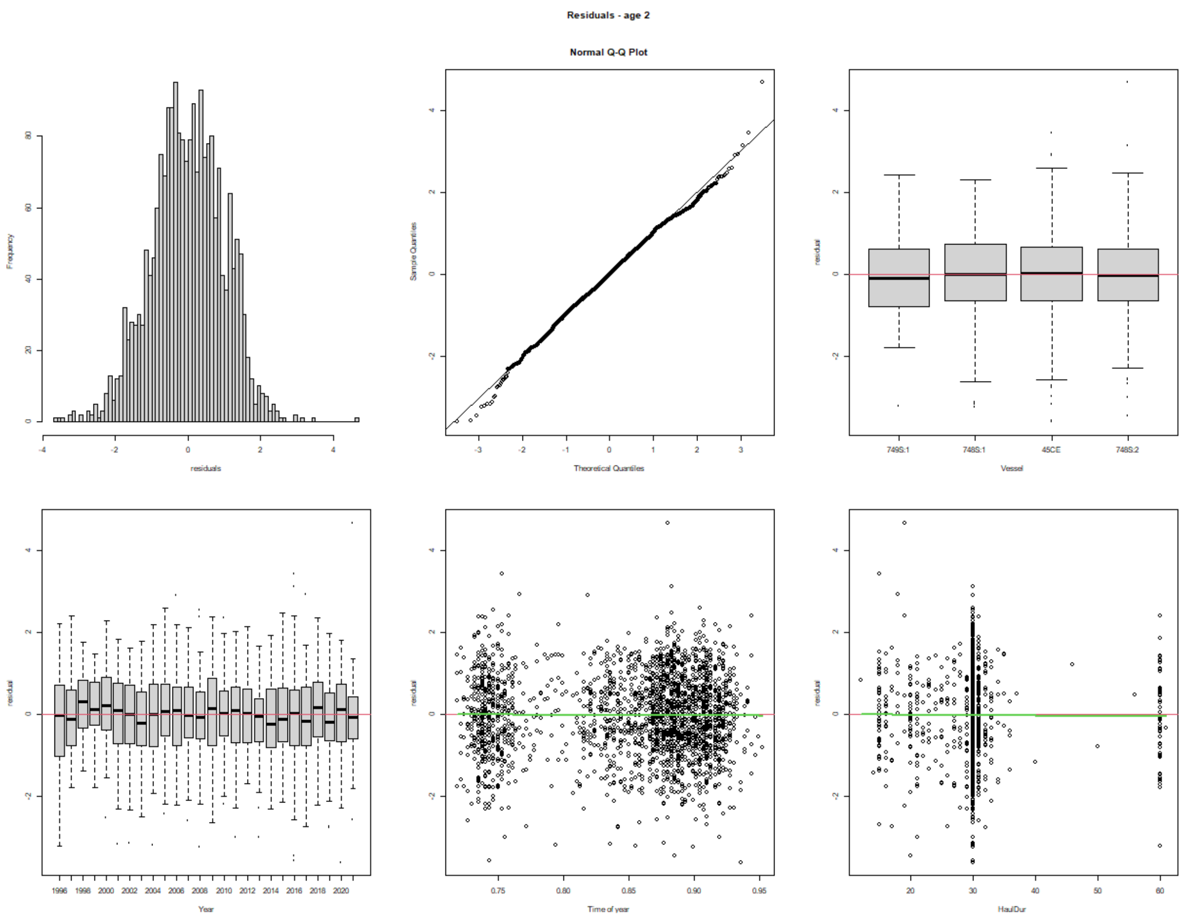
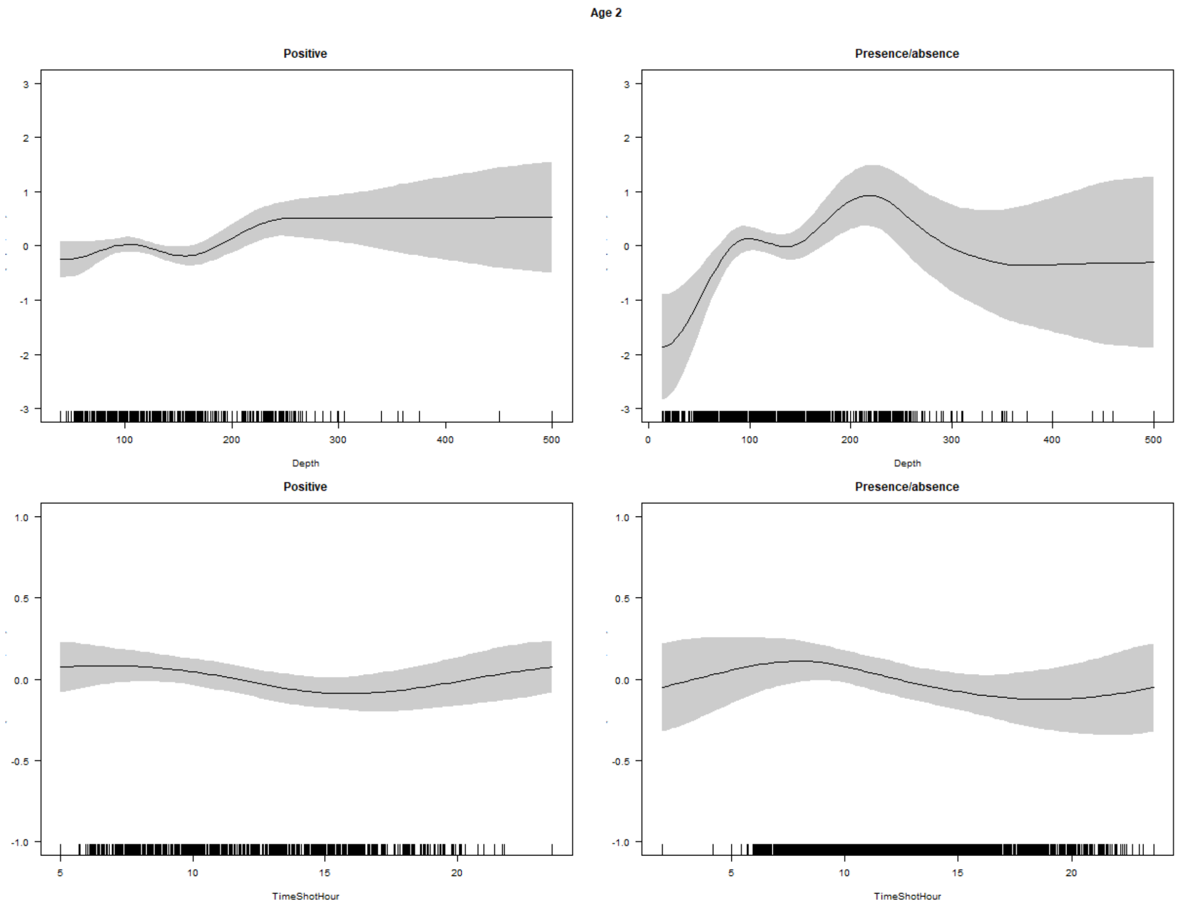

Residuals - age 2
Normal Q-Q Plot
Frequency
residuals
Sample Quantiles
Theoretical Quantiles
residual
749S:1
748S:1
45CE
748S:2
Vessel
Year
Time of year
HaulDur


Age 2
Positive
Presence/absence
Depth
Depth
Positive
Presence/absence
TimeShotHour
TimeShotHour

Age 3

Absolute - Age 3
1996
1997
1998
1999
2000
[0,0.79]
[0.79,1.7]
[1.7,2.6]
[2.6,4.3]
[4.3,5.9]
[6,8.4]
[8.5,15]
[15,29]
2001
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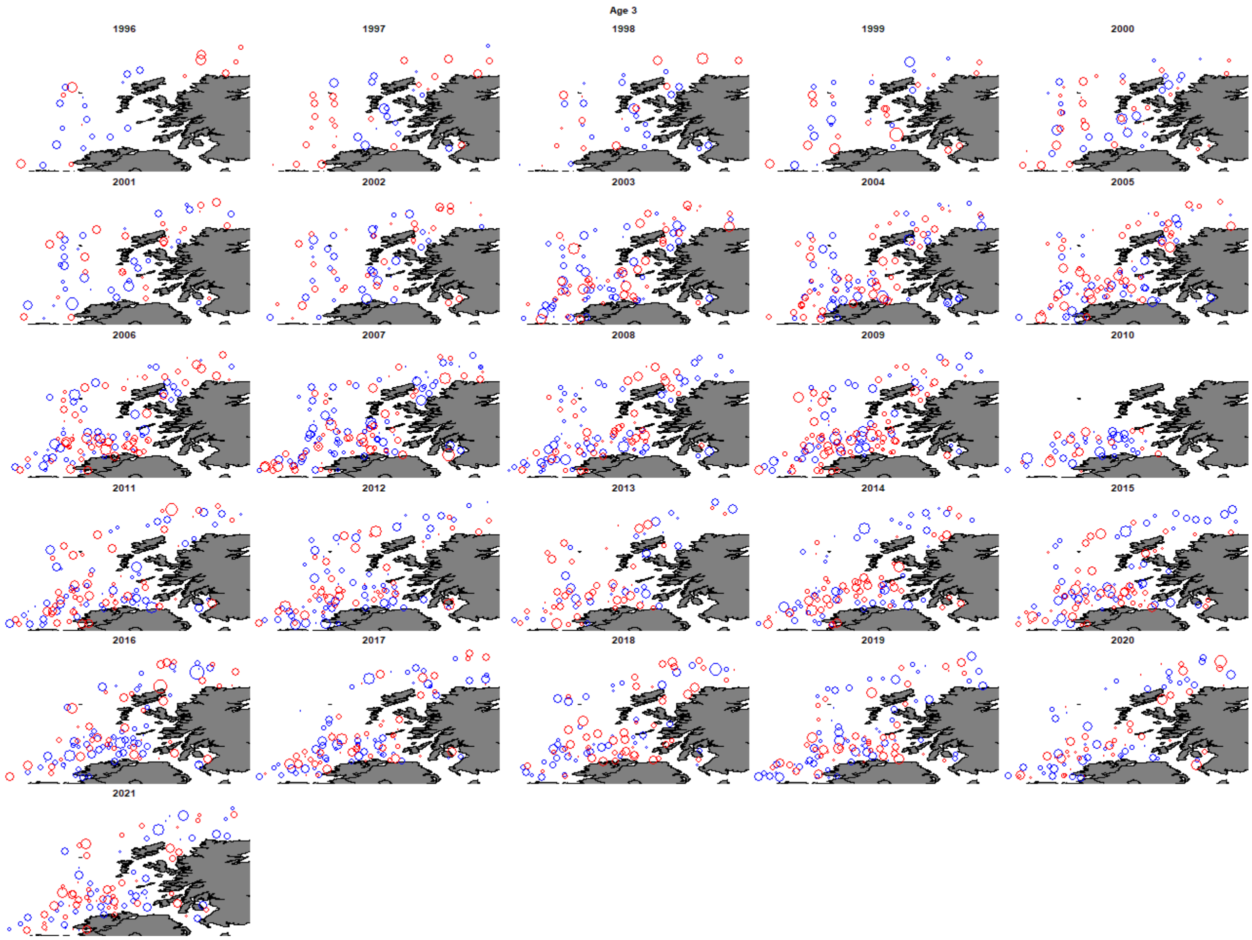
Age 3
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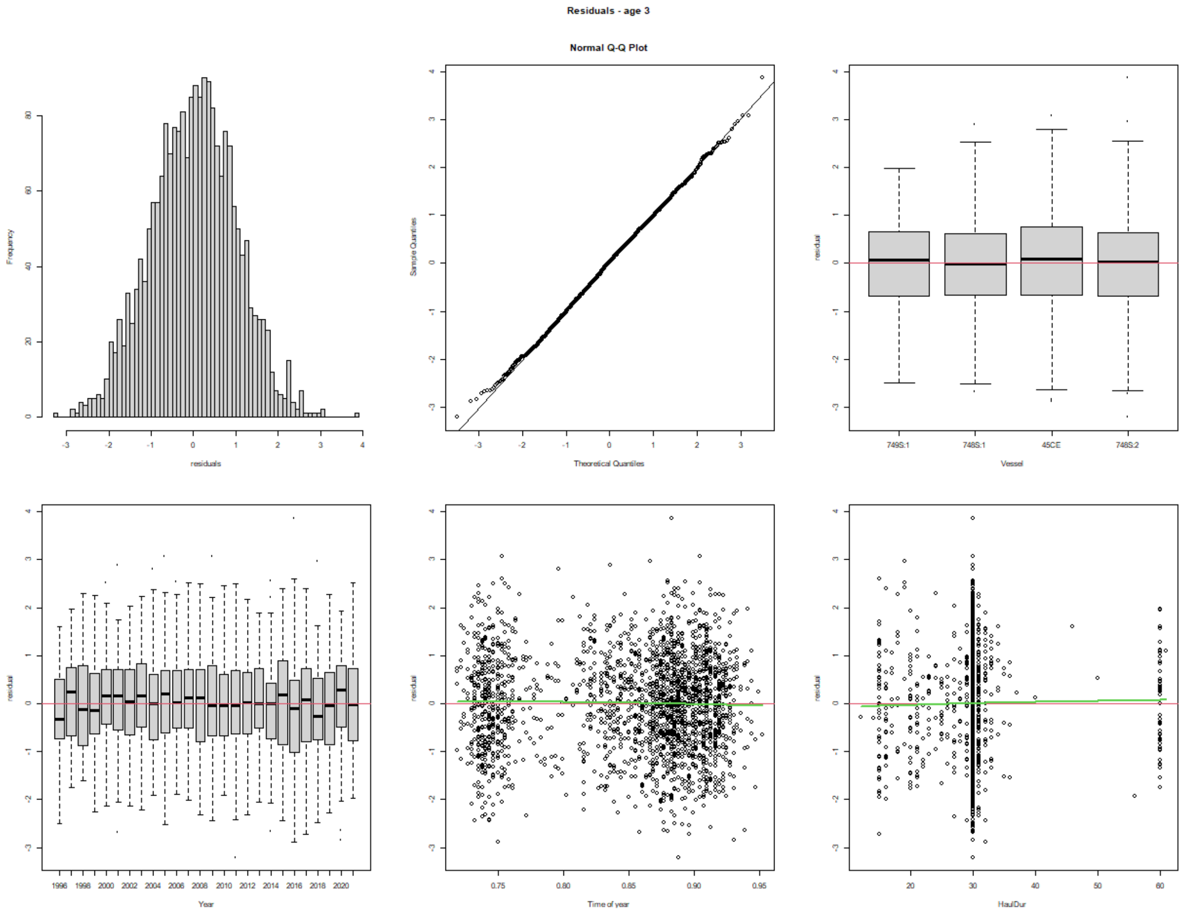
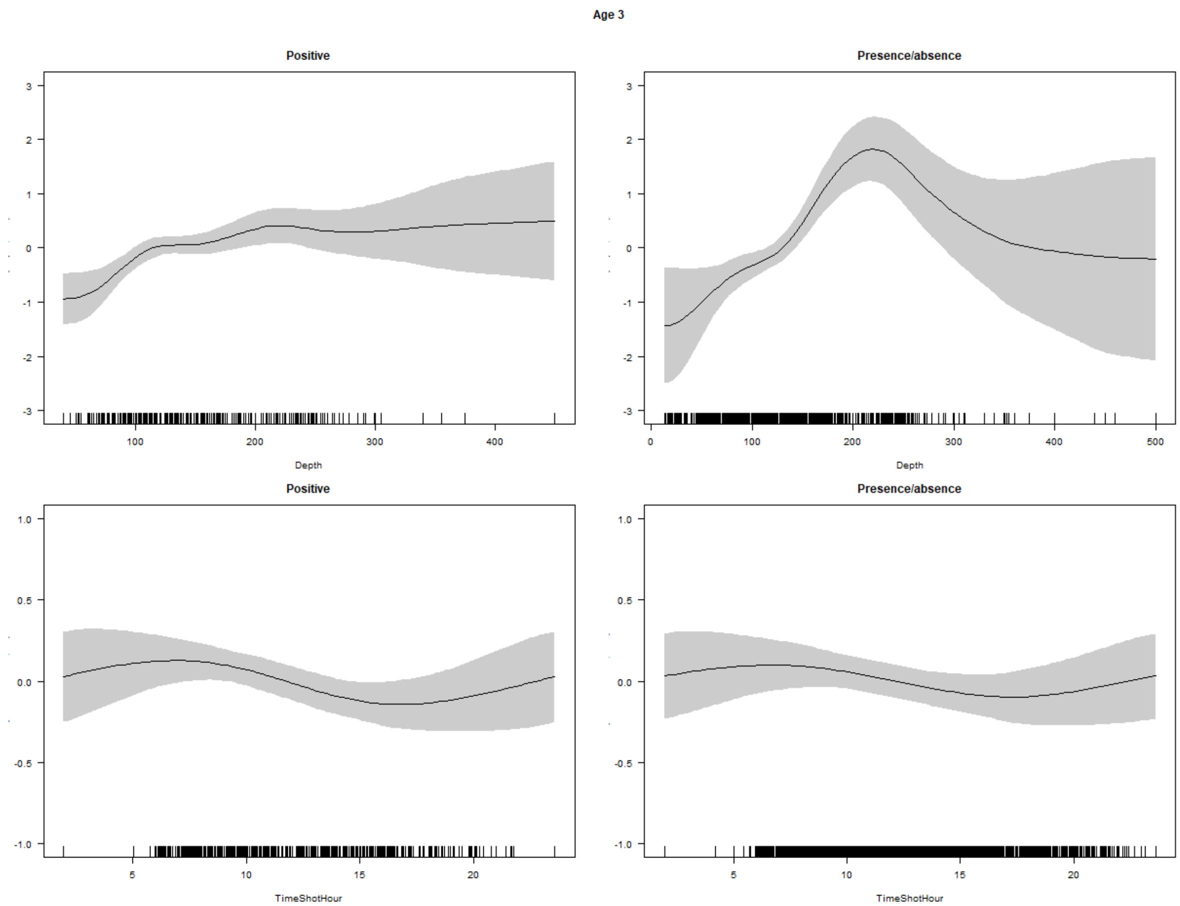
2021


Residuals - age 3
Normal Q-Q Plot
Frequency
residuals
Sample Quantiles
Theoretical Quantiles
residual
Vessel
749S:1
748S:1
45CE
748S:2
Year
Time of year
HaulDur


Age 3
Positive
Presence/absence
Depth
Depth
Positive
Presence/absence
TimeShotHour
TimeShotHour

Ages 4+

Absolute - Age 4
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
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2007
2008
2009
2010
2011
2012
2013
2014
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2019
2020
2021
[0,1.1]
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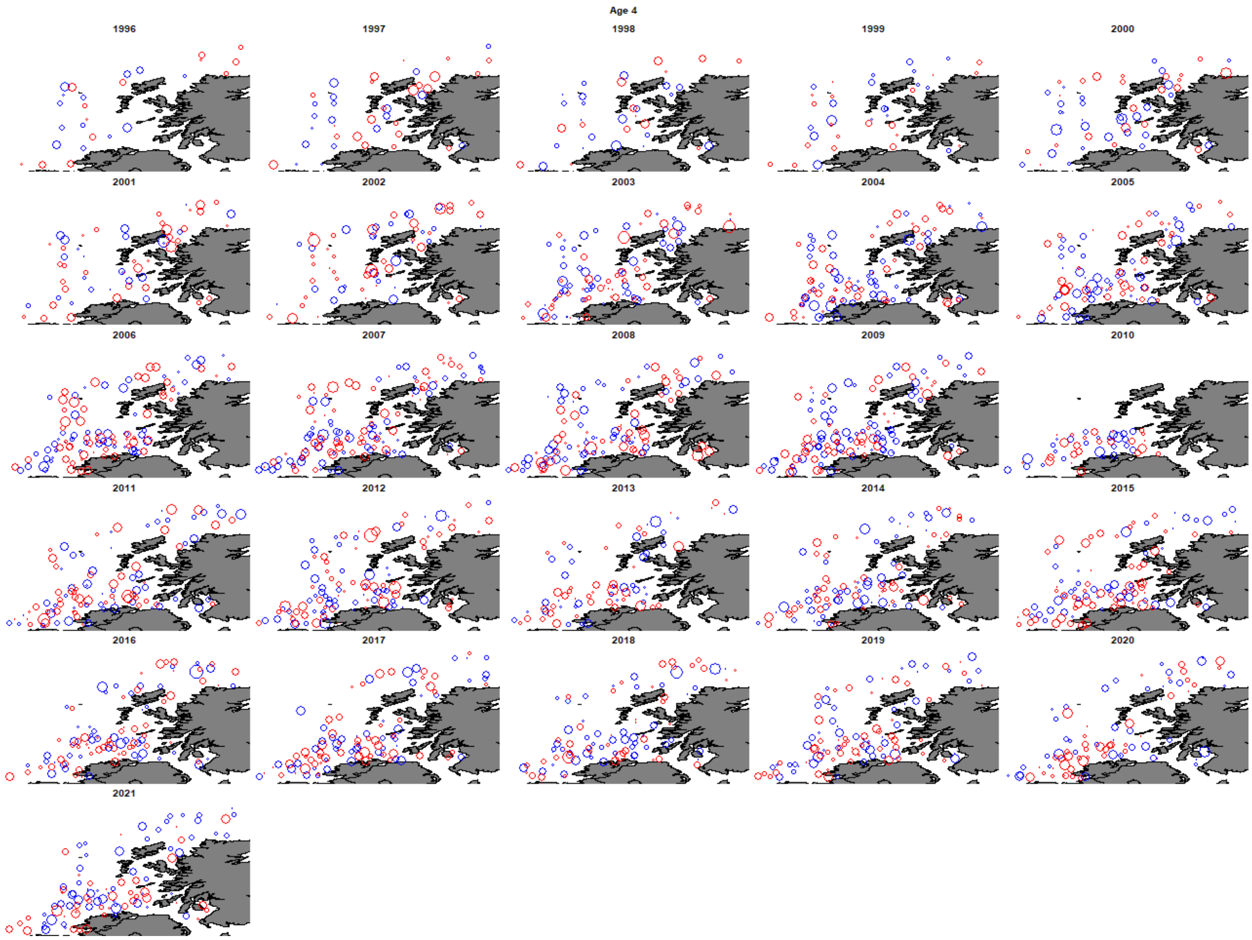
[3,6.3]
[6.4,11]
[11,22]
[23,41]
[41,53]
[54,110]


Age 4
1996
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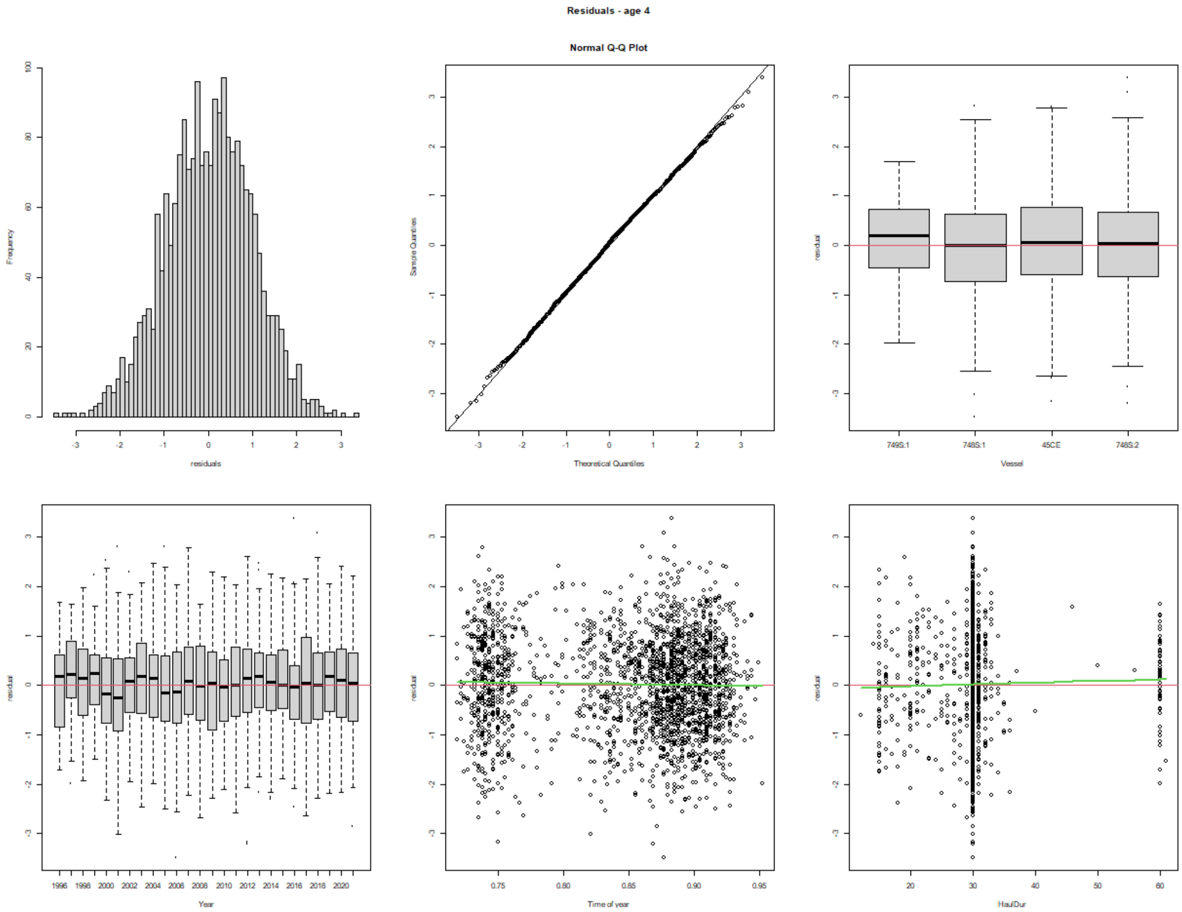
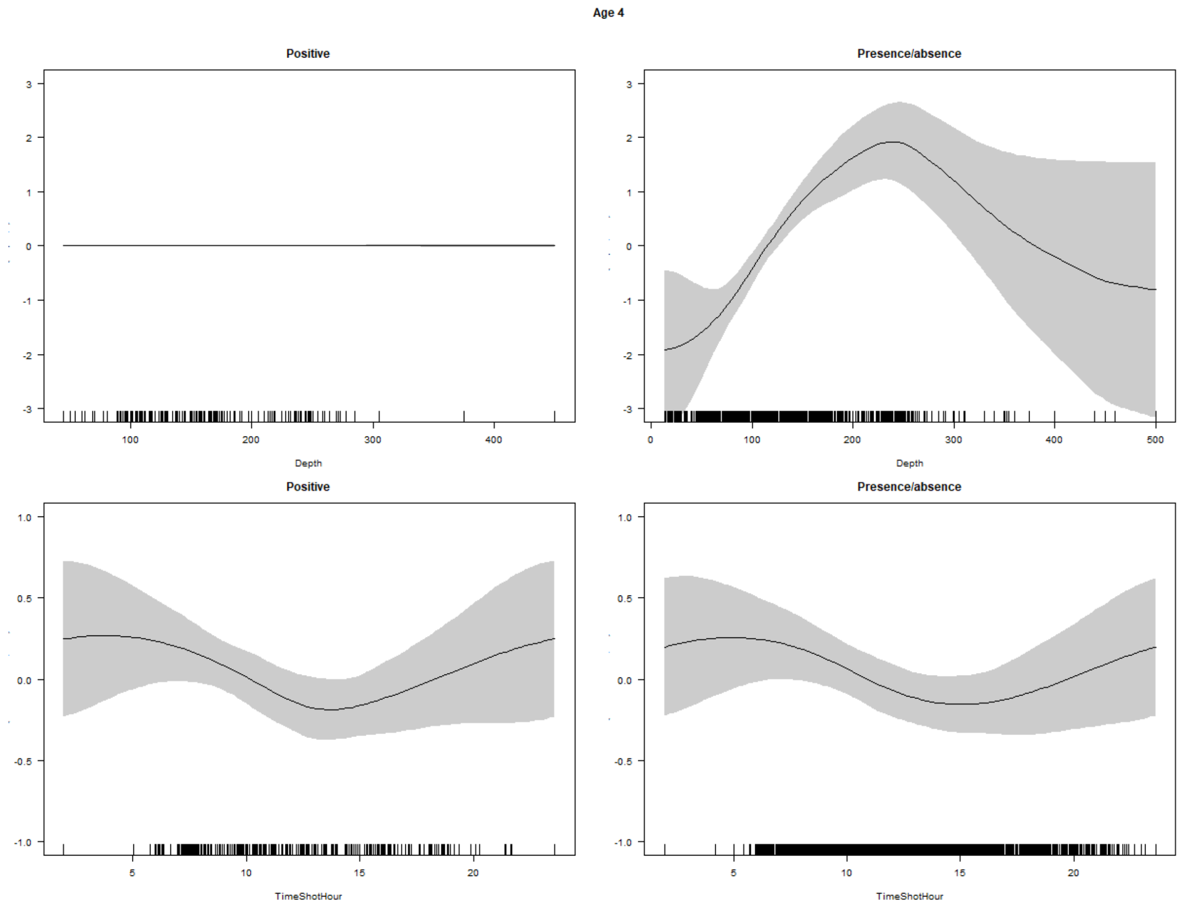
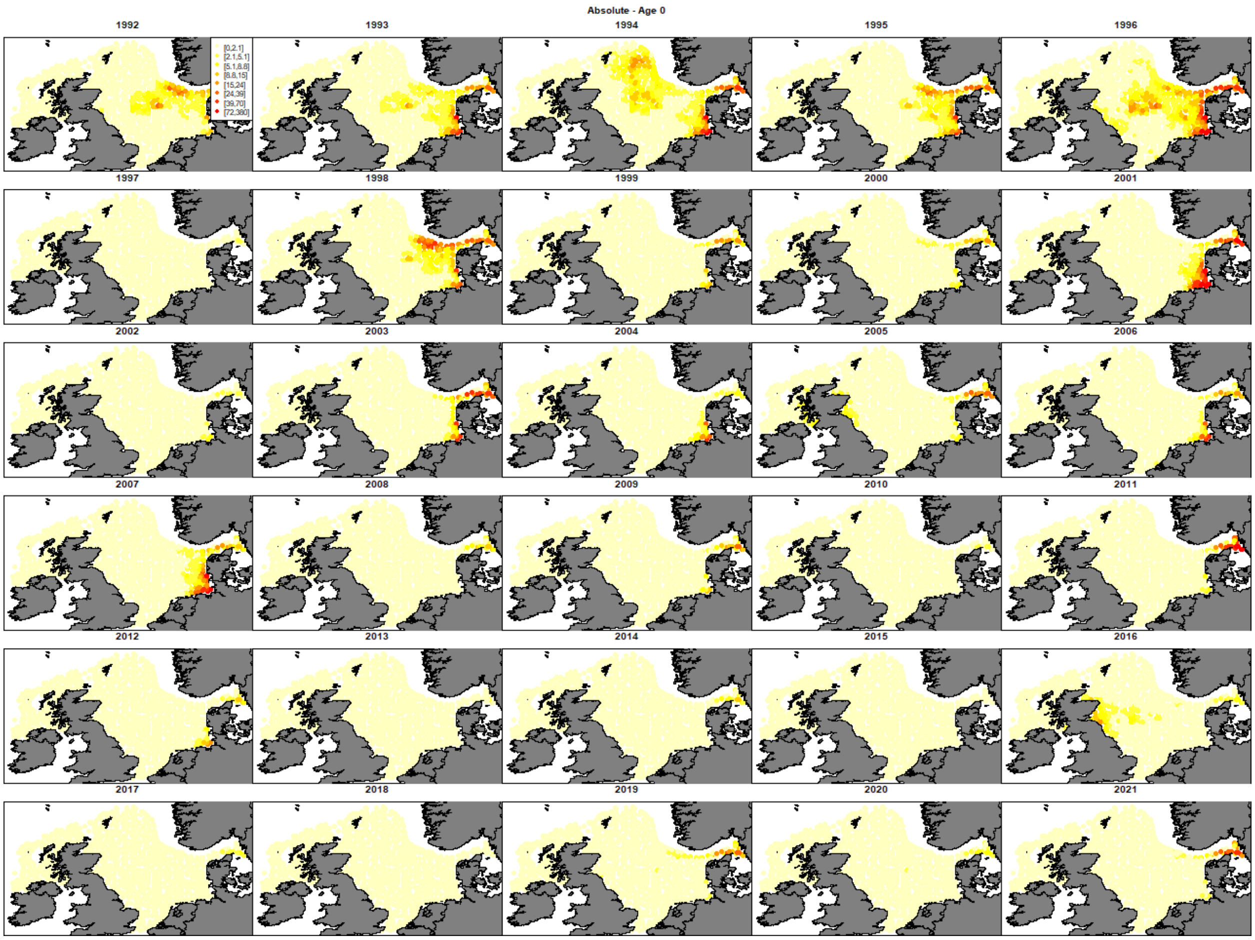
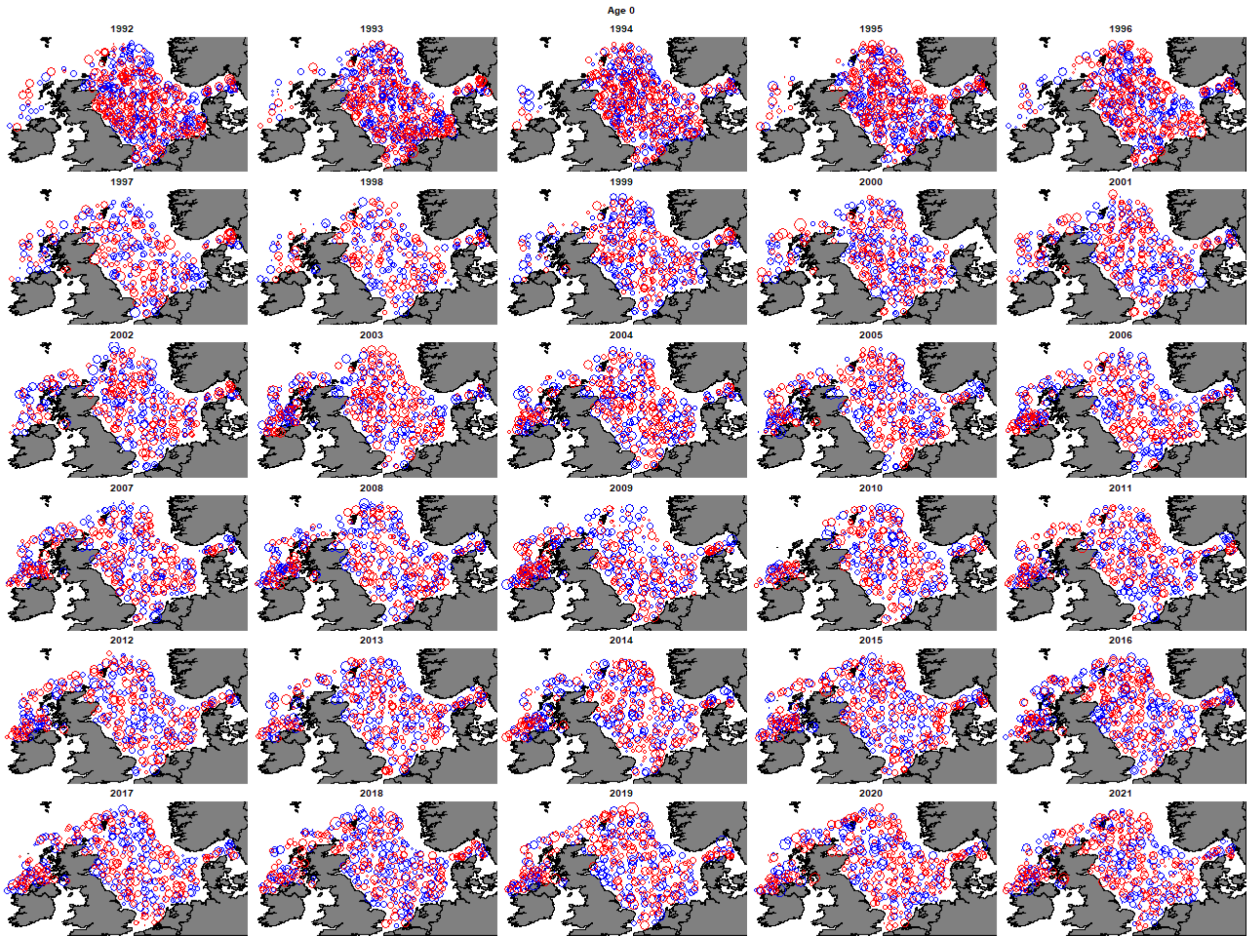

Residuals - age 4
Normal Q-Q Plot
Frequency
residuals
Sample Quantiles
Theoretical Quantiles
residual
749S:1
748S:1
45CE
748S:2
Vessel
Year
Time of year
HaulDur


Age 4
Positive
Presence/absence
Depth
Depth
Positive
Presence/absence
TimeShotHour
TimeShotHour

Quarter 3 + Quarter 4

Age 0




Age 0
1992
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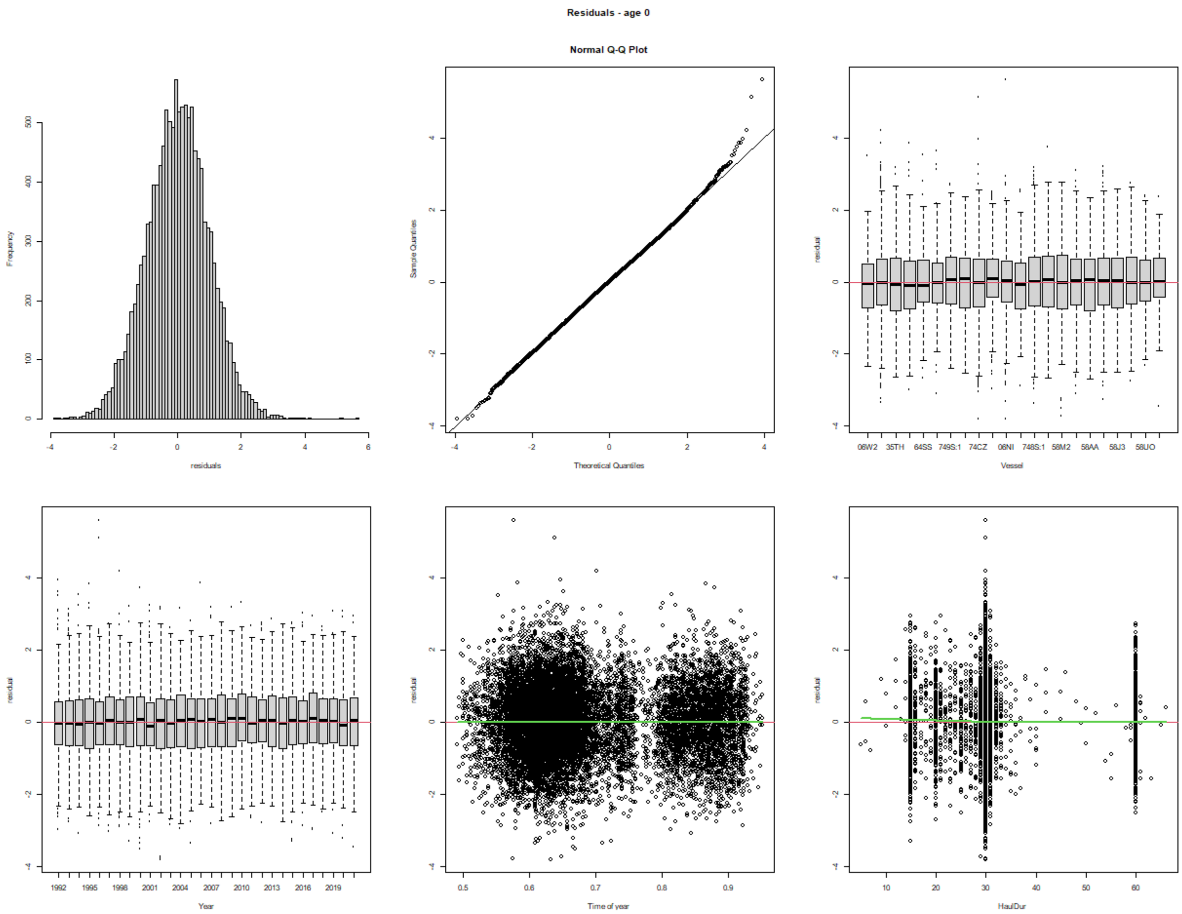
2021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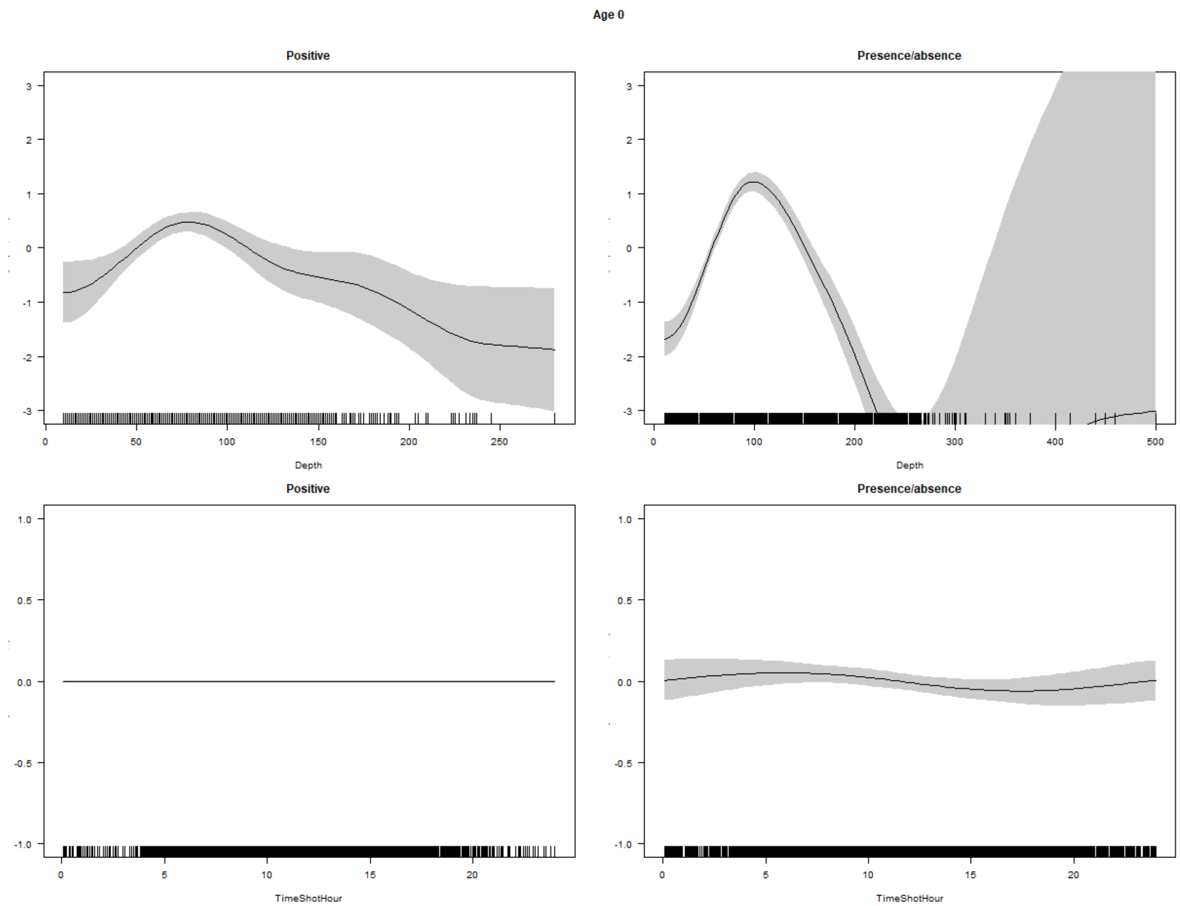
Vessel
residual
Year
residual
Time of year
residual
HaulDur



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Presence/absence
Depth
Positive
Presence/absence
TimeShotHour

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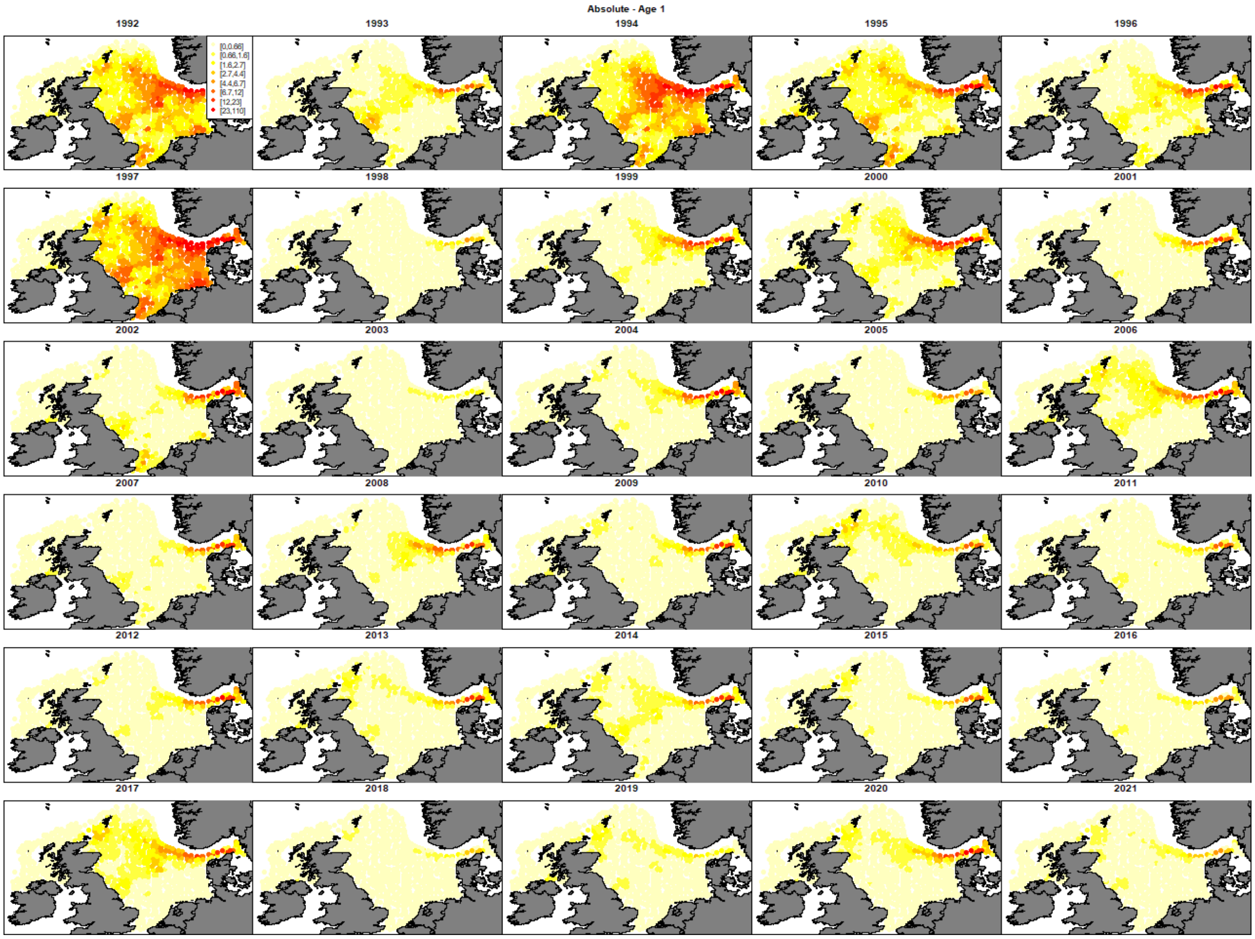
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[6.7,12]
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[23,110]
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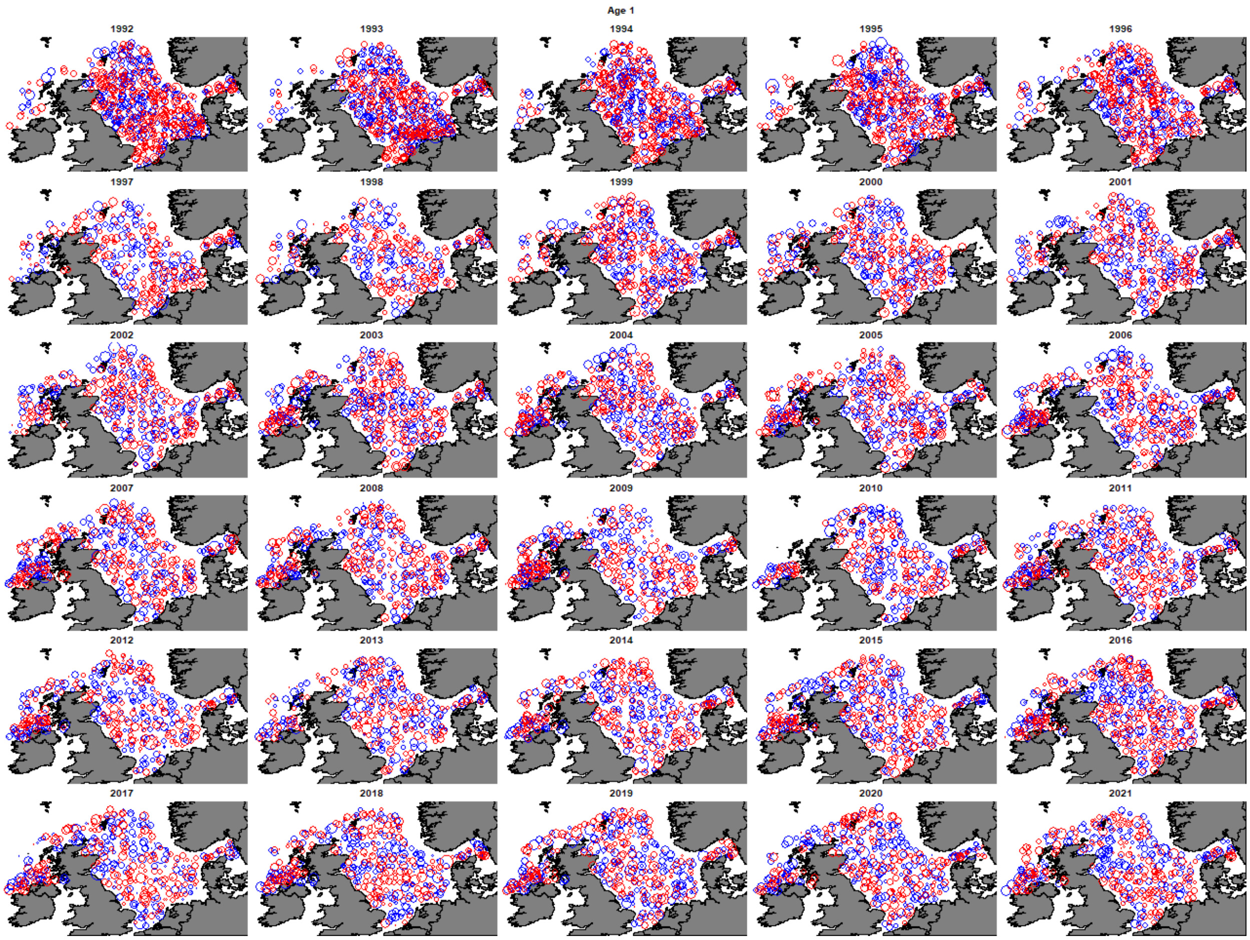
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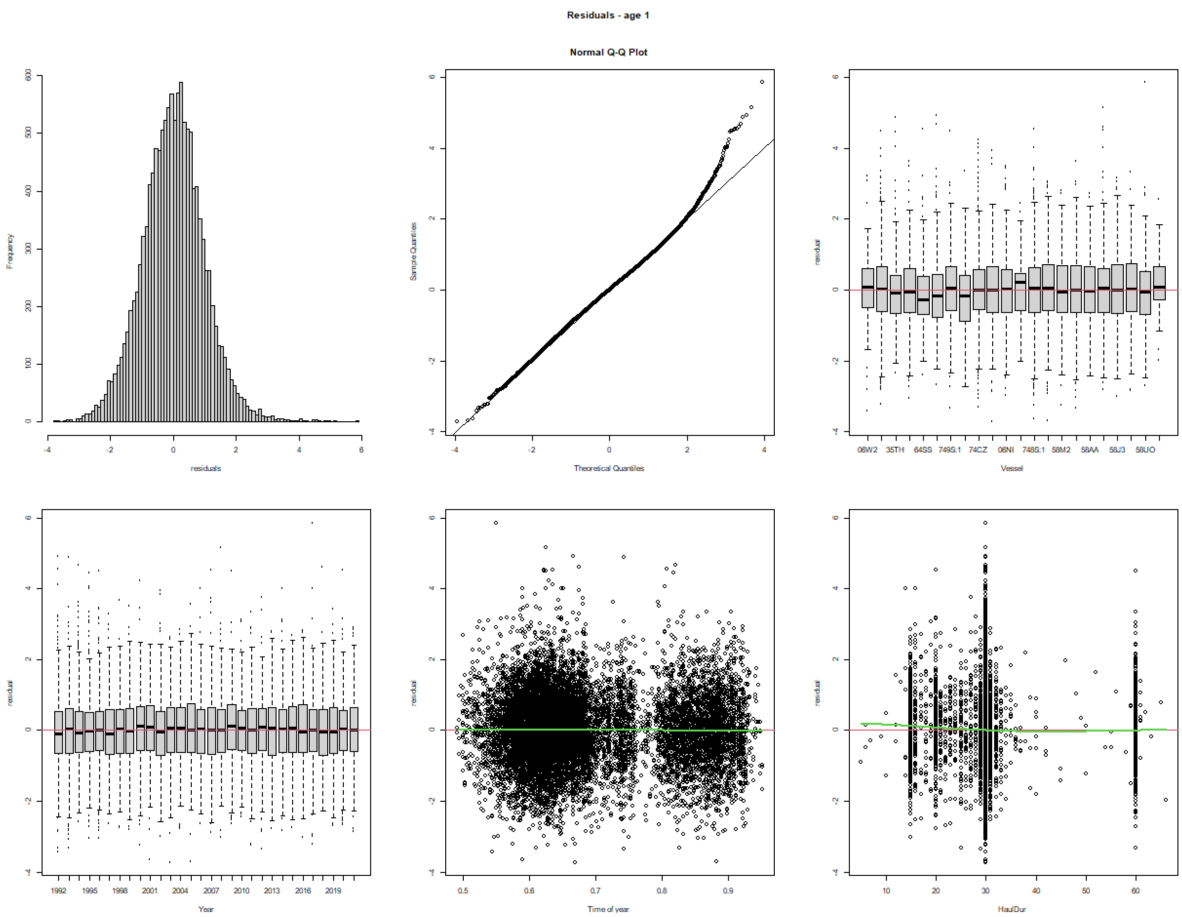
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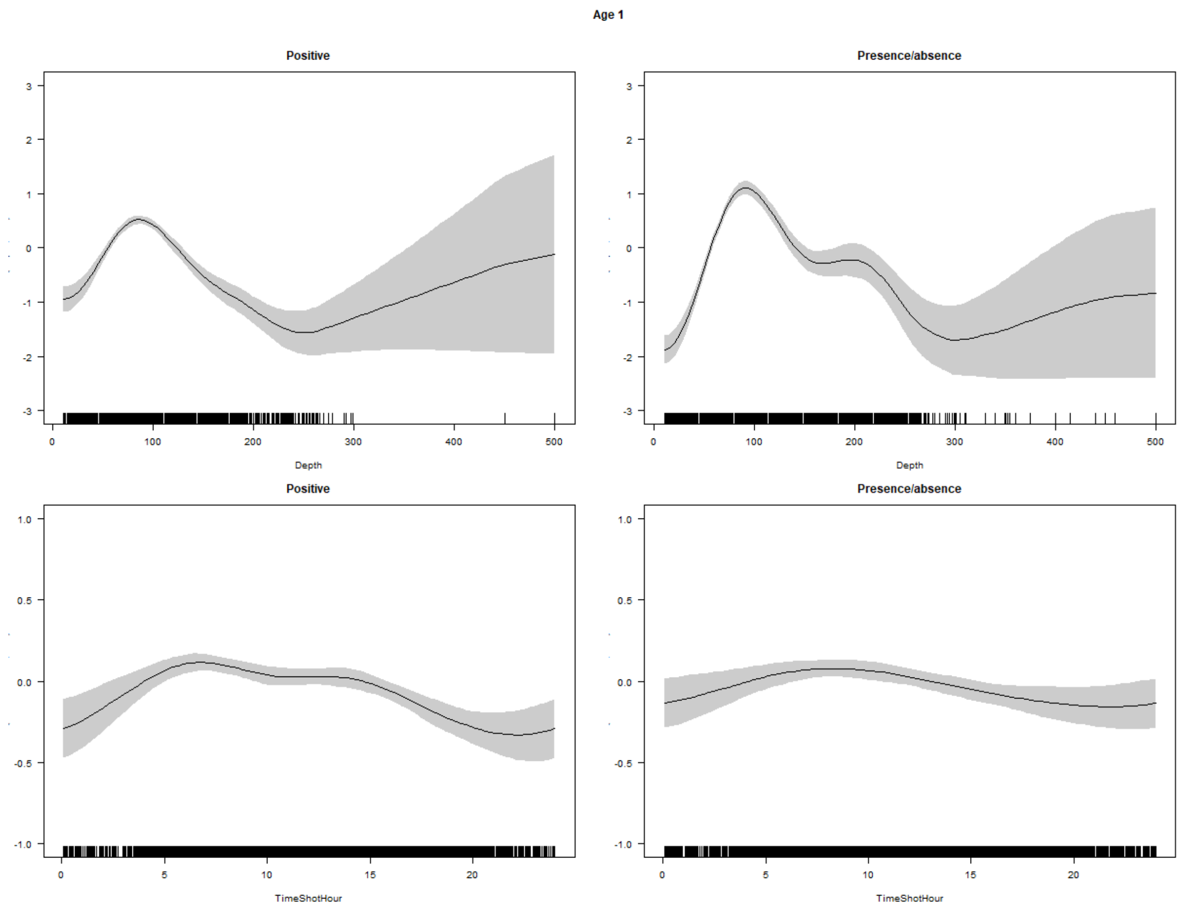
Vessel
Year
Time of year
HaulDur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TimeShotHour

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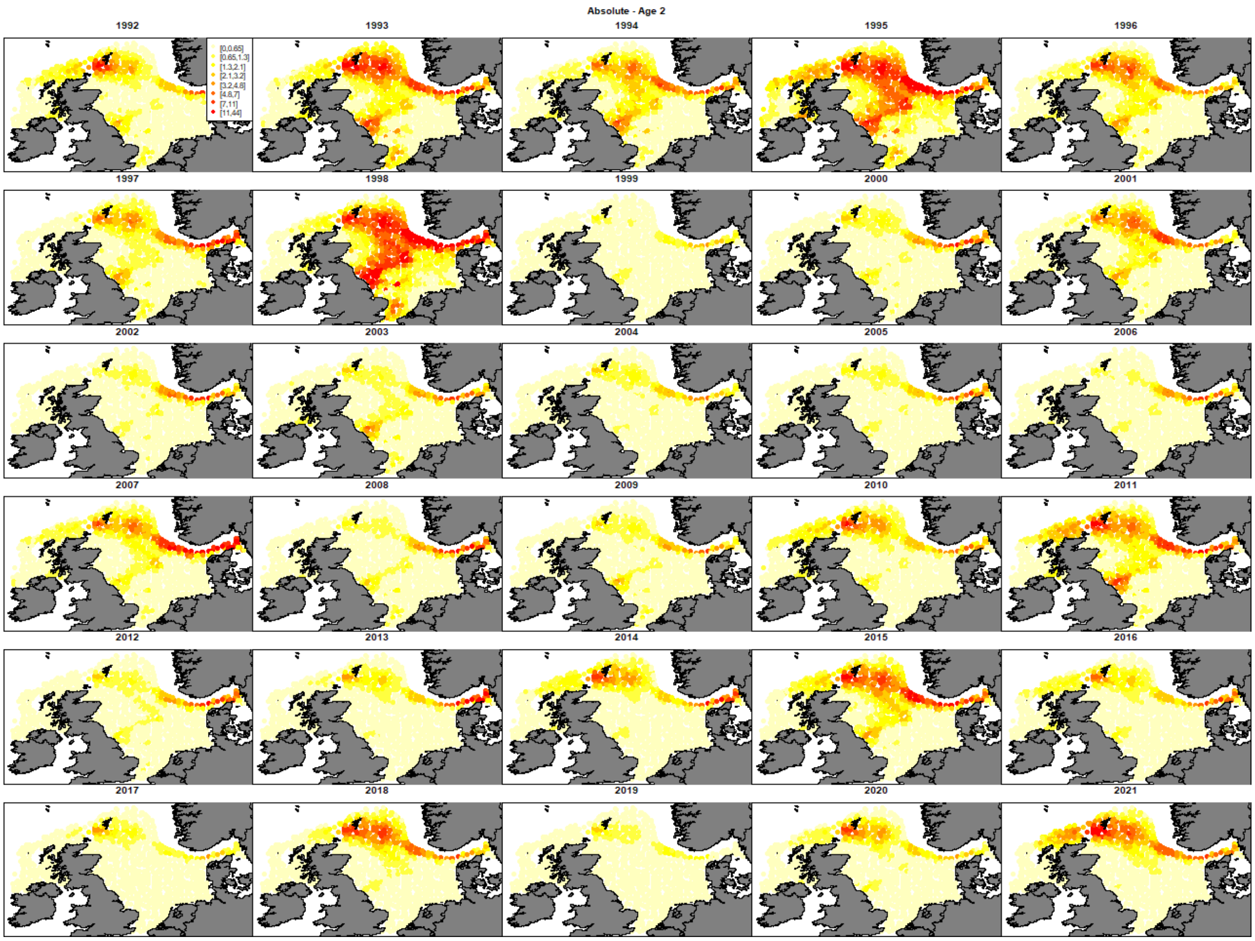
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2019
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2021
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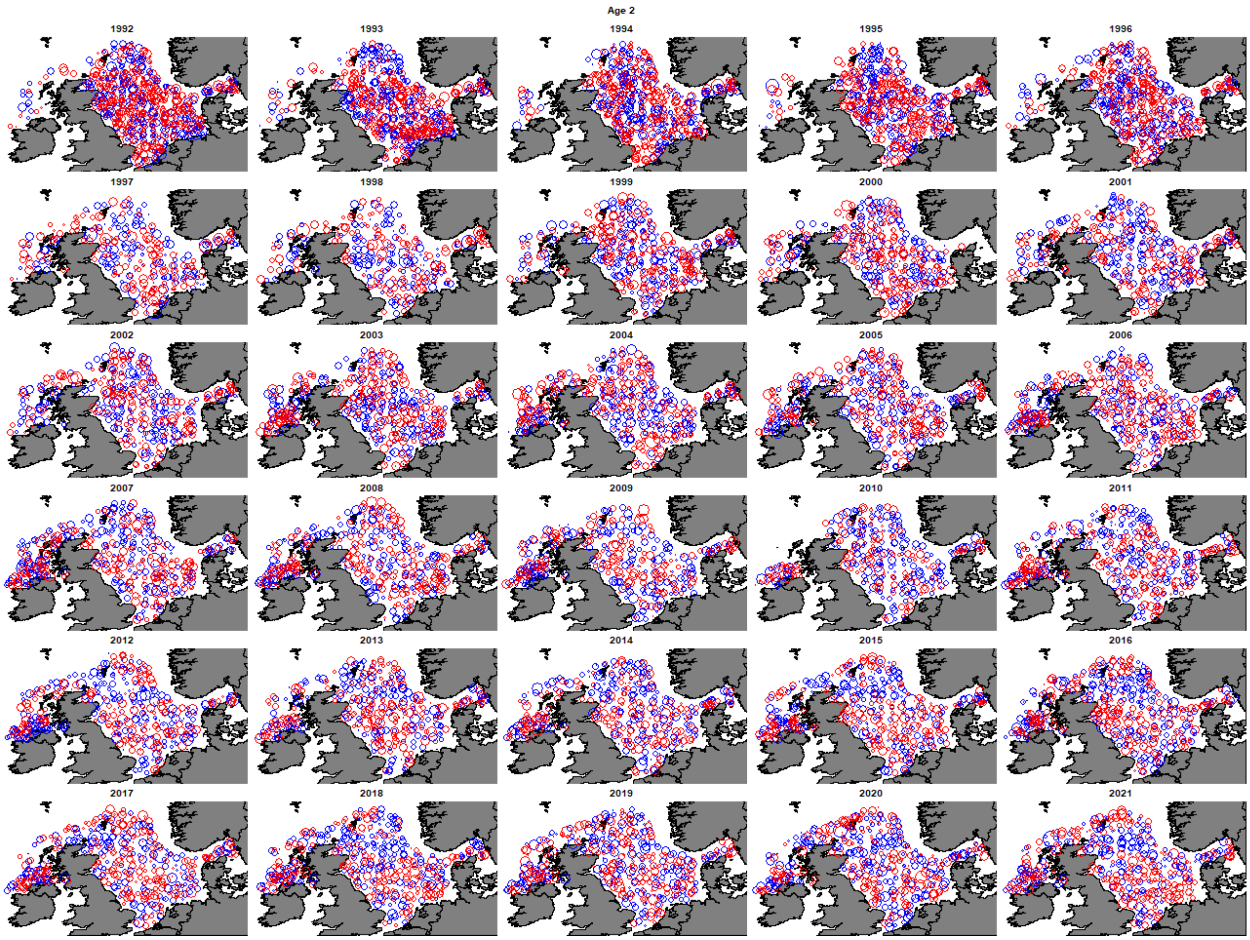
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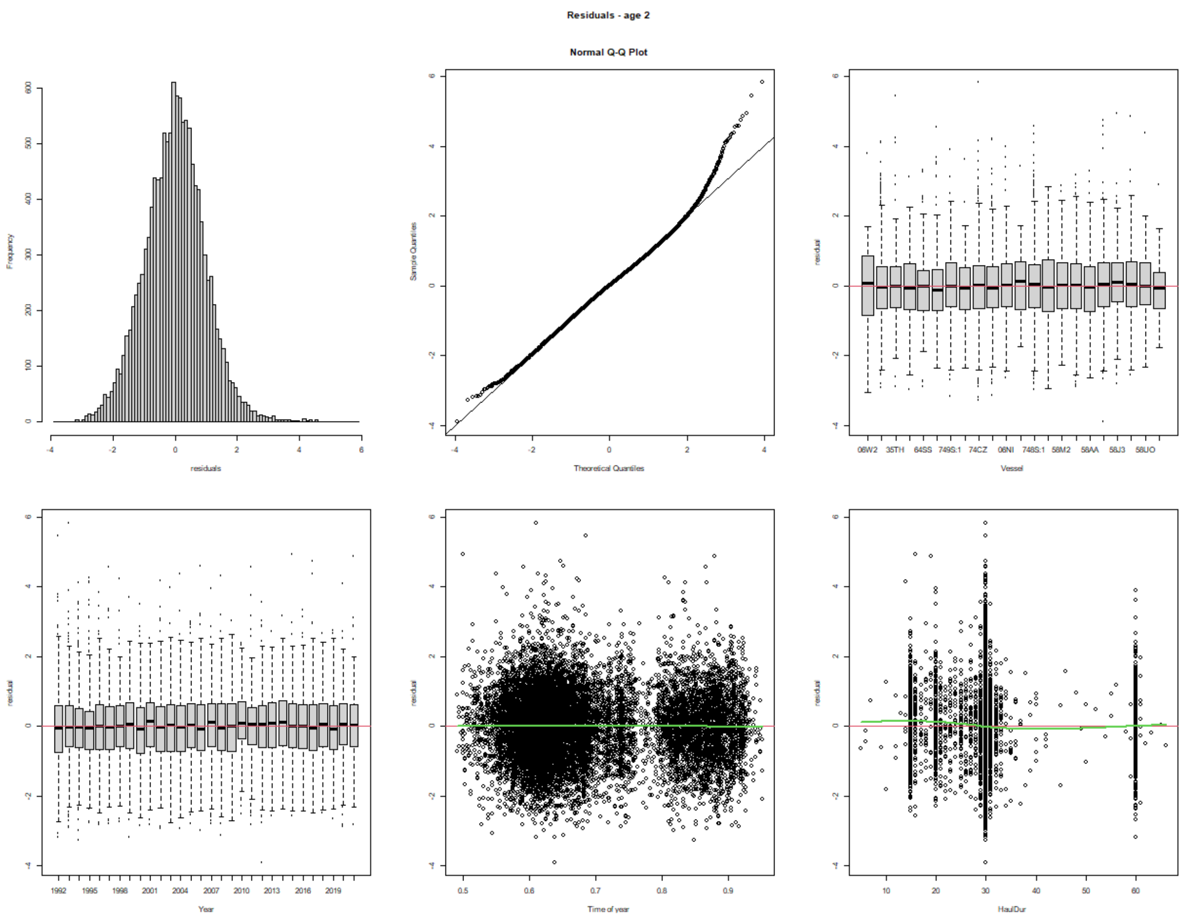
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Sample Quantiles
Theoretical Quantiles
residual
Vessel
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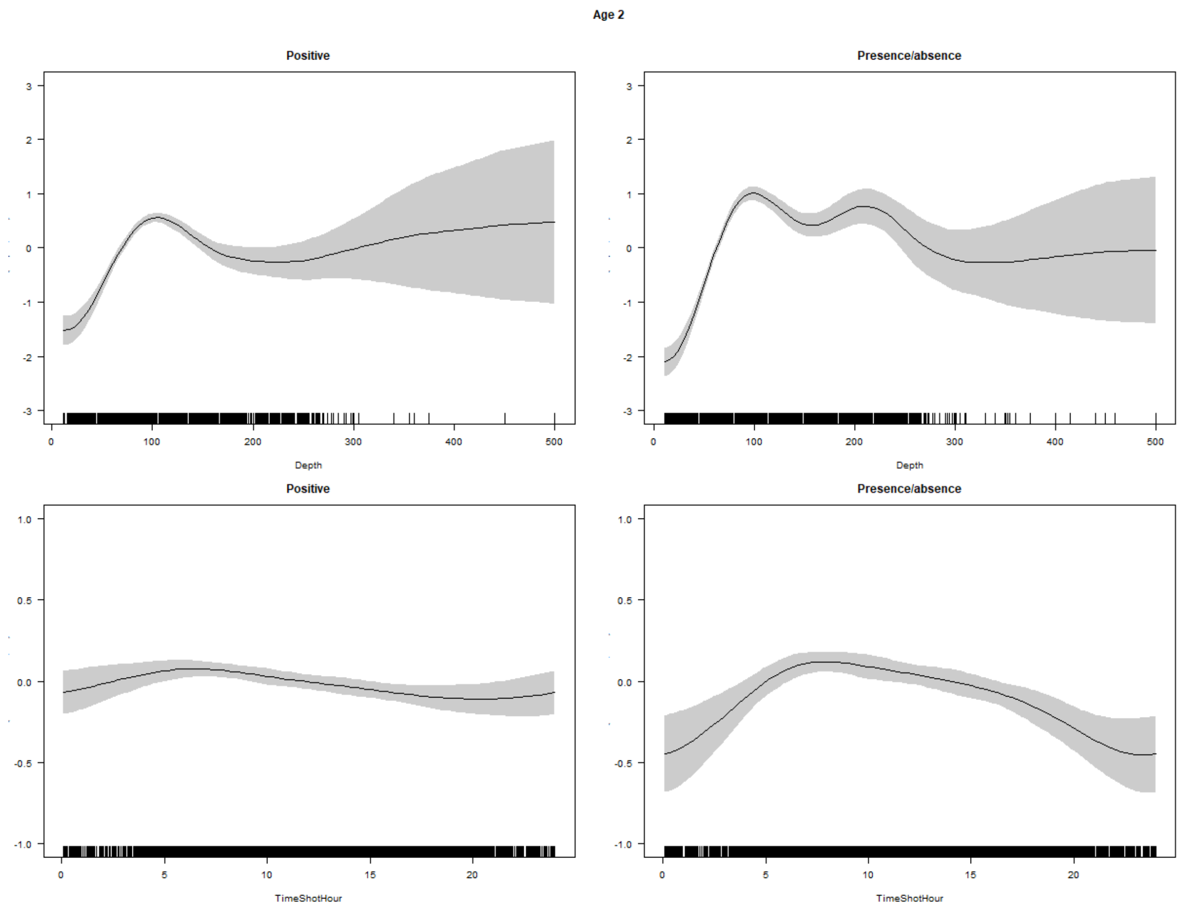
Year
1992 1995 1998 2001 2004 2007 2010 2013 2016 2019
Time of year
HaulDur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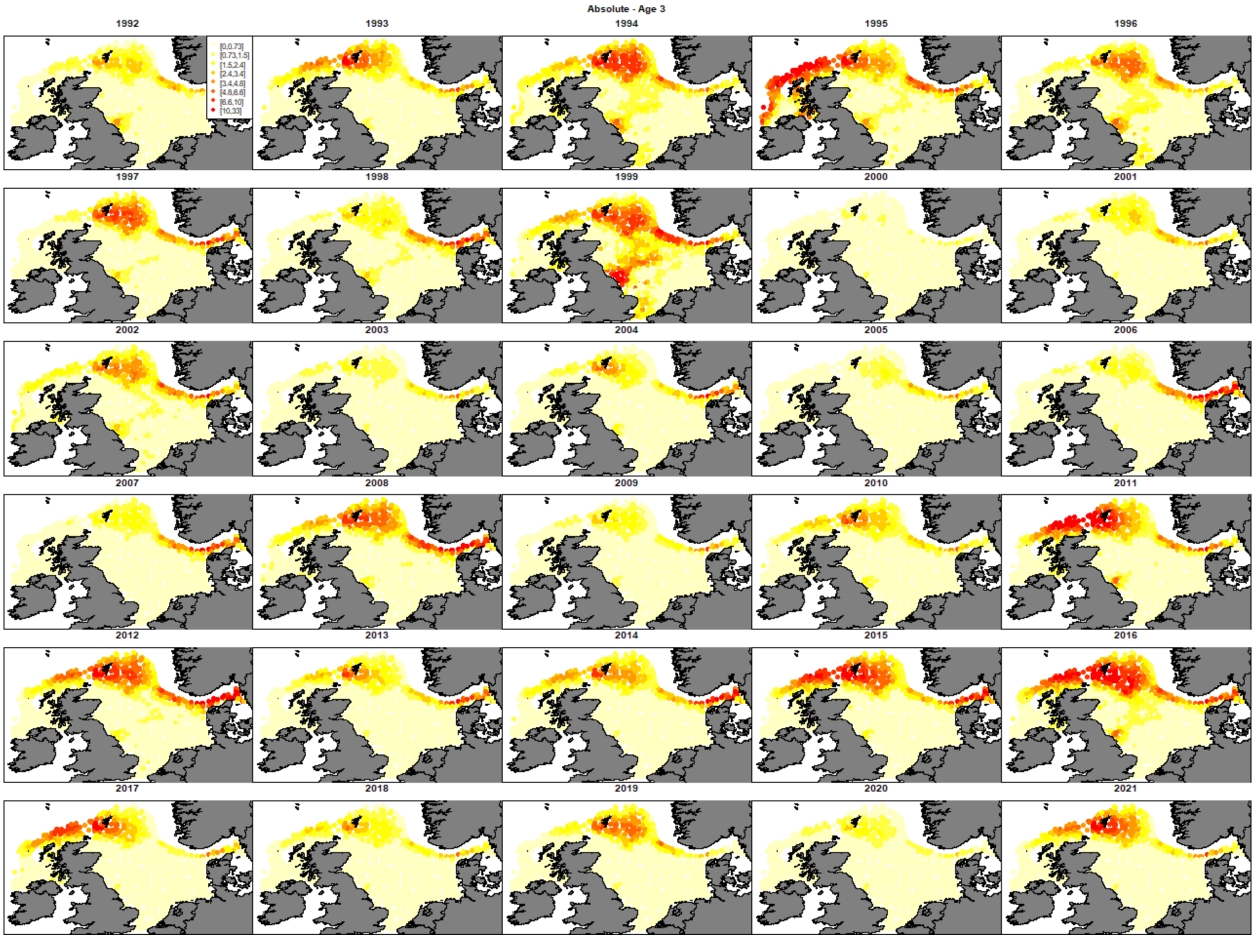
Presence/absence
TimeShotHour

Age 3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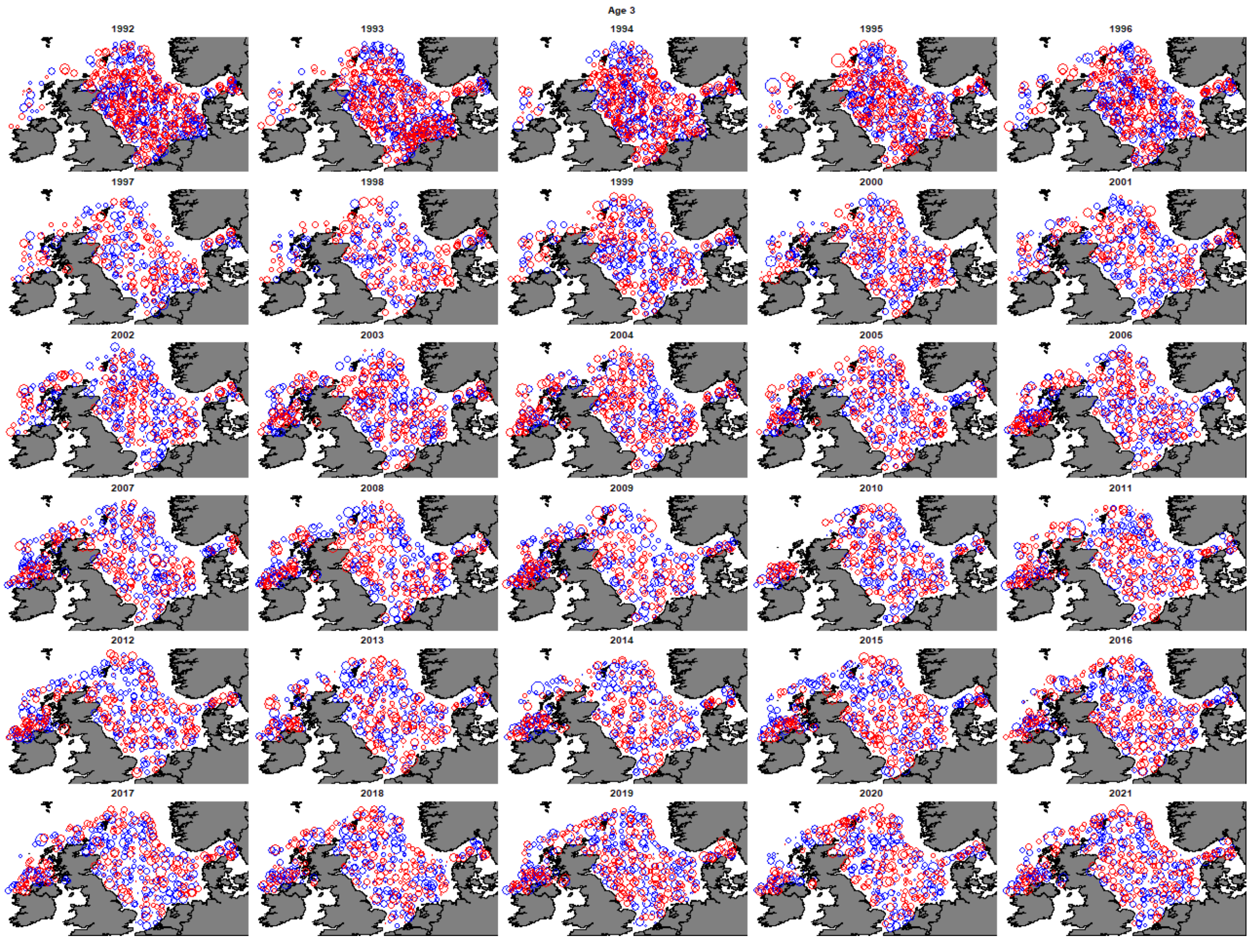
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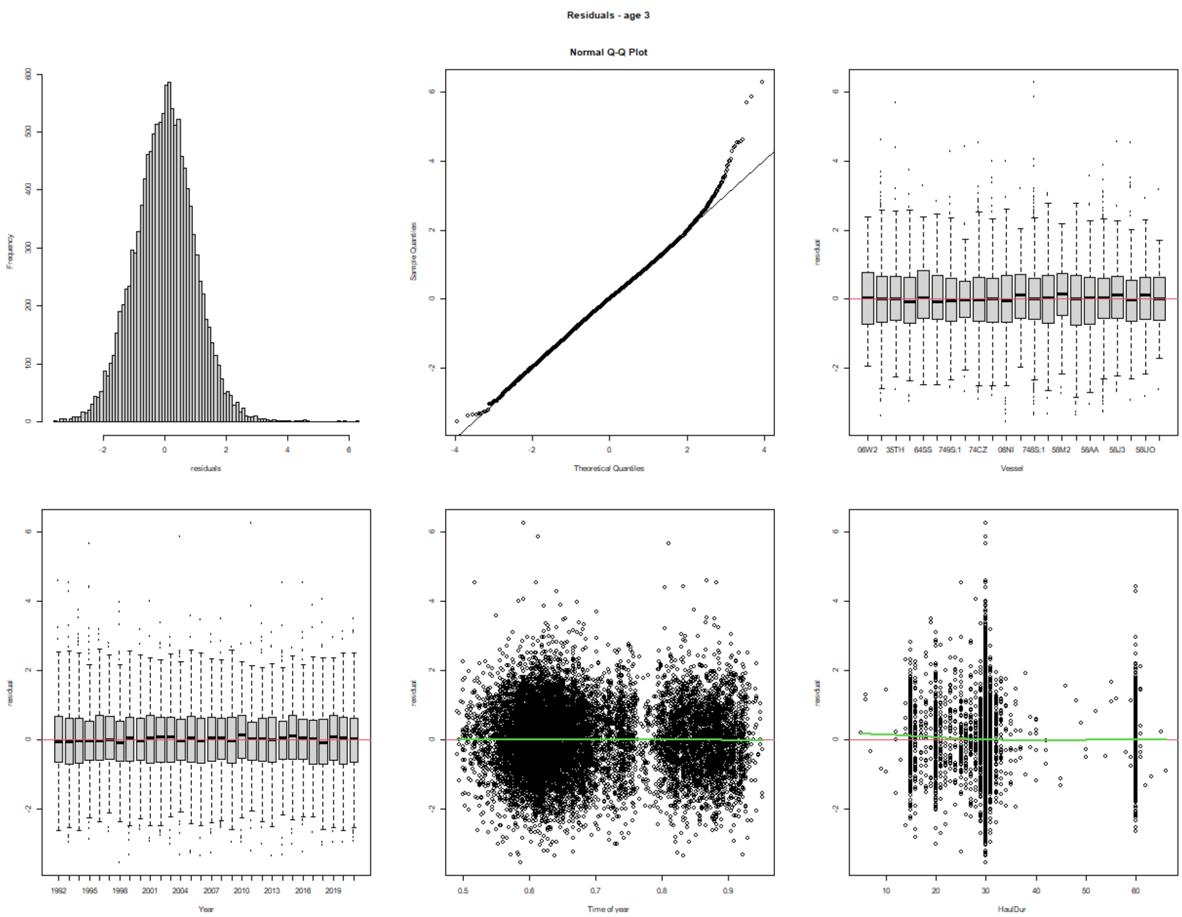
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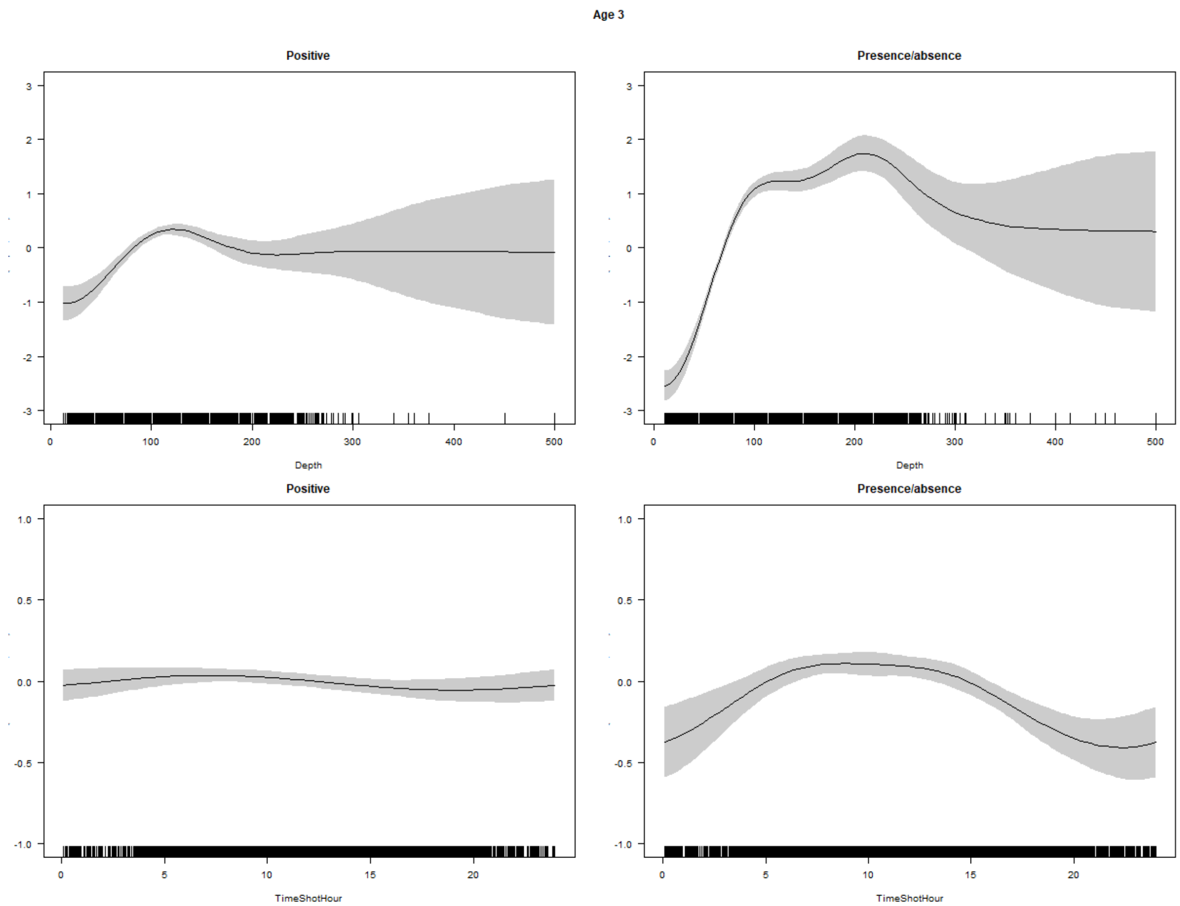
Frequency
residuals
Sample Quantiles
Theoretical Quantiles
residual
Vessel
Year
Time of year
HaulDur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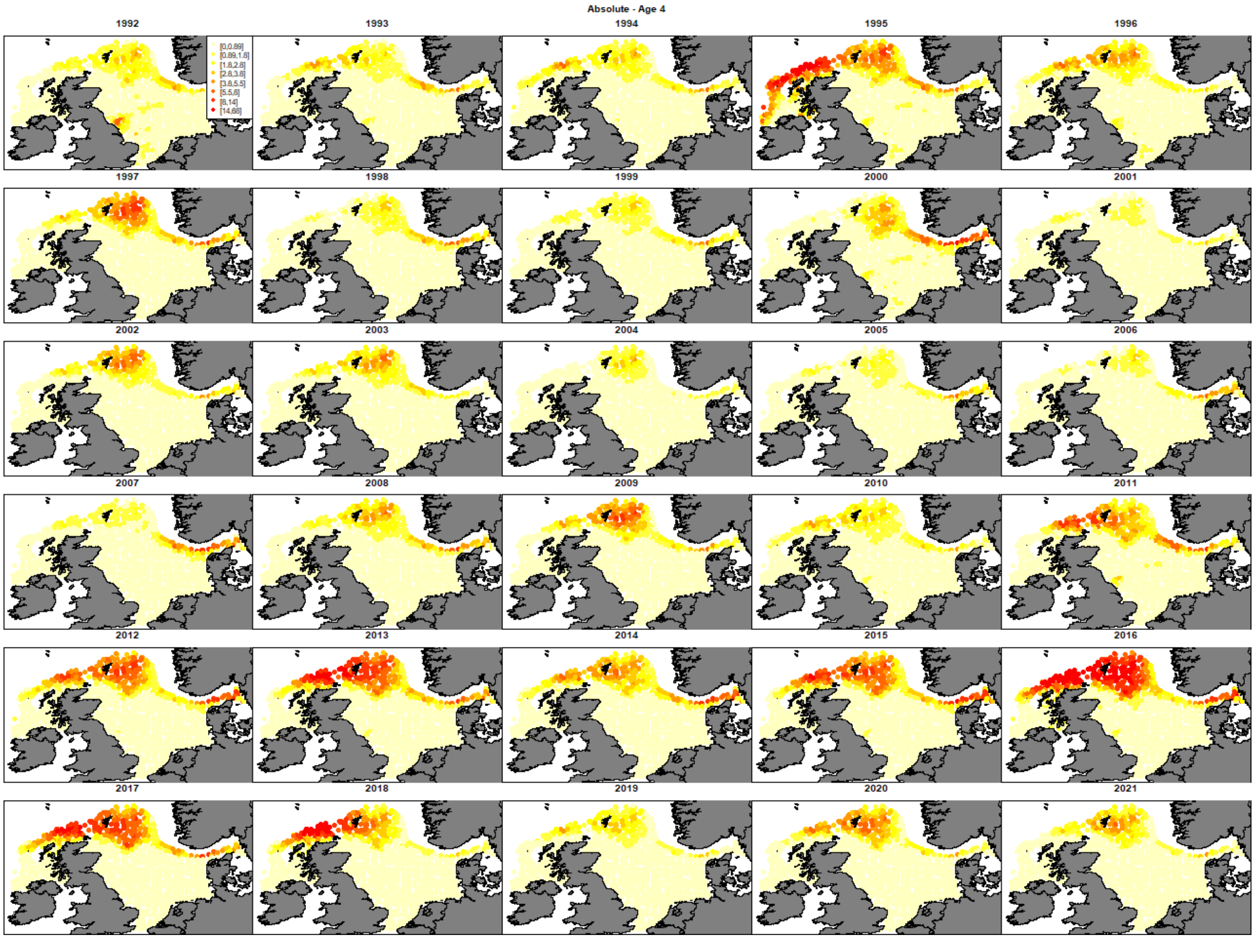
Presence/absence
Depth
Depth
Positive
Presence/absence
TimeShotHour
TimeShotHour

Age 4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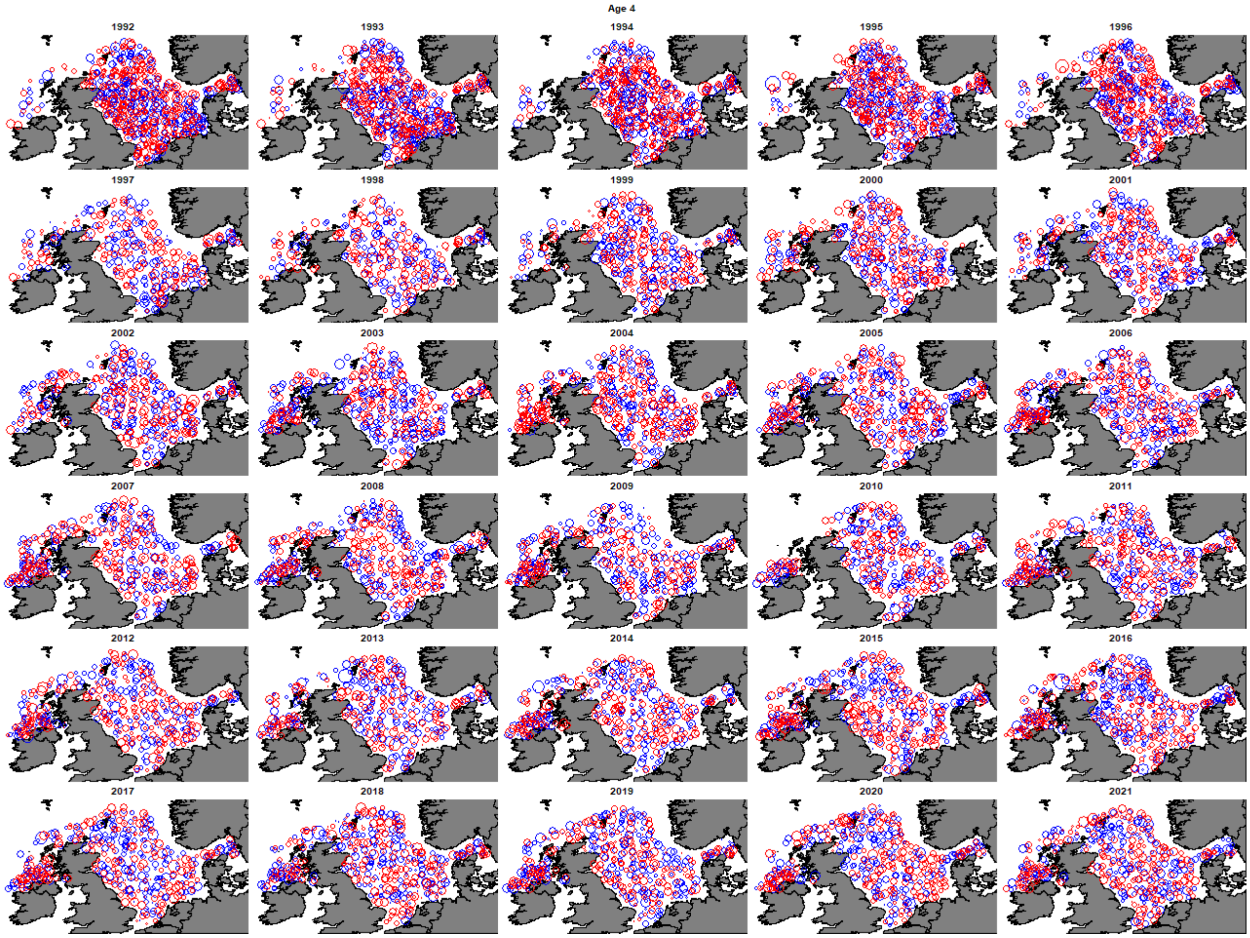
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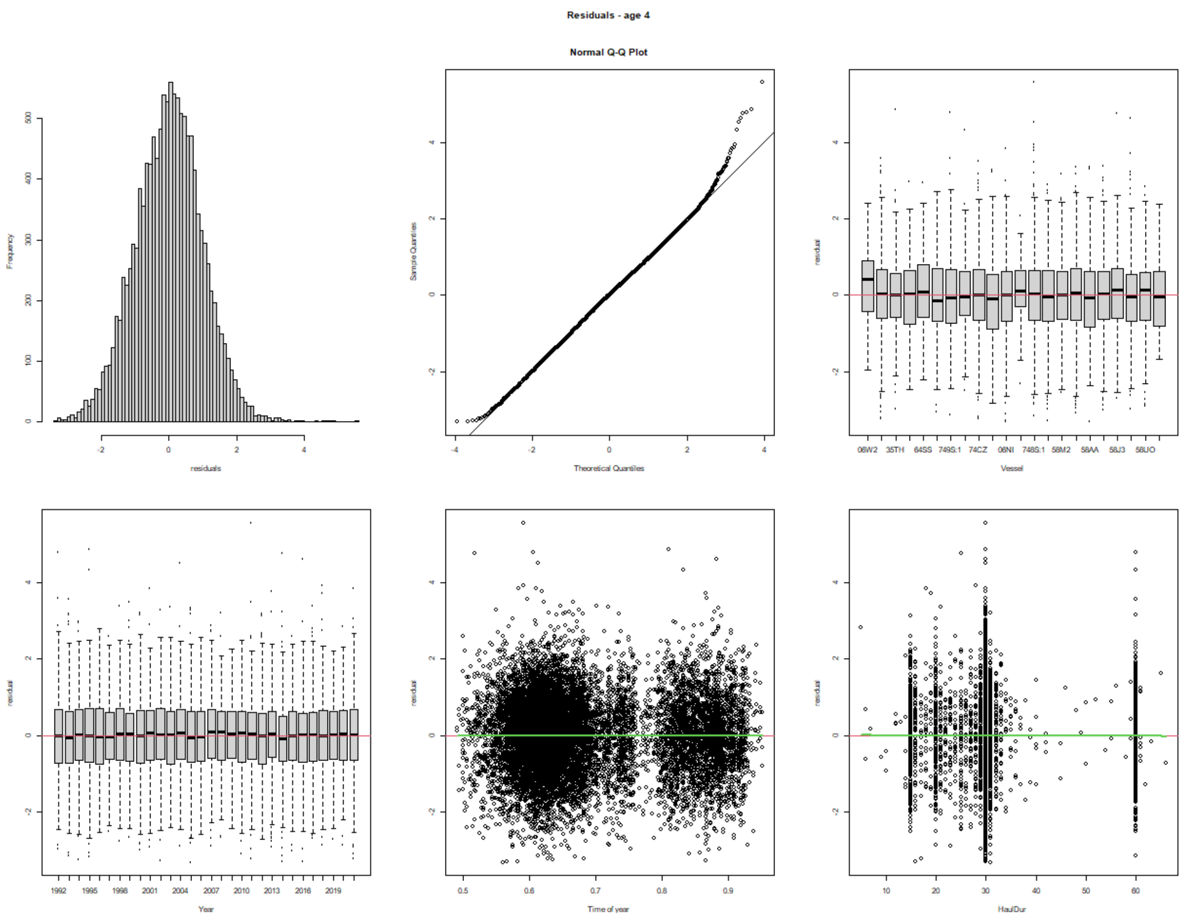
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Frequency
residuals
Sample Quantiles
Theoretical Quantiles
residual
Vessel
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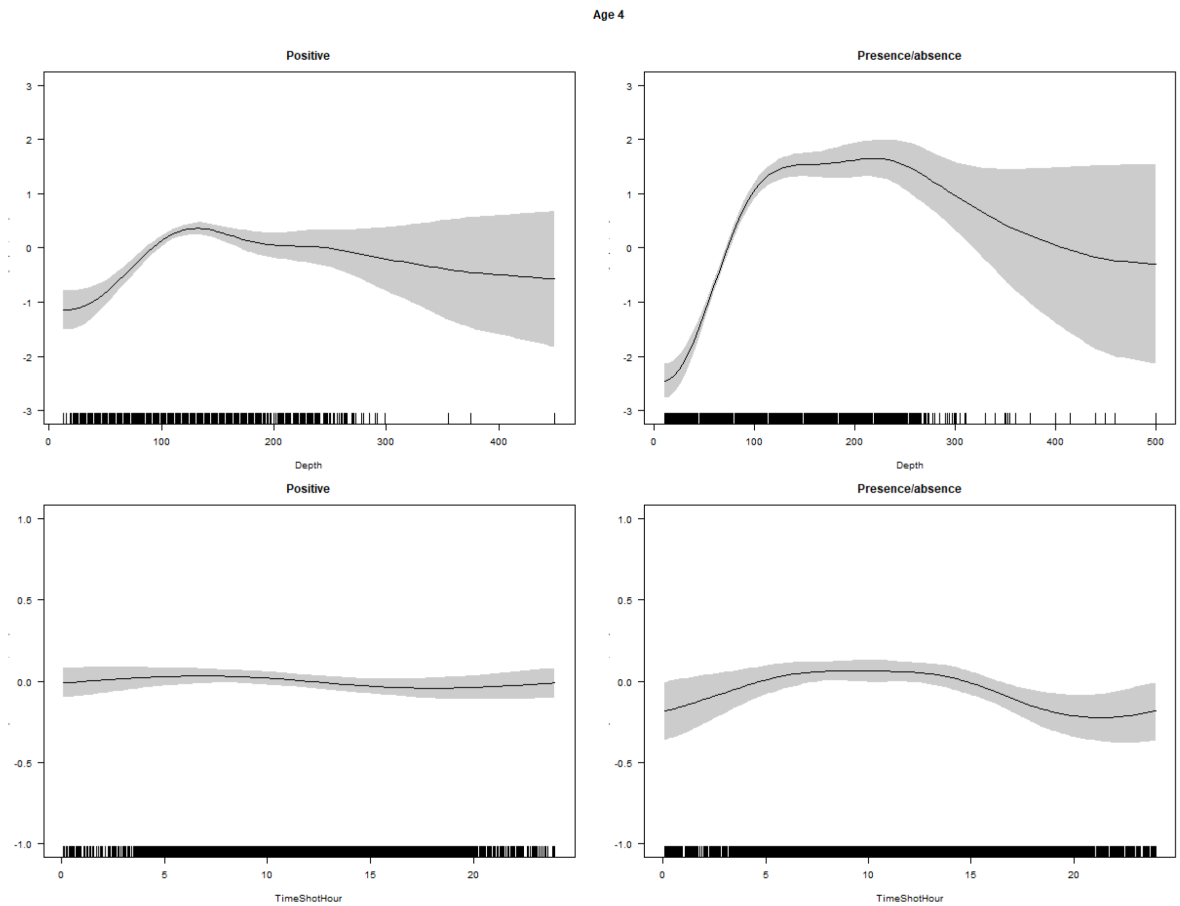
residual
Year
1992 1995 1998 2001 2004 2007 2010 2013 2016 2019
residual
Time of year
residual
HaulDur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Presence/absence
Depth
Depth
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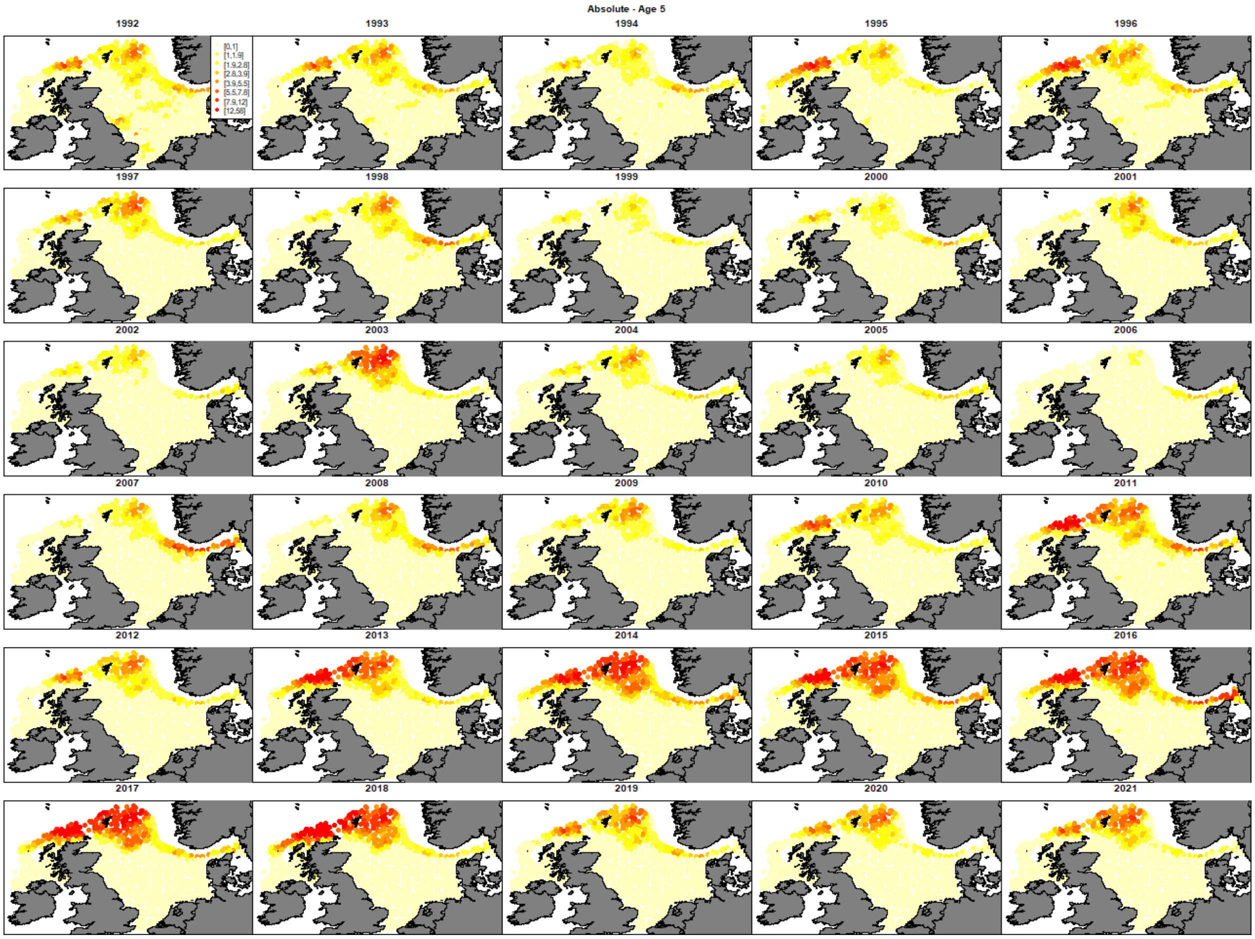
Presence/absence
TimeShotHour
TimeShotHour

Ages 5+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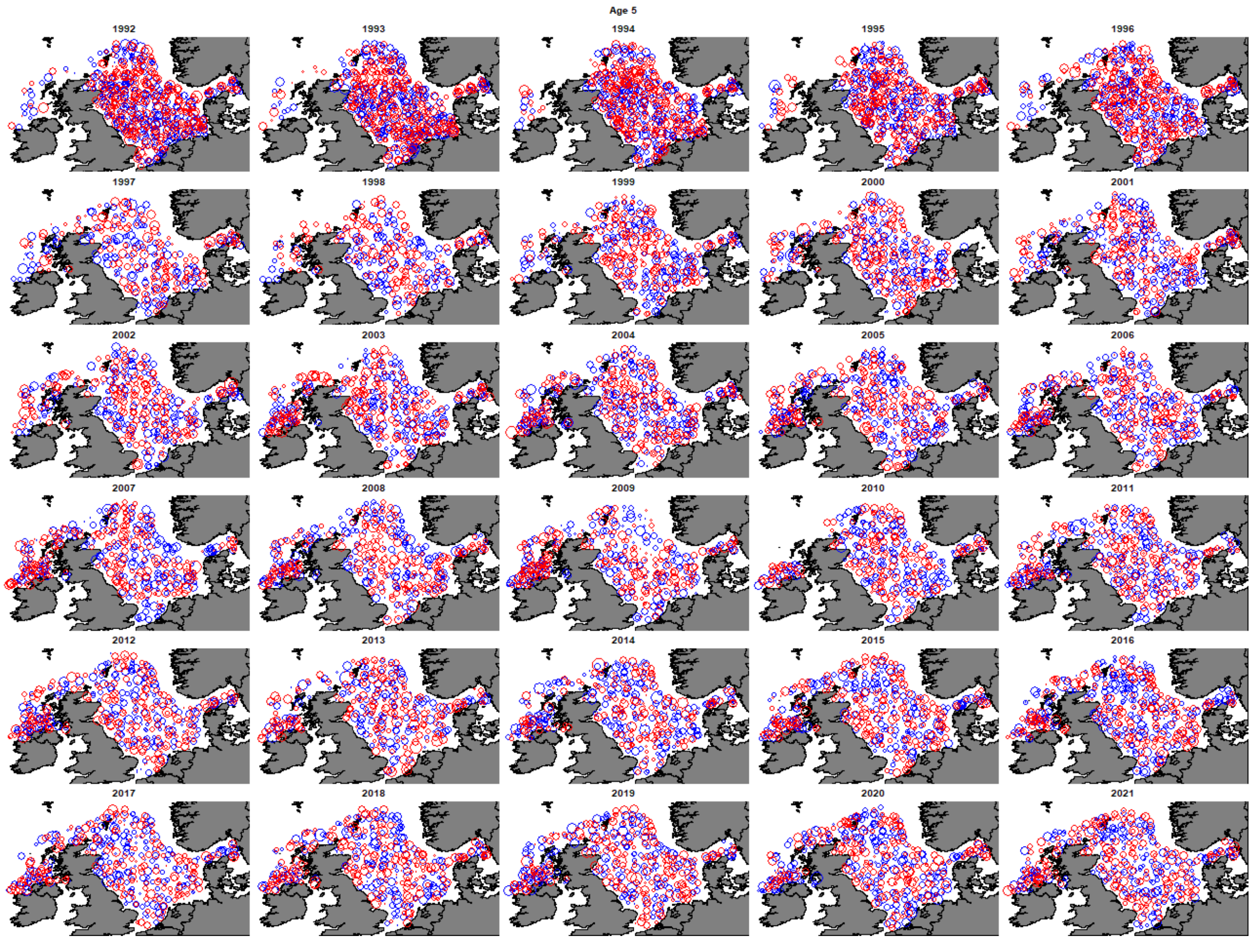
Age 5
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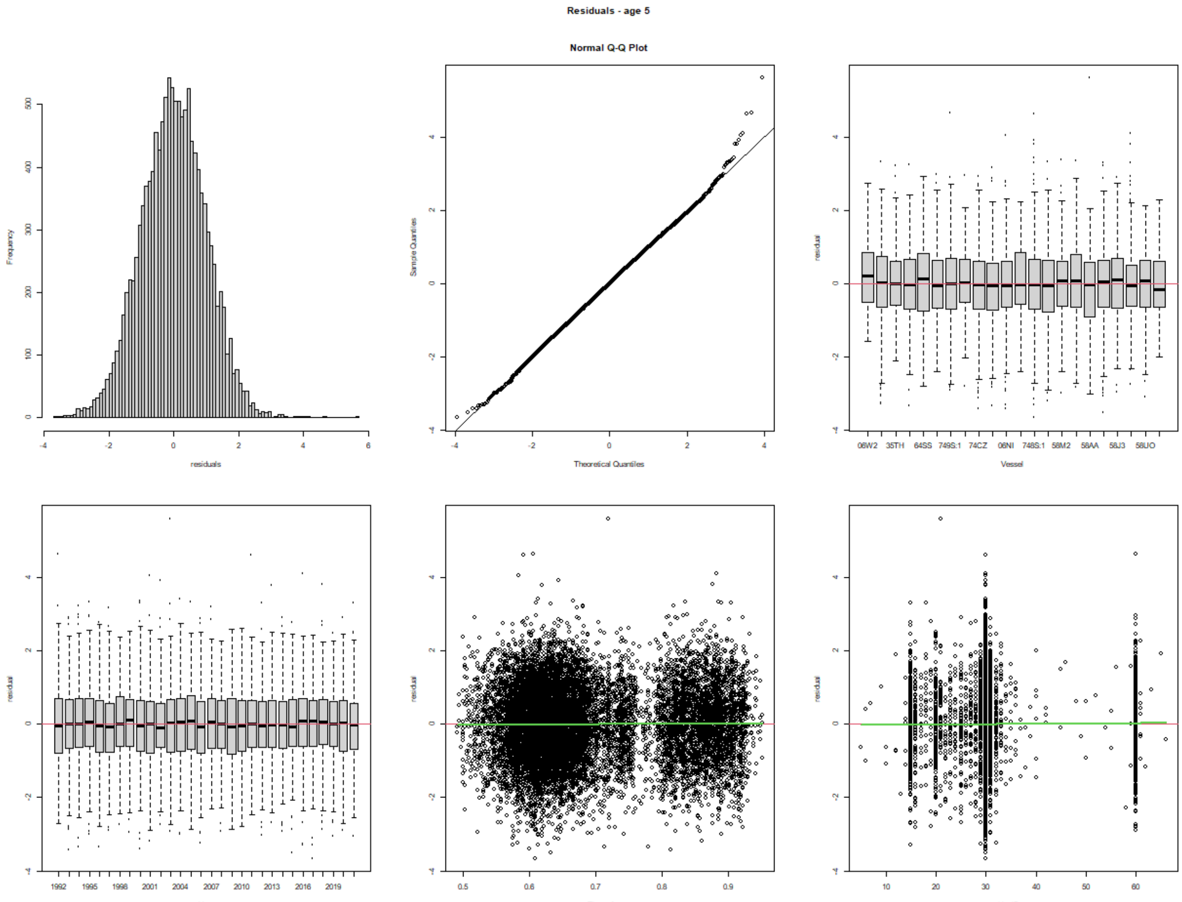
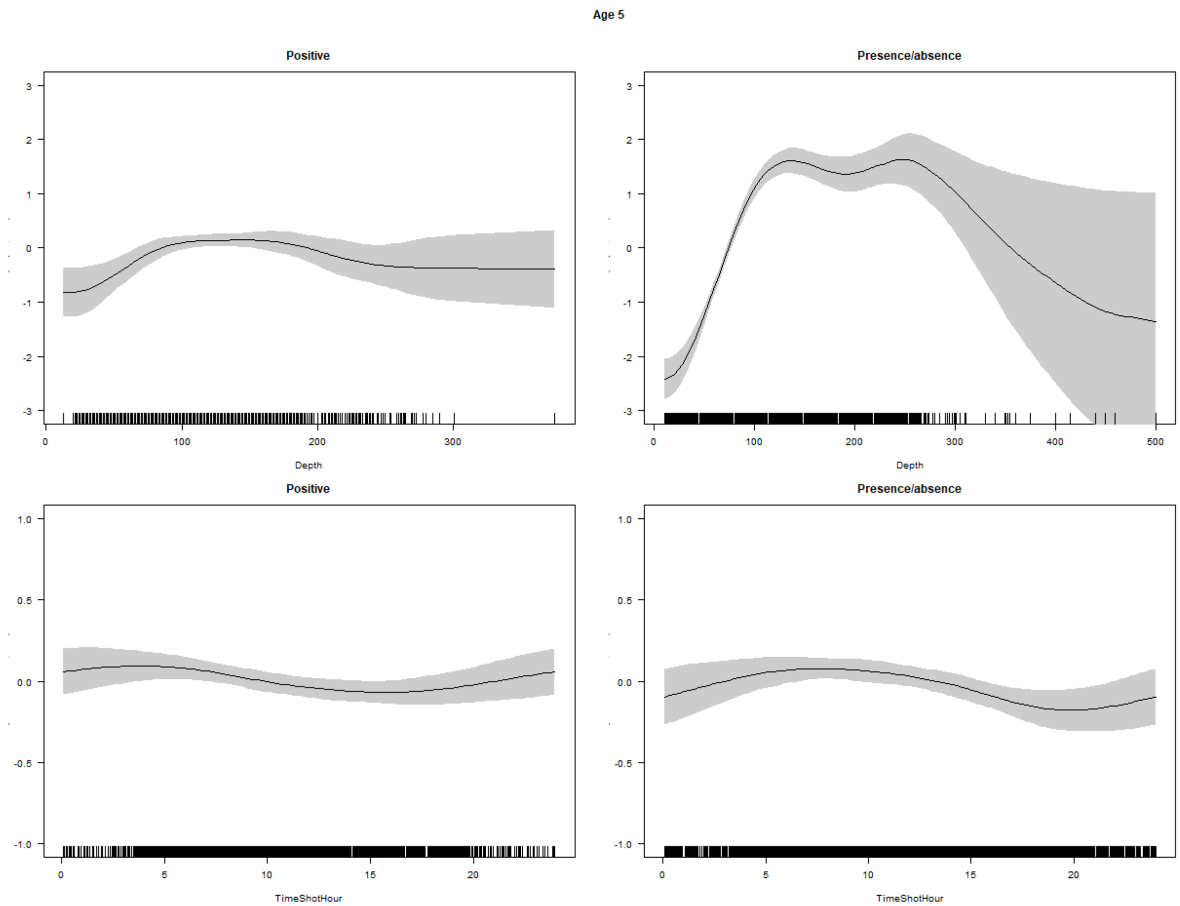

Residuals - age 5
Normal Q-Q Plot
Frequency
residuals
Sample Quantiles
Theoretical Quantiles
residual
Vessel
06W2 35TH 64SS 749S:1 74CZ 06NI 748S:1 58M2 58AA 58J3 58UO
Year
Time of year
HaulDur


Age 5
Positive
Presence/absence
Depth
Depth
Positive
Presence/absence
TimeShotHour
TimeShotHour

21.8 Survey index diagnostics for Northern Shelf cod

Survey index diagnostics for Northern Shelf cod

Nicola Walker and Helen Dobby

15 February, 2023

Contents

Summary

Four sets of delta-GAM based survey indices were presented to the data compilation workshop: one for each quarter with survey data (Q1, Q3 and Q4) and one which combines the data from quarters 3 and 4 to give full area coverage. As sub-stocks are considered separate in Q1 and mixed in other quarters, the decision was taken to proceed with indices by sub-stock for Q1 and to combine the data for quarters 3 and 4 to produce a single index representative of mixed sub-stocks in the later part of the year. Following request by the data compilation workshop, we have reproduced the selected indices by extending the age range to a 7+ group (but otherwise follow the same methodology), to allow testing with as many ages as possible in SAM.

Here, we present the updated indices as selected by the data compilation workshop and present a range of index diagnostics that can be considered alongside the SAM model runs to interpret results, make decisions on which data to include or exclude, and to help pinpoint any potential issues associated with the survey data.

Indices

Indices were calculated using a model-based approach to account for nuisance factors caused by changes or differences in experimental conditions. The methodology is described in Berg and Kristensen (2012) and Berg, Nielsen, and Kristensen (2014) and was implemented in Microsoft R Open 4.0.2 based on the DATRAS and surveyIndex packages.

Data

The final survey data sets used are:

- Quarter 1:
  - North Sea International Bottom Trawl Survey (NS-IBTS-Q1): covering the North Sea and Skagerrak from 1983.
  - Scottish West Coast Bottom Trawl Survey (SWC-IBTS-Q1): covering the West of Scotland for the period 1985-2010.
  - Scottish West Coast Groundfish Survey (SCOWCGFS-Q1): covering the West of Scotland from 2011.
- Quarters 3 and 4:
  - North Sea International Bottom Trawl Survey (NS-IBTS-Q3): covering the North Sea and Skagerrak from 1992.
  - Scottish West Coast Bottom Trawl Survey (SWC-IBTS-Q4): covering the West of Scotland for the period 1996-2009.
  - Scottish West Coast Groundfish Survey (SCOWCGFS-Q4): covering the West of Scotland from 2011.
  - Irish Groundfish Survey (IE-IGFS-Q4): covering the southern portion of 6.a since 2003.

ALKs

Smooth spatially-varying age-length keys were estimated using the methodology described in Berg and Kristensen (2012). Briefly, the procedure combines generalised additive modelling with continuation ratio logits to estimate the probability distribution of age as a smooth function of length and geographical coordinates, and is applied to each combination of year and quarter group (Q1 and Q34). Numbers-at-age were then calculated from numbers-at-length and the estimated ALKs.

Survey indices

Survey indices by age were calculated following the methodology described in Berg, Nielsen, and Kristensen (2014). The delta-GAM model formulation currently used for the North Sea cod stock was retained and comprises a high resolution stationary spatial model with low resolution yearly independent deviations and includes ship, year, depth, time of day and haul-duration effects. Each age group and quarter group was modelled independently, and a gear effect was included in the Q34 models to account for use of the Aberdeen Trawl between 1992-1997.

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Presence/absence:Year + s(lon, lat, bs = "ds", k = 80, m = c(1, 0.5)) + s(lon,
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    m = c(1, 0), k = 6) + s(TimeShotHour, bs = "cc", k = 6) + s(Ship, bs = "re") +
    offset(log(HaulDur))
```

Detailed model results, including standardised abundance maps, spatial residuals, residual plots and the estimated effects of bottom depth and time of day, are presented in the previous working document to the data compilation workshop. The fitted models were used to sum the expected catches over a fine grid by year and age (Figure 1). Confidence intervals were estimated following a bootstrap procedure. Figures 2-3 show the indices-at-age for the two quarter groups considered.

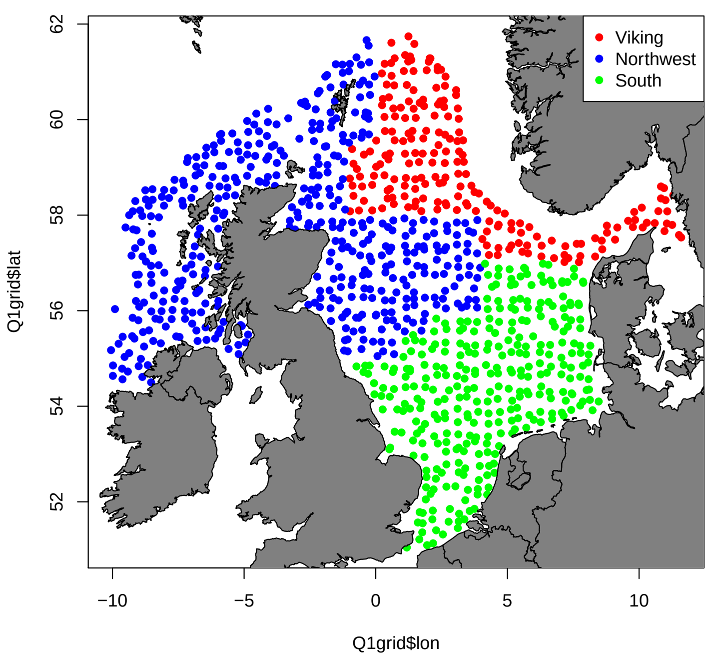


Figure 1: Haul positions over which expected catches are summed to produce indices.

Indices by sub-stock were produced for Q1 by summing the expected catches over the grid by year, age and sub-stock area. This is based on the assumption that any mixing during Q1 is small/negligible, such that all fish observed during the Q1 surveys can be allocated to sub-stock based on where they were found. A similar assumption can be made for age 0 cod in Q34 (which is forward-shifted to provide a recruitment index representative of age 1 on 1st January the following year), as these cod won't have had much chance to move from their sub-stock areas since spawning. Mixing is expected for older ages during other quarters, and the Q34 indices therefore retained to be mix of all three sub-stocks.

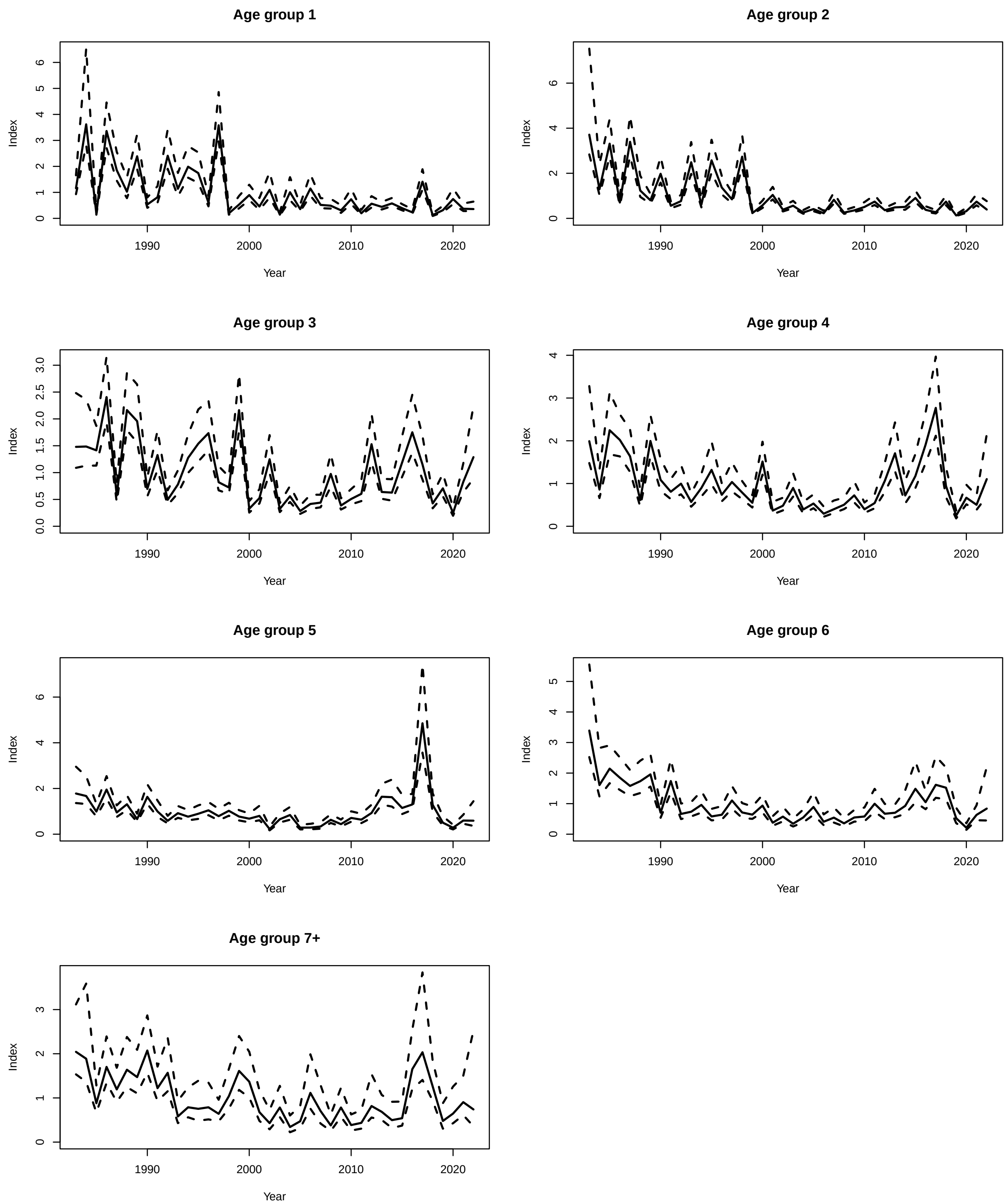


Figure 2: Indices-at-age for the total stock based on the Q1 model.

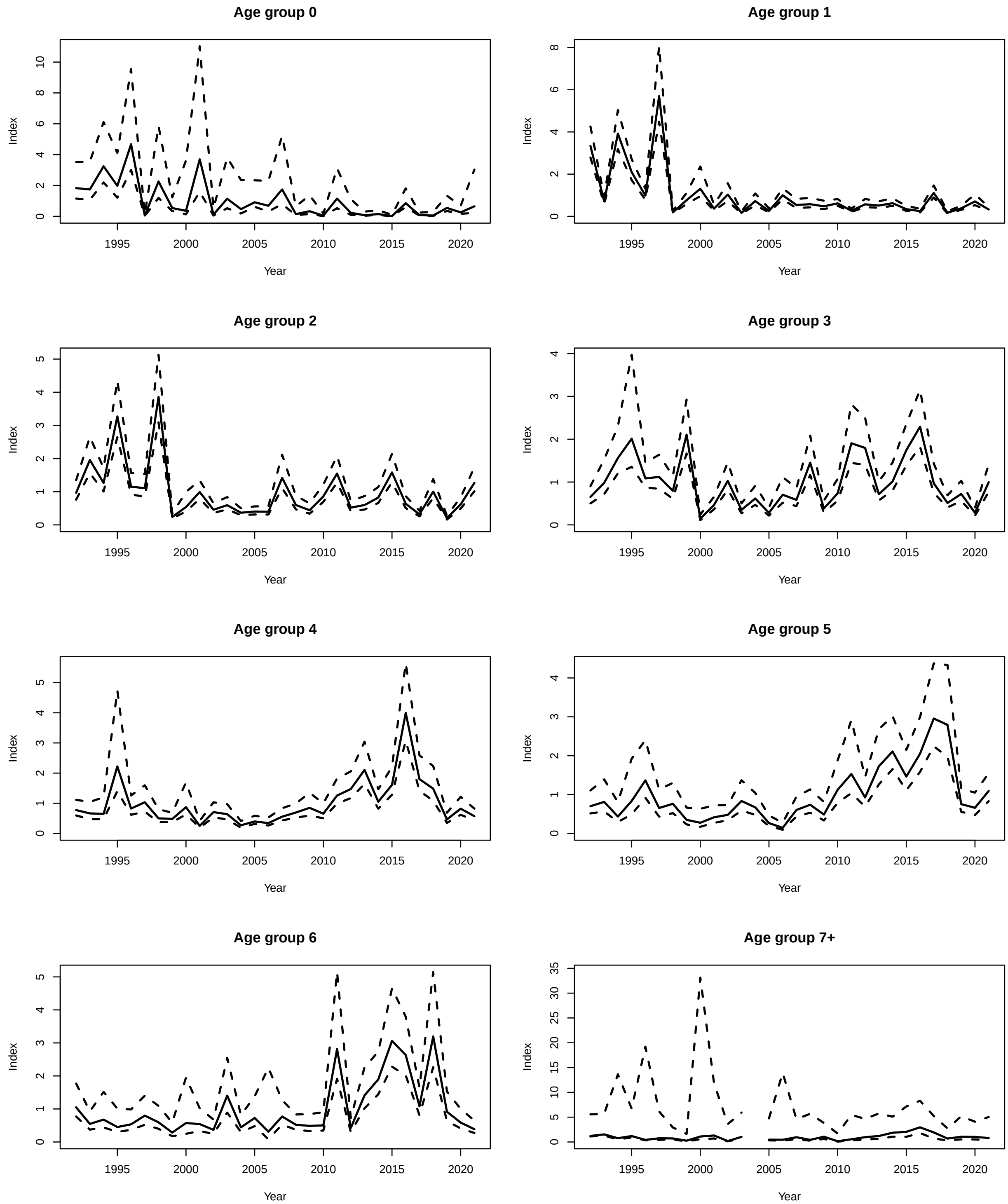


Figure 3: Indices-at-age for the total stock based on the Q34 model.

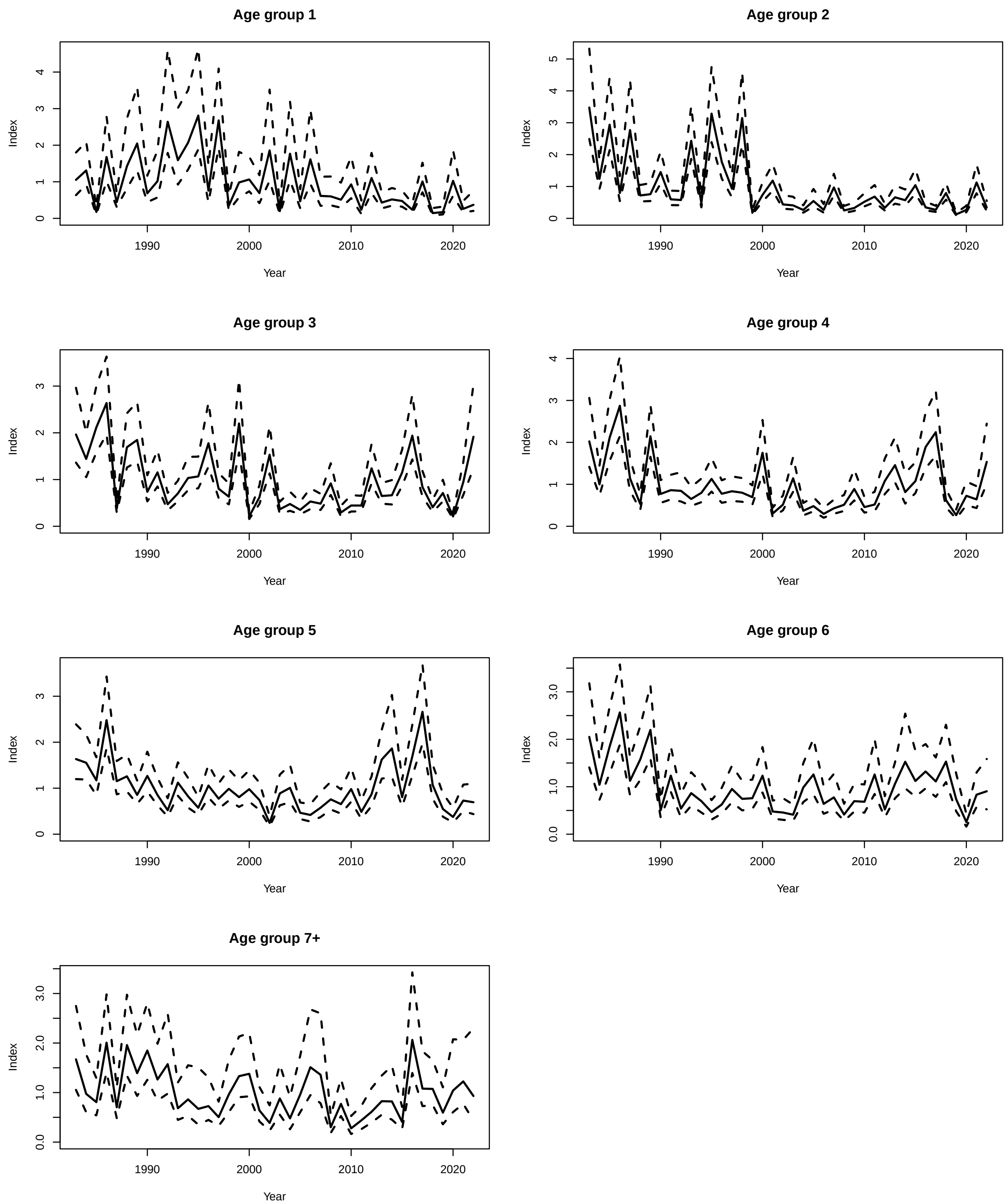


Figure 4: Indices-at-age for the Viking sub-stock in Q1.

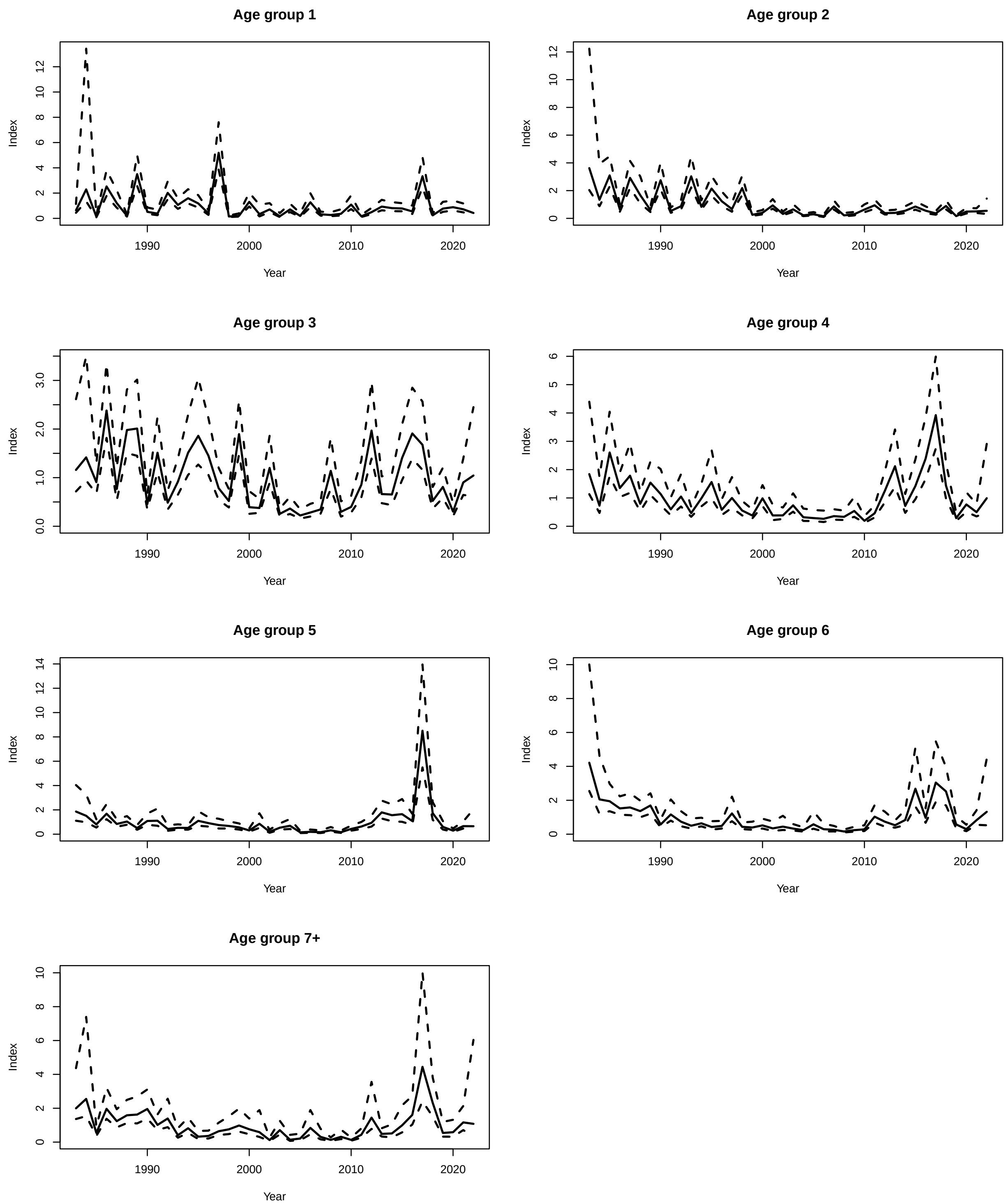


Figure 5: Indices-at-age for the Northwestern sub-stock in Q1.

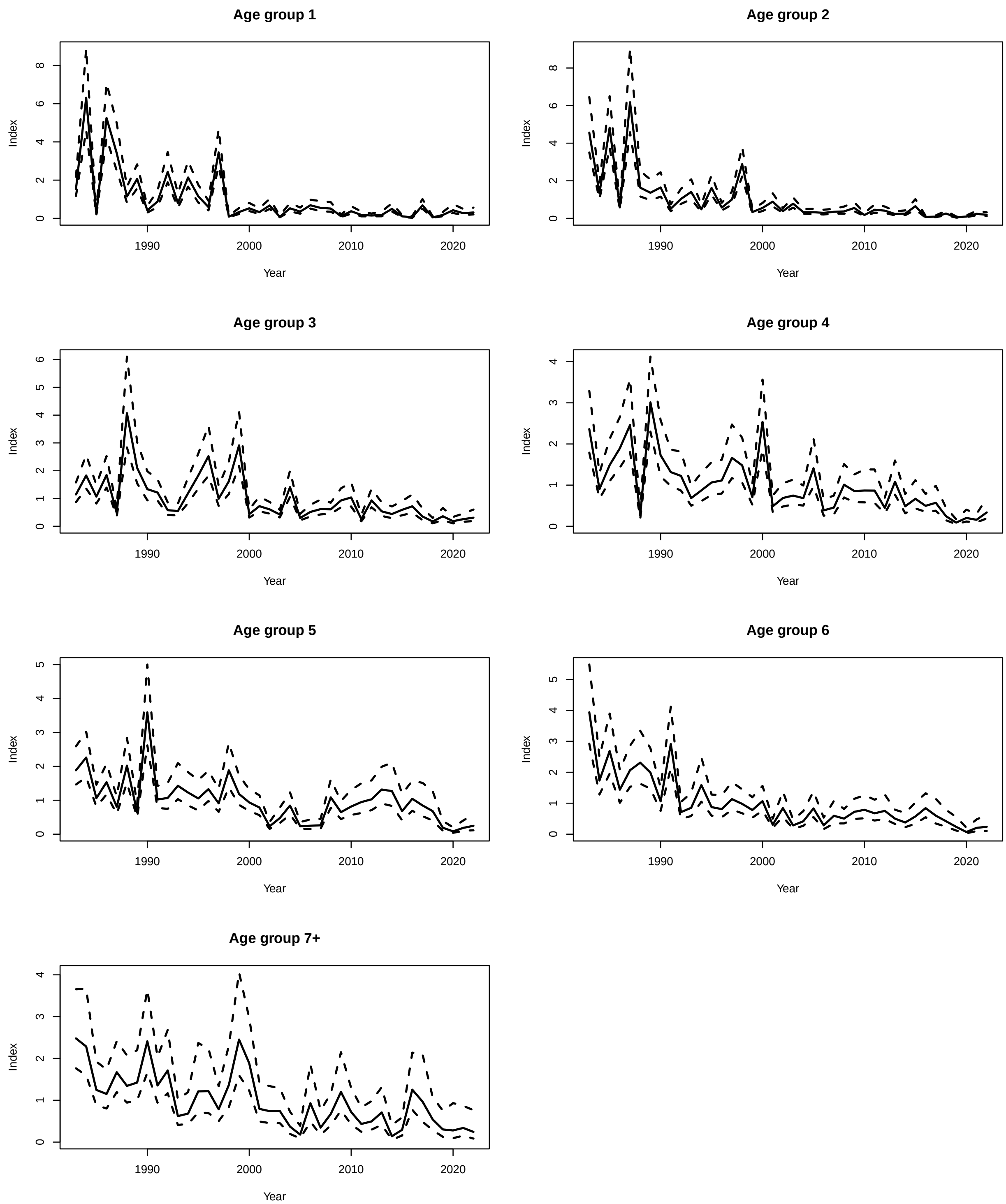


Figure 6: Indices-at-age for the Southern sub-stock in Q1.

Index diagnostics

Retrospective analysis

Retrospective analyses with three peels are plotted in Figures 7-8 and give average Mohn's rho values of 0.04 and -0.02 across ages 1-7+ for the Q1 and Q34 indices, respectively, indicating robustness of the models to new data. The highest Mohn's rho value is 0.22 for age 0 cod in Q34, although this value is not considered problematic for an index indicative of recruitment.

Table 1: Monh's rho values-at-age for the Q1 and Q34 indices.

0	1	2	3	4	5	6	7+
NA	0.03	0.02	0.04	0.01	-0.02	0.06	0.11
0.22	-0.01	-0.03	0.02	-0.03	-0.03	-0.06	0.00

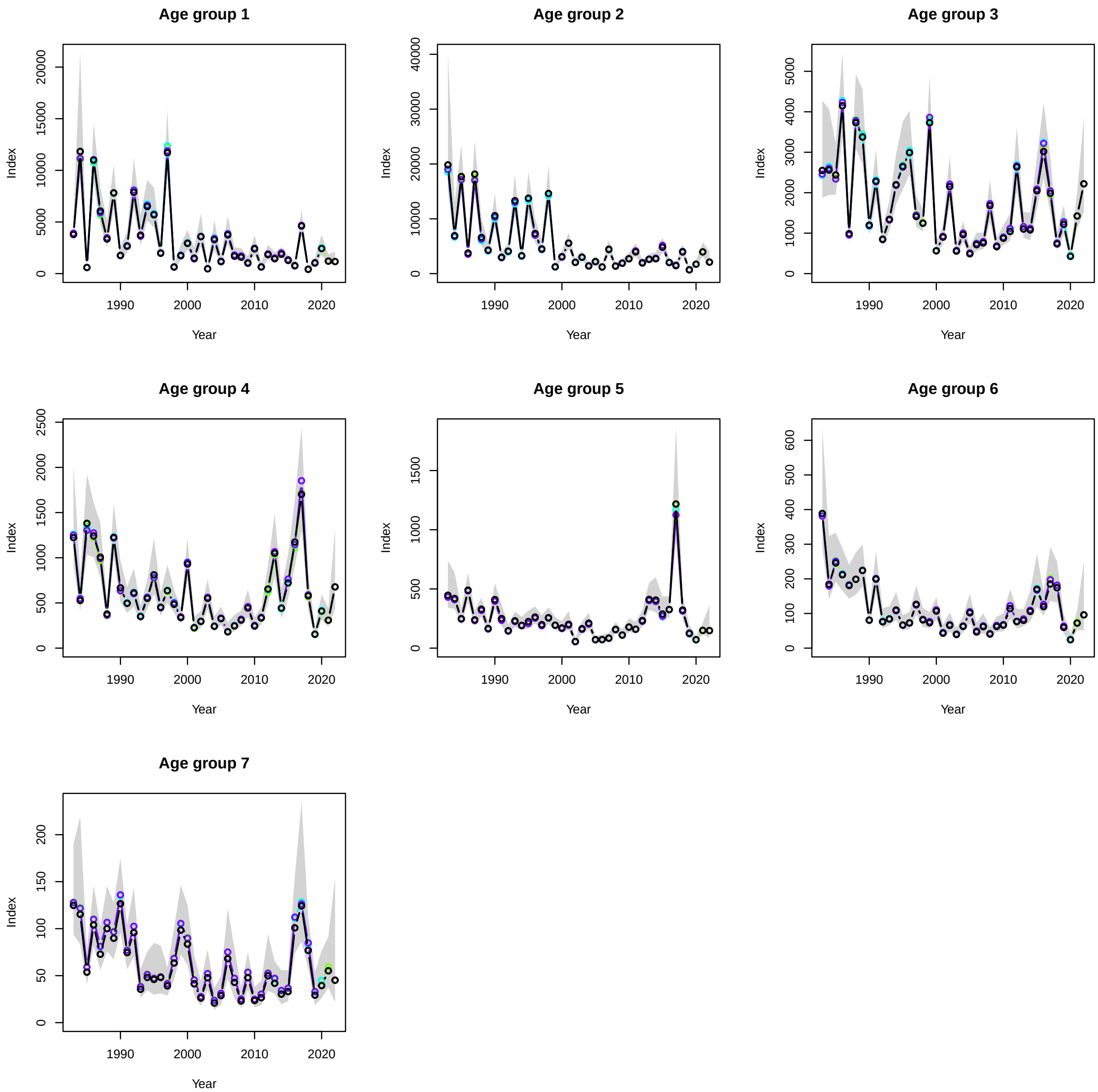


Figure 7: Retrospective plots for Q1. The black points represent the full indices at age and coloured points the peels. The shaded regions show the 95% confidence intervals for the full indices.

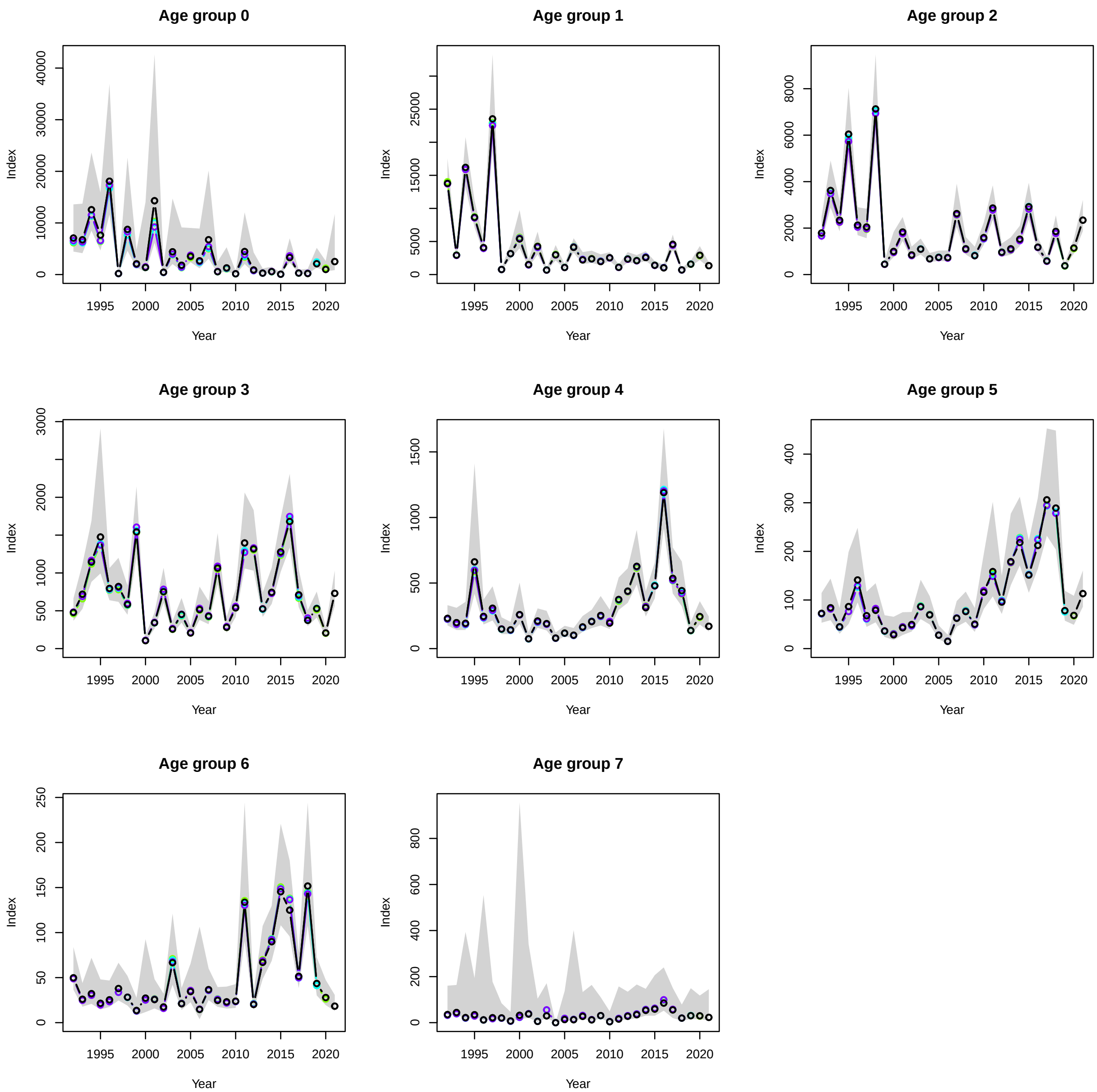


Figure 8: Retrospective plots for Q34. See caption to Figure 7 for further details.

Log catch-curve analyses

The survey abundance indices are plotted in log-mean standardised form by year (Figures 9, 13, 17, and 21) and cohort (Figures 10, 14, 18, and 22) for each sub-stock in Q1 and for the mixed stock in Q34. These plots show the log-mean standardised curves to track cohort signals well (as confirmed by high internal consistencies in the following section) although, as noted for the current North Sea cod stock, there is some loss of signal between the 2012 and 2013 cohorts associated with an apparent positive year effect towards the end of 2016 (Q34) into the beginning of 2017 (Q1). This is most apparent for the Northwestern sub-stock, with all ages except age 2 at a relatively high level in that year, and is likely compounded by the addition of data for 6a which includes a single very large haul in Q1 in 2017 (see Appendix). This positive year effect is apparent to a lesser extent for the other sub-stocks, with all three displaying larger recruitment in 2017.

Log-abundance curves (Figures 11, 15, 19, and 23) and associated negative gradients for reference ages 2-4 (Figures 12, 16, 20, and 24) are plotted for each sub-stock in Q1 and for the mixed stock in Q34, and give an indication of total mortality trends over time. The negative gradients for the mixed stock have shown a gradual decrease over time but with a steep increase for the 2013-2016 cohorts and a sharp decline in the most recent years following the 2017 cohort, likely due to reductions in catches from 2019. This recent steep increase and decrease is most pronounced in the Viking and Northwestern sub-stocks.

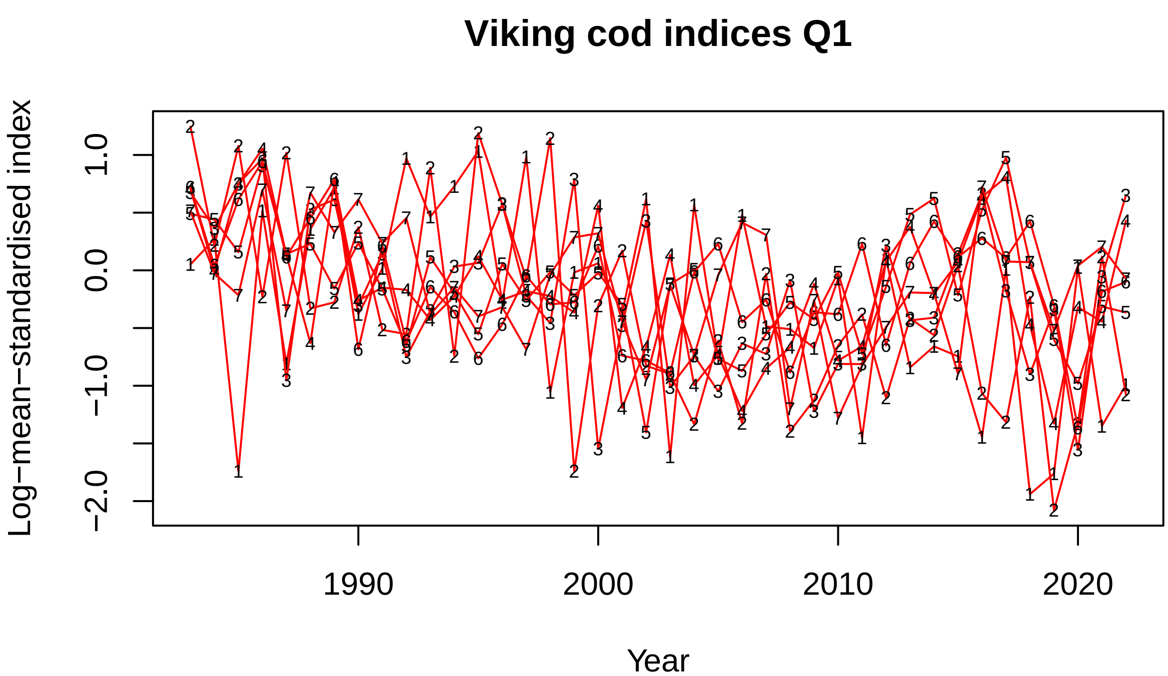


Figure 9: Log-mean standardised indices plotted by year for the Viking sub-stock in Q1.

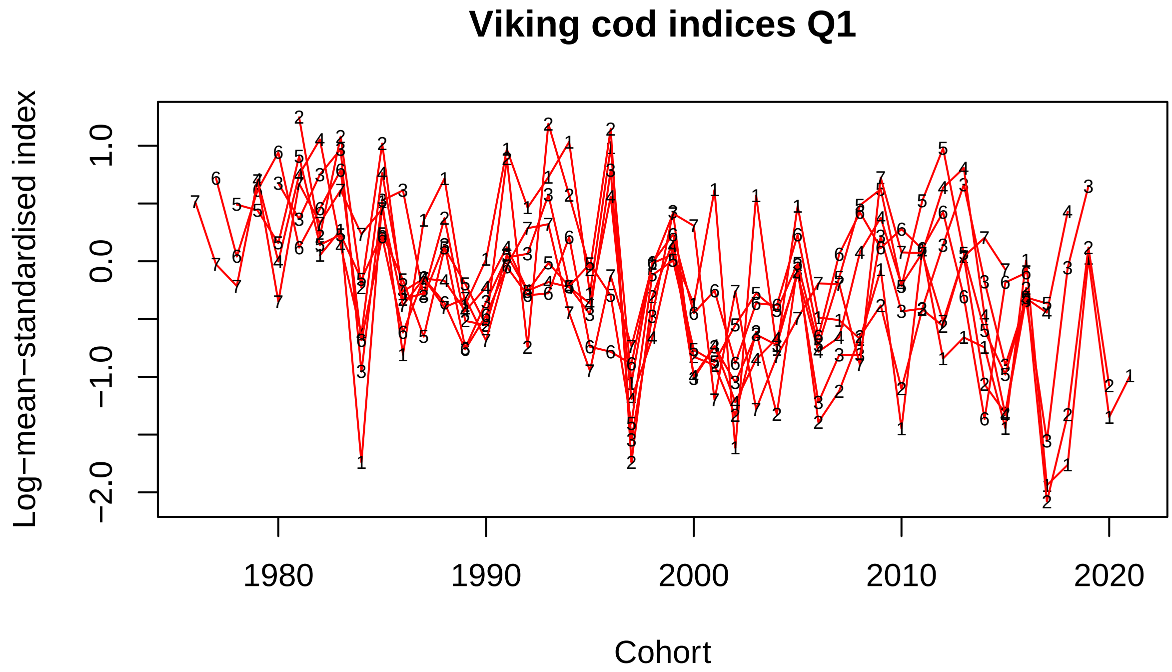


Figure 10: Log-mean standardised indices plotted by cohort for the Viking sub-stock in Q1.

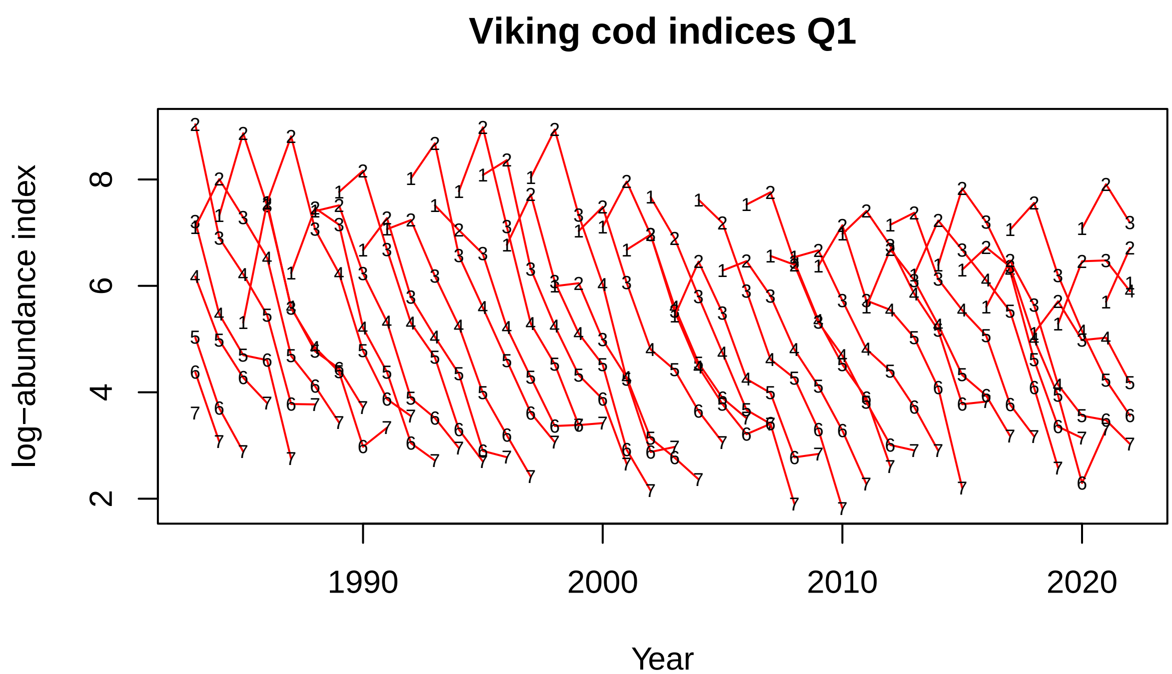


Figure 11: Log abundance curves for the Viking sub-stock in Q1.

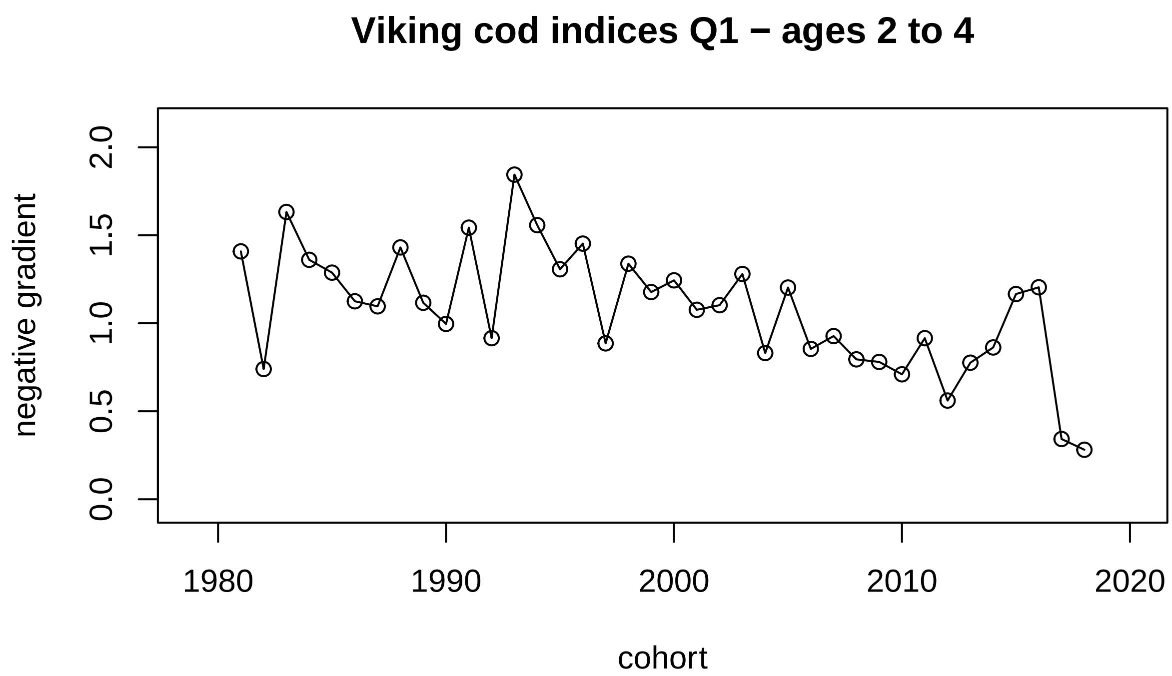


Figure 12: Negative gradients of the log abundance curves across reference ages 2-4 for the Viking sub-stock in Q1.

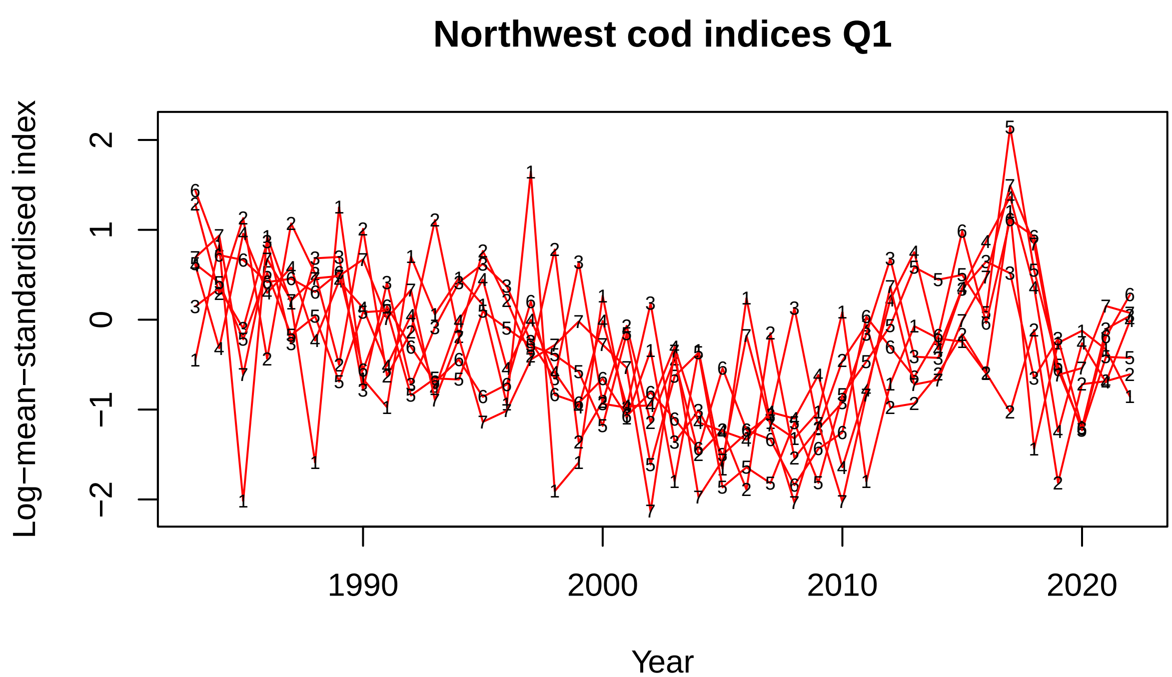


Figure 13: Log-mean standardised indices plotted by year for the Northwestern sub-stock in Q1.

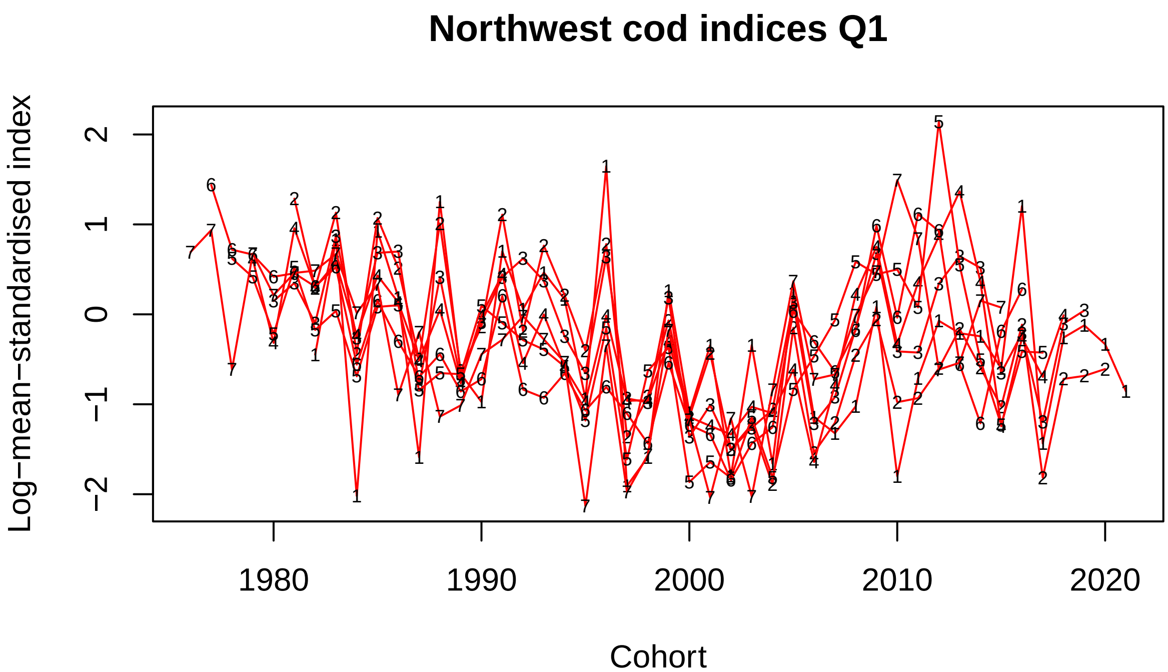


Figure 14: Log-mean standardised indices plotted by cohort for the Northwestern sub-stock in Q1.

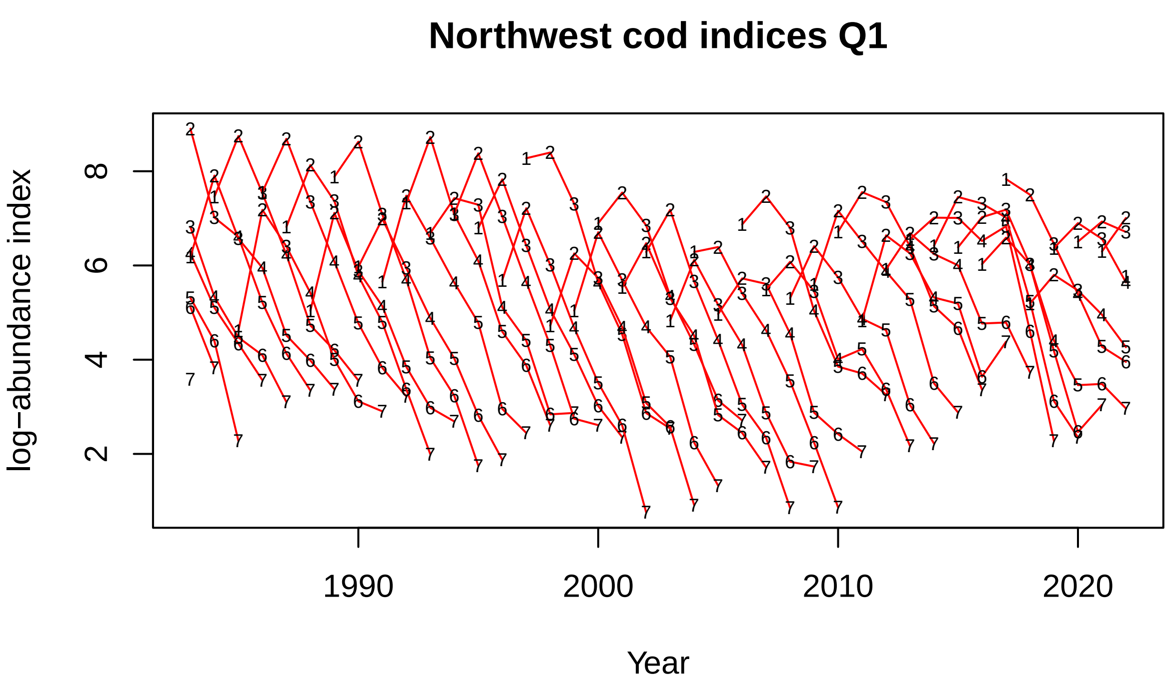


Figure 15: Log abundance curves for the Northwestern sub-stock in Q1.

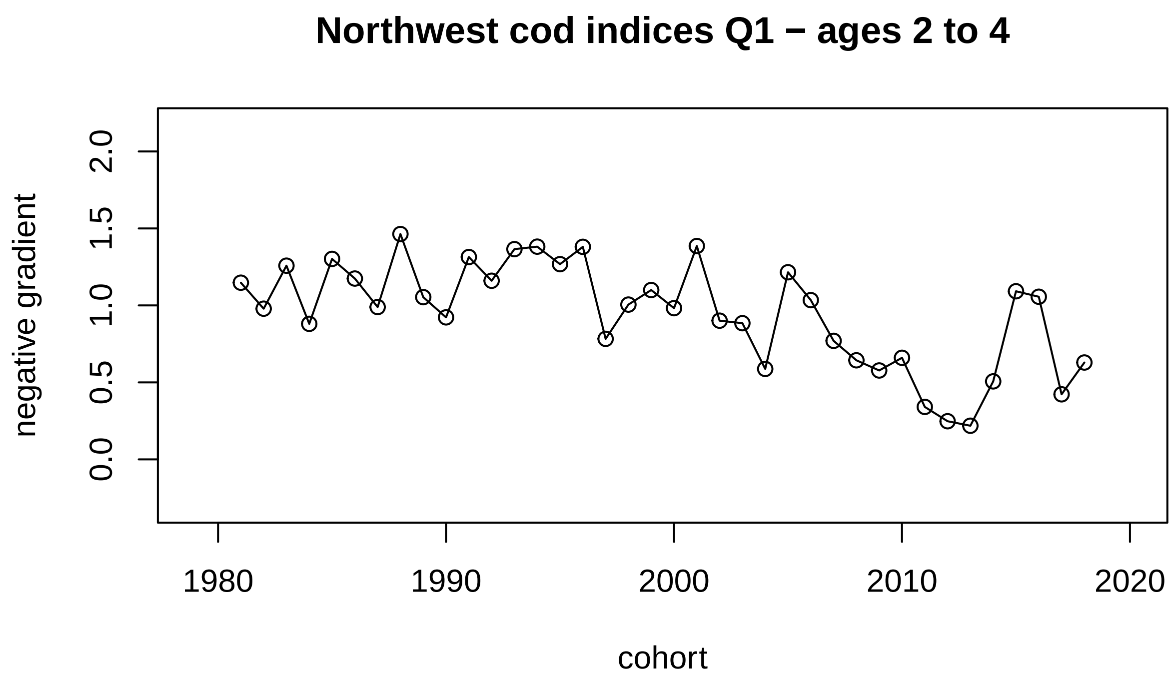


Figure 16: Negative gradients of the log abundance curves across reference ages 2-4 for the Northwestern sub-stock in Q1.

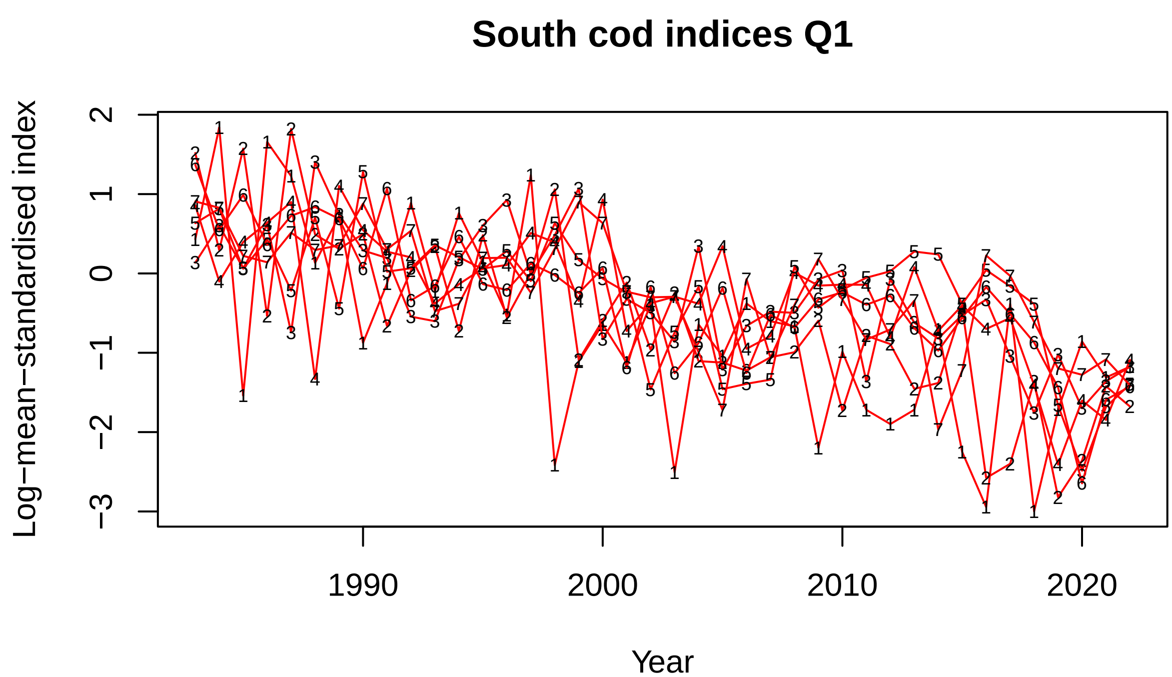


Figure 17: Log-mean standardised indices plotted by year for the Southern sub-stock in Q1.

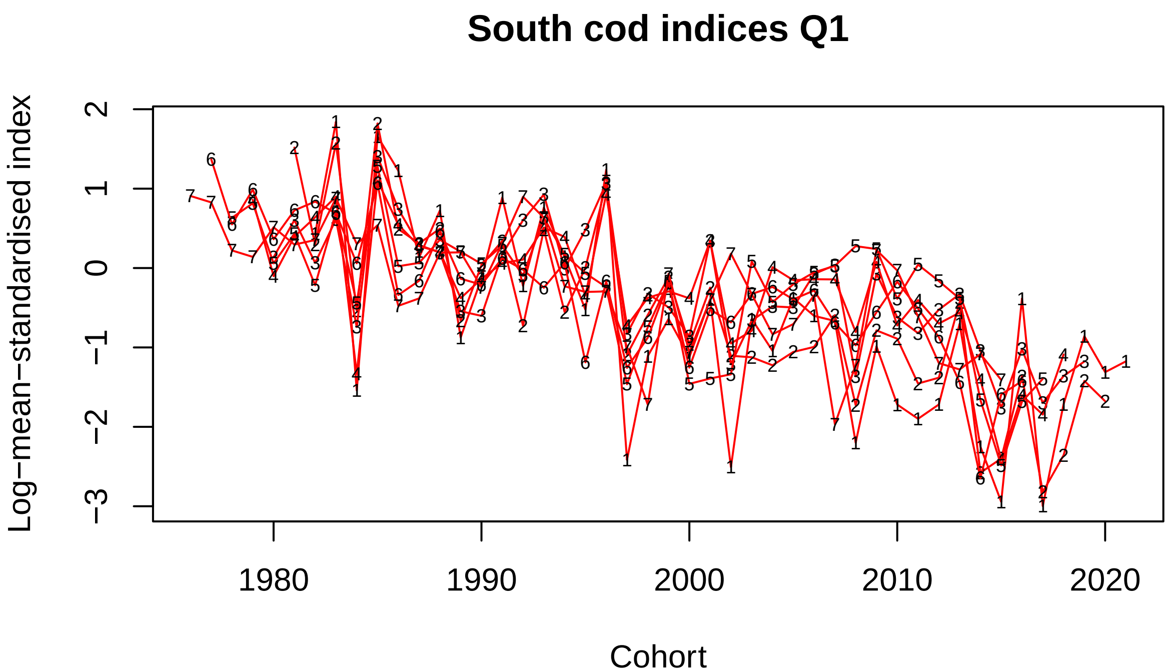


Figure 18: Log-mean standardised indices plotted by cohort for the Southern sub-stock in Q1.

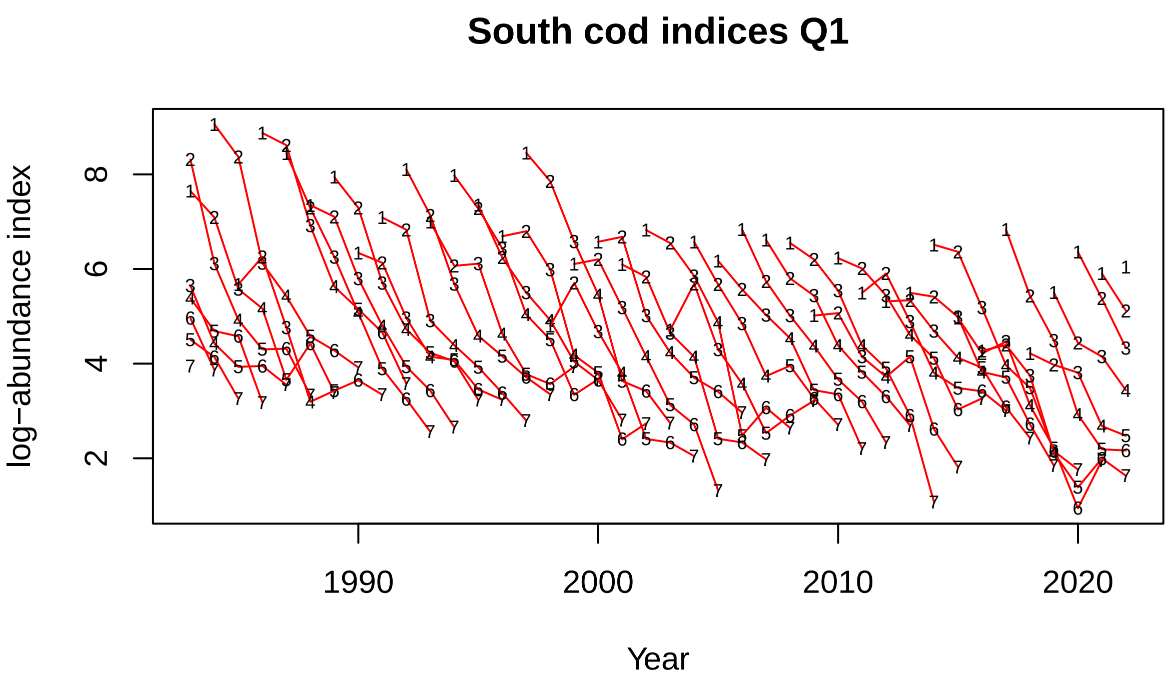


Figure 19: Log abundance curves for the Southern sub-stock in Q1.

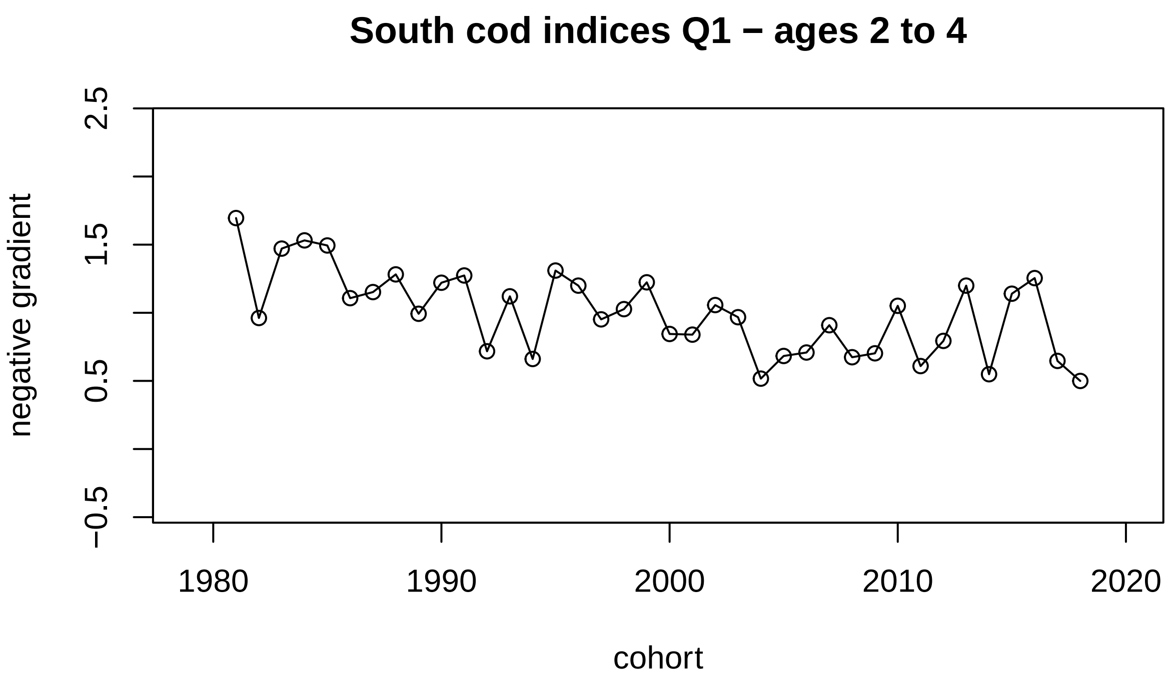


Figure 20: Negative gradients of the log abundance curves across reference ages 2-4 for the Southern sub-stock in Q1.

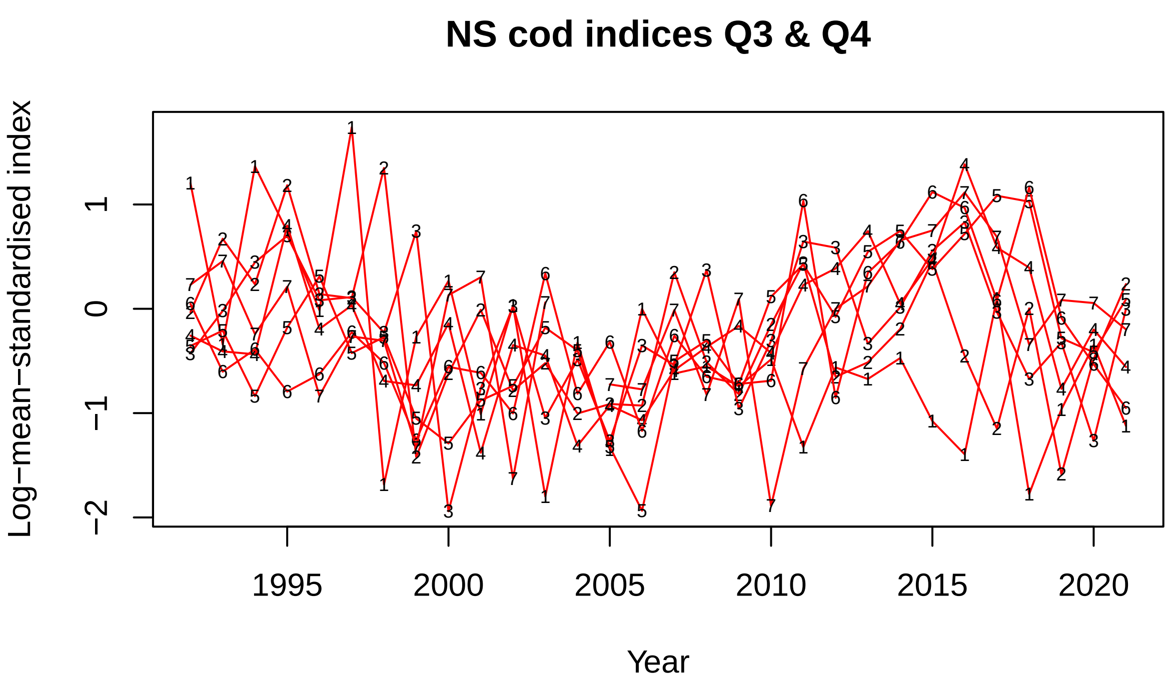


Figure 21: Log-mean standardised indices plotted by year for the Q34 surveys.

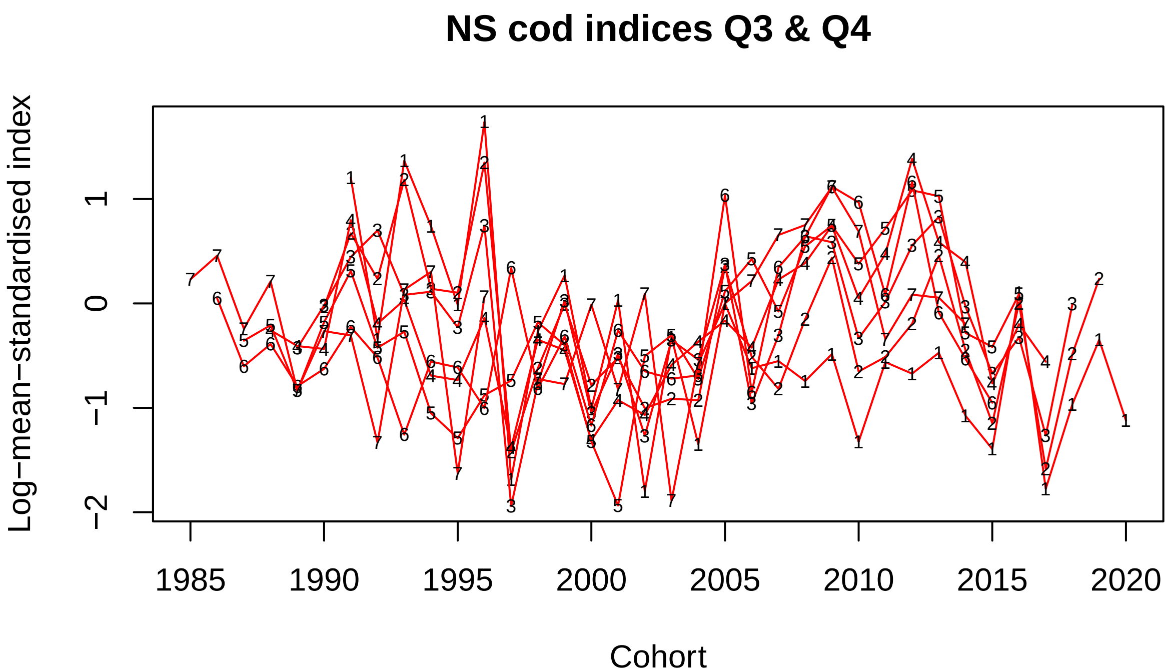


Figure 22: Log-mean standardised indices plotted by cohort for the Q34 surveys.

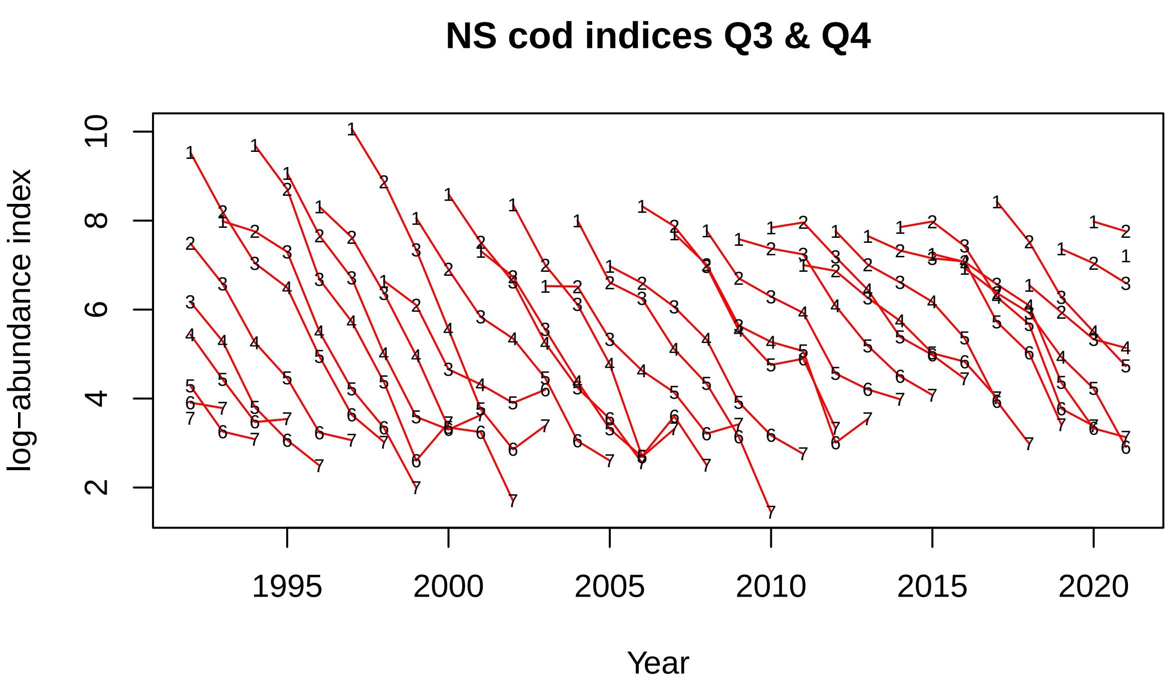


Figure 23: Log abundance curves for the Q34 surveys.

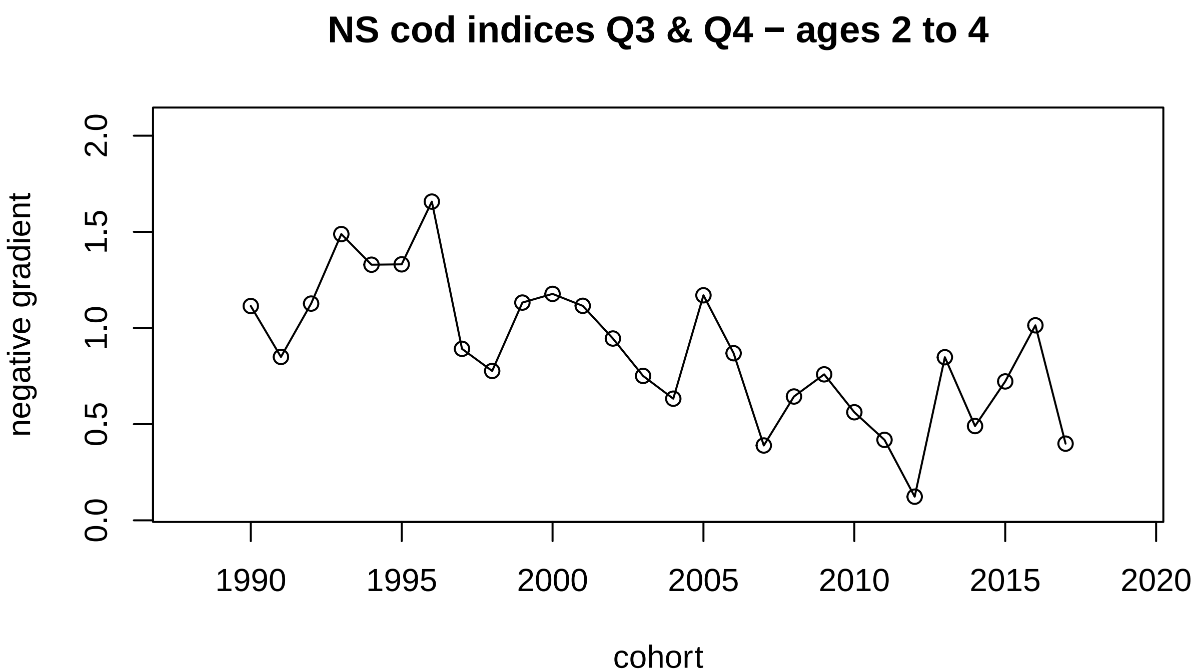


Figure 24: Negative gradients of the log abundance curves across reference ages 2-4 for the Q34 surveys.

Internal Consistency

Two measures of internal consistency are routinely presented in Working Group meetings: (1) within index correlations between adjacent age groups and (2) coefficients of determination (r^2) from linear regressions of non-equal age groups. Both measures are presented for individual sub-stocks in Q1 and for the mixed stock in Q34 (Figures 25-32) and demonstrate a tendency for the correlation coefficient to yield values closer to 1 (indicative of higher self-consistency). These plots show good internal consistency, particularly for the Northwestern and Southern sub-stocks where correlations and $r^2 \geq 0.5$ for all adjacent ages, justifying their use for survey tuning. There is some deterioration with age in all indices, but particularly for ages 5+ in both the Viking sub-stock in Q1 and for the mixed stock in Q34.

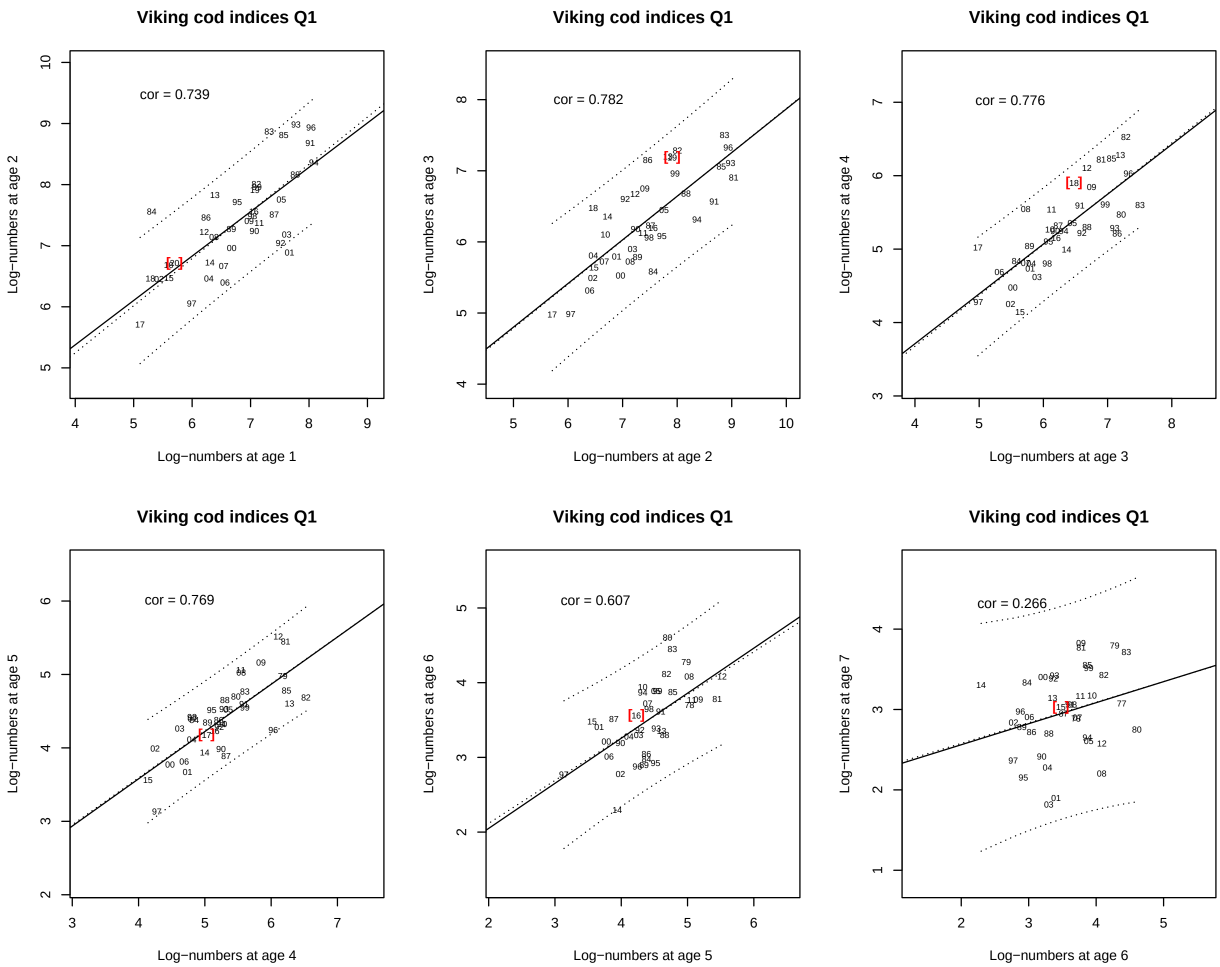


Figure 25: Within index correlations for the Viking sub-stock in Q1 for the period 1983-2022. Individual points are given by cohort (year-class), the solid line is a standard linear regression line, the broken line nearest to it a robust linear regression line, and “cor” denotes the correlation coefficient. The pair of broken lines on either side of the solid line indicate prediction intervals. The most recent point appears in red square brackets.

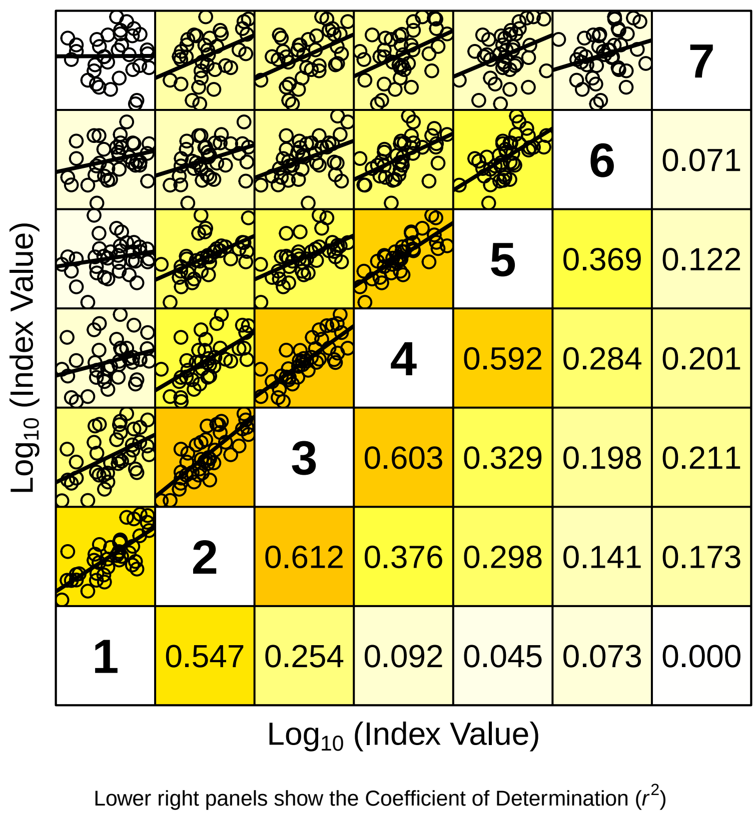


Figure 26: Within index consistency for the Viking sub-stock in Q1 for the period 1983-2022. The upper triangle shows linear regressions between age classes while the lower triangle shows the associated r^2 values.

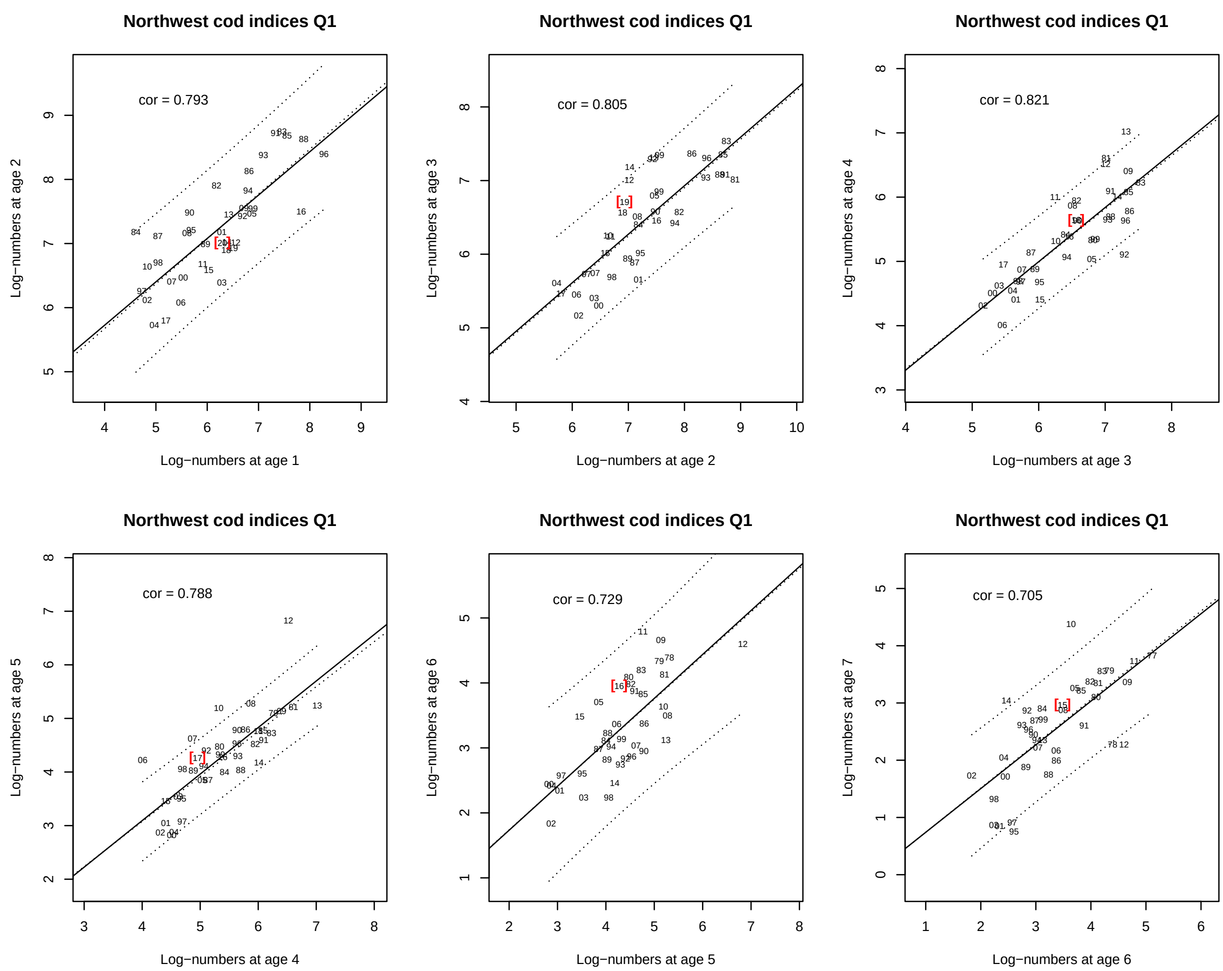


Figure 27: Within index correlations for the Northwestern sub-stock in Q1 for the period 1983-2022. See caption to Figure 25 for further details.

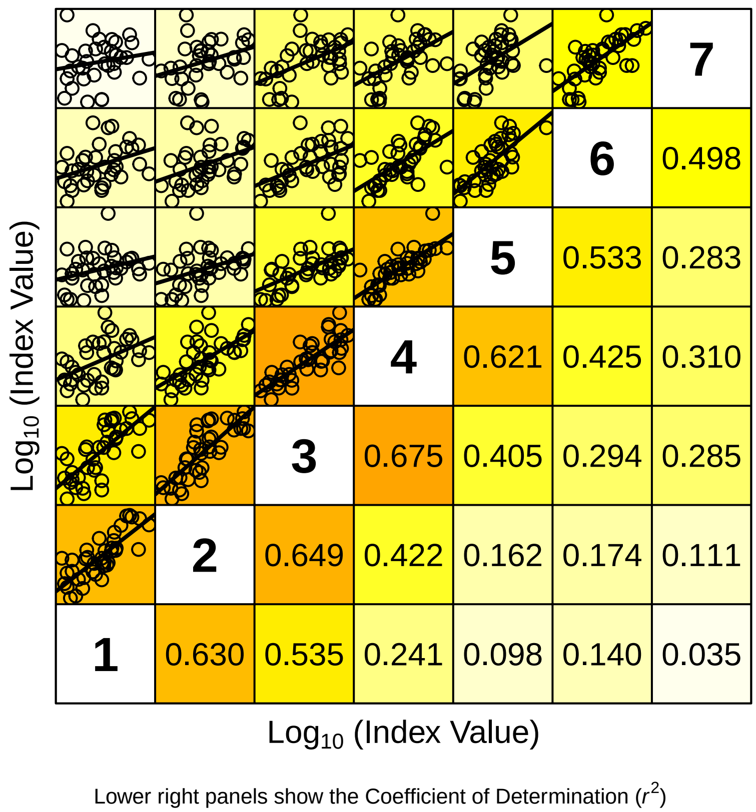


Figure 28: Within index consistency for the Northwestern sub-stock in Q1 for the period 1983-2022. The upper triangle shows linear regressions between age classes while the lower triangle shows the associated r^2 values.

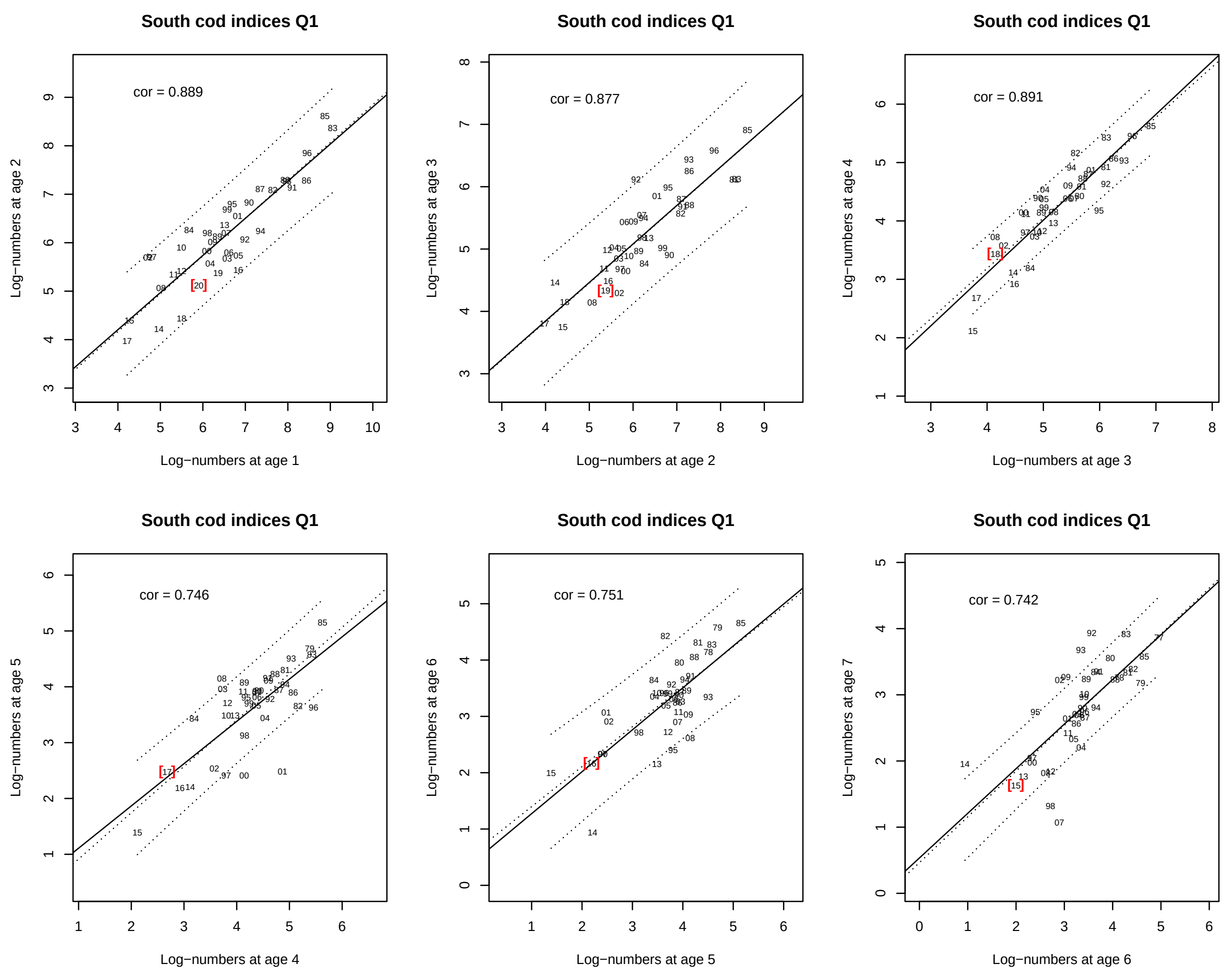


Figure 29: Within index correlations for the Southern sub-stock in Q1 for the period 1983-2022. See caption to Figure 25 for further details.

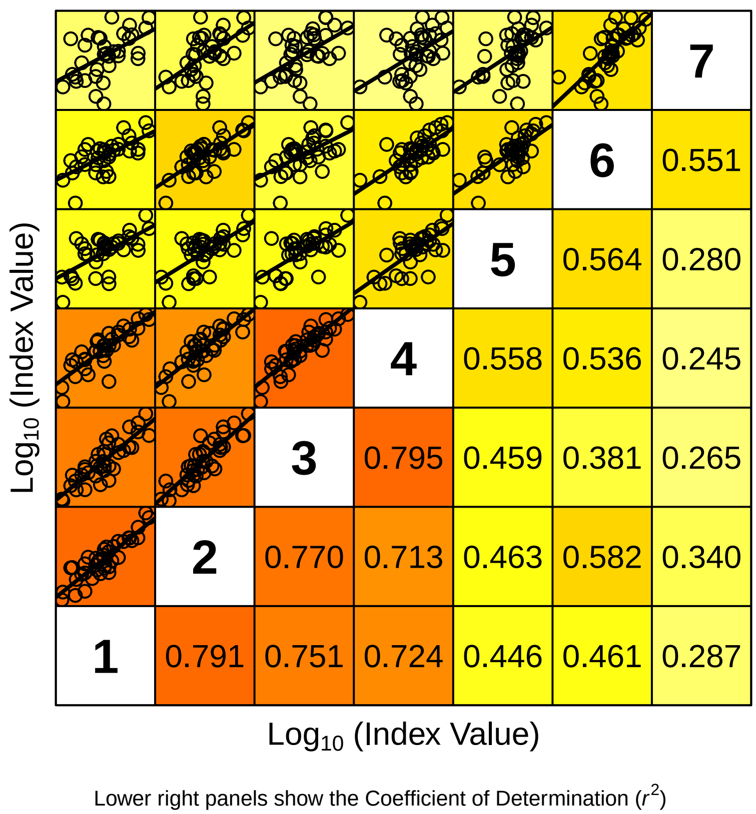


Figure 30: Within index consistency for the Southern sub-stock in Q1 for the period 1983-2022. The upper triangle shows linear regressions between age classes while the lower triangle shows the associated r^2 values.

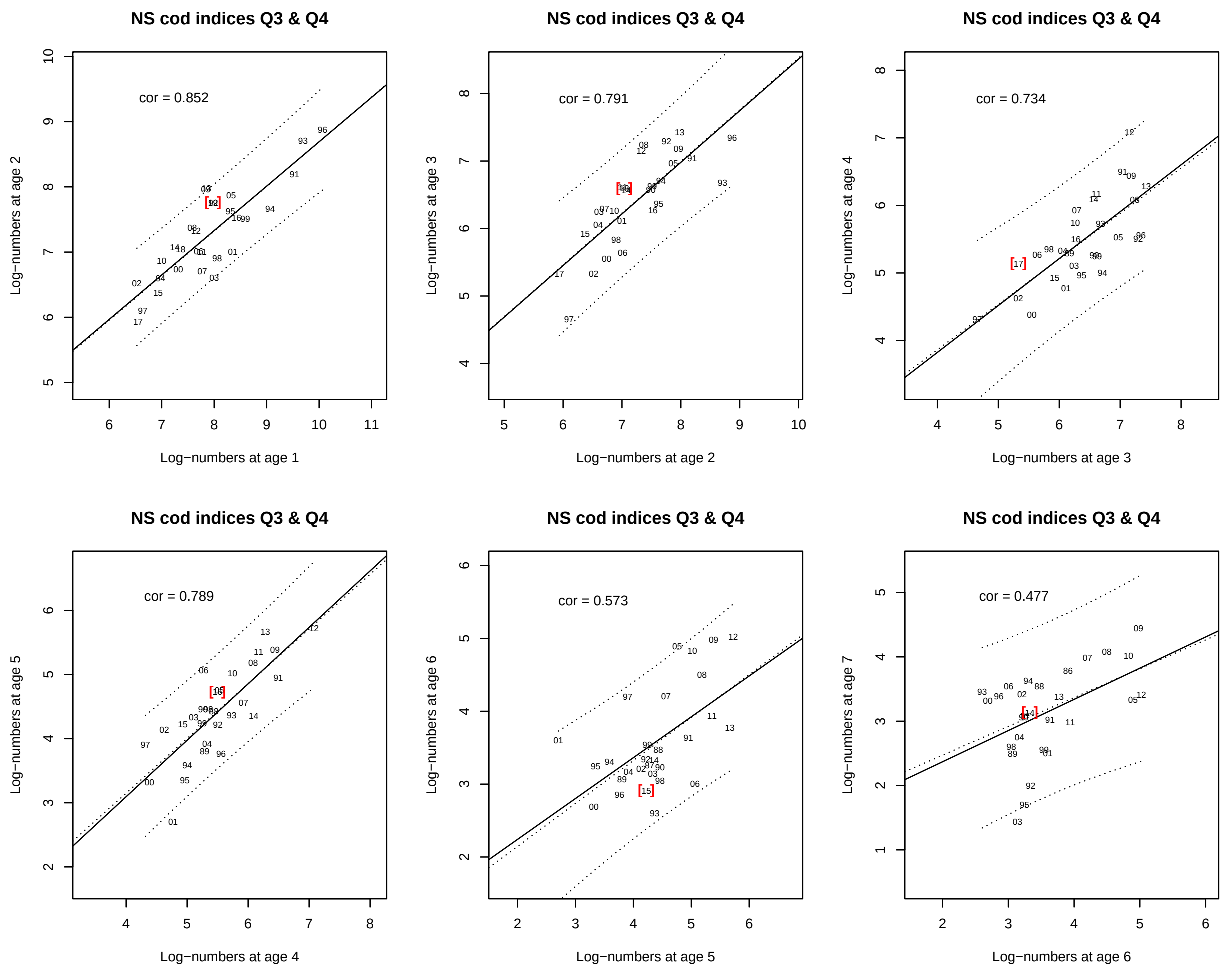


Figure 31: Within index correlations for the Q34 surveys for the period 1992-2021. See caption to Figure 25 for further details.

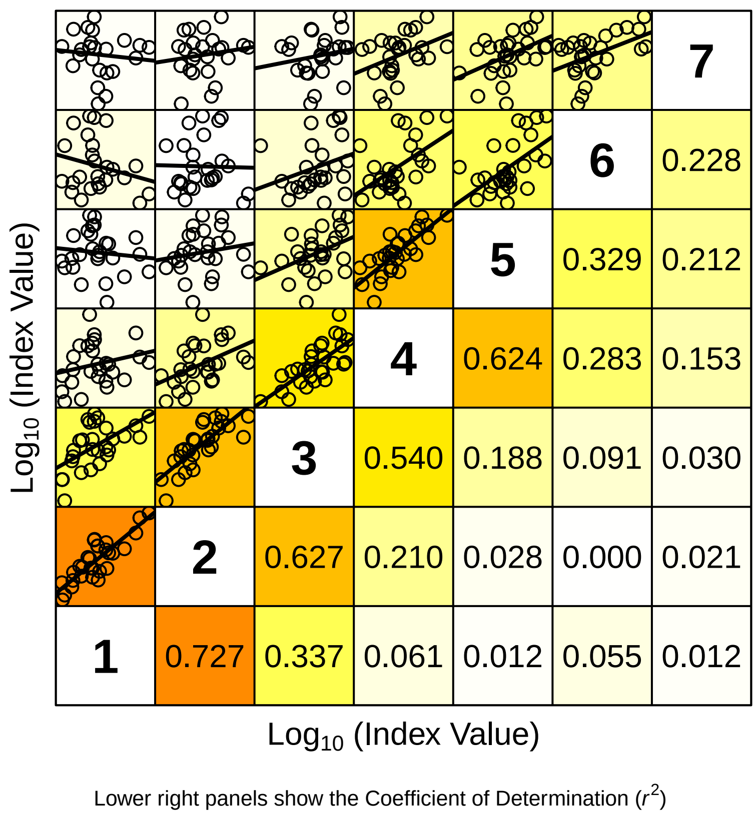


Figure 32: Within index consistency for the Q34 surveys for the period 1983-2022. The upper triangle shows linear regressions between age classes while the lower triangle shows the associated r^2 values.

External consistency

Between index correlations for the Q1 and Q34 surveys for the total stock (Figure 33) show good external consistency for ages 1-5 but with some deterioration for ages 6 (cor=0.55) and 7+ (cor=0.32).

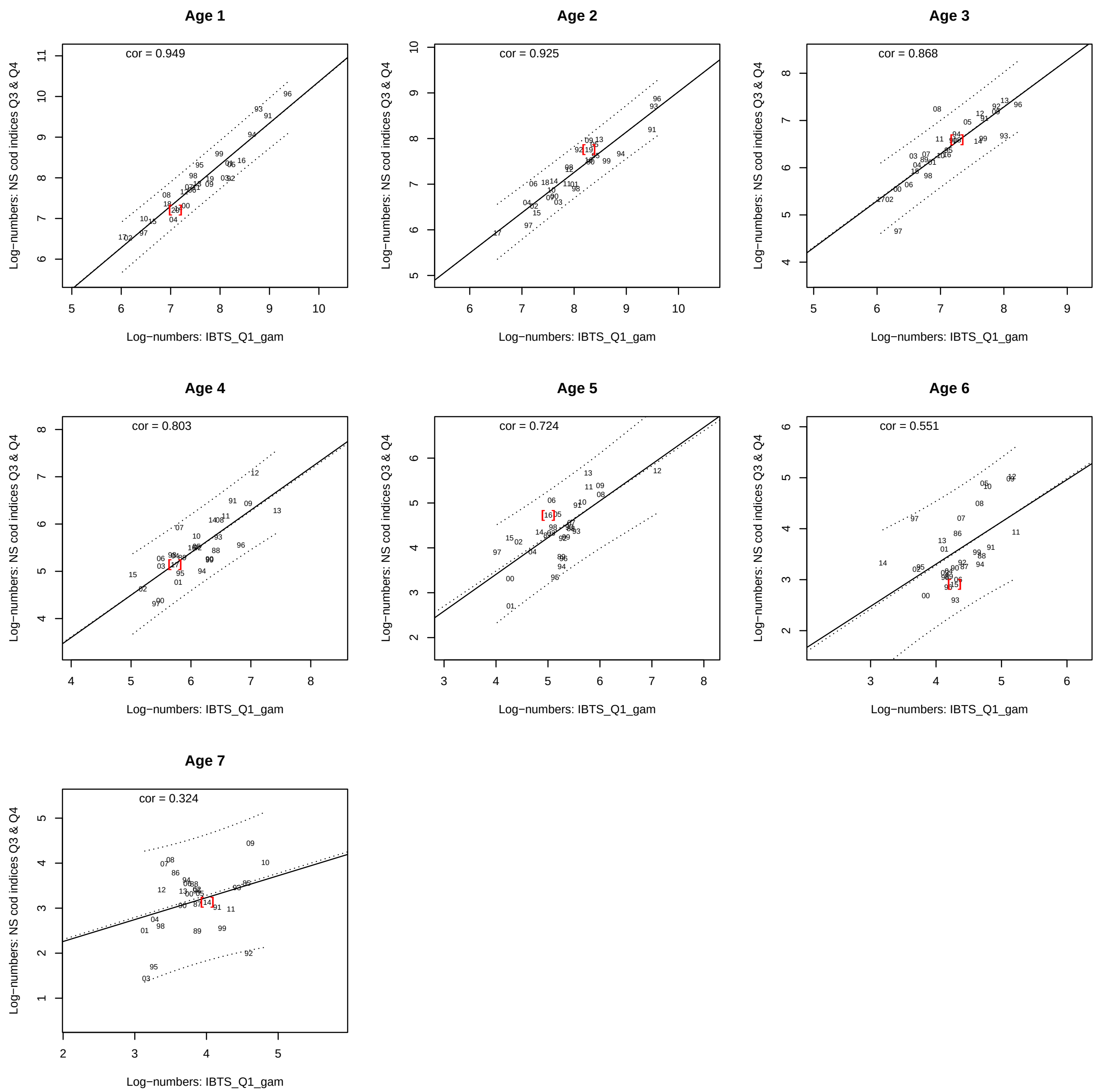


Figure 33: Between index correlations for the Q1 and Q34 surveys for the period 1992-2021. See caption to Figure 25 for further details.

Recruitment consistency

The last benchmark of North Sea cod decided to include the delta-GAM estimates of age 0 from the IBTS Q3 survey as a separate recruitment index for age 1 the following year, assumed to be taken on 1st January, with the purposes of (1) improving forecasts by providing two observations to inform the intermediate year recruitment assumption (IBTS Q3 in year $y-1$ and IBTS Q1 in year y); and (2) giving potential to account for incoming year classes earlier *via* the reopening protocol. The decision to combine the survey data for Q3 and Q4 (taken at the data evaluation meeting) will likely preclude an autumn repoening because the Q4 survey data will not be available in time. Correlations between the recruitment indices (age 0 in the Q34 surveys) and age 1 in the Q1 indices indicate strong consistency and therefore continued potential to inform the intermediate year recruitment assumption.

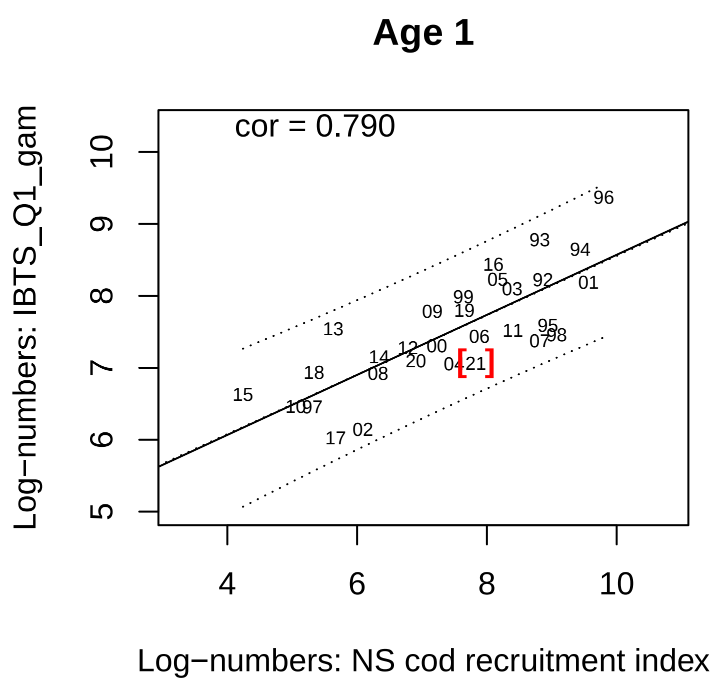


Figure 34: Between index correlations for the Q34 recruitment index (age 0 forward shifted to 1st January the following year) and age 1 in the Q1 surveys for the total stock between 1993-2022. See caption to Figure 25 for further details.

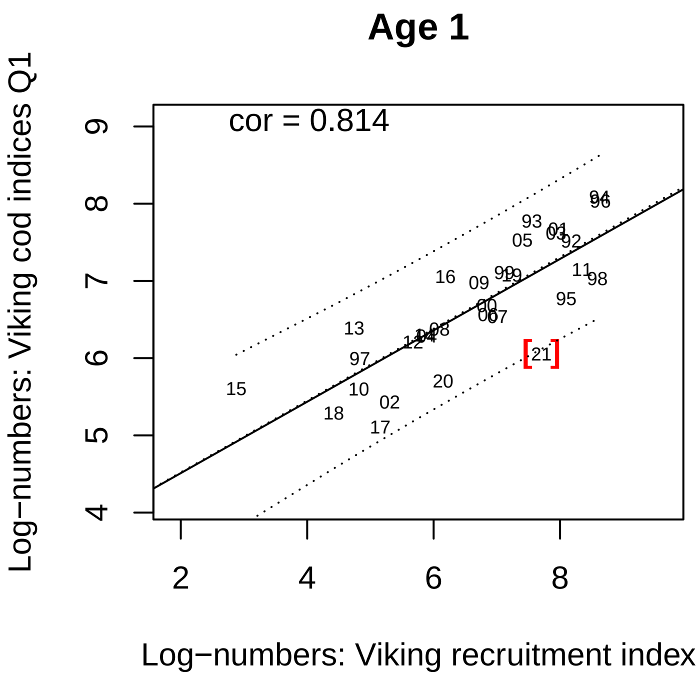


Figure 35: Between index correlations for the Q34 recruitment index (age 0 forward shifted to 1st January the following year) and age 1 in the Q1 surveys for the Viking sub-stock between 1993-2022. See caption to Figure 25 for further details.

Figure 36: Between index correlations for the Q34 recruitment index (age 0 forward shifted to 1st January the following year) and age 1 in the Q1 surveys for the Northwestern sub-stock between 1993-2022. See caption to Figure 25 for further details.

Figure 37: Between index correlations for the Q34 recruitment index (age 0 forward shifted to 1st January the following year) and age 1 in the Q1 surveys for the Southern sub-stock between 1993-2022. See caption to Figure 25 for further details.

Index uncertainty

Average index standard deviations (across years) for the Q1 indices range from 0.17-0.31, with the values tending to decline from age 1 to age 2 and increase from ages 5+ (Table 2). Average standard deviations are higher for ages 2+ for the Northwestern sub-stock compared to the other sub-stocks, and this remains the case when excluding the most recent data from 2022, where a combination of several major storms and mechanical issues resulted in reduced survey coverage.

Table 2: Average standard deviations-at-age for the Q1 indices.

	1	2	3	4	5	6	7+
Viking	0.26	0.19	0.17	0.18	0.18	0.20	0.25
Northwestern	0.24	0.20	0.20	0.24	0.24	0.26	0.31
Southern	0.21	0.19	0.19	0.20	0.21	0.24	0.29

Average index standard deviations (across years) for the Q34 surveys follow a similar pattern (Table 3) but with a much higher average standard deviation for the 7+ group (sd=0.62) because fewer 7+ fish are observed in those surveys. This increased uncertainty for the plus group can also be seen in Figure 3.

Table 3: Average standard deviations-at-age for the Q34 indices.

1	2	3	4	5	6	7+
0.15	0.14	0.16	0.18	0.22	0.26	0.62

There is more uncertainty about the index for age 0 in the Q34 surveys (Figure 3) and hence higher average standard deviations for the recruit indices (age 0 in Q34 forward shifted to age 1 1st January), both for the mixed stock (sd=0.46) and individual sub-stocks (Viking=0.49, Northwestern=0.54, Southern=0.7).

However, high uncertainty about the indices should not preclude inclusion in the SAM assessment, since higher uncertainty is reflected by higher standard deviations which can be carried through to the SAM assessment.

Conclusions

- Mohn's rho values based on three peels indicate robustness of the index models.
- Log-mean standardised abundance indices demonstrate similar traits to those noted for the current North Sea cod stock, i.e., an apparent positive year-effect towards the end of 2016 into the beginning of 2017 and associated loss of signal between the 2012 and 2013 cohorts.
- There is a very large haul in 6.a. in 2017 that influences the Q1 indices for ages 4+ in that year.
- Internal consistency is generally very good but deteriorates for ages 5+ in both the Viking sub-stock index and the Q34 index for the mixed stock.
- External consistency between the Q1 and Q34 indices is very good for ages 1-5 but weaker for age 6 and the 7+ group.
- There is strong consistency between the Q34 recruitment indices (age 0 forward shifted to age 1 1st January) and the Q1 indices for age 1.
- The Q34 indices for recruitment (age 0 forward shifted to age 1 1st January) and the 7+ group are highly uncertain, although this diagnostic alone should not preclude inclusion in the assessment as the associated standard deviations feed through to SAM.

References

Berg, C. W., and K. Kristensen. 2012. "Spatial Age-Length Key Modelling Using Continuation Ratio Logits." *Fisheries Research* 129: 119–26.

Berg, C. W., A. Nielsen, and K. Kristensen. 2014. "Evaluation of Alternative Age-Based Models for Estimating Relative Abundance from Survey Data in Relation to Assessment Models." *Fisheries Research* 151: 91–99.

Apendix: Large haul in Q1

Survey biomass plots show a single very large haul with high numbers of older individuals in the SCOWCGFS-Q1 survey in 6a in 2017 (Figure 38). A comparison of the Q1 indices presented here (Figure 2) to Q1 indices calculated without the large haul included shows an influence of this haul for ages 4+ in 2017 (Figure 39).

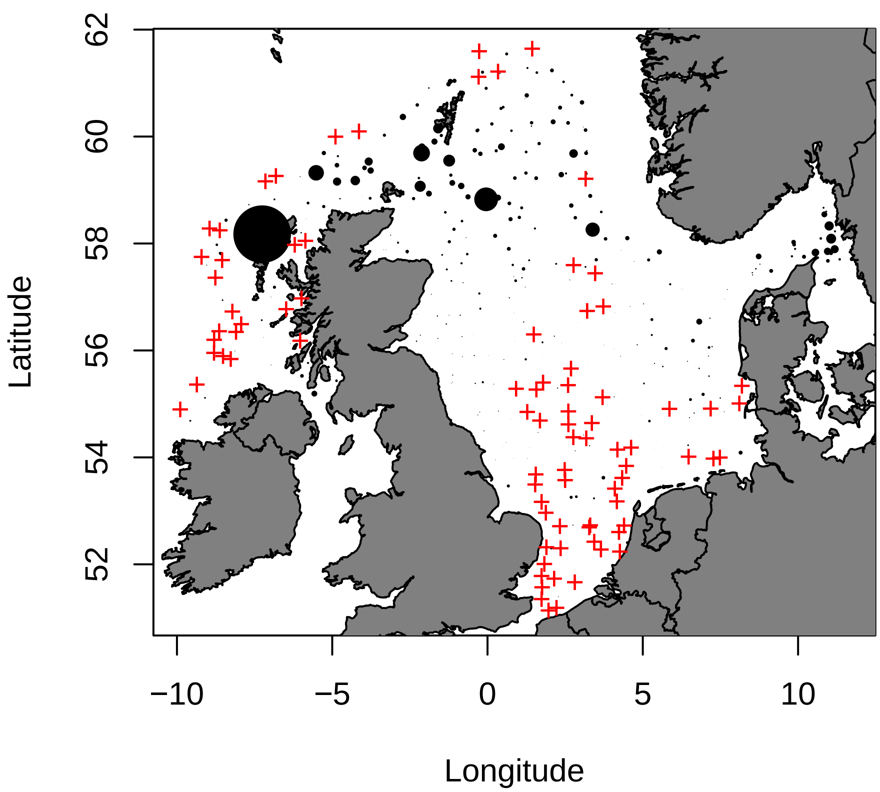


Figure 38: Bubble plot of the observed survey biomass of cod by haul in the Q1 surveys in 2017.

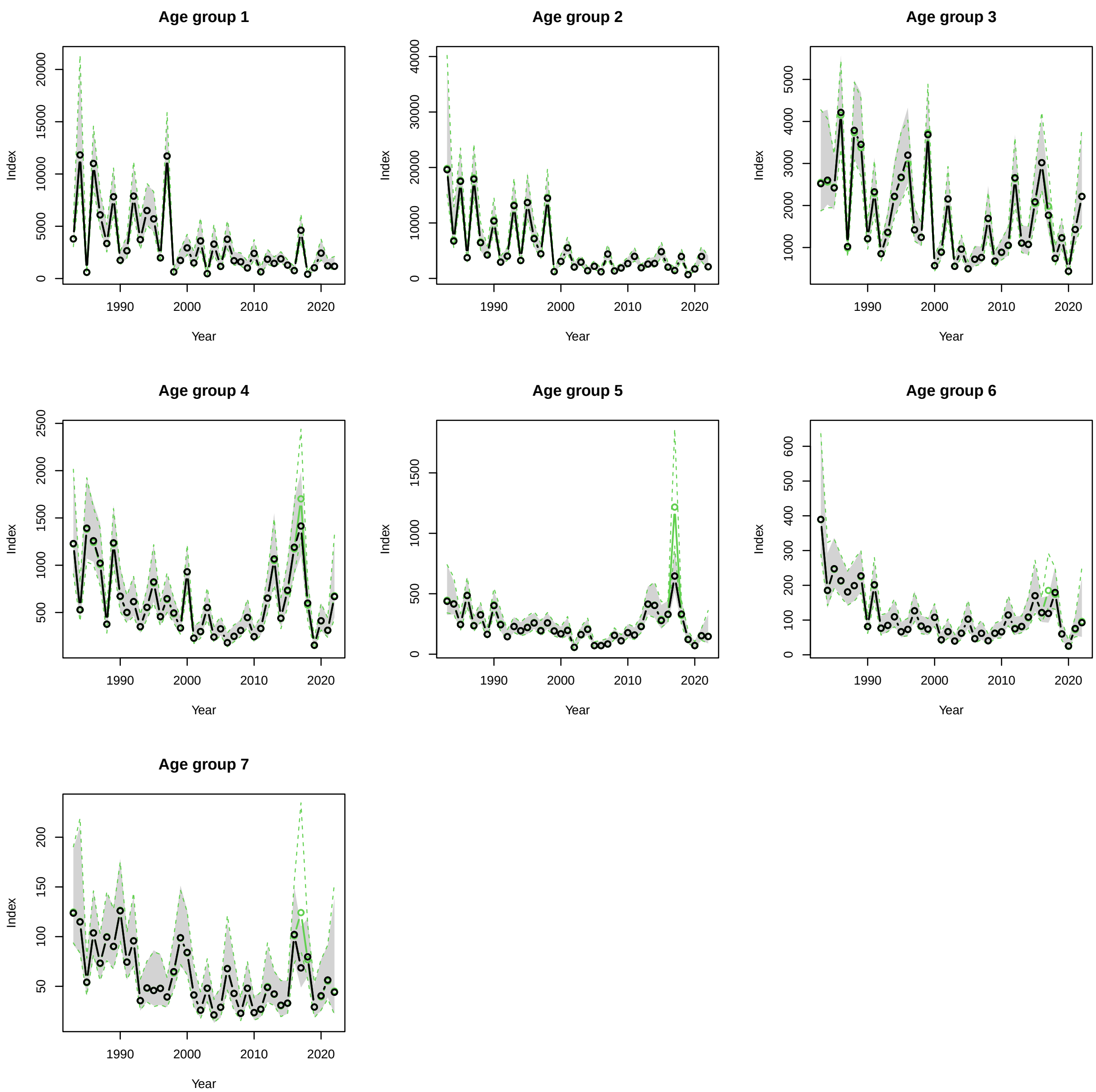


Figure 39: A comparison of the Q1 indices with (green) and without (black) the single very large haul in 2017 included in the calculations.

21.9 Maturity ogives for substocks of Northern Shelf cod

Maturity ogives for sub-stocks of Northern Shelf cod

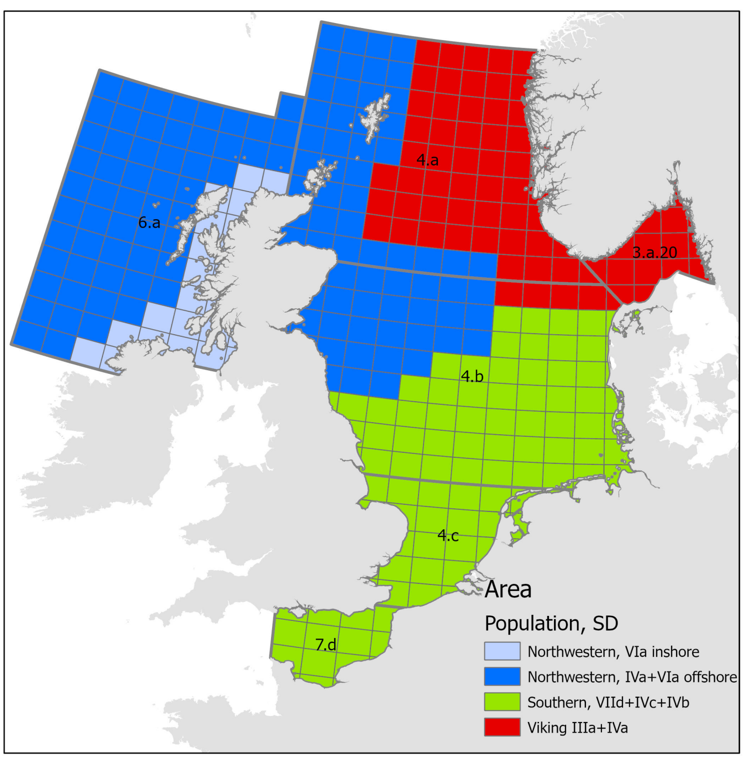
Nicola Walker and Tanja Miethe

11 November, 2022

Summary

The current advisory units for Northern Shelf cod stocks are North Sea cod in ICES Subarea 4 (North Sea), Division 7.d (English Channel) and Subdivision 20 (Skagerrak), and West of Scotland cod in ICES Division 6.a. The ICES Workshops on Stock Identification of North Sea cod (WKNSCodID, 2020) and West of Scotland Sea cod (WK6aCodID, 2022) concluded (1) genetic populations of Viking and Dogger cod; (2) spatial heterogeneity in the Dogger cod population; and (3) linkages between inshore and offshore sub-populations of cod in 6.a cod with cod in 4.a.

These conclusions have led to the proposal to develop an assessment framework that determines both metapopulation-level stock and sub-stock status. Here we present maturity ogives corresponding to three (Viking, Northwestern and Southern) and four (splitting Northwestern into inshore and offshore components) sub-stock hypotheses.



Background

Area-weighted annually varying maturity ogives have been used in the assessment of North Sea cod since 2015. Since introduction for North Sea cod, the methodology has been refined as other North Sea gadoids have gone through benchmark and a standardised approach is now being used in the assessments of North Sea whiting, Northern Shelf haddock and West of Scotland cod, the latter of which is part of this benchmark. We therefore employ this standard approach but provide a comparison to the current North Sea cod method in Appendix 2.

Available data

The quarter 1 survey data sets used are:

- North Sea International Bottom Trawl Survey (NS-IBTS): covering the North Sea and Skagerrak from 1983.
- Scottish West Coast Bottom Trawl Survey (SWC-IBTS): covering the West of Scotland for the period 1985-2010 but with biological sampling starting in 1996.
- Scottish West Coast Groundfish Survey (SCOWCGFS): covering the West of Scotland from 2011 to 2021.

Methods

Data formatting

Data were downloaded from the ICES database of trawl surveys (DATRAS; http://datras.ices.dk) in exchange format on 18-10-2022, and read into R as DATRASraw objects. These data contain three components: haul meta-data (HH), species length-based information (HL; all fish caught) and species age-based information (CA; only fish sampled for biological information). Data were read in using function readExchange with strict=FALSE to avoid dropping of age data, and the data subset to consider only Q1 valid hauls. Fish in the CA data were assigned as either immature or mature following the table below. Records with abnormal or missing maturity were removed. The raw number of observed individuals per length group (HL data) was added to the HH data and scaled to 60 minutes of effort. Each record was assigned to a sub-stock area following the definitions in the figure above (where Northwestern Inshore and Northwestern offshore are combined for the three sub-stock hypothesis).

Code	Description	Mature
1	Juvenile/Immature	0
2	Maturing	1
3	Spawning	1
4	Spent	1
6	Abnormal	-
61/A	Juvenile/Immature	0
62/B	Maturing	1
63/C	Spawning	1
64/D	Spent	1
65/E	Resting/Skip	1
66/F	Abnormal	-
I	Immature	0
M	Mature	1

Sub-stock specific weights

Although the objective of this WD is to produce maturity ogives by sub-stock, we calculate a single sub-stock area weighted maturity ogive for the whole Northern shelf for comparison to the current North Sea method. Sub-stock area specific catch rates were derived for this purpose, and were calculated as the weighted standard stratified mean of catches in each sub-stock area:

$$w^p = \frac{q^p \overline{N_y^p}}{\sum_p^P q^p \overline{N_y^p}}$$

Where q_p is the proportion of ICES rectangles in sub-stock area p and $\overline{N_y^p}$ is the mean catch rate in p, taken as the mean within a rectangle and then the mean across rectangles.

Statistical weights

Statistical weights were calculated as follows to appropriately account for length stratified sub sampling of biological data:

1. Define a raising factor for each fish with biological data in a haul:

$$r_l = \frac{n_l}{m_l}$$

Where n_l is the number of fish measured within a length group l and m_l is the number of fish sub sampled in the same length group.

2. Calculate the sum of the raising factors for each age group a:

$$R_a = \sum_{a_i=a} r_l$$

Where a_i denotes the age of fish i.

3. Assign statistical weight to fish i in length group l and age a:

$$w_i = m_a \frac{r_l}{R_a}$$

Where m_a is the number of fish aged a sampled for biological data.

Maturity ogive estimation

Maturity ogives were produced by modelling maturity data as a binomial GLM with logit link. The models for the whole Northern shelf included age and year as factors as well as their interactions. The models for sub-stocks also included sub-stock area as a factor. The maturity ogives were produced as predictions from the fitted models with 95% confidence intervals estimated from the standard errors of the model.

Results

Three sub-stock hypothesis

Combined area-weighted ogive

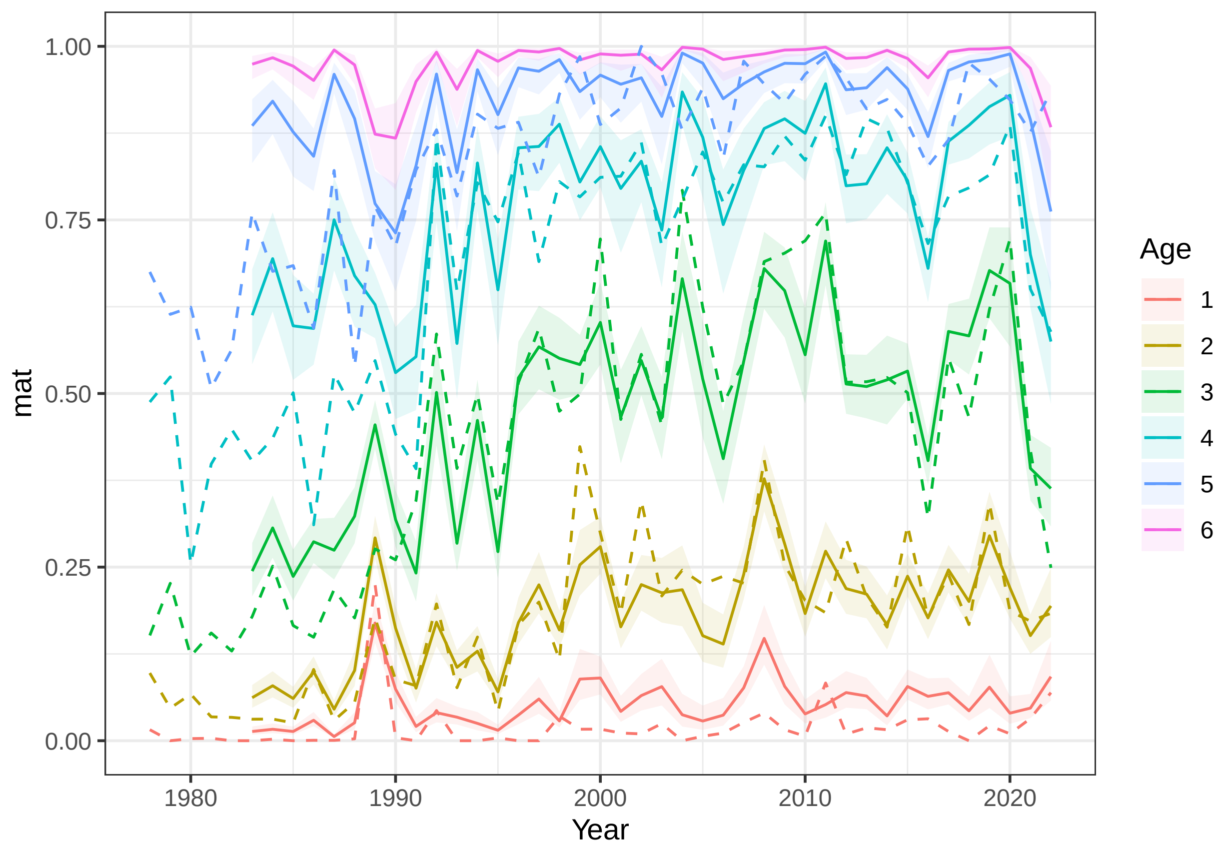
The best fit was provided by a model including an age effect and a year effect as well as their interaction.

```
ogive.mod3 <- glm(Maturity ~ Age * Year, weight = wi * wtC, family = binomial,
    data = mat_data)
```

Table 2: Analysis of Deviance Table

	Df	Deviance	Resid. Df	Resid. Dev	Pr(>Chi)
NULL	NA	NA	62943	39784	NA
Age	1	12214	62942	27570	0
Year	39	1314	62903	26256	2.562e-250
Age:Year	39	347.2	62864	25909	4.425e-51

The following figure shows the sub-stock area weighted maturity ogive for the Northern shelf (solid) against an ogive produced using the North Sea method (dashed; see Appendix 2). This shows the resulting maturities-at-age to be similar between methods except (1) early in the time-series where an increase in maturity-at-age is more pronounced using the North Sea method; (2) for age 1 where maturity is generally higher using the standard method presented here; and (3) for ages 6+, which is assumed constant at 1 in the North Sea method.



Sub-stock ogives

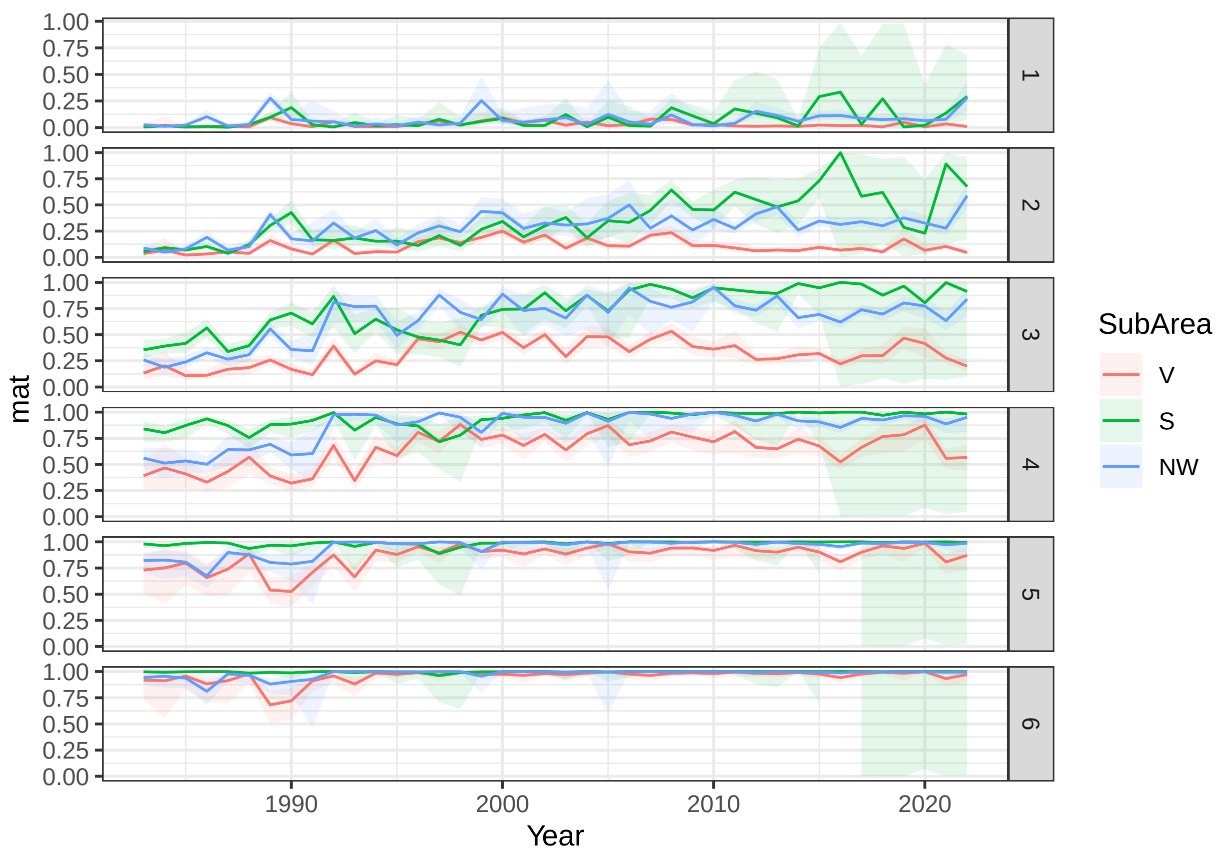
The best fit was provided by a model including an age effect, a year effect and a sub-stock area effect as well as their interactions, indicating that maturity is significantly different between sub-stock areas.

```
ogive.mod4 <- glm(Maturity ~ Age * Year * SubArea, weight = wi * wtC, family = binomial,
    data = mat_data)
```

Table 3: Analysis of Deviance Table

	Df	Deviance	Resid. Df	Resid. Dev	Pr(>Chi)
NULL	NA	NA	62943	39784	NA
Age	1	12214	62942	27570	0
Year	39	1314	62903	26256	2.562e-250
SubArea	2	1639	62901	24617	0
Age:Year	39	332	62862	24285	3.882e-48
Age:SubArea	2	164	62860	24121	2.386e-36
Year:SubArea	78	409.3	62782	23712	2.05e-46
Age:Year:SubArea	78	191	62704	23521	1.823e-11

Plots of maturity by sub-stock show maturity to be lower in the Viking sub-stock compared to the Dogger sub-stocks (Northwestern and Southern). The large confidence intervals around the Southern sub-stock in recent years are due to low sample sizes in those years (Appendix 1).



Four sub-stock hypothesis

Combined area-weighted ogive

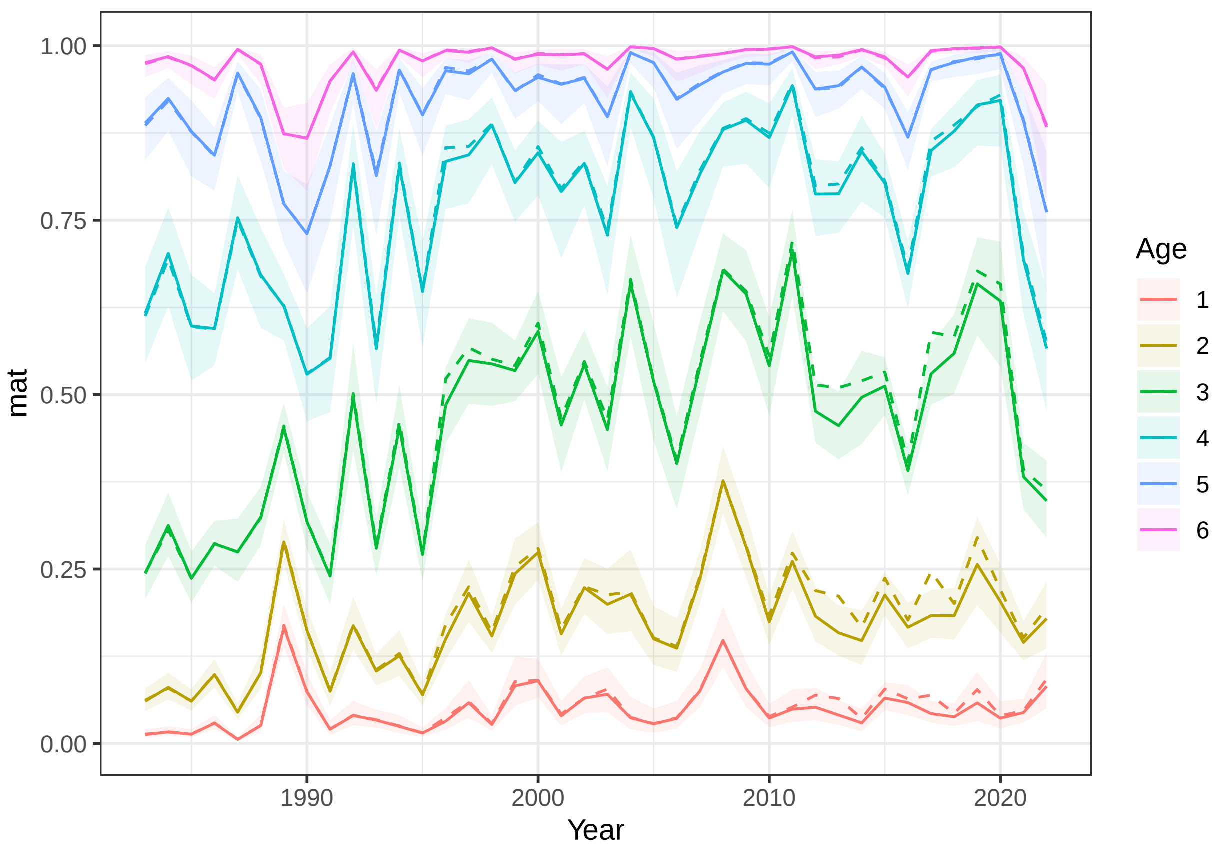
As for the three sub-stock hypothesis, the best fit was provided by a model including an age effect and a year effect as well as their interaction.

```
ogive.mod3_4 <- glm(Maturity ~ Age * Year, weight = wi * wtC, family = binomial,
    data = mat_data_4)
```

Table 4: Analysis of Deviance Table

	Df	Deviance	Resid. Df	Resid. Dev	Pr(>Chi)
NULL	NA	NA	62943	37997	NA
Age	1	11982	62942	26015	0
Year	39	1152	62903	24863	2.403e-216
Age:Year	39	338.7	62864	24524	1.982e-49

The following figure shows the sub-stock area weighted maturity ogive for the Northern shelf under the four sub-stock hypothesis (solid) against the ogive produced under the three sub-stock hypothesis (dashed; confidence intervals not plotted). This shows the resulting maturities-at-age to be very similar between hypotheses but with more pronounced differences for ages 1-3 from 2011.



Sub-stock ogives

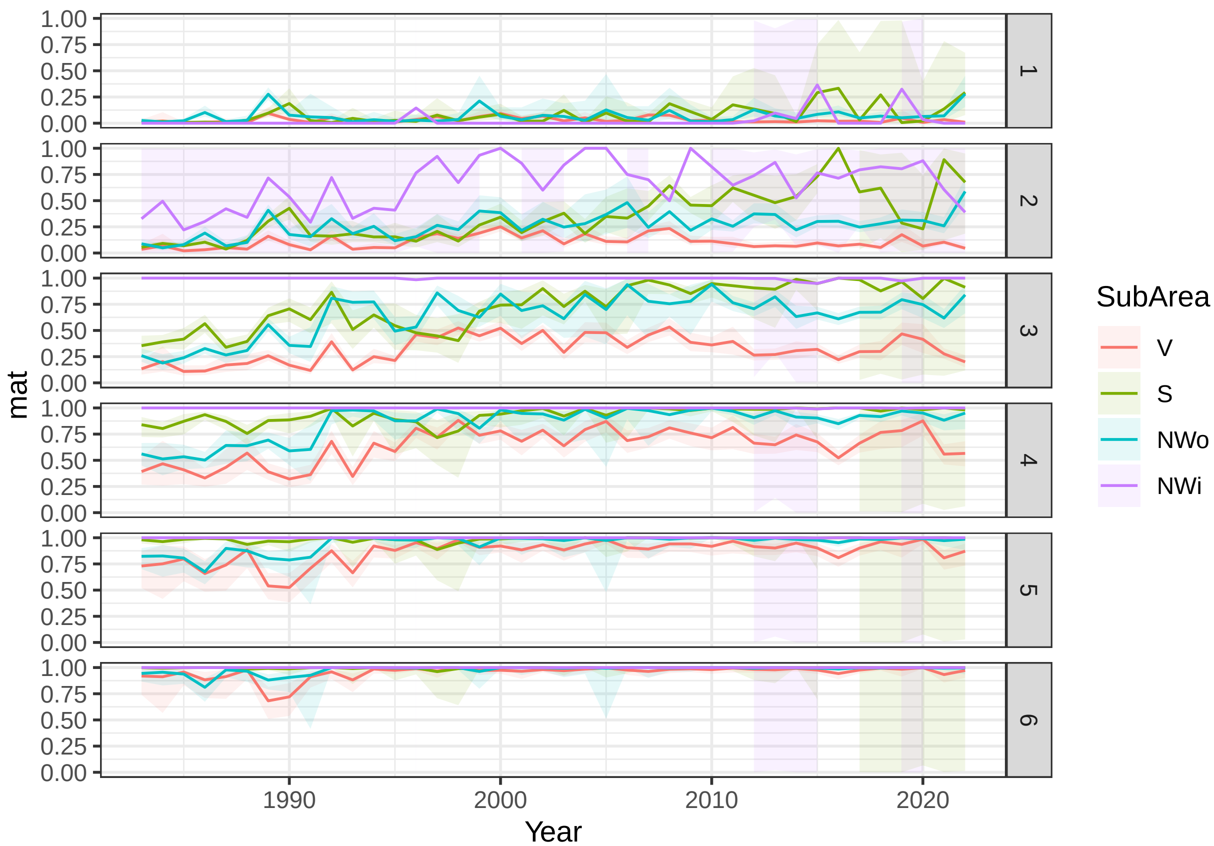
As for the three sub-stock hypothesis, the best fit was provided by a model including an age effect, a year effect and a sub-stock area effect as well as their interactions.

```
ogive.mod4_4 <- glm(Maturity ~ Age * Year * SubArea, weight = wi * wtC, family = binomial,
    data = mat_data_4)
```

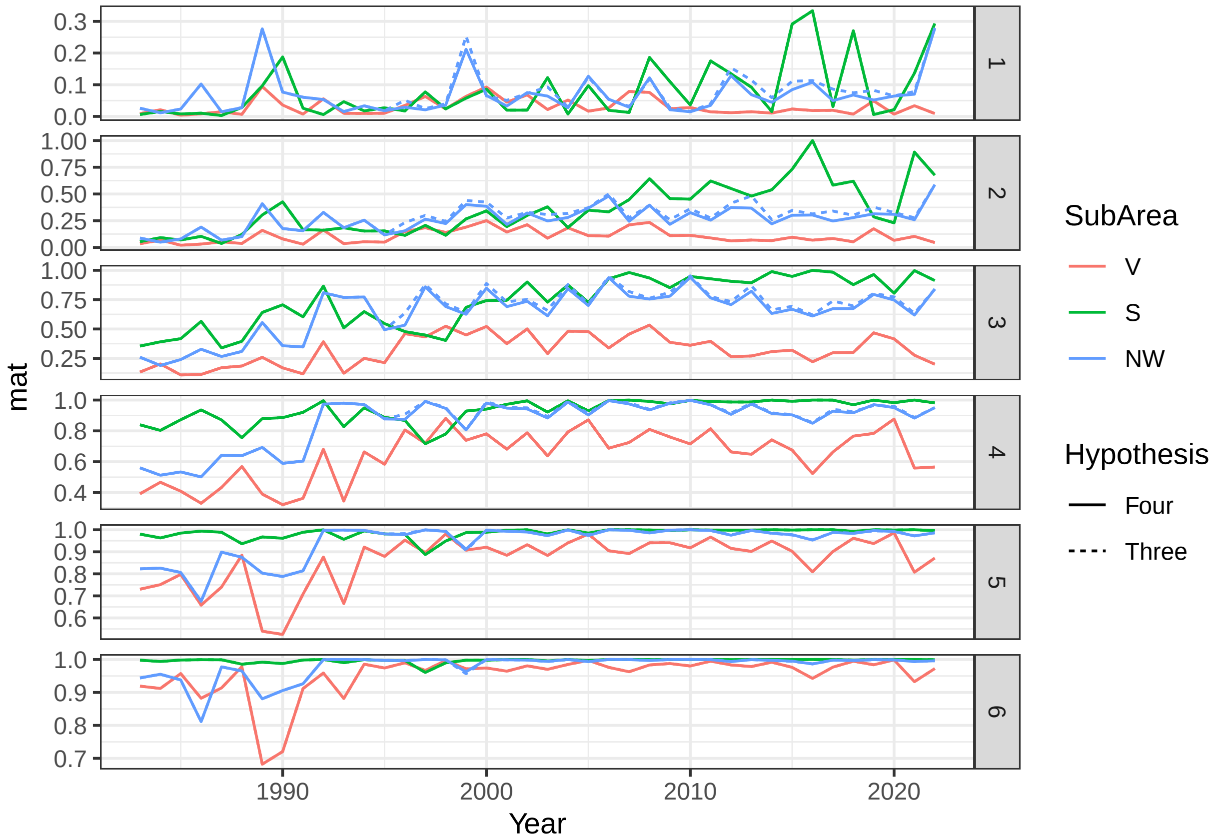
Table 5: Analysis of Deviance Table

	Df	Deviance	Resid. Df	Resid. Dev	Pr(>Chi)
NULL	NA	NA	62943	37997	NA
Age	1	11982	62942	26015	0
Year	39	1152	62903	24863	2.403e-216
SubArea	3	1444	62900	23418	6.756e-313
Age:Year	39	325.7	62861	23092	6.299e-47
Age:SubArea	3	167.8	62858	22925	3.814e-36
Year:SubArea	103	396.4	62755	22528	5.147e-36
Age:Year:SubArea	103	180.3	62652	22348	3.866e-06

The following plot shows maturity ogives by sub-stock under the four sub-stock hypothesis. The ogive for the Northwestern Inshore sub-stock is not well estimated due to lower levels of biological sampling in that area. In particular, confidence intervals, where they could be derived, are large and a constant maturity of 1 is estimated for all ages 3+.



Plots of sub-stock ogives show almost no difference in maturity between the three- and four- sub-stock hypotheses for the Viking and Southern sub-stocks and minor differences between the Northwestern (three) and Northwestern Offshore (four) sub-stocks (the Northwestern Inshore is not plotted). This suggests that the ogive for the Northwestern sub-stock under the three sub-stock hypothesis is primarily driven by the offshore component.



Conclusions

The authors recommend to:

- Adopt the standard methodology to derive maturity ogives for Northern shelf cod, which appropriately weighs the input data and provides ogives that are of wider utility.
- Consider adopting a three sub-stock hypothesis, as maturity cannot be estimated reliably for the Northwestern Inshore population.
- Consider use of the GMRF process to model maturity in SAM, which is currently used for the North Sea cod stock given low sample sizes in the Southern region.
- Consider feeding uncertainty from the GLM into the SAM assessment (not yet possible in SAM).

Apendix 1: Biological sampling

The following tables show the number of fish-at-age sampled in each of the cod sub-stock areas. The first row corresponds to the three sub-stock hypothesis. In the second row, the Northwestern sub-stock is separated into Offshore, Inshore and Clyde components. Based on an earlier version of this analysis (not presented), the Clyde was not explored separately and instead treated as part of the Inshore sub-stock. Any entries with <20 observations are highlighted yellow and entries with <5 observations are highlighted red.

Southern

	1	2	3	4	5	6
1983	390	827	77	77	49	100
1984	717	435	208	32	73	68
1985	78	1302	149	79	42	113
1986	1223	162	216	97	51	61
1987	707	1418	58	147	44	120
1988	310	398	464	12	54	62
1989	539	213	211	160	20	103
1990	90	229	113	58	87	47
1991	211	112	83	36	20	55
1992	399	63	19	14	9	23
1993	36	198	44	17	21	14
1994	255	219	128	29	31	47
1995	63	218	55	20	15	20
1996	46	166	81	17	17	20
1997	20	74	29	22	8	8
1998	9	248	14	12	8	10
1999	144	105	279	26	25	42
2000	158	150	45	91	21	32
2001	222	219	64	22	24	20
2002	173	108	53	27	3	27
2003	30	234	55	33	15	13
2004	151	65	130	28	14	11
2005	83	53	15	33	3	6
2006	114	51	24	6	5	7
2007	187	149	49	19	7	10
2008	308	134	68	48	28	13
2009	42	384	148	38	17	16
2010	155	81	148	42	20	18
2011	49	231	31	52	28	17
2012	49	105	85	20	23	12
2013	65	83	55	42	20	11
2014	352	67	52	22	22	2
2015	26	299	61	32	9	7
2016	15	5	52	16	15	9
2017	113	12	30	28	10	8
2018	7	47	11	10	13	9
2019	36	9	22	2	1	7
2020	101	13	9	3	1	
2021	55	38	18	1	4	2
2022	83	19	14	6	3	1

Viking

	1	2	3	4	5	6
1983	7	300	119	101	29	17
1984	10	172	101	33	22	15
1985	1	502	155	66	13	13
1986	22	89	452	146	56	15
1987	18	448	34	70	26	7
1988	22	125	184	32	36	18
1989	101	264	337	140	28	35
1990	21	533	102	79	43	24
1991	139	470	252	116	51	43
1992	180	326	105	79	26	37
1993	127	655	178	72	50	26
1994	140	271	247	68	33	25
1995	263	838	212	131	23	17
1996	127	549	273	82	48	16
1997	159	459	275	96	38	26
1998	104	884	207	114	58	33
1999	180	83	461	67	39	30
2000	161	421	46	128	35	43
2001	154	401	149	24	17	10
2002	165	273	357	67	14	10
2003	49	240	87	107	32	15
2004	158	99	129	47	61	29
2005	116	291	93	43	25	46
2006	186	185	190	28	22	38
2007	155	453	131	38	37	43
2008	130	212	194	57	38	18
2009	111	283	74	75	29	30
2010	144	406	120	51	36	17
2011	63	329	70	41	15	16
2012	162	232	294	89	37	16
2013	121	310	199	117	66	35
2014	108	235	156	52	29	24
2015	120	572	293	120	31	20
2016	91	260	438	155	75	45
2017	306	231	230	197	77	32
2018	70	362	103	52	31	26
2019	71	106	139	30	18	20
2020	253	131	44	59	16	18
2021	111	609	168	61	28	32
2022	65	135	209	70	13	11

Northwestern

	1	2	3	4	5	6
1983	59	627	124	137	42	53
1984	127	421	287	44	52	47
1985	12	746	125	101	26	52
1986	150	254	655	217	83	25
1987	100	948	100	97	24	53
1988	14	317	402	50	60	41
1989	469	237	233	108	26	89
1990	75	566	55	19	31	44
1991	11	109	97	22	6	11
1992	147	206	73	56	2	6
1993	49	688	125	33	41	15
1994	89	233	131	49	27	25
1995	85	538	150	33	12	9
1996	28	319	271	43	27	10
1997	119	185	123	63	27	30
1998	27	611	89	44	28	13
1999	32	87	396	27	13	12
2000	277	146	52	76	12	9
2001	14	212	38	32	42	9
2002	124	104	207	22	6	9
2003	28	208	45	52	13	9
2004	179	78	67	12	17	1
2005	38	84	35	16	5	7
2006	220	35	41	15	3	4
2007	64	260	41	24	2	3
2008	47	78	231	24	10	1
2009	73	83	49	44	4	1
2010	274	216	67	7	20	6
2011	35	517	253	41	30	30
2012	109	234	425	108	28	29
2013	178	281	153	200	77	10
2014	124	251	137	62	69	17
2015	259	409	316	150	77	73
2016	121	282	309	229	39	30
2017	451	238	287	231	180	50
2018	64	385	130	178	83	90
2019	164	97	181	15	23	12
2020	165	263	67	65	10	7
2021	141	206	214	50	33	23
2022	75	72	38	15	9	18

Northwestern Offshore

1	2	3	4	5	6
59	627	124	137	42	53
127	421	287	44	52	47
12	746	125	101	26	52
150	254	655	217	83	25
100	948	100	97	24	53
14	317	402	50	60	41
469	237	233	108	26	89
75	566	55	19	31	44
11	109	97	22	6	11
147	206	73	56	2	6
49	688	125	33	41	15
89	233	131	49	27	25
85	538	150	33	12	9
18	280	209	31	22	7
89	172	113	56	21	19
17	581	83	42	26	12
29	72	385	26	12	12
253	134	38	74	12	9
10	191	34	31	42	9
114	99	196	21	6	7
21	183	42	50	11	9
166	72	56	7	15	1
35	83	33	16	5	6
214	31	38	14	3	3
58	240	34	22	2	3
45	78	224	24	10	1
69	77	43	43	4	1
266	199	60	5	20	6
32	489	242	41	29	28
68	171	407	104	28	29
137	191	137	197	75	10
96	207	130	60	69	17
240	361	296	145	76	73
110	268	302	228	38	30
444	141	265	229	178	50
59	368	120	167	79	87
145	85	173	14	23	12
136	253	59	65	10	7
137	187	208	50	32	23
75	72	38	15	9	18

Northwestern Inshore

1	2	3	4	5	6
8	28	34	9	5	2
11	13	8	7	6	11
4	25	6	2	2	1
2	7	6	1	1	
9	11	9	2		
1	14	3	1		
6	4	10	1		2
5	24	3	2	2	
5		5	5	2	
2		2			1
6	3	1	1		1
3	17	5	2		
2		7			
2	2	3	1		
8	14	7	2		
1	17	2		1	2
31	40	15	3		
37	23	8	2	2	
18	42	7	2		
17	44	20	5	1	
6	8	5	1	1	
5	18	12		2	
	11	4	9	4	3
17	6	7	1		
24	10	3			
	14	5		1	

Clyde

1	2	3	4	5	6
2	11	28	3		1
19		2			
6	5				
1	8	5			
15	1	5			
3	7	1			
4	1	1			
2	1				
8	6	6			
1	1				
	1	2			
3	3	2			
2	4	3			
	3				
2	11	9			
10	23	3	1		
4	67	8	1		
10	2				
2	4				
5	6	2			
2	79	10	2		
5	6	6	2		
2	6	1			
5		5			
4	5	1			

Appendix 2: North Sea method

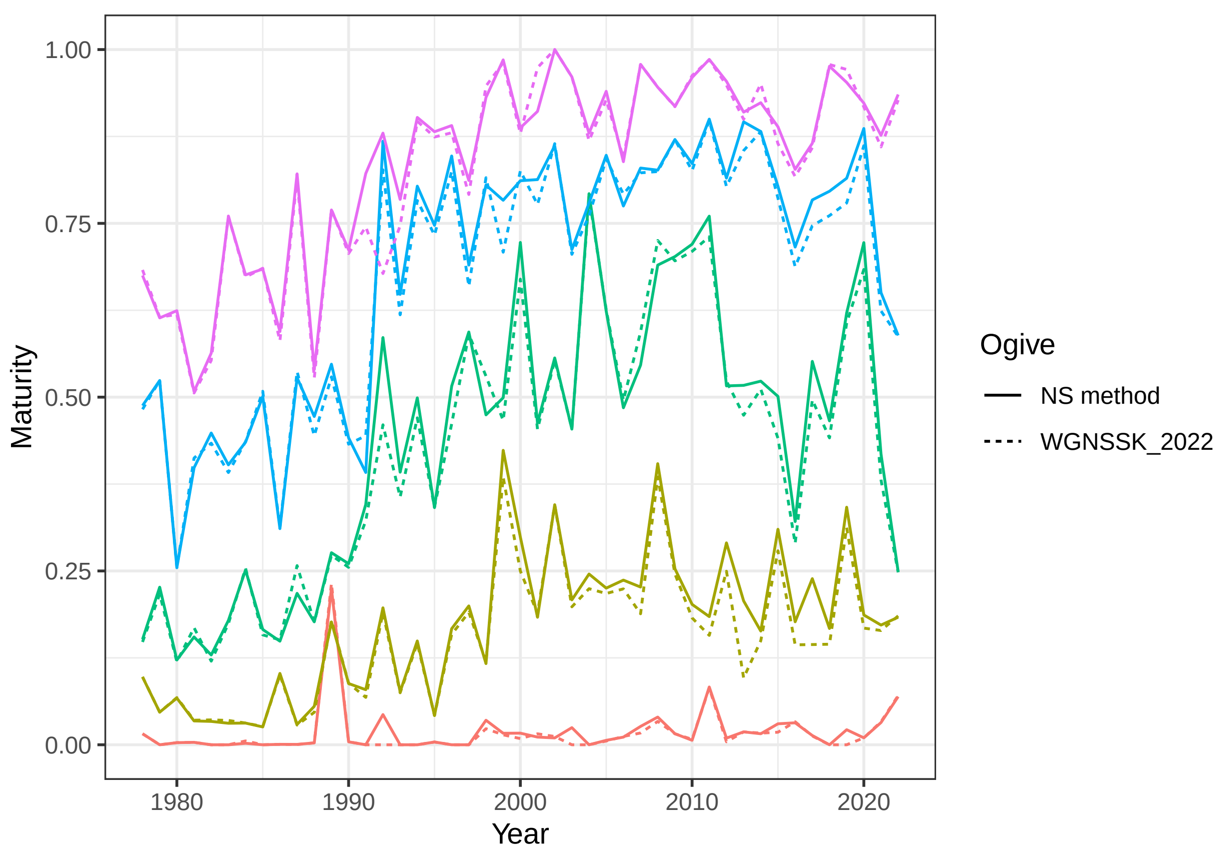
The North Sea method consists of the following steps:

1. Assign all fish sampled for biological information (CA data) as either immature or mature following Table 1.
2. Scale length data (HL data; all fish caught) to 60 minutes of effort and assign to a population sub-area.
3. Calculate numbers-at-age per subarea $n_{a,y,p}$ by multiplying by the scaled numbers-at-length by ALKs fit to the CA data.
4. Calculate the proportion of fish mature-at-age per subarea $M_{a,y,p}$ from the CA data.
5. Calculate maturity-at-age for the stock as:

$$M_{a,y} = \frac{\sum n_{a,y,p} M_{a,y,p}}{\sum n_{a,y,p}}$$

Essentially, the two main differences between the methods are: (1) the standard method assigns weights to the fish sampled for biological information (CA data) while the North Sea method scales those fish up to the level of survey (HL data); and (2) the North Sea method calculates maturity while the standard method uses a model-based (GLM) approach.

The following plot shows the sub-stock weighted maturity ogive for the Northern shelf produced using the North Sea method under the three sub-stock hypothesis (solid; presented as a dashed line in the three sub-stock hypothesis section) against maturity ogives produced by WGNSSK for the assessment of North Sea cod in 2022. The two main differences are (1) inclusion of data from 6.a; and (2) use of the three sub-stock area definitions, as opposed to the four sub-regions currently presented in the advice (Viking 4.a, Viking 20, Northwest (not including 6.a) and South).



21.10 Stock and catch weights-at-age for Northern Shelf Cod

WD for the DCWK for WKCOD, November 2022

Stock and catch weights-at-age for Northern Shelf Cod

Helen Dobby, Tanja Miethe and Nicola Walker

Introduction

The current assessments for North Sea (NS) cod and West of Scotland (WoS) cod take different approaches in their calculation of stock weights at age. In the North Sea, for ages 1 and 2, stock weights are derived from the Q1 survey and for ages 3 and above, are based on Q1 catch mean weights-at-age. Where survey weights are scarce (pre-2002), the mean ratio-at-age from 2002-2019 between Q1 survey and annual catch weights was used to scale the annual catch weights to the level of the survey weights for ages 1 and 2. Similarly, quarterly catch mean weights are available only from 2002 onwards and so the mean ratio-at-age from 2002-2019 between Q1 and annual catch mean weights is used to scale the annual catch weights back in time. In contrast, in the WoS, stock mean weights are estimated as gam smoothed annual catch mean weights-at-age for all ages (1 to 7+). The current stock mean weights are compared in Figure 1 and show substantial differences between the two stock assessments. The differences at younger ages are potentially related to the use of different data sources – survey data for NS and catch data for WoS with gear selectivity/fishery targeting behaviour likely causing the greater weights in the catch data (WoS). At older ages, stock weights for both assessments are derived from catch data, however, quarter 1 data are used for NS while annual values are used for WoS due to a lack of quarterly sampling data in this area which may go some way to explaining the observed differences.

Despite having previously rejected the use of survey data for estimating stock mean weights at older ages (3 and above) at previous NS cod benchmarks (2015 and 2021), the data are revisited here as: i) historical literature suggests that there are spatial differences in growth rate (Daan, 1974; Rijnsdorp et al.,1991), and ii) these are the only data from which sub-stock dependent mean weights can be derived. There are additional difficulties associated with the use of survey data for stock mean weights-at-age in that the surveys start in the mid-1980s while the stock assessment starts earlier. Although the start year for a combined assessment has yet to be agreed, the current NS cod assessment begins in 1963 and the WoS in 1981. An approach for deriving historical sub stock weights at age is proposed.

Data and Methods

Survey data

Stock mean weights-at-age are used to calculate spawning stock biomass, usually at spawning time, which is known to occur in quarter 1. This also represents the time during the year when the sub-stock components are considered to be separated. Therefore the Q1 survey data are used in the estimation of stock mean weights.

A number of different surveys cover the distribution of Northern Shelf cod: i) NS-IBTS covering the North Sea and Sub-division 3.a.20, and ii) SWC-IBTS & SCOWCGFS (Scottish groundfish surveys covering the West of Scotland, Division 6.a). The full data set covers the North Sea, Sub-division 3.a.20 and the West of Scotland from 1985 onwards, with coverage of the North Sea only in 1983 and 1984.

Scottish survey data covering the West of Scotland are denoted using two separate survey identifier codes (Table 1 & 2) due to changes in survey design and GOV groundgear in 2011. While the Scottish survey design has changed, the spatial extent of the survey within 6.a has not changed although the SCOWCGFS has no stations in Division 4.a (unlike SWC-IBTS). The NS-IBTS is an internationally co-ordinated survey and operates according to standard procedures (ICES, 2012). Table 1 provides a summary of surveys used in the analysis and Table 2, the number of hauls in the data set.

While survey coverage started in the mid-1980s, sampling for individual weights was sporadic prior to the early 2000s and Scotland did not begin sampling individual weights until 2011. Hence full spatial coverage of individual weight sampling did not begin until 2011 (Table 3). Table 4 shows the number of individuals sampled by age by sub stock area indicating that for some year/sub stock area combinations, some ages are sampled in very low numbers.

Analysis

The general approach to deriving mean weights at age from the survey data follows that used previously to derive age 1 and 2 stock weights for NS cod and is as follows:

1. Fit a length weight relationship $\boldsymbol{W(L) = aL^b}$ to the individual length and weight data (in the 'CA' data table in Datras). Data are log transformed.
2. For each year/sub stock combination, derive the overall proportion at length (p_l)
3. For each year/sub stock/age, calculate the length-at-age distribution using the age-length key ($p_{a|l}$) and the length distribution:

$$p_{l|a} = \frac{p_{a|l}p_l}{\sum_k p_{a|k}p_k}$$

4. For each year/sub stock/age, derive the weight-at-age from the length-at-age distribution and the weight-at-length (from the weight-length relationship):

$$w_a = \sum_k p_{k|a}W_k$$

Analysis of the individual weight length data was restricted to 2011 onwards due to the more limited spatial coverage in earlier years i.e. no coverage of the Northwest Inshore sub stock pre-2011. Trends in the estimated model parameters and resulting predicted weights-at-length over time were explored.

Confidence intervals were derived for the sub stock area weights at age by bootstrapping the hauls. Each bootstrap replicate consists of resampling the hauls with replacement, ensuring the same number of hauls as in the original data set, and repeating steps 2 to 4 above to calculate weight-at-age. A fixed (sub stock dependent) weight length relationship was used to derive weights-at-age for each replicate. Five hundred bootstrap replicates were carried out for each sub stock area and summary statistics derived. (500 was chosen after trialling options between 100 and 1000 and considering the resulting distribution of weights-at-age). Analysis was carried out for both the three and four sub stock scenarios.

In order to derive historical sub stock weights-at-age (i.e. pre 1983), an age (a) and sub stock (s) dependent scaling factor is calculated as $fac_{as} = \overline{\left(\frac{sw_{ays}}{cw_{ay}}\right)}$ i.e. the average ratio over years y (1983 to 2021) between sub stock area survey weights at age (sw) and the annual catch weight at age (cw) for the combined stock. Historical, pre-1983 sub stock weights-at-age are then calculated as:

$$sw_{ays} = fac_{as} cw_{ay}$$

This is similar in approach to that taken to derive the historical stock weights at age currently used in the North Sea cod assessment. Combined stock (whole Northern Shelf) annual catch mean-weights at age have been derived as a weighted average of the annual catch mean-weights from the two current assessment areas (weighted by the catch numbers-at-age).

Results

Weight-length relationship

Initially, separate weight length relationships were fitted by year and sub stock area. Figure 2 shows the variability in the parameter estimates over time and Figure 3 how this translates into variability in weight at length for a number of length classes. There are no obvious trends over time, in either the parameters or predicted weights at length. Estimates for the Northwest Inshore sub stock are more uncertain than for the other sub stocks and there are no estimates for this area in 2022 due to lack of survey coverage. Given that there is no apparent trend over time, time independent weight-length parameters are used in the estimation of weight-at-age (estimated from data from 2011 onwards, the period which includes samples from Division 6a). The parameter estimates are as follows:

	loga	**b**
Northwest	-5.21902	3.173161
South	-5.04607	3.11862
Viking	-5.05038	3.116983
Northwest Inshore	-5.05054	3.137089
Northwest Offshore	-5.23821	3.177357

Survey weight-at-age estimates

Figure 4 shows bootstrap estimates of survey weights at age by sub stock area (median and confidence intervals) for the 3 sub stock assumption. The Viking area estimates in general appear to be lower than for the other two subareas, particularly the South. The Viking is also the most precisely estimated while the South has the greatest uncertainty.

In those year/subarea/age combinations with a low number of sampled fish, some bootstrap replicates result in no weight-at-age being calculated as none of the sampled hauls contain fish at that age. The lower panels in Figure 4 exclude those year/subarea/age combinations in which greater than 5% of bootstrap replicates resulted in no estimate. This results in missing estimates for some year/subarea/age combinations, particularly age 6+ in the Northwest sub stock area.

Non bootstrapped estimates of survey weights-at-age for both the three and four sub stock hypotheses are shown in Figure 5. Values have been excluded in cases where five or fewer age samples are available (a somewhat arbitrary cut off to exclude poorly sampled). This results in a number of gaps in the time series of ages, particularly ages 5 and 6+ in the Northwest sub stock in the three sub stock hypothesis. Catches of older ages in the Northwest Inshore area are very low, and using the 5 individual cut off results in no estimates of weights-at-age for ages 5 and 6+ in this area over the full time series.

The 2022, age 1 value in the Northwest sub stock area is somewhat odd. (Northwest Offshore in the four sub stock hypothesis). This appears to be due to a lack of small fish (<15 cm) and also to a number of large fish (> 30 cm and up to 36 cm) being aged as 1 year old, with the length distribution-at-age 1 in this year/sub stock area appearing quite different to others.

Historical stock weights (pre-1983)

Estimated annual catch weights-at-age are shown in Figure 6. The combined stock weights are almost identical to the North Sea values due to the relative quantity of the catches in the two separate assessment areas. Values for the West of Scotland tend to be higher than for the North Sea for ages 2 to 4. It's not clear if this is related to differences in the seasonal timing of the fisheries in the two areas or due to real differences in the stock weights-at-age in the two areas.

The average annual catch to Q1 sub stock survey weight scaling factors (fac_{as}) are:

	1	2	3	4	5	6+
Northwest	0.2203	0.6095	0.7968	1.0032	1.0722	1.1240
South	0.2167	0.7312	0.9397	1.0775	1.1943	1.2964
Viking	0.1527	0.5038	0.6292	0.8226	0.8485	0.9653

These scaling factors are calculated based on those years where there are greater than 5 individuals sampled in the relevant age class.

The application of the relevant scaling factor (above) to the pre-1983 annual catch weights-at-age results provides the historical sub stock weights at age. These are given in Table 5 and Figure 7 along with the post 1983 values from surveys.

Conclusions

Based on the analysis conducted, the authors suggest the following:

1. the survey data indicate differences in weights-at-age across sub stocks which should be accounted for in the stock assessment
2. the use of sub stock dependent weights-at-age derived from survey data and scaled annual catch mean weights should be used as sub stock weights in the assessment

3. for the purpose of stock weights, consider using the three sub stock hypothesis given the limited data for the Northwest Inshore area
4. consider modelling the mean stock weights-at-age in SAM to help deal with those year/subarea/age combinations with very low numbers of sampled individuals
5. as an alternative to 4. the 'missing' values could potentially be filled using a scaled annual catch weight (as per the historical sub stock weight estimates).

References

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Table 1.

Quarter	Survey	Acronym	Gear	Spatial coverage	Years	Source
Quarter 1	North Sea International Bottom Trawl Survey	NS-IBTS-Q1	GOV	4.a, 4.b, 4c, 3.a.20	1983 – 2022	DATRAS
	Scottish West Coast Groundfish Survey	SWC-IBTS	GOV	6.a, 4.a (limited)	1985 - 2010	DATRAS
		SCOWCGFS	GOV	6.a	2011 - 2021	DATRAS

Table 2. Quarter 1 survey data. Number of hauls per survey per year (NS-IBTS: North Sea IBTS, SWC-IBTS: Scottish West Coast Survey - old, SCOWCGFS: Scottish West Coast Survey – new) and per sub stock area.

	NS-IBTS	SWC-IBTS	SCOWCGFS	NW.Inshore	NW.Offshore	South	Viking
1983	367	0	0	0	92	195	80
1984	447	0	0	0	112	230	105
1985	506	59	0	25	170	259	111
1986	512	37	0	19	132	275	123
1987	525	47	0	21	155	266	130
1988	387	52	0	21	134	176	108
1989	408	46	0	21	124	208	101
1990	358	44	0	21	122	155	104
1991	409	53	0	23	136	186	117
1992	353	40	0	18	111	163	101
1993	352	41	0	20	114	161	98
1994	341	43	0	22	114	141	107
1995	318	28	0	13	97	136	100
1996	307	43	0	18	115	117	100
1997	345	39	0	18	114	147	105
1998	387	38	0	16	127	180	102
1999	339	47	0	24	119	144	99
2000	367	48	0	24	126	164	101
2001	411	40	0	17	126	207	101
2002	401	44	0	20	135	189	101
2003	398	55	0	24	145	184	100
2004	355	48	0	22	129	156	96
2005	371	49	0	18	142	159	101
2006	362	55	0	22	140	158	97
2007	339	67	0	24	139	150	93
2008	356	56	0	21	142	155	94
2009	361	55	0	21	135	157	103
2010	370	59	0	20	151	161	97
2011	362	0	57	25	137	162	95
2012	345	0	64	31	141	142	95
2013	349	0	66	26	149	148	92
2014	304	0	61	24	134	139	68
2015	346	0	62	24	143	143	98
2016	333	0	63	19	150	134	93
2017	344	0	62	23	145	136	102
2018	336	0	60	21	141	137	97
2019	325	0	62	24	135	126	102
2020	309	0	57	20	134	119	93
2021	346	0	63	25	145	129	110
2022	212	0	0	0	43	105	64

Table 3. Number of individual weight-length samples by survey and by sub stock area.

	NS-IBTS	SWC-IBTS	SCOWCGFS	NW.Inshore	NW.Offshore	South	Viking
1983	0	0	0	0	0	0	0
1984	0	0	0	0	0	0	0
1985	0	0	0	0	0	0	0
1986	0	0	0	0	0	0	0
1987	0	0	0	0	0	0	0
1988	0	0	0	0	0	0	0
1989	0	0	0	0	0	0	0
1990	0	0	0	0	0	0	0
1991	246	0	0	0	0	37	209
1992	220	0	0	0	0	0	220
1993	0	0	0	0	0	0	0
1994	0	0	0	0	0	0	0
1995	0	0	0	0	0	0	0
1996	0	0	0	0	0	0	0
1997	208	0	0	0	56	152	0
1998	0	0	0	0	0	0	0
1999	0	0	0	0	0	0	0
2000	161	0	0	0	17	144	0
2001	133	0	0	0	13	120	0
2002	527	0	0	0	28	147	352
2003	449	0	0	0	56	106	287
2004	862	0	0	0	167	198	497
2005	842	0	0	0	82	184	576
2006	996	0	0	0	175	197	624
2007	1096	0	0	0	134	188	774
2008	999	0	0	0	141	208	650
2009	734	0	0	0	25	260	449
2010	1331	0	0	0	303	270	758
2011	1450	0	170	45	835	204	536
2012	1797	0	238	126	812	268	829
2013	1594	0	390	151	748	228	857
2014	1400	0	185	71	545	353	616
2015	2260	0	400	89	1072	346	1153
2016	1687	0	432	34	879	143	1063
2017	2232	0	384	105	1220	208	1083
2018	1396	0	186	49	798	97	638
2019	844	0	77	38	413	81	389
2020	1001	0	166	44	496	127	500
2021	1609	0	135	30	595	118	1001
2022	780	0	0	0	169	99	512

Table 4. Number of individuals sampled at each age by sub stock area.

	Viking						South					
	1	2	3	4	5	6+	1	2	3	4	5	6+
1983	34	403	143	88	43	37	418	1103	178	113	60	132
1984	39	482	195	60	43	22	801	498	249	50	88	94
1985	2	715	217	94	23	20	80	1314	150	83	45	122
1986	35	166	623	235	132	73	1302	205	263	106	55	72
1987	69	1036	80	117	61	21	814	1505	58	161	48	133
1988	27	333	313	48	52	51	318	439	502	12	63	76
1989	132	287	352	141	28	38	615	289	244	199	26	123
1990	61	794	121	85	45	25	114	311	142	65	95	52
1991	147	495	312	119	57	50	226	206	173	74	30	102
1992	183	327	105	79	26	38	451	278	90	59	35	42
1993	129	655	178	72	50	26	102	511	90	39	37	23
1994	147	271	248	70	33	25	273	224	139	31	33	47
1995	265	838	212	132	23	17	69	218	55	20	15	20
1996	134	549	273	82	48	16	49	168	83	17	18	20
1997	201	459	275	97	38	26	107	101	45	35	14	24
1998	104	885	207	114	58	33	9	249	14	12	8	10
1999	182	83	461	68	40	30	144	105	279	26	25	42
2000	177	421	46	128	35	43	205	150	45	93	21	32
2001	156	401	149	24	18	10	222	219	64	22	24	20
2002	169	275	358	67	14	10	173	108	53	27	3	27
2003	49	241	87	107	32	15	30	234	55	33	15	13
2004	160	99	129	47	61	29	152	66	130	28	14	11
2005	116	291	93	43	25	46	83	53	15	33	3	6
2006	198	185	190	28	22	38	121	52	24	6	5	7
2007	169	453	131	38	37	43	124	144	49	19	7	10
2008	144	215	230	59	39	18	320	113	65	48	29	13
2009	115	285	75	77	30	30	40	251	117	37	17	16
2010	174	407	123	56	36	19	135	76	112	34	19	17
2011	65	333	72	41	15	17	64	221	29	47	26	17
2012	167	233	295	90	37	17	48	90	81	18	21	11
2013	140	313	199	120	66	36	53	65	47	40	19	10
2014	125	235	156	52	29	24	213	60	48	20	22	2
2015	132	572	293	120	31	20	28	212	60	32	10	7
2016	94	263	444	159	78	48	23	13	58	20	18	12
2017	329	232	230	198	77	32	128	13	30	21	10	8
2018	70	362	103	53	32	26	8	47	11	10	13	9
2019	81	109	140	30	19	20	43	8	23	2	1	6
2020	255	132	44	59	16	18	104	13	8	3	1	1
2021	116	609	168	61	28	32	55	38	18	1	4	2
2022	69	135	213	72	13	11	83	18	14	6	3	1

Northwest Offshore							Northwest Inshore					
	1	2	3	4	5	6+	1	2	3	4	5	6+
1983	72	583	116	122	39	61						
1984	154	417	288	43	53	50						
1985	19	777	149	101	27	55						
1986	178	265	712	235	100	38	4	15	41	8	8	11
1987	127	1012	127	159	37	73	91	34	29	32	3	3
1988	15	383	454	61	65	49	0	98	24	5	4	0
1989	483	241	276	125	29	95	17	21	127	17	3	1
1990	81	748	66	46	41	46	3	45	5	25	7	4
1991	62	238	285	48	36	40	6	10	38	8	22	5
1992	170	241	91	75	10	10	11	21	8	11	4	7
1993	55	797	137	38	44	17	7	95	36	4	3	1
1994	129	254	171	58	29	26	27	35	54	13	2	0
1995	94	538	151	33	12	9	0	0	0	0	0	0
1996	18	281	209	31	22	7	10	39	62	12	5	3
1997	174	178	122	66	22	20	30	13	10	7	6	11
1998	18	582	83	42	26	12	10	30	6	2	2	1
1999	29	72	387	26	12	12	3	15	11	1	1	0
2000	266	135	38	74	12	9	24	12	14	2	0	0
2001	10	191	34	31	42	9	4	21	4	1	0	0
2002	114	100	196	22	6	7	11	7	11	1	0	2
2003	21	184	42	50	11	9	7	27	4	2	2	0
2004	167	72	56	7	15	2	13	6	11	5	2	0
2005	35	83	33	16	5	6	3	1	3	0	0	1
2006	214	31	38	14	3	3	6	4	3	1	0	1
2007	58	240	34	22	2	3	6	20	7	2	0	0
2008	45	79	224	24	10	1	2	0	7	0	0	0
2009	69	77	43	43	4	1	4	6	6	1	0	0
2010	266	199	64	5	20	6	9	17	7	2	0	0
2011	32	490	242	41	29	28	3	28	11	0	1	2
2012	68	172	409	104	28	32	41	63	18	4	0	0
2013	137	191	137	198	75	10	41	90	16	3	2	0
2014	100	207	130	60	69	17	28	44	7	2	0	0
2015	242	361	296	145	76	73	19	50	20	5	1	0
2016	115	269	305	229	38	30	11	14	7	1	1	0
2017	449	141	266	229	178	50	7	97	22	2	2	0
2018	59	369	120	167	79	88	5	17	10	11	4	3
2019	145	85	173	14	23	12	19	12	8	1	0	0
2020	139	254	59	66	10	7	30	10	8	0	0	0
2021	137	187	209	50	32	23	4	19	6	0	1	0
2022	79	72	38	15	9	18	0	0	0	0	0	0

Table 5. Sub stock weights-at-age from Q1 survey data (post 1983) and derived as scaled annual catch weights (pre 1983).

Viking						
Year	1	2	3	4	5	6+
1983	0.0554	0.4637	1.5837	3.2947	5.1883	8.6755
1984	0.0391	0.3702	1.5647	2.6863	4.7428	9.2469
1985	NA	0.3116	1.2014	3.2097	4.8484	8.0027
1986	0.0389	0.2814	1.0544	2.6479	4.0756	7.3107
1987	0.0633	0.3413	1.1147	3.1536	4.4800	8.2226
1988	0.0669	0.1850	1.0911	2.8284	4.5869	6.5160
1989	0.0568	0.3144	0.7977	2.9164	3.9797	8.2029
1990	0.0592	0.3471	1.1919	3.1152	5.0790	9.1502
1991	0.0510	0.4218	1.3780	2.8040	5.4117	7.9090
1992	0.0519	0.5394	1.6242	3.8677	4.8071	8.8083
1993	0.0524	0.3314	1.3543	3.3441	4.4190	8.9396
1994	0.0349	0.3580	1.2652	4.0226	6.4478	9.8042
1995	0.0426	0.3444	1.0950	3.1774	5.5401	8.9785
1996	0.0310	0.3148	1.2261	3.6288	5.2612	9.1428
1997	0.0403	0.3103	1.1786	3.3420	5.0740	8.2013
1998	0.0630	0.2409	1.1742	3.4402	5.4433	8.9300
1999	0.0481	0.2631	0.8193	2.6785	4.9533	8.2242
2000	0.0400	0.3780	1.1743	2.7170	4.8240	7.4385
2001	0.0698	0.3485	1.4968	3.0806	4.4204	7.3240
2002	0.0510	0.2913	0.8212	3.0795	6.1544	9.1586
2003	0.0506	0.3887	0.9410	2.4148	5.2681	9.0986
2004	0.0585	0.3542	1.3846	3.2381	4.6039	8.1288
2005	0.0596	0.4470	1.2550	2.9349	5.0246	8.0117
2006	0.0542	0.4342	1.4517	3.1148	4.3228	8.7235
2007	0.0479	0.4591	0.9067	3.4572	5.3235	8.5716
2008	0.0495	0.5313	1.4999	3.2232	5.5140	8.0174
2009	0.0507	0.4835	1.5993	3.6856	4.6303	7.8431
2010	0.0486	0.5245	1.6019	3.4409	4.6690	6.7585
2011	0.0446	0.4043	1.4508	3.6529	4.3814	7.8726
2012	0.0583	0.4745	1.3591	3.2197	5.4411	8.2180
2013	0.0525	0.4182	1.2644	3.1785	4.4729	7.2265
2014	0.0422	0.4415	1.4546	3.4568	5.6211	9.2470
2015	0.0581	0.4618	1.5592	3.3220	4.5632	7.6551
2016	0.0636	0.5210	1.5656	3.1232	4.3293	8.0843
2017	0.0500	0.5443	1.6057	3.3223	4.5298	7.9448
2018	0.0527	0.5033	1.0247	3.0407	5.5009	7.8755
2019	0.0602	0.4293	1.2245	2.6922	6.2482	8.3818
2020	0.0575	0.5164	1.3829	3.6795	5.7689	9.0147
2021	0.0489	0.4278	1.3616	2.7175	5.4676	7.4142
2022	0.0550	0.3710	1.4181	3.2309	4.9794	9.8352

South						
Year	1	2	3	4	5	6+
1983	0.0757	0.6912	2.2058	4.7953	7.4102	10.9912
1984	0.0835	0.6008	1.8522	3.3011	7.5282	11.3365
1985	0.0468	0.5699	2.2889	5.0399	7.2293	11.1730
1986	0.0701	0.2988	1.7479	3.8711	7.2819	10.9369
1987	0.0834	0.4498	1.0180	5.1171	7.4875	11.6369
1988	0.0572	0.7253	2.1512	3.5654	7.6965	11.3769
1989	0.0616	0.8021	2.1948	3.6970	6.9428	11.2068
1990	0.0742	0.6309	2.5183	4.4918	7.3395	12.1095
1991	0.0577	0.7340	1.9205	4.9375	7.5408	11.4749
1992	0.0665	0.2657	1.8360	5.3903	7.5607	11.9289
1993	0.0428	0.6082	2.3416	5.3690	8.3666	12.8832
1994	0.0386	0.4067	1.9778	5.1847	8.7505	10.7243
1995	0.0450	0.3361	1.3497	4.6472	6.8175	11.9584
1996	0.0441	0.4944	1.5246	2.8470	6.7193	13.2632
1997	0.0301	0.1942	2.2312	3.5119	7.0474	8.3647
1998	0.0373	0.4005	0.9528	2.8657	8.9127	11.8417
1999	0.1652	0.5949	1.5444	3.6702	7.9783	11.0617
2000	0.0578	0.5127	1.5616	3.8351	4.6244	11.4429
2001	0.1457	0.3247	1.2098	3.0163	7.3638	9.8259
2002	0.0878	0.4317	1.7676	5.2252	NA	11.2234
2003	0.0892	0.6454	1.1744	4.7328	7.1560	12.5737
2004	0.0495	0.1564	2.0146	3.6107	7.9539	11.8711
2005	0.0547	0.5252	1.5714	3.6152	NA	11.4845
2006	0.0711	0.7520	2.4721	4.4324	NA	10.2629
2007	0.0719	0.3602	2.2816	4.5187	6.6069	12.1604
2008	0.1153	1.0505	2.0589	3.8360	6.3100	11.6156
2009	0.0768	0.8944	2.7353	4.5556	6.5794	11.4289
2010	0.0787	0.6873	2.8775	5.3953	6.7220	11.8269
2011	0.0704	0.5660	2.0371	5.5414	8.1370	10.5609
2012	0.0667	1.0646	2.3884	4.1453	8.7465	10.7663
2013	0.0635	0.4973	2.6338	3.7442	5.7075	11.0660
2014	0.0685	0.8602	2.4082	4.2148	7.3086	NA
2015	0.1147	0.8846	1.9054	3.8609	6.6584	11.8877
2016	0.0981	0.7885	2.6246	3.8260	7.3788	8.5353
2017	0.0600	0.5864	1.5753	3.3486	4.8038	11.6521
2018	0.1076	0.5013	1.0070	2.6044	6.5772	9.3143
2019	0.0592	0.5055	1.8214	NA	NA	9.3287
2020	0.0701	0.4715	1.6140	NA	NA	NA
2021	0.0879	0.6385	1.5428	NA	NA	NA
2022	0.0822	0.7072	1.9538	3.5445	NA	NA

Northwest						
Year	1	2	3	4	5	6+
1983	0.0649	0.5682	1.4668	4.2004	7.3390	11.8488
1984	0.0445	0.4310	1.8237	4.3576	7.0128	11.0702
1985	0.0761	0.3527	1.9568	4.3888	5.7162	9.8388
1986	0.0495	0.5515	1.6015	3.5064	6.5070	10.0621
1987	0.0911	0.3368	1.3887	4.3976	7.2698	10.4488
1988	0.0869	0.5254	1.5635	3.4852	7.3537	11.1248
1989	0.0740	0.4107	1.4245	3.5722	5.7183	10.4207
1990	0.0486	0.3801	1.4092	4.2331	6.9981	10.5696
1991	0.0823	0.5219	1.6687	4.0687	7.4477	11.6264
1992	0.0491	0.6196	2.0903	4.7516	7.1444	11.3748
1993	0.0372	0.4658	2.1797	5.0841	7.7954	11.7940
1994	0.0413	0.4014	1.7334	5.4182	8.6177	11.0069
1995	0.0606	0.2666	1.2305	4.4837	6.4432	11.7557
1996	0.0802	0.5767	1.3711	4.3070	6.7153	10.6380
1997	0.0192	0.3691	1.6791	4.1825	7.3376	10.3067
1998	0.1098	0.3049	1.8312	4.5814	7.3061	10.6434
1999	0.1039	0.4536	0.6468	2.4469	7.3010	10.4702
2000	0.0785	0.5450	2.0024	2.5299	5.0085	9.9984
2001	0.0971	0.3826	1.5106	4.5241	6.0841	8.8443
2002	0.0896	0.3690	1.3474	3.9886	4.9571	9.4892
2003	0.0938	0.4930	0.8952	2.8689	5.8353	10.4839
2004	0.0714	0.3454	1.3827	3.9717	6.4737	NA
2005	0.0860	0.3867	1.2793	2.3558	NA	10.2975
2006	0.0671	0.4809	1.3802	2.7111	NA	NA
2007	0.0635	0.3886	1.6781	3.9774	NA	NA
2008	0.0747	0.5724	1.8546	5.0655	7.0352	NA
2009	0.0689	0.4871	1.5306	3.6019	NA	NA
2010	0.0884	0.6217	2.0069	3.5608	5.9305	8.1988
2011	0.0933	0.5110	1.9933	4.2107	5.7484	8.5158
2012	0.1139	0.6825	1.5519	3.6404	6.3061	10.8533
2013	0.0989	0.7794	2.0035	3.6114	5.5748	6.9386
2014	0.0660	0.6112	1.8735	3.5969	5.2016	7.2512
2015	0.0801	0.5757	1.6853	3.7570	5.9464	6.8718
2016	0.0712	0.7237	1.7478	3.4963	5.7785	8.5024
2017	0.0649	0.6307	1.9471	4.2098	6.2699	7.7065
2018	0.0704	0.3913	1.7502	3.2879	5.3271	6.4231
2019	0.0628	0.4351	1.2918	3.8164	5.3419	8.3093
2020	0.0770	0.5148	1.8692	3.4004	5.0781	8.8513
2021	0.0978	0.4861	2.0287	4.0497	5.7939	8.0546
2022	0.2077	0.4869	1.3735	4.5767	5.9968	8.4713

Figure 1. Current stock mean weights at age for North Sea cod and West of Scotland cod. Lower plot has 6a adjusted to 6+ group.

Figure 2. Estimated weight-length parameters by sub stock area and year. Upper panels show results based on the 3 sub stock assumption and the lower panels from 4 sub stocks.

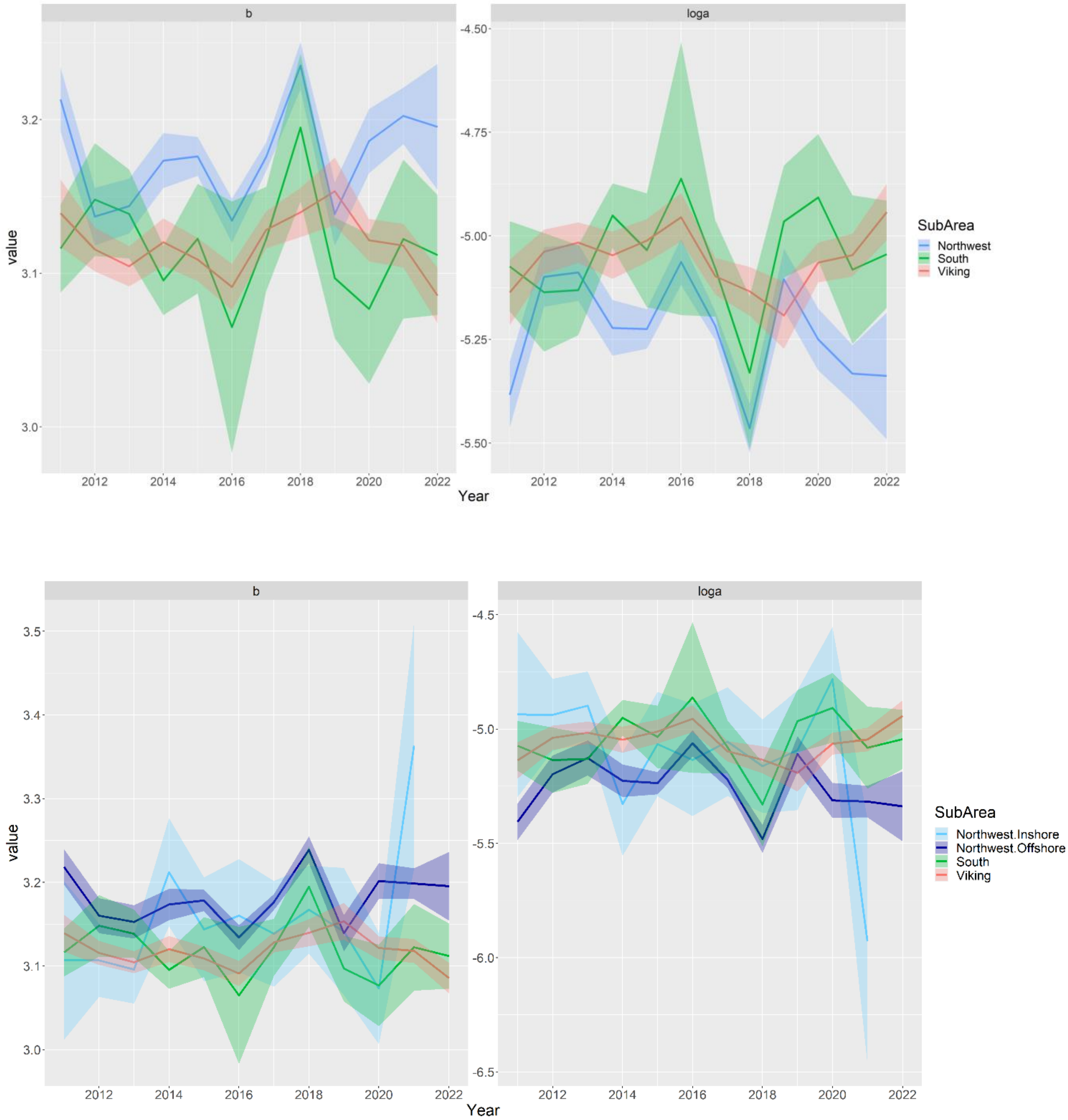


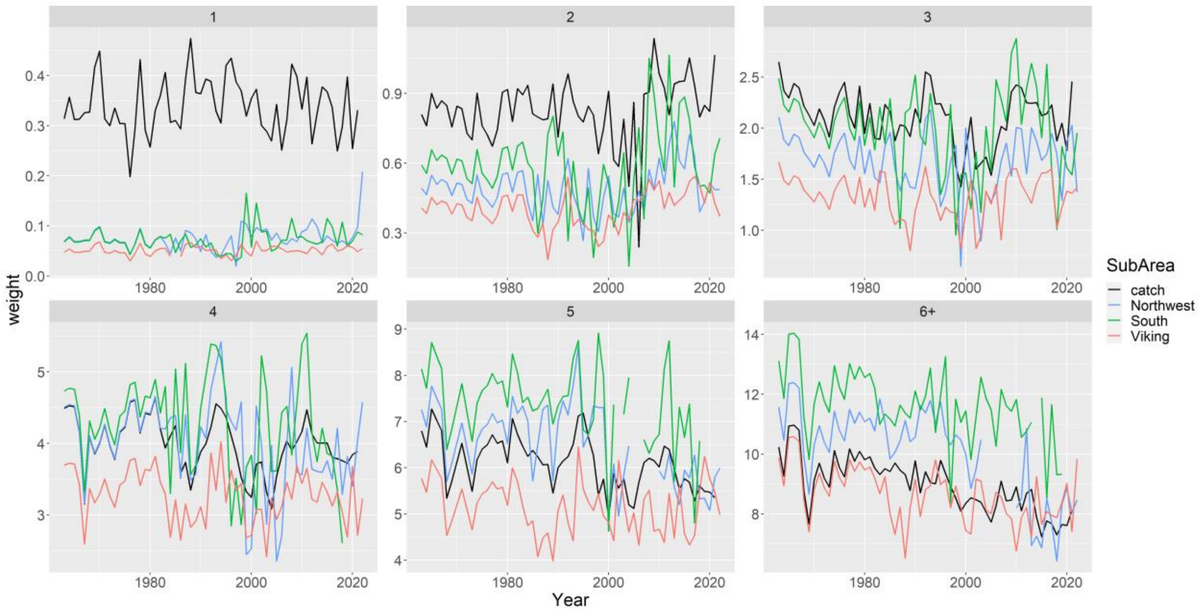
Figure 3. Predicted mean weight-at-length (for 5 different lengths: 25cm, 50cm, 75cm, 100cm & 125cm) by sub stock area and year. Upper panels show results based on the 3 sub stock assumption and the lower panels from 4 sub stocks.

Figure 4. Bootstrap estimates of weight-at-age by sub stock area and year using an area dependent weight-length relationship which is fixed over time. Upper panels show full results, lower panels exclude year/subarea/age combinations in which greater than 5% of replicates had zero observations.

Figure 5. Non-bootstrapped estimates of weight-at-age by sub stock area and year using an area dependent weight-length relationship which is fixed over time. Year/subarea/age combinations with 5 or fewer age samples are excluded. Upper panels show results based on the 3 sub stock assumption and the lower panels from 4 sub stocks.

Figure 6. Annual catch mean weights-at-age for the combined Northern Shelf derived as a weighted average of North Sea and West of Scotland values.

Figure 7. Sub stock mean weights-at-age: based on Q1 survey data and extended back to 1963 using an age & sub stock dependent annual catch mean weight to Q1 survey weight scaling factor (averaged over 1983-2021).



21.11 Natural mortality estimates for Northern Shelf cod

Natural mortality estimates for Northern Shelf cod

Alex Holdgate, Nicola Walker and Alan Baudron

2022-11-16

Contents

1 Summary

Informed by the findings of two stock ID workshops (WKNSCodID, 2020 and WK6aCodID, 2021), the benchmark of Northern Shelf cod (WKCOD 2023) aims to develop a new assessment framework that addresses the stock identity and migration issues of the North Sea cod (cod.27.47d20) and West of Scotland cod (cod.27.6a) stocks. The proposed population structure is a combined meta-population of cod.27.47d20 and cod.27.6a comprised of several sub-stocks (i.e. 'Northwestern', 'Southern' and 'Viking'). Depending on data availability, a further split of the north-western sub-stock into an inshore and offshore component may also be considered. To support the development of a new assessment framework, methods to estimate natural mortality - both at the meta-population level and the sub-stock level - are explored in this working document.

2 Review of methods: natural mortality for cod.27.6a and cod.47d20

The following sections review the current methods used to produce natural mortality estimates for the assessments of cod.27.6a and cod.47d20.

2.1 North Sea cod (cod.27.47d20)

Since 2009, variable natural mortality estimates are used in the assessment for North Sea cod produced using the stochastic multi-species model SMS (Lewy & Vinther, 2004). SMS is a stock assessment model including biological interaction estimated from a parameterized size-dependent food selection function. The model is formulated and fitted to observations of total catches, survey catch-per-unit-effort (CPUE) and stomach contents for the North Sea area. In the assessment for cod.27.47d20, the raw estimates of natural mortality from the latest SMS keyrun are smoothed to reduce the effects of interannual variability whilst maintaining overall trends. New natural mortality estimates are produced by the Working Group on Multi Species Stock Assessment Methods (WGSAM) every three years in so-called 'keyruns'.

2.2 West of Scotland cod (cod.27.6a)

Age-dependent natural mortality was first implemented in the assessment for cod.27.6a at WKROUND (2012) where natural mortality-at-age was derived from mean stock weight-at-age over the full time-series of data using the Lorenzen parameters for fish in natural ecosystems (Lorenzen, 1996):

$$M_a = 3\overline{W}_a^{\,-0.29}$$

Where:

- M_a = the natural mortality M at age a
- $\overline{W}_a$ = the mean stock weight W at age a
- Constants $(3; -0.29)$ = the modelled Lorenzen mortality-weight parameters for fish in natural ecosystems

Since 2019, observed trends in mean weights gave good reason to allow natural mortality to vary over time and so since 2020, natural mortality-at-age is derived from stock weight-at-age (which are the modelled mean catch weights-at-age).

3 Comparison of SMS and Lorenzen natural mortality estaimtes for cod.27.6a and cod.27.47d20

The following sections compare and contrast the two methods currently used to estimate natural mortality for cod.27.6a and cod.27.47d20 to determine the suitability of each method for estimating natural mortality for the Northern Shelf cod meta-population.

3.1 Lorenzen estimates for North Sea cod (cod.27.47d20)

Figure 1 compares natural mortality estimates for cod.27.47d20 using the Lorenzen method (currently applied to cod.27.6a) to the smoothed natural mortality outputs from SMS. The consistency between the two methods is poor, with the Lorenzen method estimating lower natural mortality for ages 1 and 2 compared to SMS.

This trend inverts from age 3 onwards, where the Lorenzen estimates are higher than the smoothed SMS outputs.

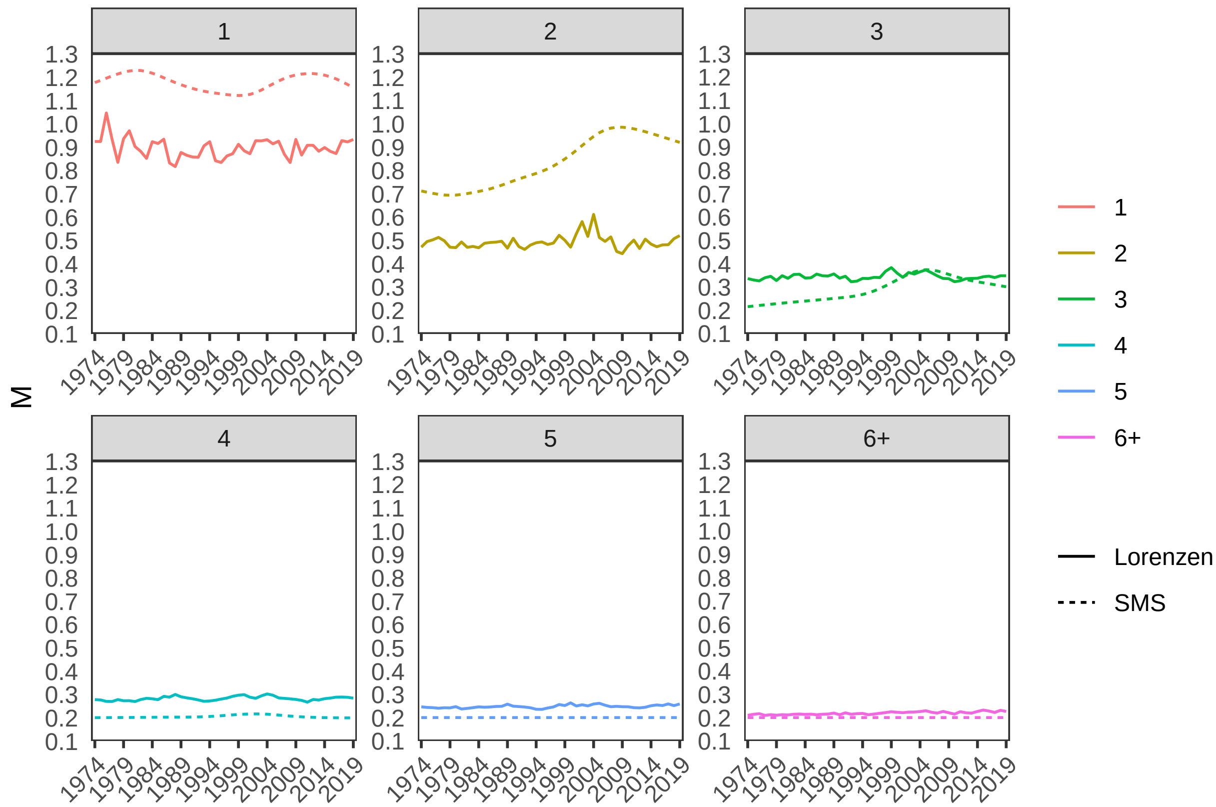


Figure 1: Comparison of M-at-age estimates for North Sea cod derived from the Lorenzen approach (solid line) vs. the smoothed estimates of M-at-age output by SMS for North Sea cod (dashed line).

3.2 SMS estimates for West of Scotland cod (cod.27.6a)

Figure 2 compares natural mortality estimates for cod.27.6a using the Lorenzen method to the smoothed natural mortality outputs from SMS (currently used in North Sea cod). As with, the consistency between the two methods is poor, with the Lorenzen method again estimating lower natural mortality at younger ages and slightly higher natural mortality at older ages compared to SMS.

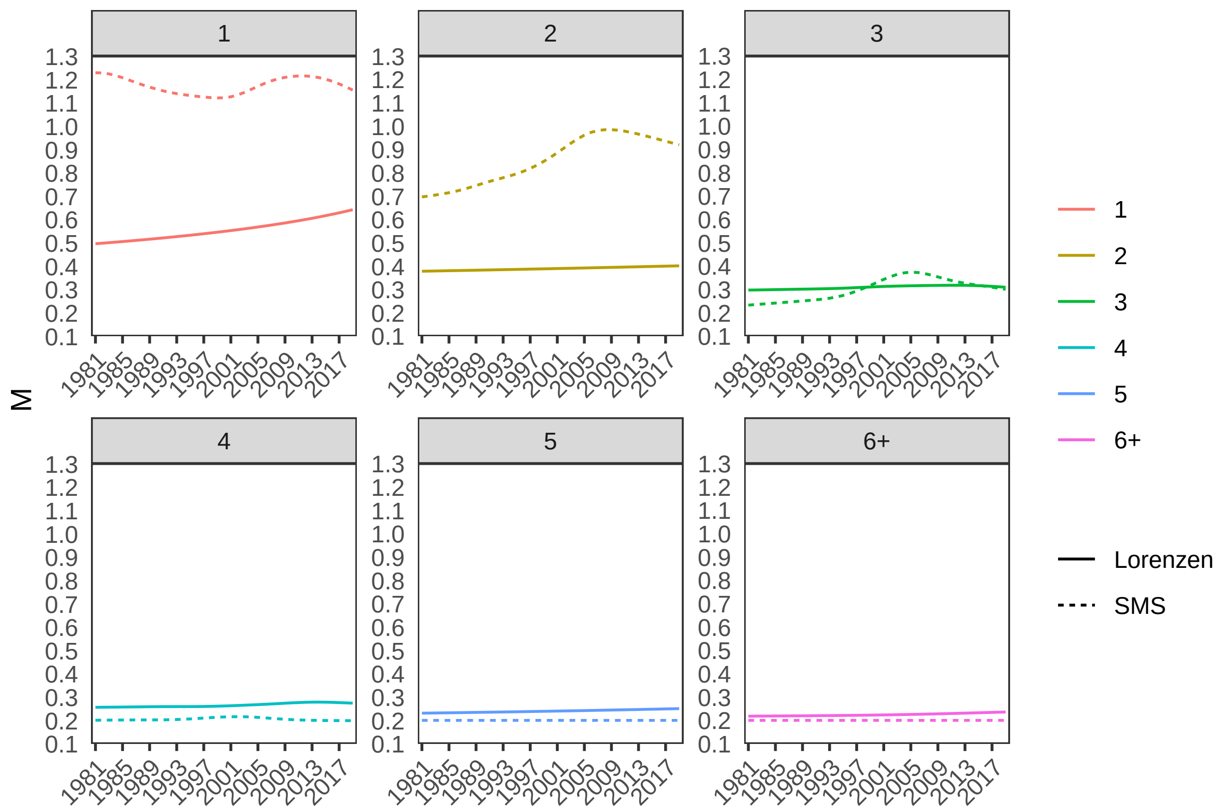


Figure 2: Comparison of M-at-age estimates for West of Scotland cod derived from the Lorenzen approach (solid line) vs. the smoothed estimates of M-at-age output by SMS for North Sea cod (dashed line)

4 Using SMS estimates of natural mortality for Northern Shelf cod

4.1 ICES Stocks

A number of stocks currently assessed by ICES provide precedent for using SMS estimates of natural mortality for stocks with spatial distributions that extend beyond the North Sea into the West of Scotland.

4.1.1 Herring in division 6a.N (West of Scotland)

Since 2015, natural mortality estimates from the latest SMS 'keyrun' have been used in the assessment of herring in division 6a.N. The benchmark meeting decided that there was enough overlap of predator species between the North Sea and divisions 6.a and 7b-c to justify using North Sea SMS estimates of natural mortality in the assessment. The main differences in predation rates between North Sea cod and West of Scotland cod are likely to be driven by grey seals. Grey seal numbers have increased dramatically in recent decades, and they are considered an important driver of non-fishing mortality for cod West of Scotland.

4.1.2 Grey seal predation on cod in division 6a

There is evidence in the literature that suggests SMS can capture some of the trends in natural mortality for cod in division 27.6a, including the increased predation pressure by the larger grey seal population West of Scotland.

The effect of seal predation on estimates of natural mortality was carried out by Trijoulet et al. (2018), where several models with different assumptions of seal predation rates on cod in division 27.6a were compared:

1) Varying seal predation through time (Model A)
2) Constant seal predation through time
3) No explicit assumption on seal predation (assumed part of the background mortality rate)

The model assuming variable seal predation through time showed similar trends as SMS in the estimates of natural mortality for ages 2 and 3, albeit with higher magnitude. Whilst the trend for age 1 is broadly similar between SMS and Model A, SMS estimates a much higher magnitude of natural mortality compared with Model A. The agreement between SMS and Model A for younger ages suggests SMS captures some of the trends in natural mortality for cod in the West of Scotland, and therefore SMS estimates could be used in the new modelling framework proposed for Northern Shelf cod. Furthermore, whilst Model A and SMS show similar trends across younger ages, both models show poor agreement with the Lorenzen estimates of natural mortality across all ages (see figure 3).

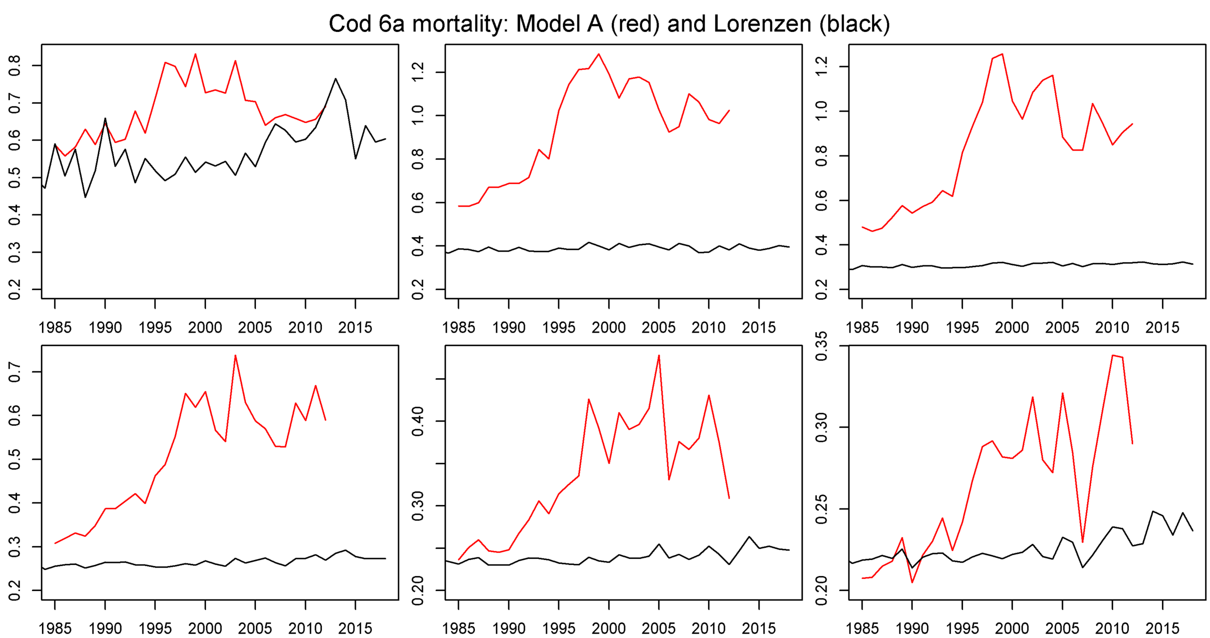


Figure 3: Comarison of natural mortality estimates at age derived using Trijoulet et al.'s model with varying seal predation through time (red) and Lorenzen estimates (black) for West of Scotland cod. Each panel represents a different age group, starting at age 1 in the top left and age 4 in the bottom left panels respectively.

4.1.3 Northern Shelf haddock (had.27.46a20)

The spatial extent of the Northern Shelf haddock stock which includes the west of Scotland (27.6a), the northern and central North Sea (27.4a), and Skagerrak (27.3a.20), is similar to the proposed Northern Shelf cod stock distribution (minus the Southern area). As such, the assessment of had.27.46a20 is a relevant case study for potential methods to provide estimates of natural mortality for WKCOD2023. Since 2014, smoothed estimates of natural mortality from the latest North Sea SMS keyrun are used in the assessment for Northern Shelf haddock (ICES, 2020). Furthermore, the modelling framework for Northern Shelf haddock is similar to the current assessments for cod.27.6a and cod.27.47d20, all which use SAM; an adapted SAM model is also the proposed framework for Northern Shelf cod.

5 Estimates of natural mortality for the sub-stock areas

Potential methods to post-process the outputs of the latest North Sea SMS key-run are being explored to provide estimates of natural mortality for the three main Northern Shelf cod sub-stock areas (i.e. Northwestern, Southern and Viking). Currently, work is focused on adapting the length-based multi-species assessment model 'LeMans' (and the associated R package 'LeMaRns') into an age-based assessment model that is able to reproduce the outputs of the latest SMS key-run. The intent is to then define sub-stock-specific vulnerability coefficients (based on distributions of predators from survey data and published studies) and re-run the deterministic SMS equations to get sub-stock-specific natural mortality estimates out. This approach requires considerable software development and there is no guarantee that usable outputs will be generated in time for the benchmark.

6 Conclusions

The authors recommend to:

- Use smoothed natural mortality outputs from the latest SMS keyrun for modelling the Northern Shelf cod meta-population
- Continue developing methods to estimate natural mortality at the sub-stock level intersessionally
- Use the smoothed SMS outputs in the absence of sub-stock-specific natural mortality estimates (if required by the new modelling framework)

7 References

Trijoulet V, Dobby H, Holmes SJ, Cook RM. Bioeconomic modelling of grey seal predation impacts on the West of Scotland demersal fisheries. ICES Journal of Marine Science. 2018 Jul 1;75(4):1374-82.

Lewy P, Vinther M. A stochastic age-length-structured multispecies model applied to North Sea stocks. ICES CM. 2004;33.

21.12 A preliminary multi-stock model for the Northern Shelf Atlantic cod complex

A preliminary multi-stock model for the Northern Shelf Atlantic cod complex

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1 Introduction

The North Sea and adjacent areas are inhabited by several cod stocks (e.g., ICES 2020, 2022). Currently, cod in the west of Scotland (27.6.a) has been assessed as one stock, while cod in the North Sea (27.4.a-c), Skagerrak (27.3.a.20) and eastern English Channel (27.7.d) has been assessed as another. However, the combined area is primarily inhabitted by the Northwestern Dogger, Southern Dogger, and Viking cod stocks. The Northwestern stock primarily inhabits both the northern North Sea (27.4.a-b) and west of Scotland (27.6.a), while the Viking stock mainly inhabits the northern parts of the North Sea (27.4.a-b) and Skagerrak. The Southern Dogger stock mainly inhabits the English Channel (27.7.d), southern parts of the North Sea (27.4.b-c). Further, Skagerrak (27.3.a.20) is a nursing area for the Southern stock. While the stocks are largely reproductively isolated, they are mixing in large parts of the North Sea in most of the year. Genetically, the Viking stock is different from the two Dogger stocks. Currently, there is no clear genetic evidence of two distinct Dogger stocks. However, spatial phenotypic and demographic structure suggests two stocks (ICES 2020). Besides the three main stocks, the area is inhabitted by several inshore populations. However, these are typically small and not covered by trawl surveys and commercial catches.

2 Model framework

To reflect the stock structure in the Greater North Sea and west of Scotland, a multi-stock SAM model was fitted to catch data and surveys from the area. The model was built to assess several biological, or genetic, stocks in a combined model (Albertsen, Nielsen, and Thygesen 2018). Therefore, individuals cannot transfer between stocks. However, the model can account for mixed catches and surveys (Albertsen and Nielsen 2023). Further, the model can include genotype samples to inform stock compositions within the assessment. Below, the procedure for fitting the model as well as the results are presented. For technical details on the model, we refer to (Albertsen and Nielsen 2023).

The code for the version of the stockassessment and multiStockassessment packages used for fitting the cod model is available on GitHub at https://github.com/fishfollower/SAM/tree/refpoint and https://github.com/calbertsen/multi_SAM/tree/shared_obs, respectively. Pre-compiled versions for installation on Windows and Mac OS are available at https://calbertsen.r-universe.dev/stockassessment and https://calbertsen.r-universe.dev/multiStockassessment, respectively. The model specific code is available in an ICES TAF repository on GitHub at https://github.com/ices-taf/2022_cod.27.47d20_benchmark-data/tree/christoffer/multistock.

3 Biological assumptions

Based on the results of the WKNSCodID (ICES 2020) and WK6aCodID (ICES 2022) workshops, it is assumed in the model, that three stocks are available for commercial catches and surveys in the area. Local inshore populations are assumed to be negligible for the assessment. Further, it is assumed that the stocks are mostly reproductively isolated, with no transfer of individuals between stocks. Outside the spawning period in quarter one, the stocks are assumed to be geographically mixing. In the first quarter, the stocks are assumed to be geographically separated (fig. 1). Finally, it is assumed that the SAM population model is reasonable for each stock. Specifically, migration in or out of the assessment area is assumed to be negligible.

4 Observations

Following data compilation workshop, all presented data sources were included in the model fit with as many ages and years as possible. Further, biological inputs were smoothed using Gaussian Markov Random Fields within SAM.

4.1 Catch-at-age

Yearly catch-at-age data was available for the North Sea (3.a.20,4.a-c,7.d N. D. Walker 2023) and West of Scotland (6.a Dobby 2023). Catches for the two areas were combined and assumed to represent the total catch-at-age for all three stocks in the area. In the model, catches were predicted as the sum of the stock-wise catches. Covariances for the three stocks had the same parameters and were averaged, giving a time-invariant covariance matrix for the mixed catch. This corresponds to the covariance structure for catch in a combined all-in-one-stock model. Catch was modelled by a multivariate normal distribution.

4.2 Survey indices

Several survey indices were available for the multi-stock SAM model (N. D. Walker, Dobby, and Berg 2023). First, a quarter 3-4 survey index was available for ages 1-7. The survey was calculated for the entire area and assumed to be proportional to the total abundance-at-age across stocks. Similar to catches,

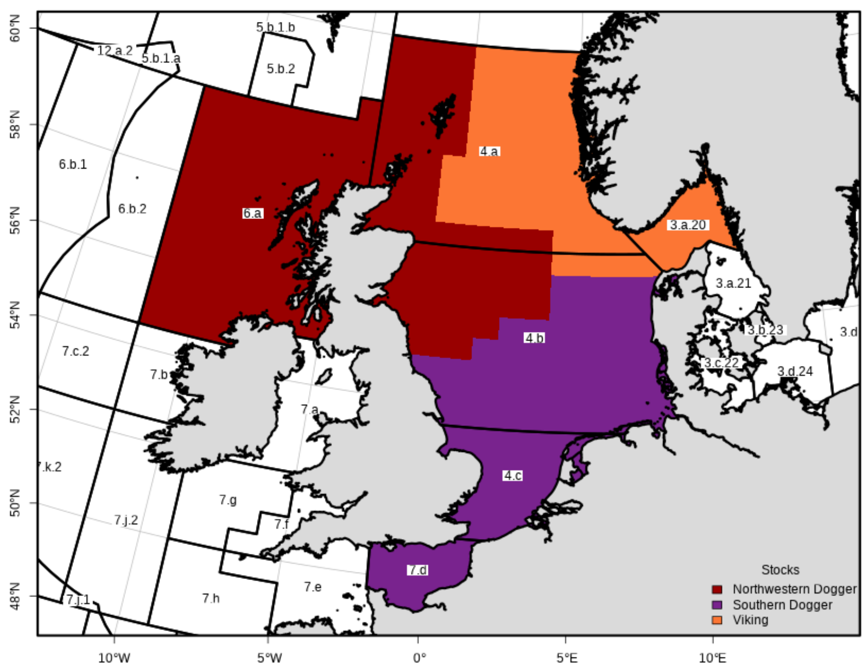


Figure 1: Cod stock areas reflecting the primary hypothesis on the spatial distribution of the stocks. Stocks are assumed to predominantly be in their corresponding cod area in quarter one while mixing in the remaining quarters.

and the combined all-in-one-stock model, the covariance was assumed to time-invariant. Second, a recruitment index was available per stock. The index was calculated from age 0 individuals in the quarter 3-4 surveys and forward-shifted to one-year-olds in the beginning of the following year. Since Skagerrak is a nursing area for both the Viking and Southern stocks, the Viking index was assumed to cover 100% of the Viking stock and 25% of the Southern stock, while the Southern index was assumed to cover 75% of the Southern stock. The Northwestern index was assumed to cover 100% of the Northwestern stock and nothing else. Finally, a quarter 1 survey index was available per stock for ages 1-7, assuming negligible spatial overlap of the stocks in this quarter. All survey indices were fitted by (multivariate) normal distributions. Standard errors were available from the GAM survey index models. However, these were not used in the final model, as they resultet in less numerical stability in the fits and issues calculating one-step-ahead residuals. A model using the standard errors was included as a sensitivity run.

As further sensitivity runs, models were fitted without the recruitment indices. Similar to the current North Sea cod assessment, a model was fitted using ages 1-5 for quarter 1 and 1-4 for quarter 3-4. Further, a model was fitted assuming the Viking and Southern recruitment indices only covers the corresponding stocks. Finally, the quarter 1 IBTS in 6.a had a single exceptionally large haul in 2017. Therefore, a model was fitted using quarter 1 indices calculated without this large haul.

4.3 Proportion of total landed weight per stock (1995-)

Through a data call before the benchmark, spatially disaggregated landings were collected (Holdgate and Dobby 2023). Landings for the first quarter, where the stocks are assumed to be spatially separated, were summarized by year and stock area (see fig. 1), and normalized to proportions. The stock proportions were fitted by an additive logistic normal. The predicted stock composition was obtained from the stock-wise total landing weights in the first quarter. These proportions were assumed to be directly related to each stock. As sensitivity runs, models without this time series was fitted.

4.4 Proportion of total landed weight per quarter (1995-)

To inform seasonal variability in fishing mortality rates, the spatially disaggregated landings were summarized by year and quarter, and normalized to proportions. The seasonal proportions were fitted by an addtivie logistic normal. The predicted seasonal proportions were obtained from the sum of the stock-wise total landing weights per quarter. The seasonal proportions were assumed to be from a mixture of all stocks. Seasons were modelled by fixed effects. As sensitivity runs, models without this time series was fitted as well as models fitting seasons by auto-regressive processes.

4.5 Proportion of total landed weight per substock area (-1994)

To extend the observed stock landing proportions back in time, the ICES historical landings database was used to calculate stock landing compositions from 1963 to 1994 (Orio and Cardinale 2023). Unlike the recent spatially disaggregated landings, historical landings were only available for the full year. Although the stocks are assumed to be mixing, the quarter one stock areas (see fig. 1) were used as an approximation. The proportions were fitted by an additive logistic normal. Predicted composition was obtained from the stock-wise yearly landing weights. As sensitivity runs, models without this time series was fitted.

4.6 Proportion of total landed weight per ICES subdivision

The two time series on stock proportions assumes that the stocks are spatially separated in the first quarter (1995-) and throughout the year (-1994), respectively. As a sensitivity analysis for these assumptions about the spatial distribution, the same underlying data was aggregated in accordance with a different assumption about the spatial distribution. As an alternative, spatial landings were aggregated by year and by five catch areas: Southern North Sea (4.c, 7.d), Middle North Sea (4.b), Northern North Sea (4.a), Skagerrak (3.a.20), and West of Scotland (6.a) (fig. 2). It was assumed that the Northwestern stock was available to catch fleets in the Middle North Sea, Northern North Sea and West of Scotland areas; the Southern stock was available in the Southern North Sea, and Middle North Sea; while the Viking stock was available in the Middle North Sea, Northern North Sea, and Skagerrak areas.

For the historical landings (ICES 2019), pre-1995, data aggregated by ICES division (see Alessandro WD) were converted to catch areas (fig. 2). In the process, landings allocated to “VI” were combined with 6.a, landings allocated to “IIIa” were combined with 3.a.20, and landings allocated to “VIId-k” and “VIId,e” were combined with 7.d. Combined, these areas, partly including areas outside the assessment area, had on average 1.21% (0.56% - 2.16%) of the landings. The time series was available from 1963-1994. For the accessions data, a similar time series was constructed based on the reported ICES areas.

5 Biological input data

Following the data compilation workshop, mean stock weight-at-age, and maturity-at-age were available per stock. Mean stock weight-at-age was available for the entire period, but with missing values for age 6 in 2008-2009 and age 7 in 2004 and 2007 for the Northwestern stock, and for age 6 in 2020 and age 7 in 2022 for the Southern stock. The weights were smoothed with a Gaussian Markov Random Field with measurement noise using the biological parameters framework in SAM. The process was used to impute missing values. Sensitivity runs were included that used the raw values and a five year average instead of

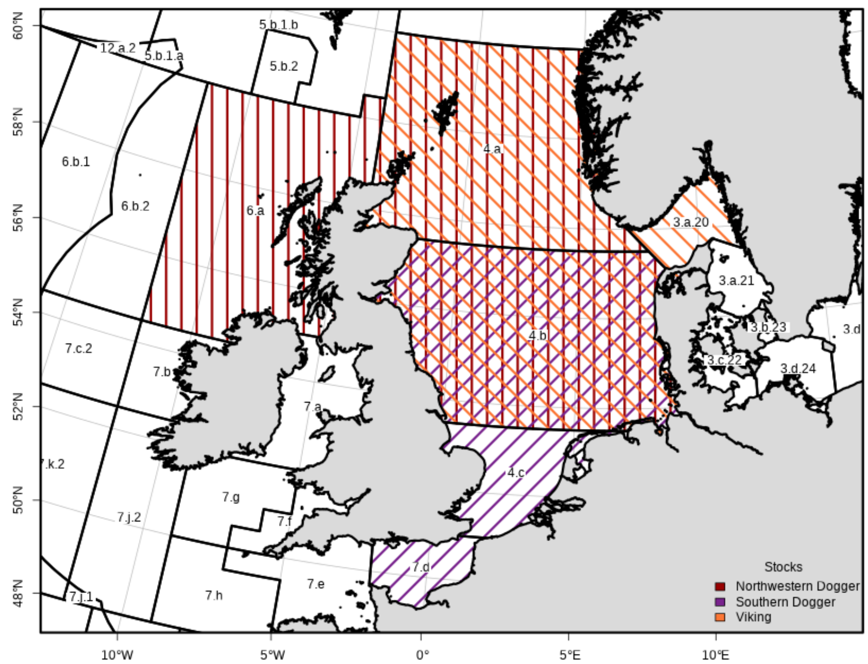


Figure 2: Cod catch areas reflecting the secondary hypothesis on the spatial distribution of the stocks. The Northwestern stock is assumed to be available for catch fleets in 4.a, 4.b, and 6.a. The Southern stock is assumed to be available for catch fleets in 4.b, 4.c, and 7.d. The Viking stock is assumed to be available for catch fleets in 3.a.20, 4.a, and 4.b.

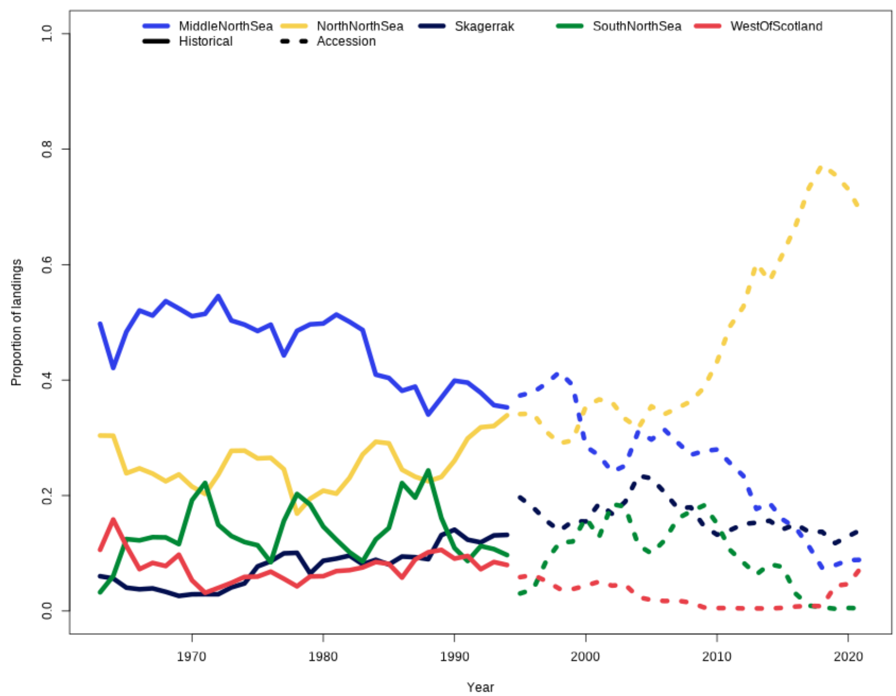


Figure 3: Calculated proportion of landings per model area from the ICES historical landing database and accessions data.

internal smoothing. In both cases, missing values were imputed with the overall mean for the same age.

Maturity-at-age data were available per stock from 1983 onwards. Similar to stock weights, maturity data was smoothed using a Gaussian Markov Random Field with measurement noise implemented in SAM. The process was used to impute missing values. Sensitivity runs were included that used the raw values and a knife-edge maturity at age 3. In the former case, missing values were imputed with the overall mean for the same age.

Natural mortality rates per age were available from the latest SMS keyrun (Holdgate, Walker, and Baudron 2023). As a result, stock-wise mortality rates could not be obtained, and the same values were used for all three stocks. Values were available from 1974 to 2019. The values were smoothed - and missing values were imputed - per stock using a Gaussian Markov Random Field with measurement noise implemented in SAM. As sensitivity runs, a model was fitted using pre-smoothed natural mortality rates where missing values were imputed using averages of the nearest years.

Landing fractions, mean landing weight-at-age, mean discard weight-at-age, and mean catch weight-at-age were available per current assessment unit. For the single-fleet fits, the values were averaged over fleets. The averages were weighted by the relevant numbers-at-age. For example, catch weight averages were weighted by catch numbers. As a sensitivity run, a single-fleet model was fitted using stock mean weights as landing weights, such that landing weights differ between the three stocks.

6 Model configuration

Starting from a default SAM configuration, the model was configured to improve performance. The model was configured in a step-wise procedure where any improved model fit was retained and used as reference for later configurations. A configuration was considered an improvement if it had lower AIC, a positive definite Hessian at the optimum, and numerically stable one-step-ahead residuals could be calculated with the "oneStepGaussianOffMode" method in TMB. Combined, the criteria values both fit to data and numerical stability.

In the procedure, different configurations were considered for all parts of the model. To reduce the number of configuration options, all stocks used the same configuration, except for configurations directly related to observations. The procedure did not include changing the data. All data inclusions defaulted to the preferred option from the data compilation workshop, as detailed above. Further, parameters that did not correspond to adjacent ages were not set to be equal, irrespective of their values, to avoid biologically implausible configurations.

7 Model results

The best configuration obtained had an AIC of -3623.1. This was an improvement of 306.1 over the starting configuration.

With this model, spawning stock biomass of the Southern stock was estimated to increase from 1963 to 1970, followed by a large decline until the mid 1980s (fig. 4). This period was followed by a steady decline until an all-time low in 2020. The Northwestern stock was estimated to be at a lower level than the Southern stock in the early data period, followed by a steady decline from the 1970s to the mid 2000s. From the mid 2000s, the stock was estimated to slowly recover. Finally, the Viking stock was estimated to be at a steady level throughout the period. The estimated trends in SSB for the entire stock complex were similar to the currently used single-stock model. The abundance per age can be seen in fig. 5.

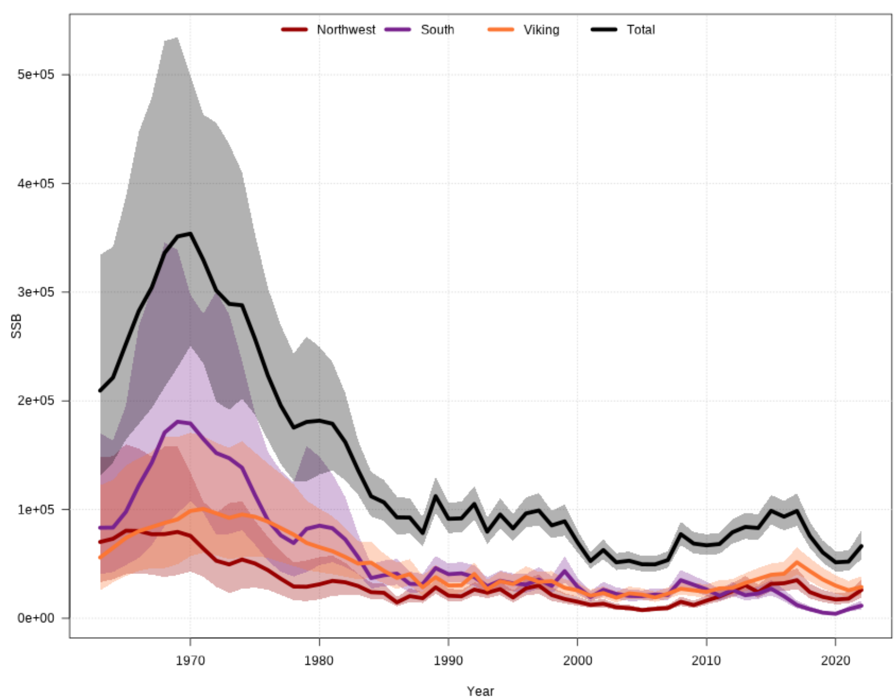


Figure 4: Estimated spawning stock biomass from the best obtained configuration using the default data.

Fishing mortality rates were generally estimated to increase from 1963 to 1990, follow by a general decrease until now, except for a period in the late 1990s and the late 2010s (fig. 6). For most of the period, the Southern stock was estimated

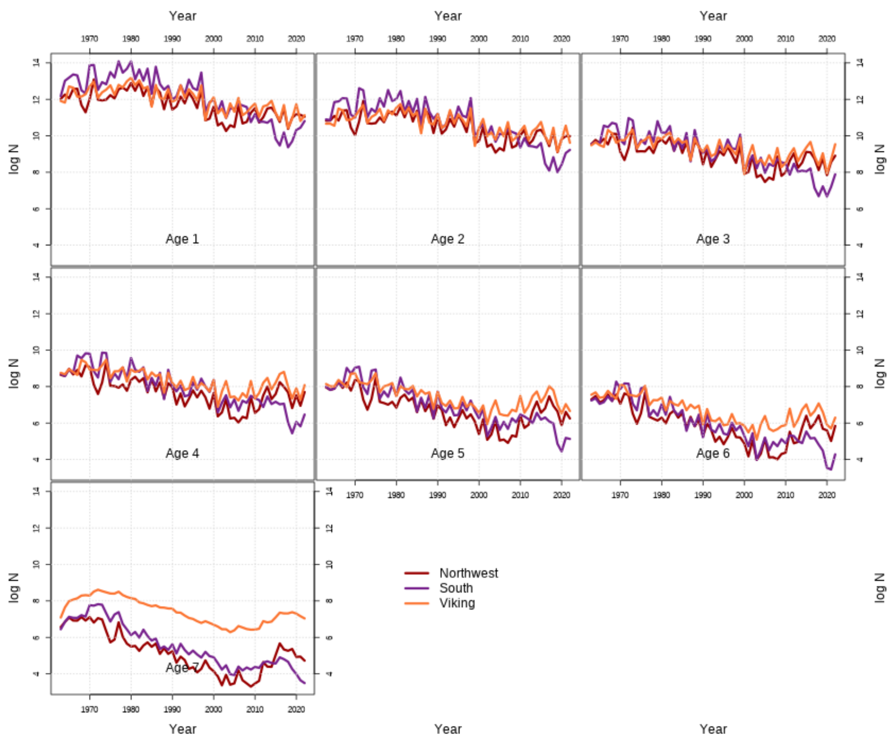


Figure 5: Estimated log abundace per age from the best obtained configuration using the default data.

to have the largest average fishing mortality rate. Again, the over-all trend for the stock complex was similar to the currently used single-stock model. The fishing mortality rate per age can be seen in fig. 7.

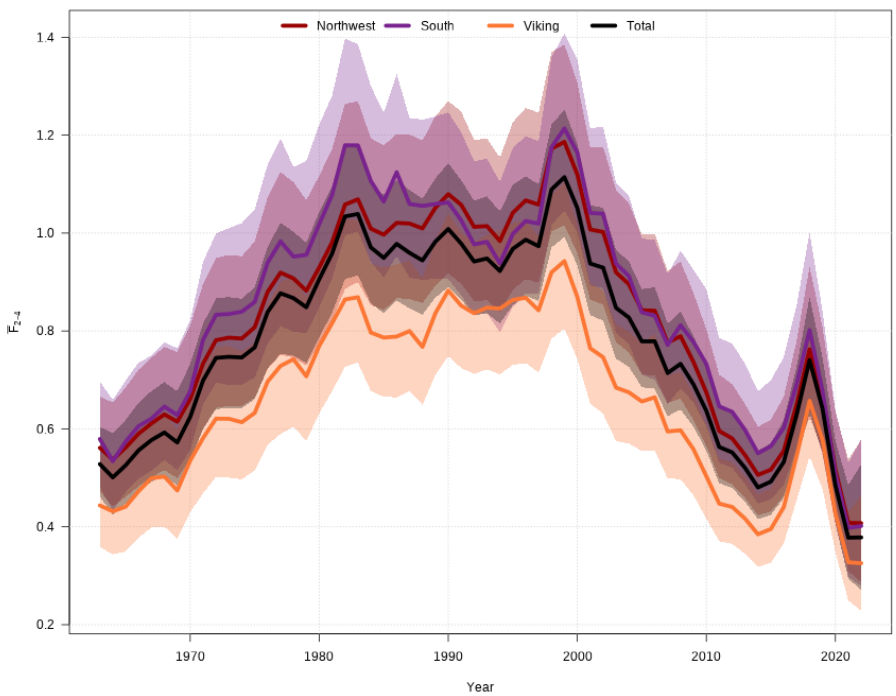


Figure 6: Estimated fishing mortality rate from the best obtained configuration using the default data.

As expected from SSB and F, the Southern stock was estimated to be the largest contributer to catch from 1963 to 2000 (fig. 8). Estimated catch for the entire stock complex followed the observed catches very well.

For the Southern stock, three distinct periods were estimated. Until 1987 had high recruitment, followed by medium recruitment from 1988 to 1997 (fig. 9). Finally, the most recent period had very low recruitment. Similar patterns were estimated for the two other stocks, but with recruitment at lower levels. The trends in recruitment for the entire stock complex followed the Southern stock, which was estimated to be the largest contributer from 1963 to 1997. In the recent period, the Southern stock has had the lowest recruitment of all three stocks.

Within the model, mean stock weights, natural mortality and maturity were smoothed using a Gaussian Markov Random Field with measurement noise

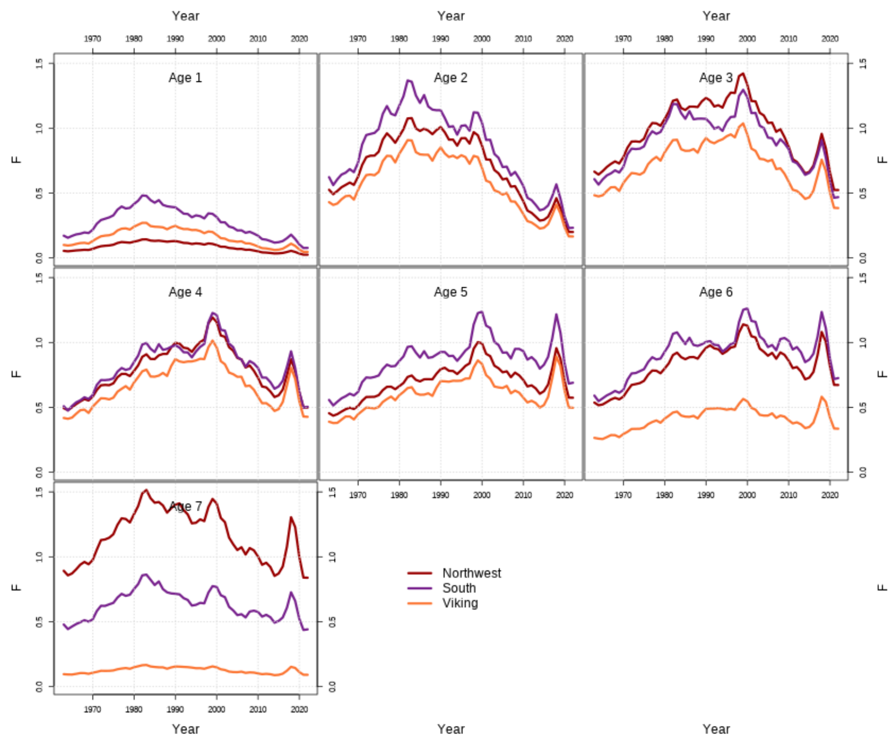


Figure 7: Estimated fishing mortality rate per age from the best obtained configuration using the default data.

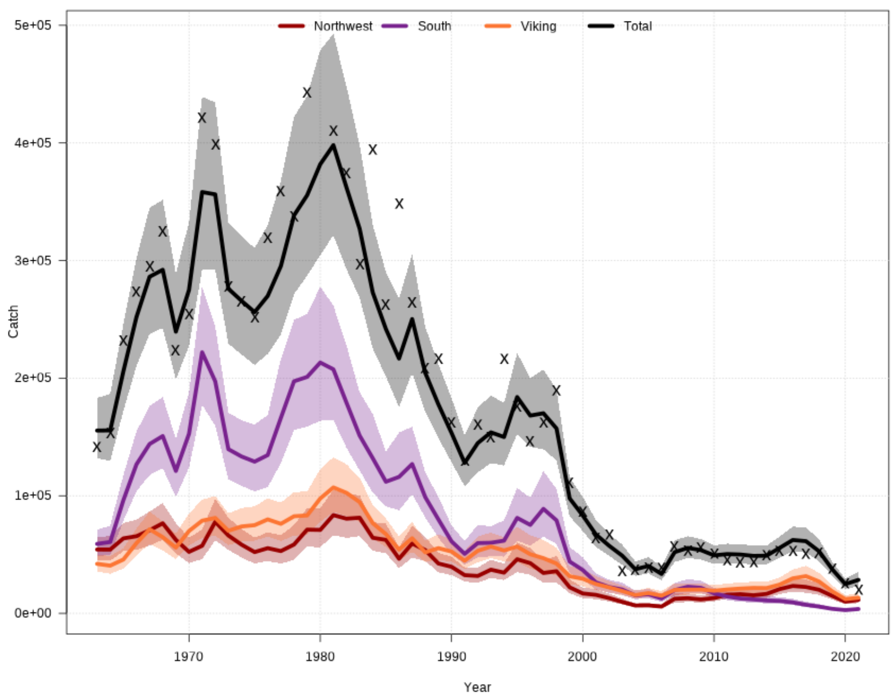


Figure 8: Estimated catch (weight) from the best obtained configuration using the default data.

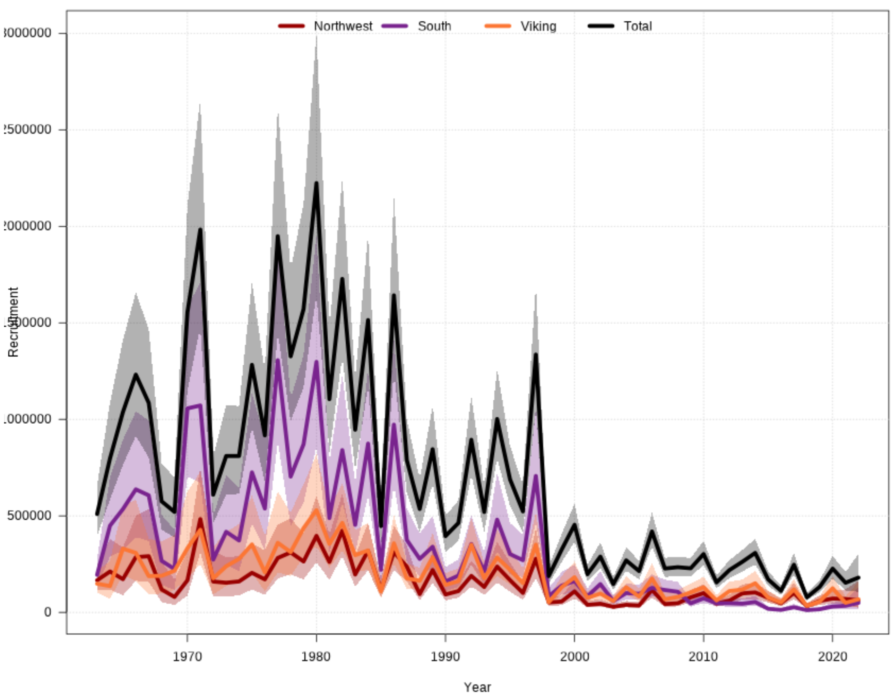


Figure 9: Estimated recruitment from the best obtained configuration using the default data.

(fig. 10). The processes were fitted with different mean parameters for the three stocks, but with the same variance and correlation parameters.

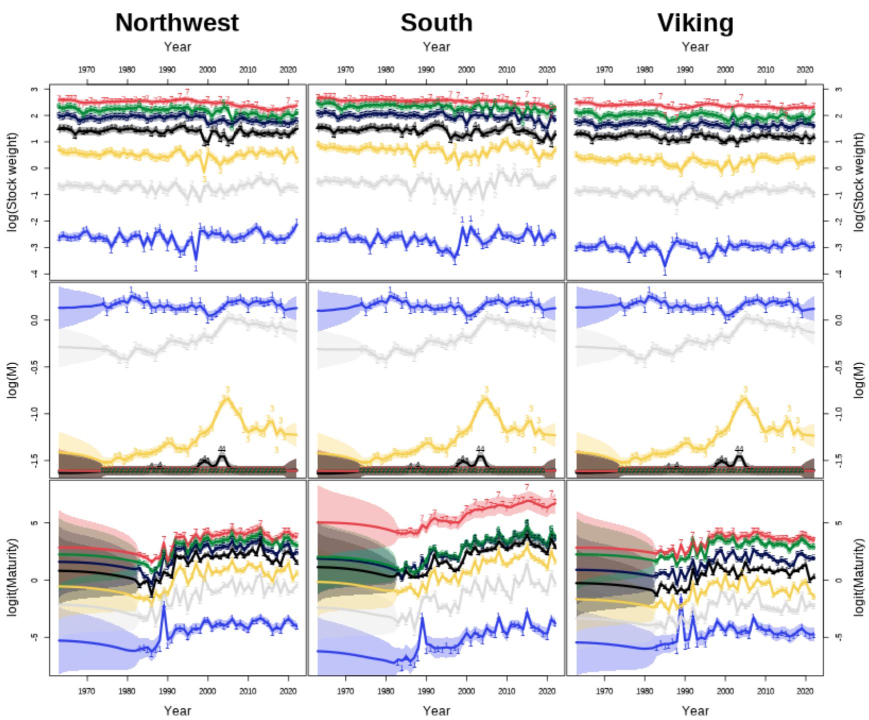


Figure 10: Biological input smoothed by a Gaussian Markov Random Field with measurement noise inside the SAM model from the best obtained configuration using the default data.

8 Model validation

To validate the model fit, one-step-ahead quantile residuals were calculated using the "oneStepGaussianOffMode" method in TMB. Further, a retrospective analysis with five peels was made. Both are plotted below. In general, the residuals seem to have none to few systematic patterns. The main exception is the stock proportions from 1995 onwards, that does seem to give higher one-step predictions in the beginning and lower predictions in the end. Note that while the figure legend goes from -6 to 4, the residuals range from -4.1644264 to 3.8267821. Combined over all fleets, the residuals closely resemble a normal distribution, as expected under the true model. Similarly, the retrospective peels are generally close to the full model fit. Only SSB for the Southern stock has a Mohn's ρ slightly above 0.2. In general, the retrospective peels are worst for 2017 and

2018, while the latest years are close to the full model.

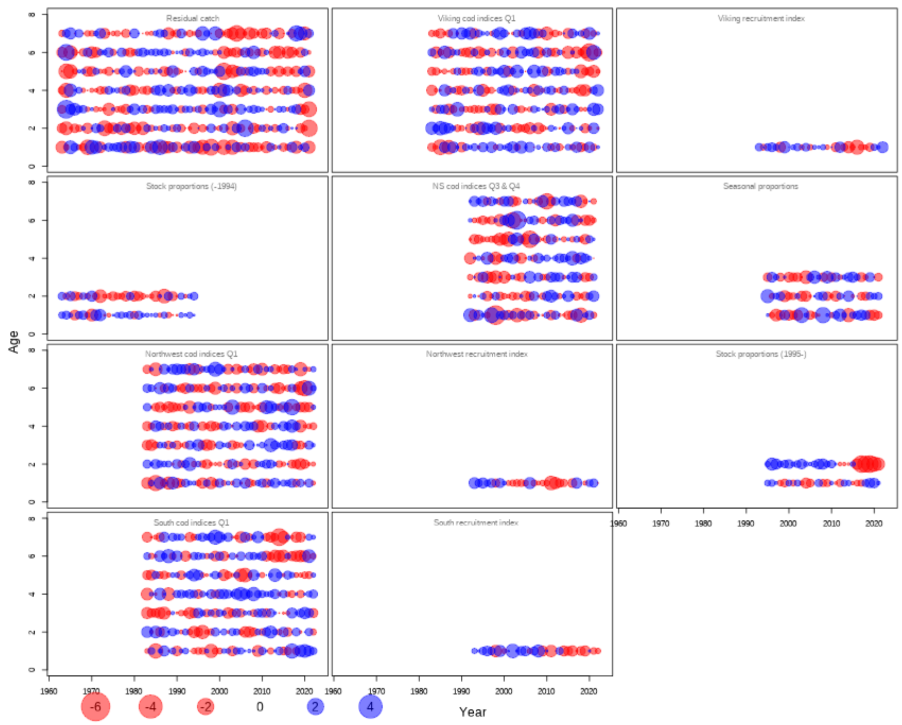


Figure 11: One-step-ahead quantile residuals using the 'oneStepGaussianOffMode' method in TMB for the best obtained configuration using the default data. The residual calculation was ordered by year, fleet, age, season/stock.

9 Sensitivity runs

Several models were fitted as sensitivity runs to test the impact of the assumptions in the model. The models were fitted using the best obtained configuration with the default data, but correcting for changes in fleets, ages, and years. For runs where that configuration did not work, a simpler configuration was attempted. For each run, the model was fitted, residuals were calculated, and retrospective runs were made. The results are illustrated in the figures below. In the figures, runs that did not converge properly are illustrated in semi-transparent colors.

Overview of sensitivity runs.

Run.ID	Description	Positive.definite.Hessian	Proper.convergence	Fitting.error
001_covCombine_0	Uses a Taylor approximation to combine covariances	TRUE	TRUE	FALSE
002_covCombine_1	Uses another Taylor approximation to combine covariances	FALSE	FALSE	FALSE
003_Fsel_Type5	Scales Fbar with random walks, same selectivity for all stocks	NA	NA	TRUE
004_Fsel_Type6	Scales Fbar with random walks, different selectivity	TRUE	TRUE	FALSE

Run.ID	Description	Positive.definite.Hessian	Proper.convergence	Fitting.error
005__Fsel__Type2	Scales Fbar with AR(1), same selectivity for all stocks	NA	NA	TRUE
006__Fsel__Type-1	Same F-at-age for all stocks	TRUE	TRUE	FALSE
007__Fsel__Type1	VAR(1) difference in F-at-age	TRUE	TRUE	FALSE
008__Fsel__TimePoly1	Scales Fbar with AR(1), selectivity scaled by 'poly(Age,3) * poly(Year,1)'	TRUE	TRUE	FALSE
009__Fsel__TimePoly2	Scales Fbar with AR(1), selectivity scaled by 'poly(Age,3) * poly(Year,2)'	TRUE	TRUE	FALSE
010__AgeRange__maxAge6	Plus group at age 6	TRUE	TRUE	FALSE
011__AgeRange__shortSurvey	Q1 survey ages 1-5, Q3-4 survey ages 1-4	FALSE	TRUE	FALSE
012__AgeRange__MaxAge6ShortSurvey	Plus group at age 6, Q1 survey ages 1-5, Q3-4 survey ages 1-4	FALSE	TRUE	FALSE
013__Input__woLH	Using indices excluding large 2017 IBTSQ1 haul from West of Scotland	TRUE	TRUE	FALSE
014__Input__woSeason	Fitted without seasons and seasonal proportions	TRUE	TRUE	FALSE
015__Input__woHistProp	Fitted without stock proportions prior to 1995	FALSE	FALSE	FALSE
016__Input__woProp	Fitted without stock proportions	FALSE	FALSE	FALSE
017__Input__SWasLW	Using stock weights as landing weights for stock proportions	TRUE	TRUE	FALSE
018__Years__1983	Starting model in 1983	TRUE	TRUE	FALSE
019__Years__1992woHistProp	Starting model in 1992, excluding historical proportions	TRUE	TRUE	FALSE
020__NPB__turnOff	Without smoothing of biological input	TRUE	TRUE	FALSE
021__NPB__sw5yr	Without smoothing of biological input, with 5 year average of stock weights	TRUE	TRUE	FALSE
022__NPB__knifeMo	Without smoothing of biological input, using knife edge maturity	TRUE	TRUE	FALSE
023__NPB__knifeMo5yrSW	Combines 021 and 022	TRUE	TRUE	FALSE
024__RecIndx__VIcover0SO	Assuming Viking recruitment index does not cover Southern stock	TRUE	TRUE	FALSE
025__RecIndx__Exclude	Excluding recruitment indices	TRUE	TRUE	FALSE
026__RecIndx__NoRecNoHistProp	Excluding recruitment indices and pre 1995 stock proportions	FALSE	FALSE	FALSE
027__F__AR1	Use VAR(1) for F-at-age instead of RW for first stock	FALSE	TRUE	FALSE
028__Spatial__oldAnewS	Use catch area proportions pre 1995, stock proportions after	TRUE	TRUE	FALSE
029__Spatial__oldAnewA	Use catch area proportions	TRUE	TRUE	FALSE
030__Spatial__oldAnewSNoRec	Use catch area proportions pre 1995, stock proportions after, exclude recruitment indices	TRUE	TRUE	FALSE
031__Spatial__oldAnewANoRec	Use catch area proportions, exclude recruitment indices	TRUE	TRUE	FALSE
032__multiFleet__oldSNewS	Separate West of Scotland fleet	NA	NA	TRUE
032__multiFleet__oldANewS	Separate West of Scotland fleet, use catch area proportions pre 1995	NA	NA	TRUE
034__multiFleet__oldANewA	Separate West of Scotland fleet, use catch area proportions	NA	NA	TRUE
035__SR__001-0	Ricker recruitment	TRUE	TRUE	FALSE
036__SR__001-1	Ricker recruitment AR(1) error	TRUE	TRUE	FALSE
037__SR__001-2	Ricker recruitment AR(2) error	TRUE	TRUE	FALSE
038__SR__002-0	Beverton-Holt recruitment	TRUE	TRUE	FALSE
039__SR__002-1	Beverton-Holt recruitment AR(1) error	TRUE	TRUE	FALSE
040__SR__002-2	Beverton-Holt recruitment AR(2) error	TRUE	TRUE	FALSE
041__SR__063-0	Bent hyperbola recruitment	FALSE	TRUE	FALSE
042__SR__063-1	Bent hyperbola recruitment AR(1) error	FALSE	FALSE	FALSE
043__SR__063-2	Bent hyperbola recruitment AR(2) error	TRUE	TRUE	FALSE
044__SR__064-0	CMP power recruitment	TRUE	TRUE	FALSE
045__SR__064-1	CMP power recruitment AR(1) error	TRUE	TRUE	FALSE
046__SR__064-2	CMP power recruitment AR(2) error	FALSE	TRUE	FALSE
047__SR__066-0	Shepherd recruitment	FALSE	FALSE	FALSE
048__SR__066-1	Shepherd recruitment AR(1) error	FALSE	FALSE	FALSE
049__SR__066-2	Shepherd recruitment AR(2) error	FALSE	TRUE	FALSE
050__SR__067-0	Hassel/Deriso recruitment	FALSE	TRUE	FALSE
051__SR__067-1	Hassel/Deriso recruitment AR(1) error	FALSE	TRUE	FALSE
052__SR__067-2	Hassel/Deriso recruitment AR(2) error	FALSE	TRUE	FALSE
053__SR__068-0	Saila-Lorda recruitment	FALSE	TRUE	FALSE
054__SR__068-1	Saila-Lorda recruitment AR(1) error	FALSE	TRUE	FALSE
055__SR__068-2	Saila-Lorda recruitment AR(2) error	FALSE	TRUE	FALSE
056__SR__069-0	Sigmoidal Beverton-Holt recruitment	TRUE	TRUE	FALSE
057__SR__069-1	Sigmoidal Beverton-Holt recruitment AR(1) error	TRUE	TRUE	FALSE
058__SR__069-2	Sigmoidal Beverton-Holt recruitment AR(2) error	NA	NA	TRUE
059__SR__090-0	CMP spline recruitment	FALSE	TRUE	FALSE
060__SR__090-1	CMP spline recruitment AR(1) error	FALSE	TRUE	FALSE
061__SR__090-2	CMP spline recruitment AR(2) error	FALSE	TRUE	FALSE
062__SR__093-0	Convex compensatory spline recruitment	NA	NA	TRUE
063__SR__093-1	Convex compensatory spline recruitment AR(1) error	NA	NA	TRUE
064__SR__093-2	Convex compensatory spline recruitment AR(2) error	FALSE	TRUE	FALSE
065__SR__201-0	Type B depensatory Ricker recruitment	FALSE	TRUE	FALSE
066__SR__201-1	Type B depensatory Ricker recruitment AR(1) error	FALSE	FALSE	FALSE
067__SR__201-2	Type B depensatory Ricker recruitment AR(2) error	FALSE	FALSE	FALSE
068__SR__202-0	Type B depensatory Beverton-Holt recruitment	FALSE	TRUE	FALSE
069__SR__202-1	Type B depensatory Beverton-Holt recruitment AR(1) error	TRUE	FALSE	FALSE
070__SR__202-2	Type B depensatory Beverton-Holt recruitment AR(2) error	FALSE	FALSE	FALSE
071__Season__AR	Use AR(1) process for seasonal F	TRUE	TRUE	FALSE
072__Request__1983-SA-SA	Start in 1983	TRUE	TRUE	FALSE
073__Request__1983-CA-SA	Start in 1983, use catch areas pre 1995	TRUE	TRUE	FALSE
074__Request__1983-NA-SA	Start in 1983, no proportional data pre 1995	TRUE	TRUE	FALSE
075__Request__1983-NA-NA	Start in 1983, no proportional data	NA	NA	TRUE
076__Xtra__useSurveySd	Scale survey covariance by GAM standard errors	FALSE	TRUE	FALSE

10 Consistency between model runs

Across sensitivity runs, the results seem robust to assumptions and modelling in the later period with two surveys. In early period, there is a difference between using area or stock proportions, depending on the spatial assumptions imposed. Figures illustrating the variability across all sensitivity runs are included below.

11 Comparison with a combined all-as-one single stock fit

Finally, the fit was compared to the results of a all-as-one single stock SAM fit. Although there are differences in the assumptions and configurations, the two model fits tend to provide similar estimated trajectories.

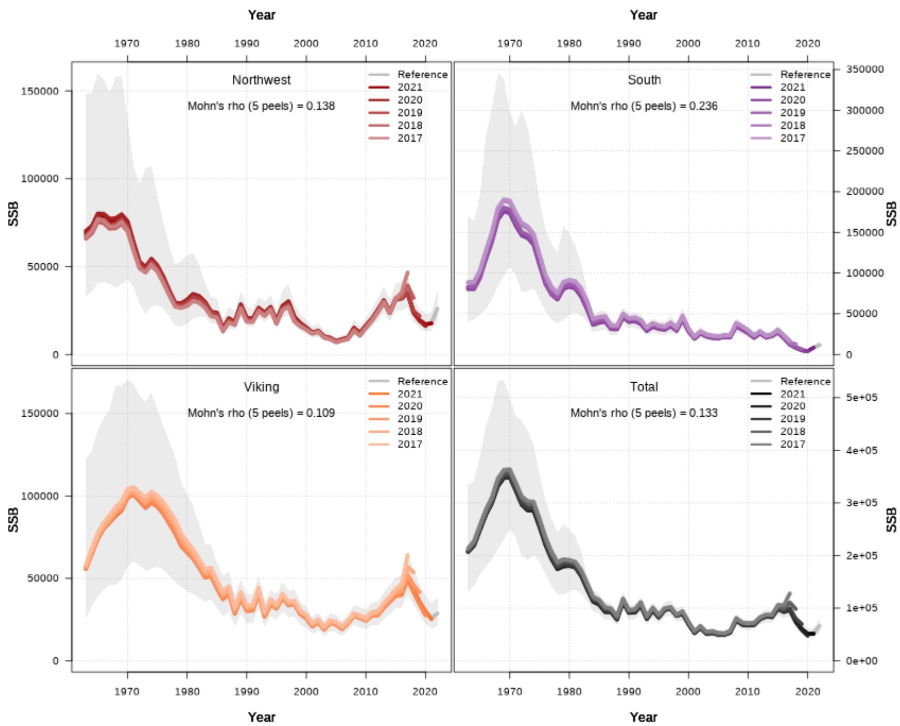


Figure 12: Retrospective peels and Mohn's ρ for SSB for the best obtained configuration using the default data

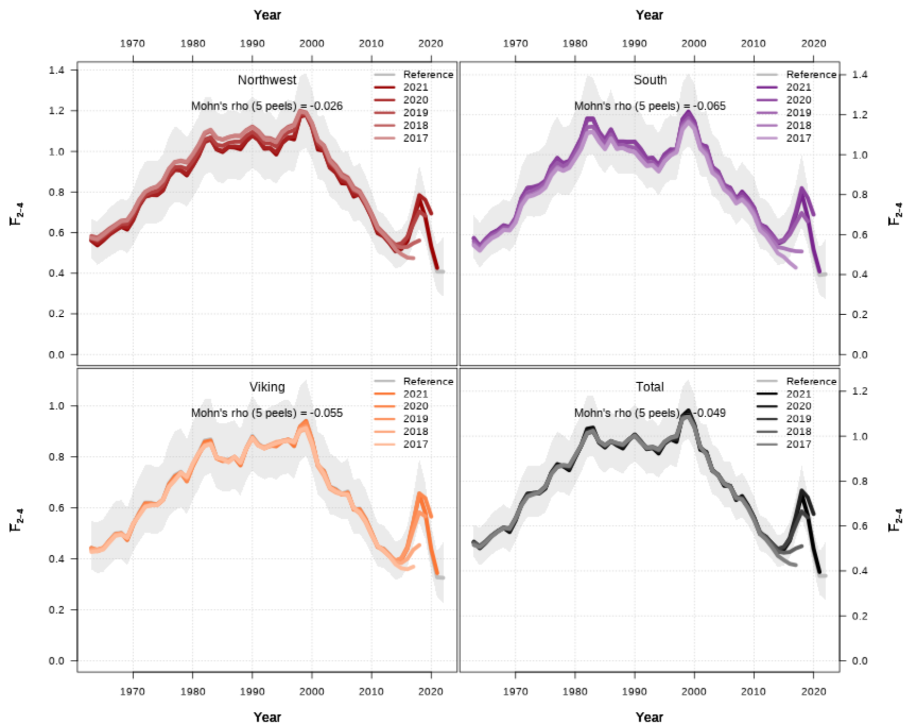


Figure 13: Retrospective peels and Mohn's ρ for average fishing mortality rate for the best obtained configuration using the default data

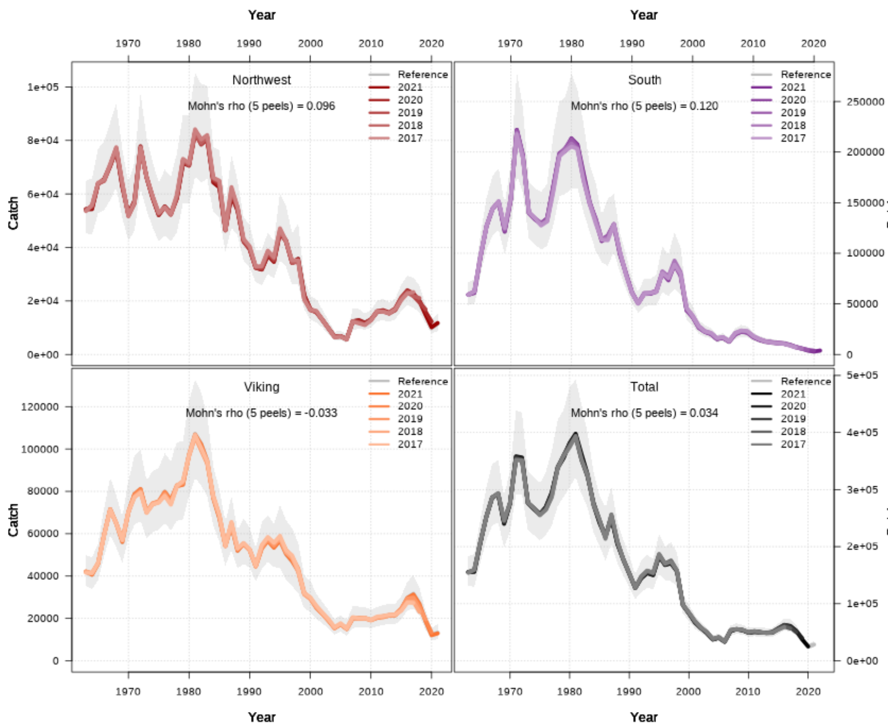


Figure 14: Retrospective peels and Mohn's ρ for catch for the best obtained configuration using the default data

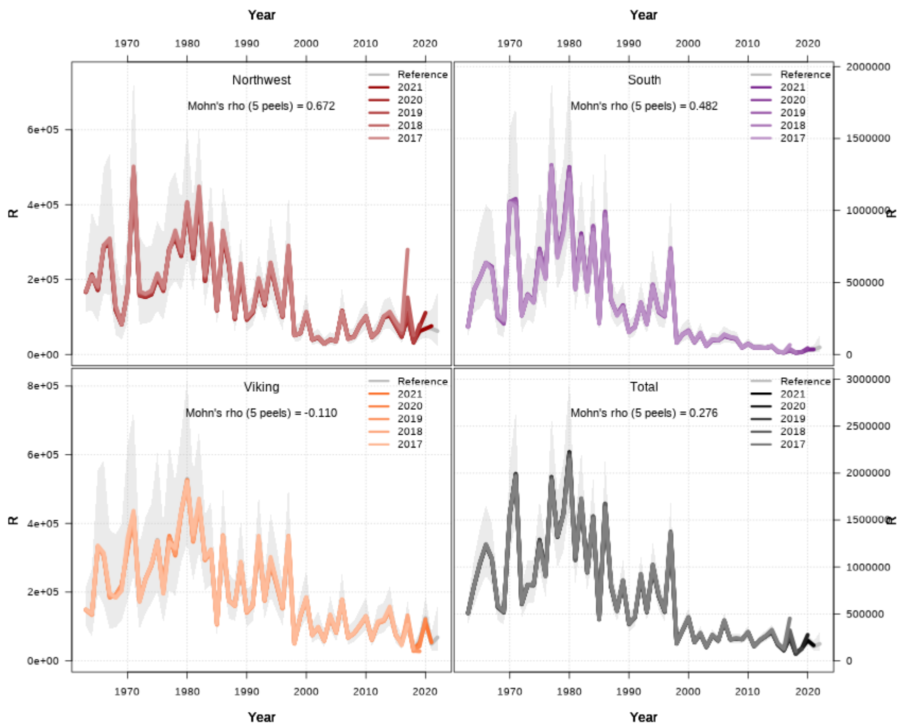


Figure 15: Retrospective peels and Mohn's ρ for recruitment for the best obtained configuration using the default data

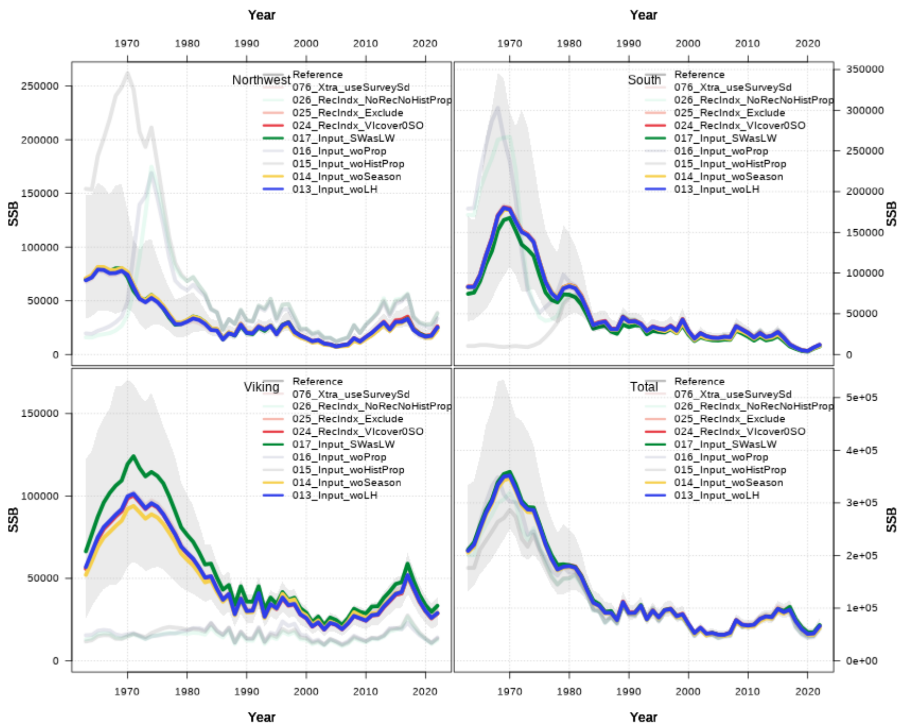


Figure 16: Estimated SSB trajectories from sensitivity runs for observational data.

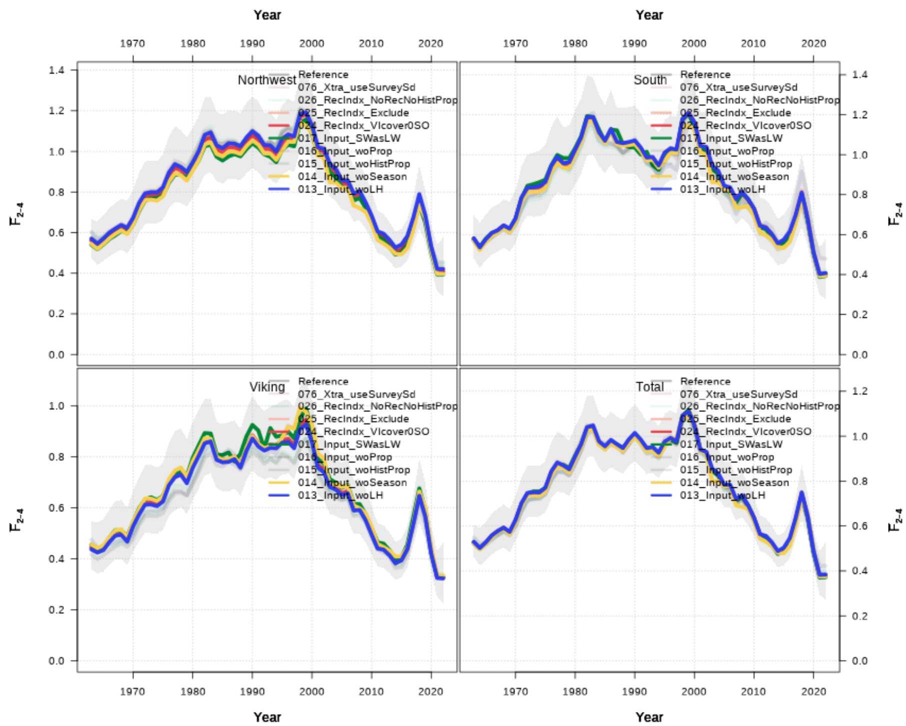


Figure 17: Estimated average fishing mortality trajectories from sensitivity runs for observational data.

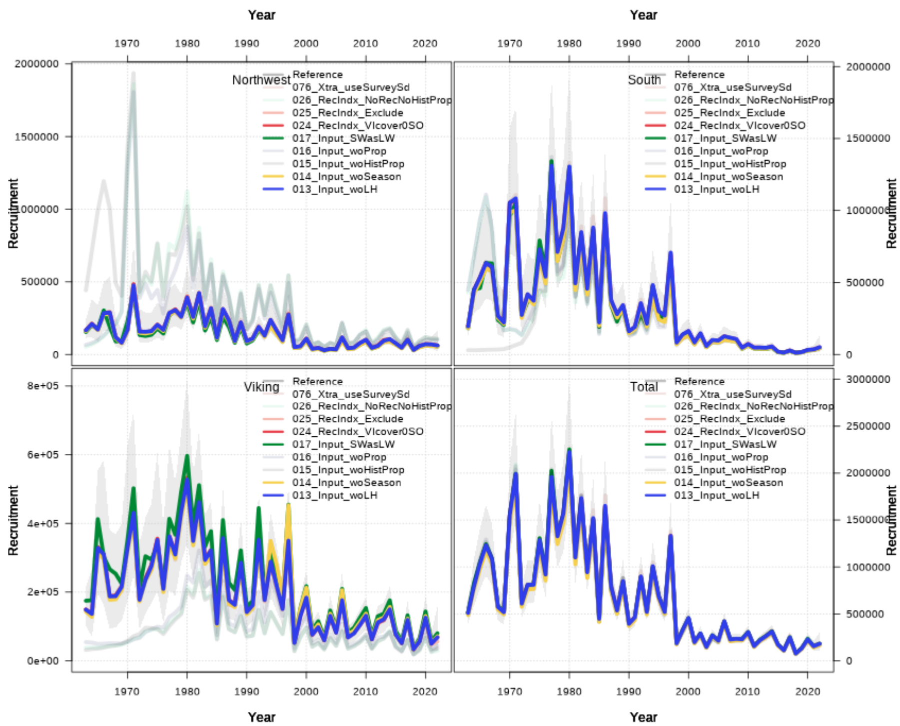


Figure 18: Estimated recruitment trajectories from sensitivity runs for observational data

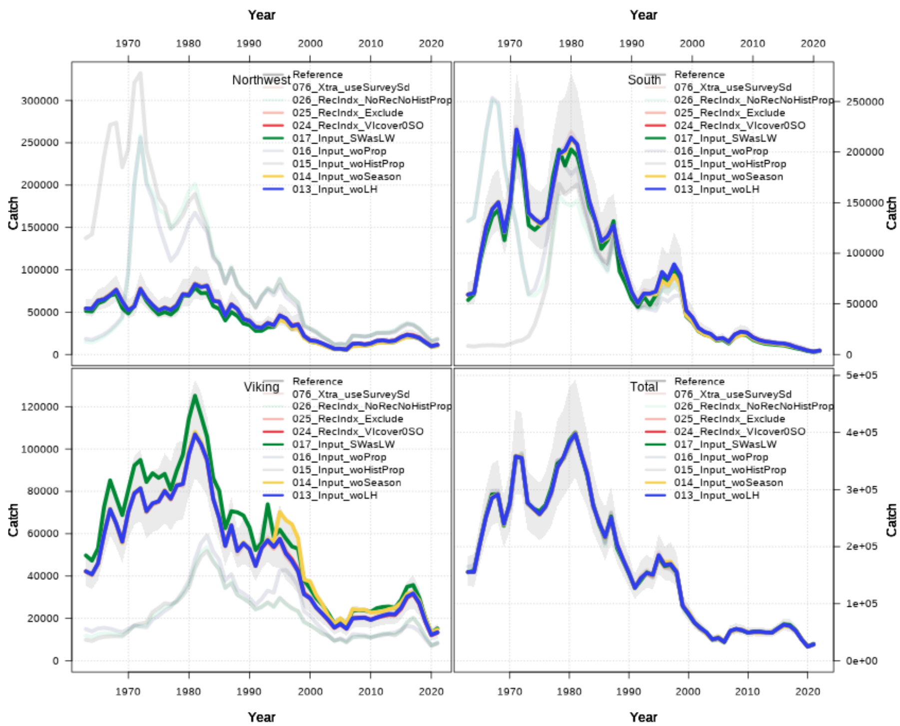


Figure 19: Estimated catch trajectories from sensitivity runs for observational data

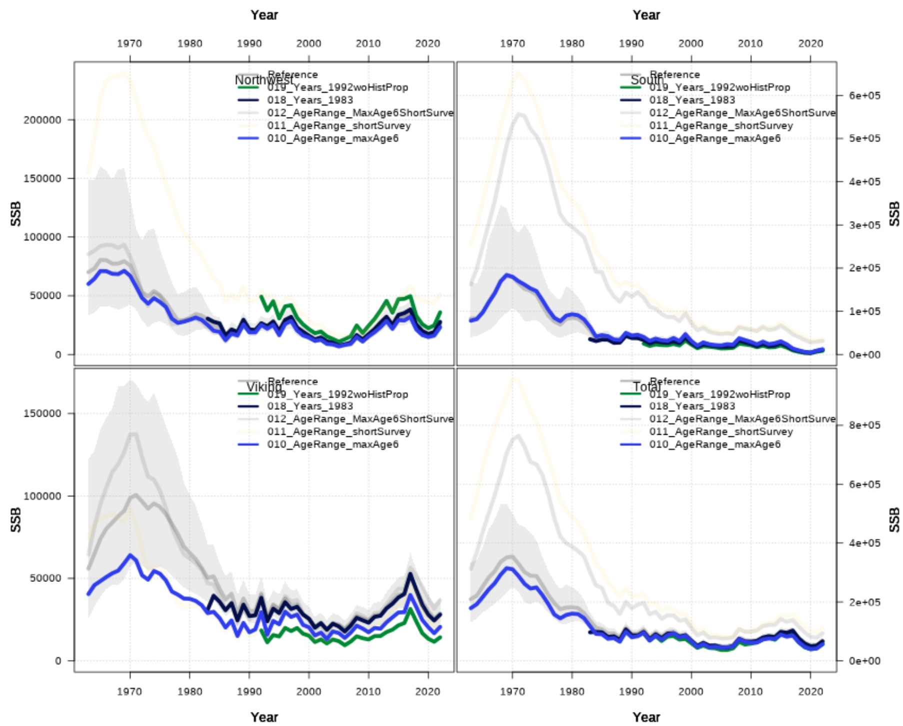


Figure 20: Estimated SSB trajectories from sensitivity runs for age and year ranges

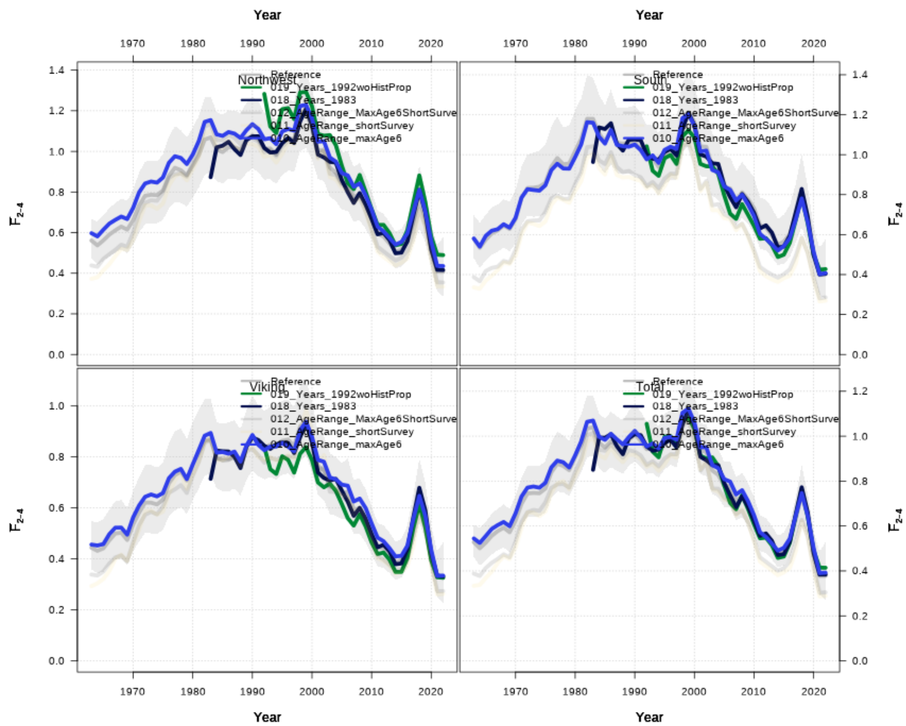


Figure 21: Estimated average fishing mortality rate trajectories from sensitivity runs for age and year ranges

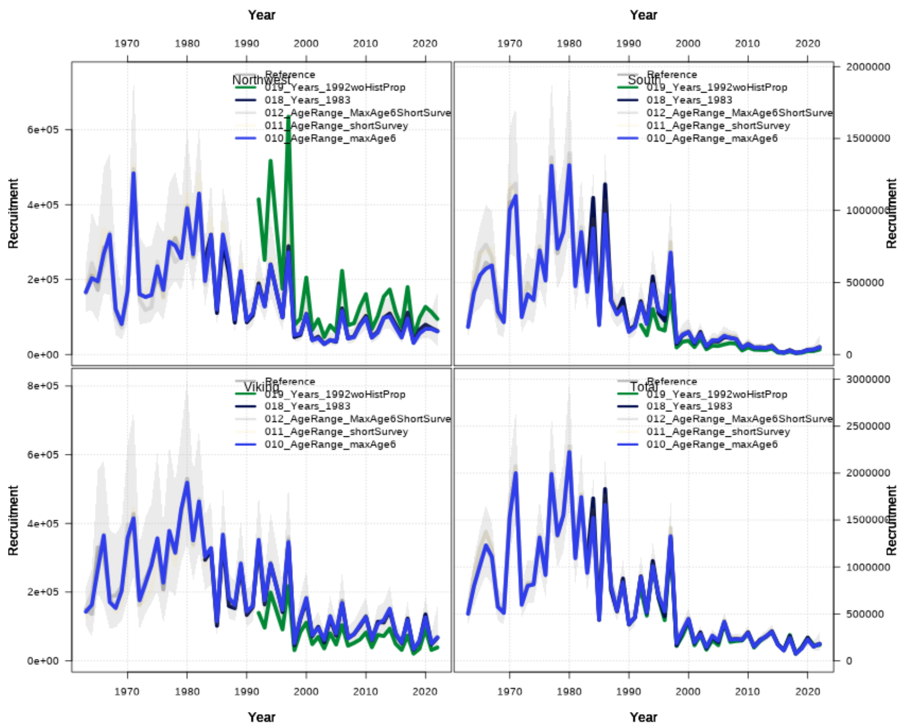


Figure 22: Estimated recruitment trajectories from sensitivity runs for age and year ranges

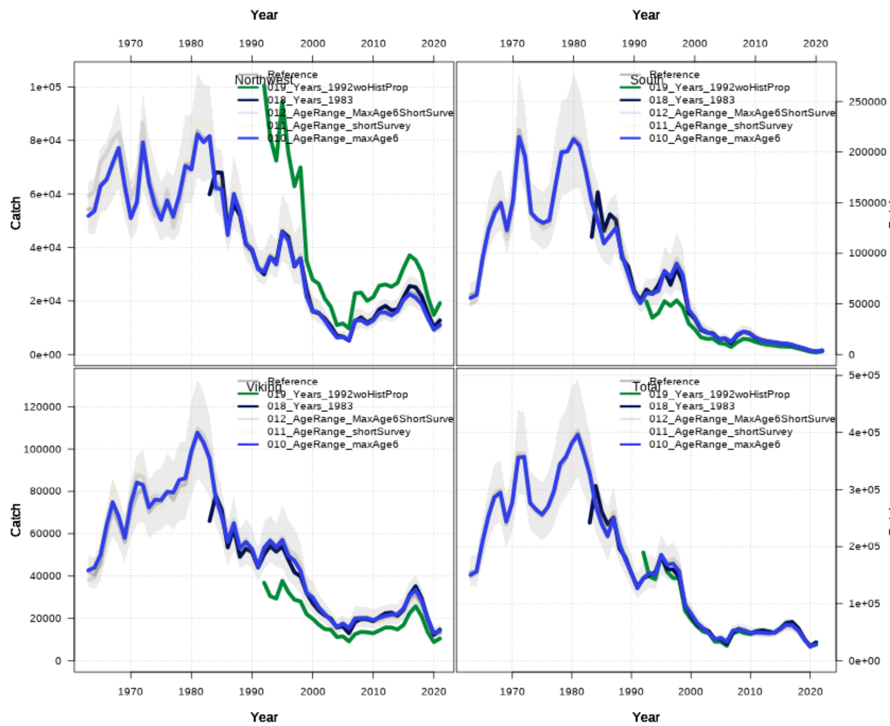


Figure 23: Estimated catch trajectories from sensitivity runs for age and year ranges

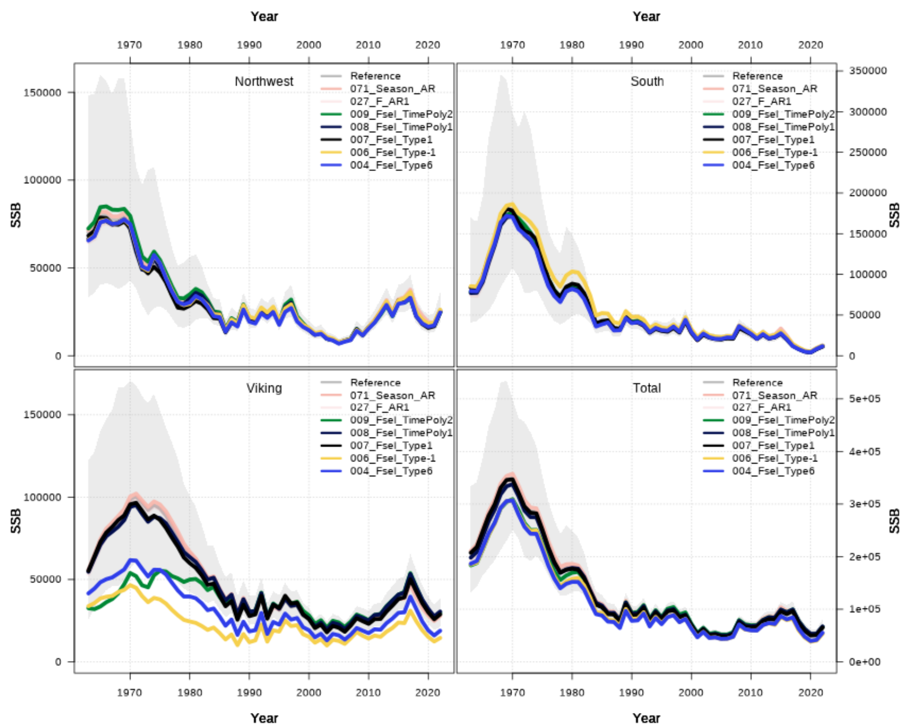


Figure 24: Estimated SSB trajectories from sensitivity runs for F

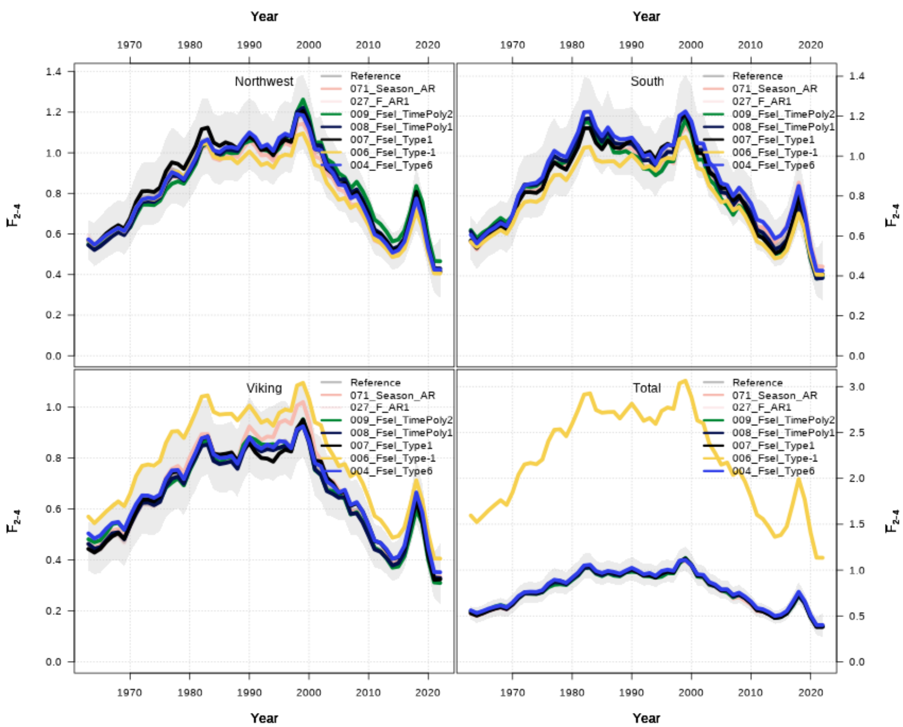


Figure 25: Estimated average fishing rate trajectories from sensitivity runs for F

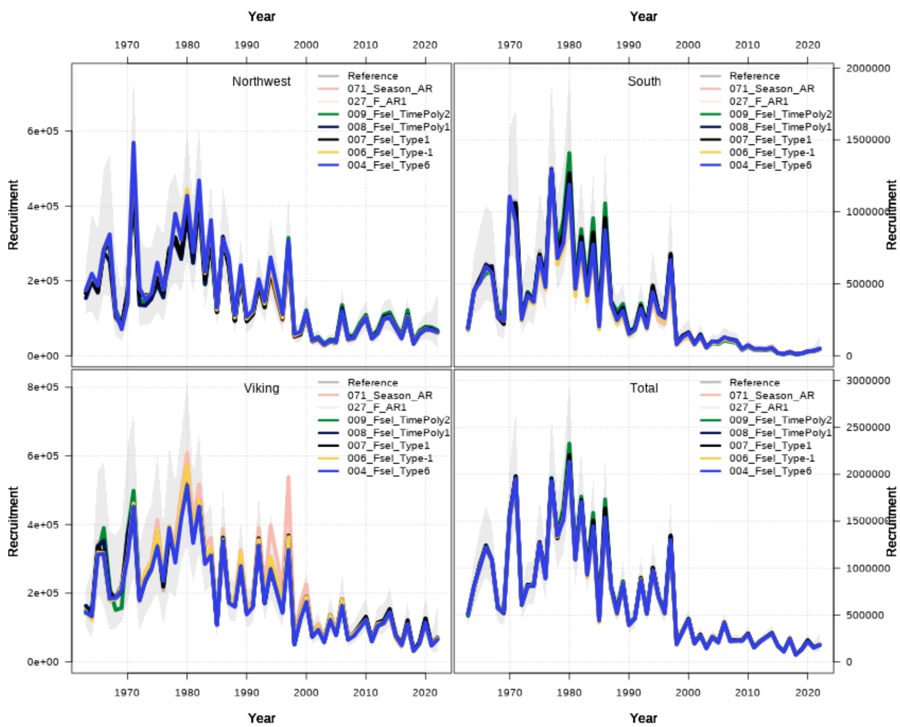


Figure 26: Estimated recruitment trajectories from sensitivity runs for F

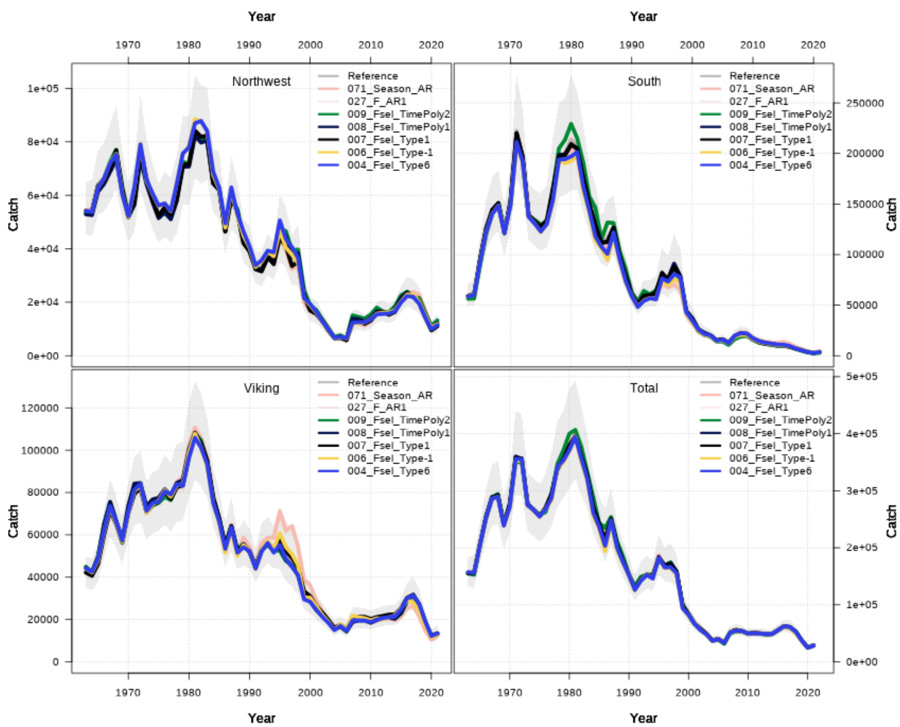


Figure 27: Estimated catch from sensitivity runs for F

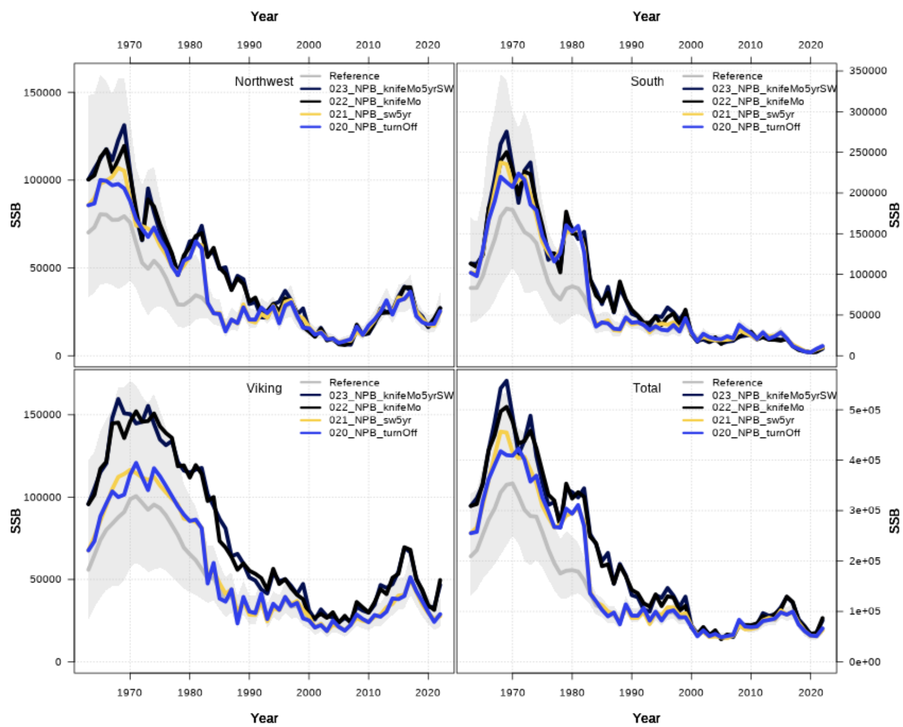


Figure 28: Estimated SSB trajectories from sensitivity runs for biological input

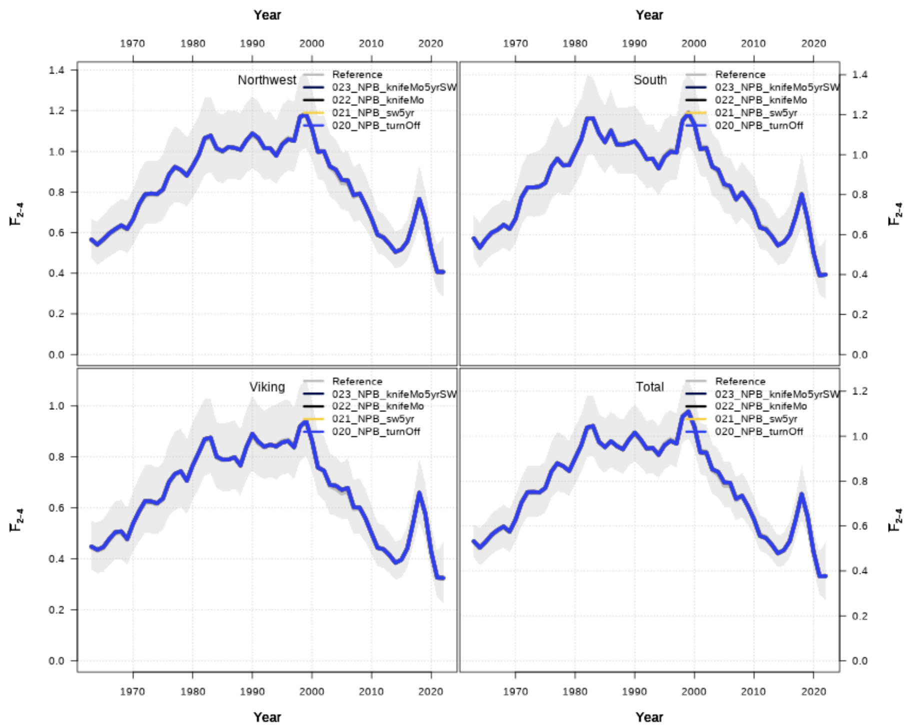


Figure 29: Estimated average fishing rate trajectories from sensitivity runs for biological input

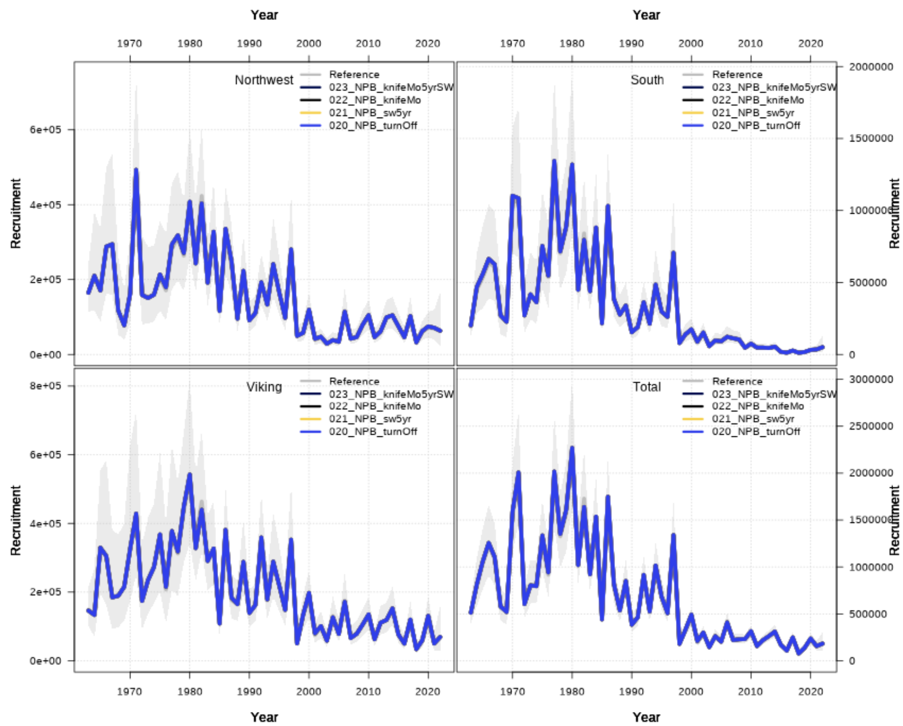


Figure 30: Estimated recruitment trajectories from sensitivity runs for biological input

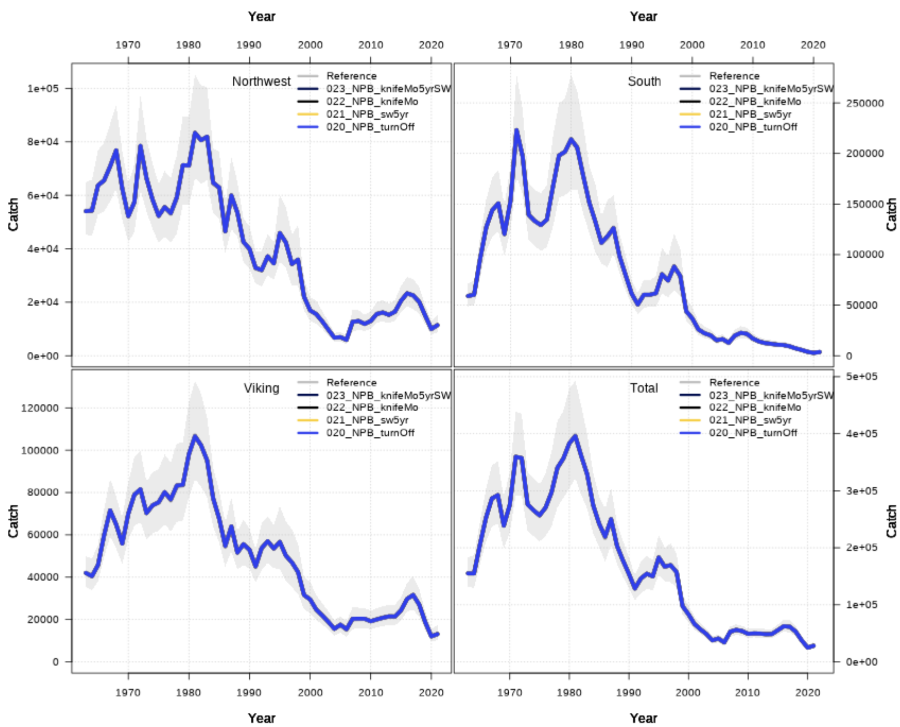


Figure 31: Estimated catch from sensitivity runs for biological input

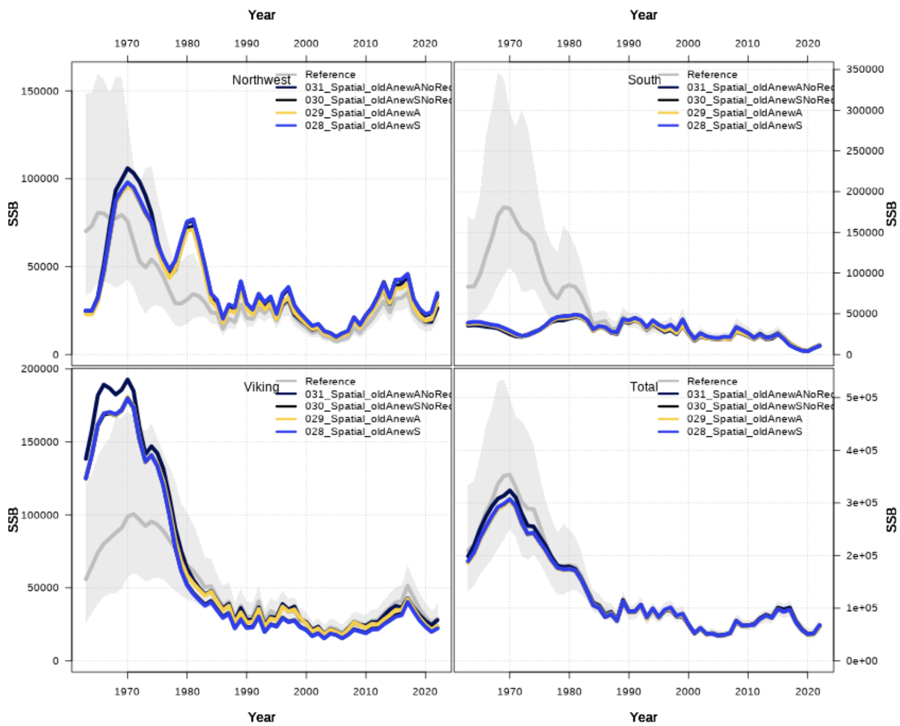


Figure 32: Estimated SSB trajectories from sensitivity runs for spatial assumptions.

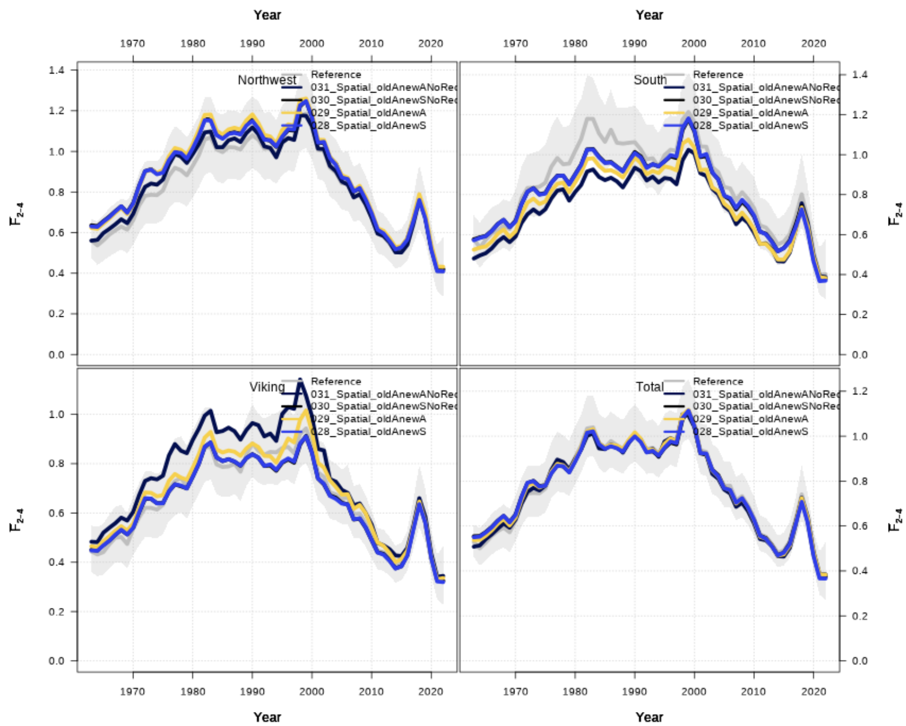


Figure 33: Estimated average fishing rate trajectories from sensitivity runs for spatial assumptions.

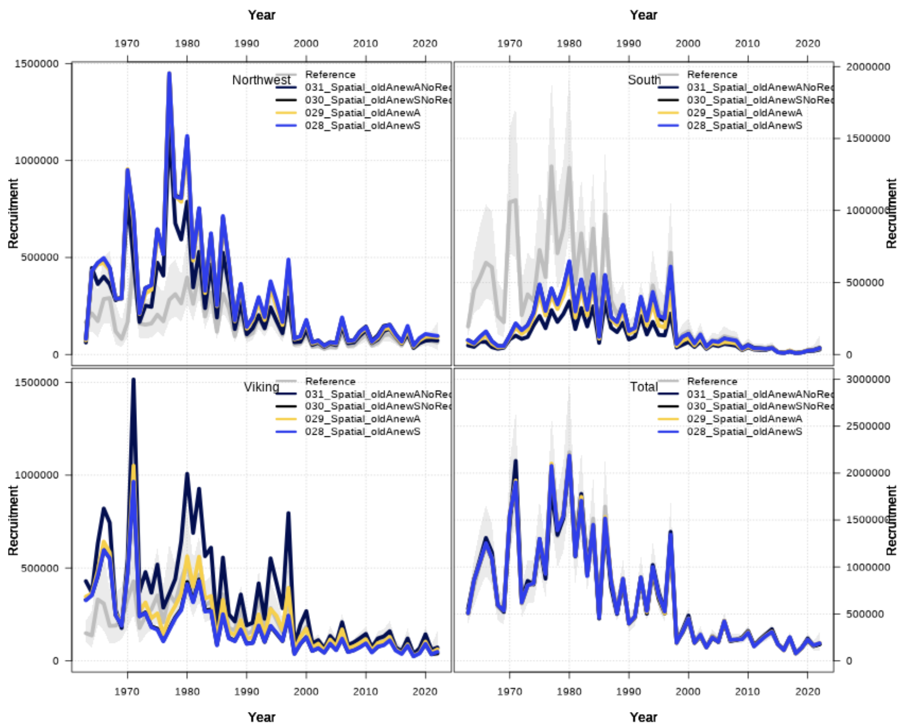


Figure 34: Estimated recruitment trajectories from sensitivity runs for spatial assumptions.

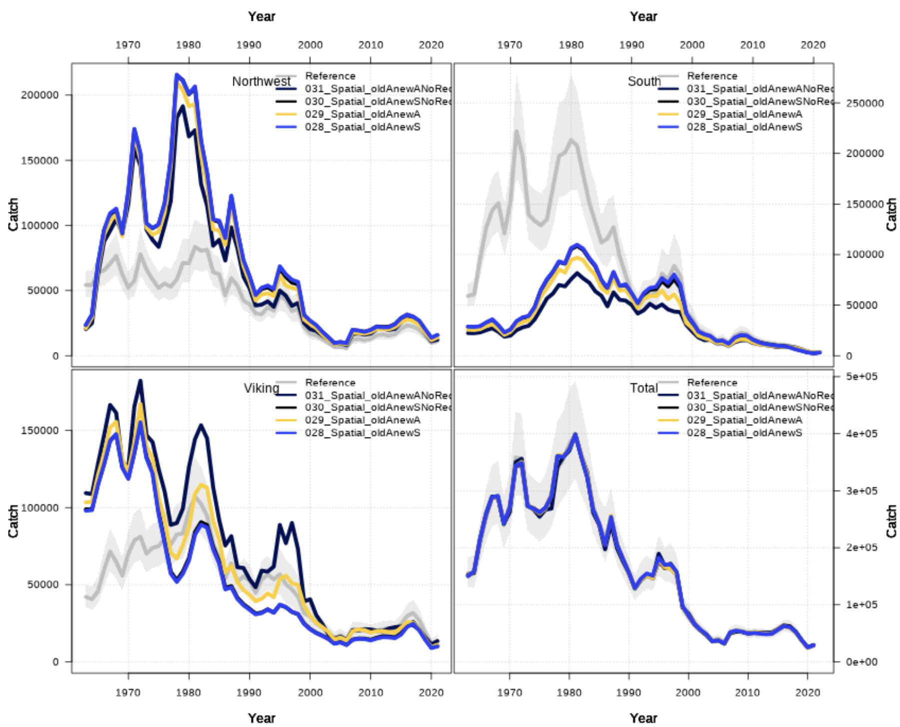


Figure 35: Estimated catch from sensitivity runs for spatial assumptions.

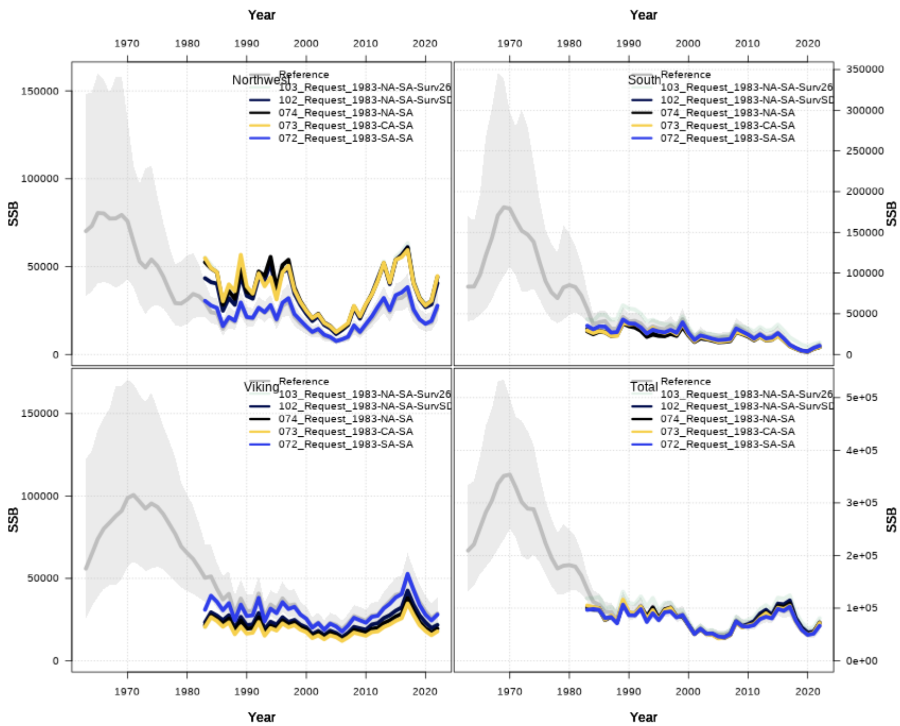


Figure 36: Estimated SSB trajectories from sensitivity runs suggested at the beginning of the benchmark workshop.

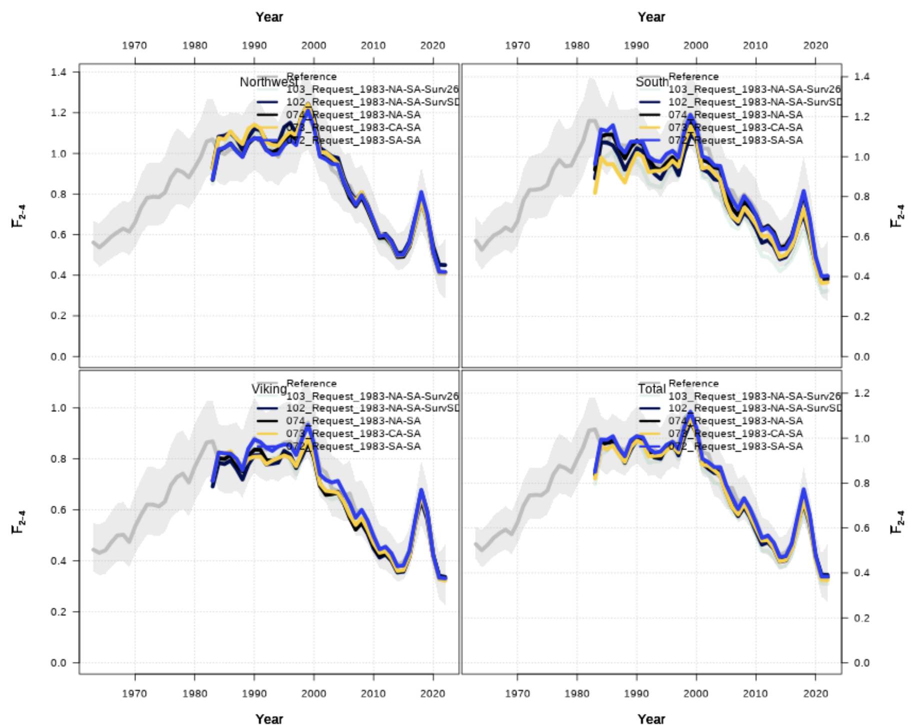


Figure 37: Estimated average fishing rate trajectories from sensitivity runs suggested at the beginning of the benchmark workshop.

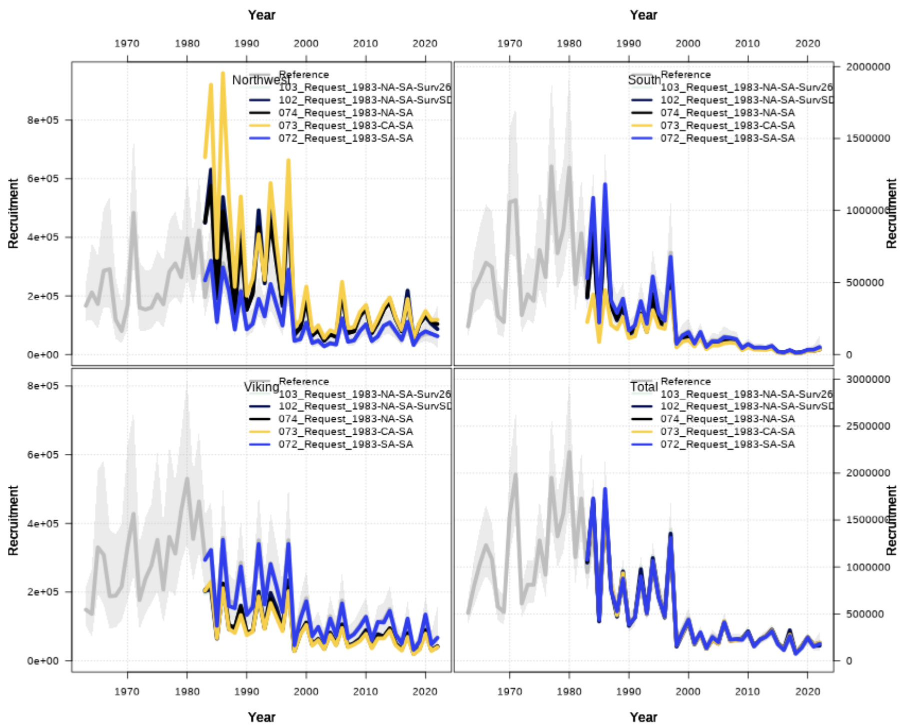


Figure 38: Estimated recruitment trajectories from sensitivity runs suggested at the beginning of the benchmark workshop.

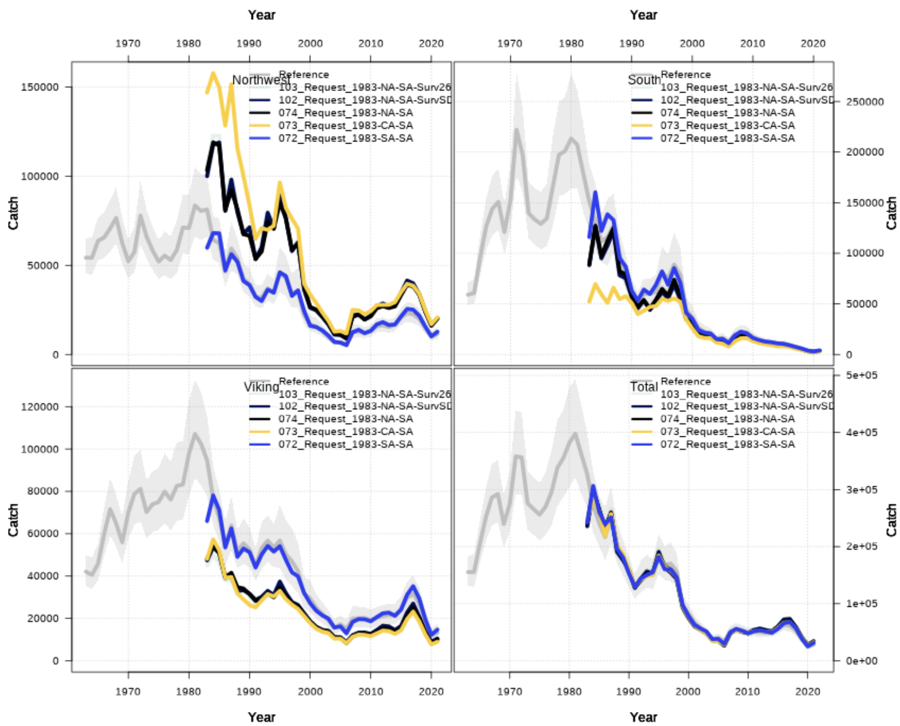


Figure 39: Estimated catch from sensitivity runs suggested at the beginning of the benchmark workshop.

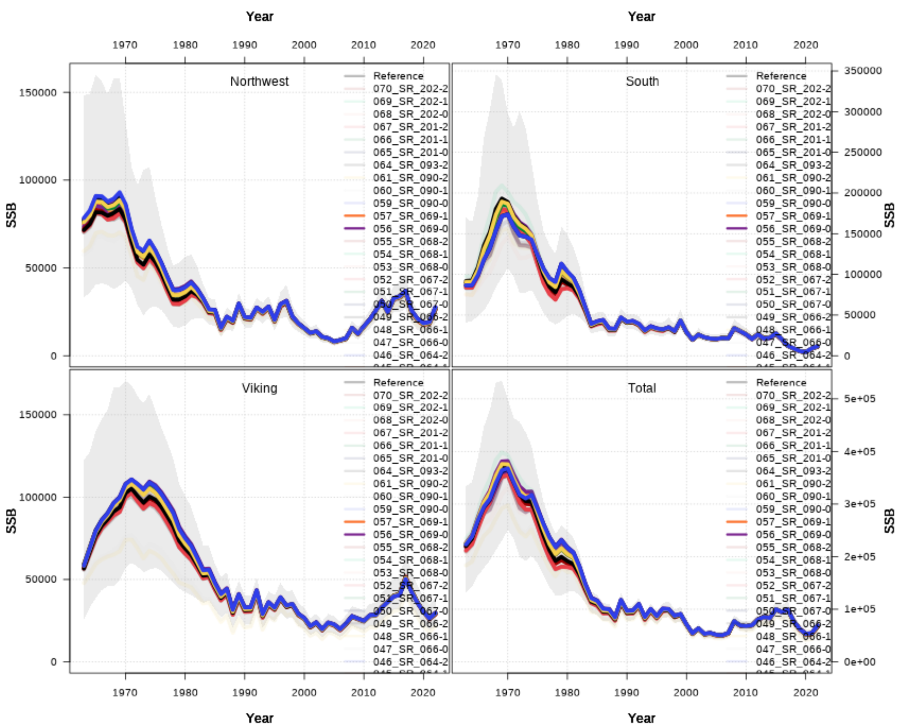


Figure 40: Estimated SSB trajectories from sensitivity runs for recruitment

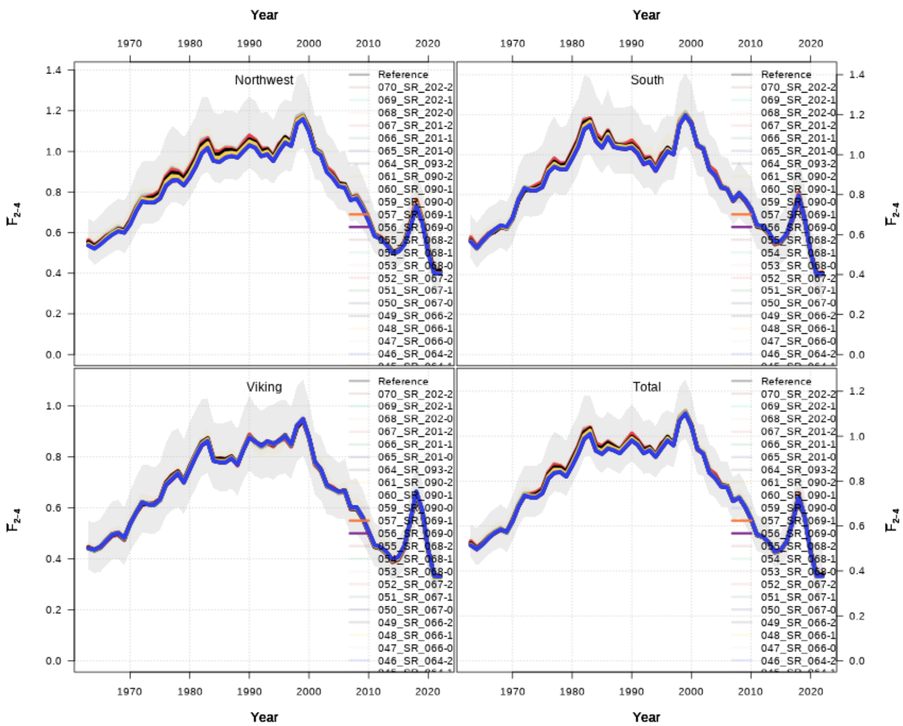


Figure 41: Estimated average fishing rate trajectories from sensitivity runs for rexruitment

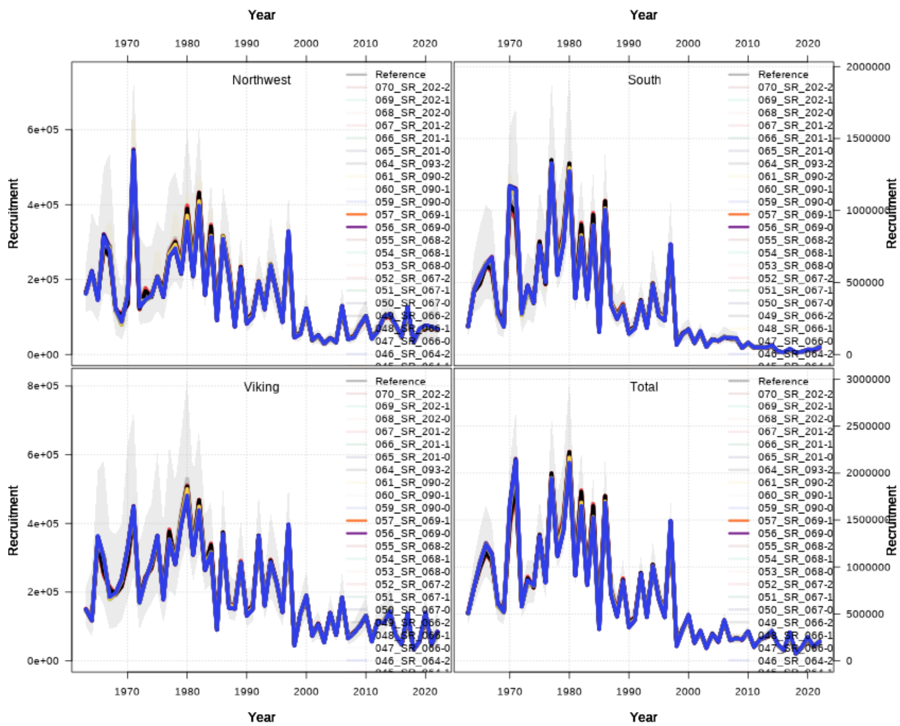


Figure 42: Estimated recruitment trajectories from sensitivity runs for recruitment

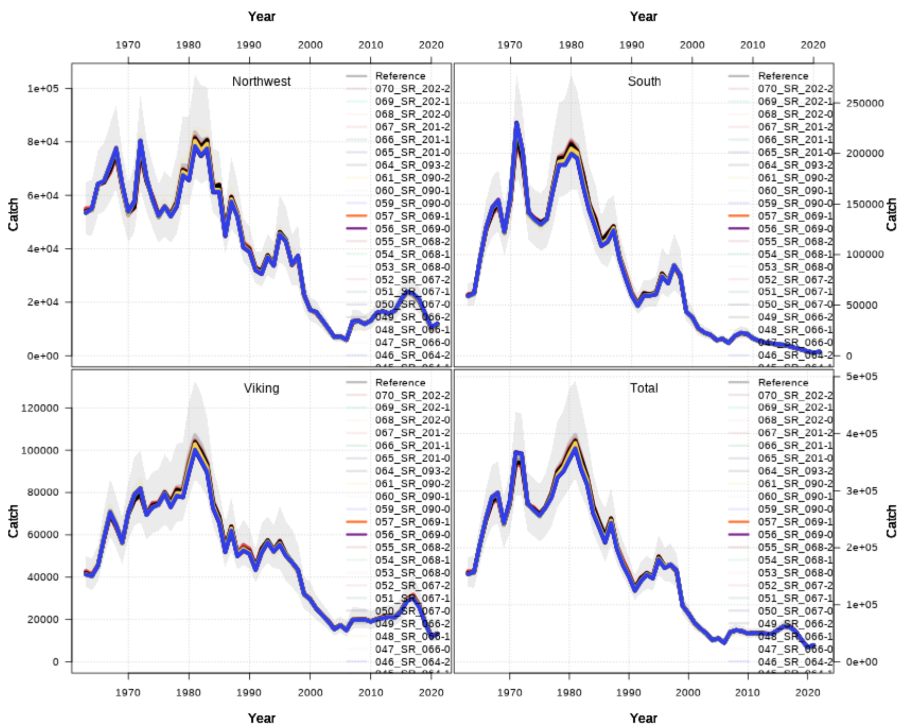
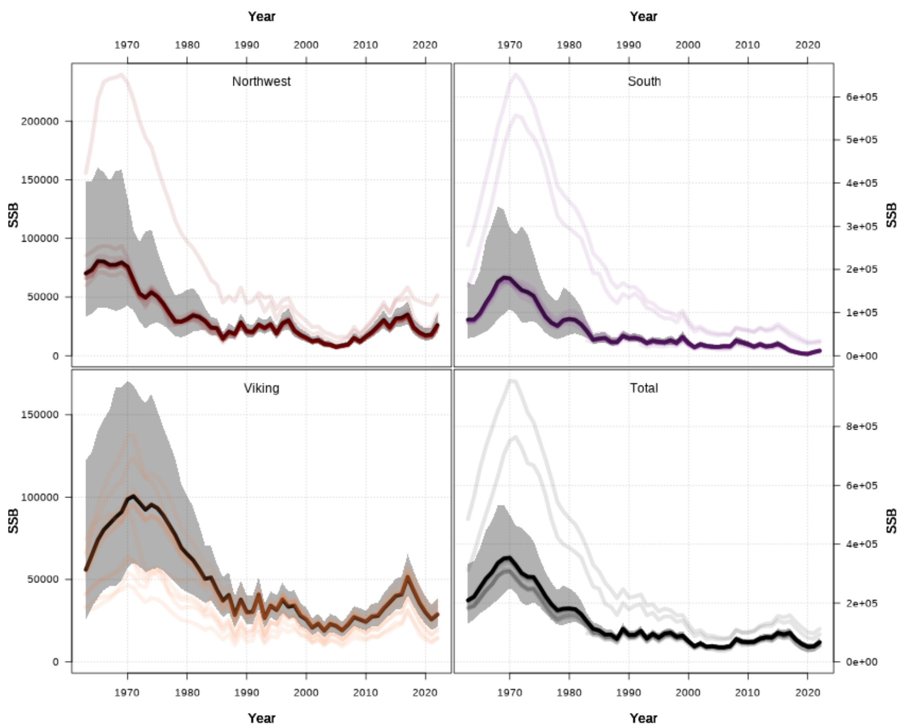
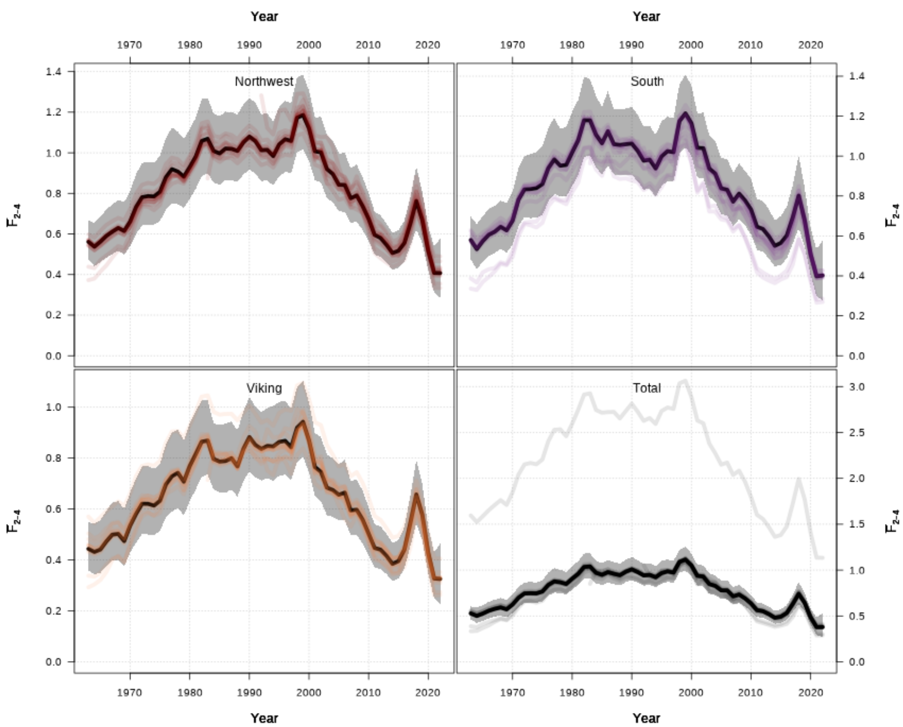
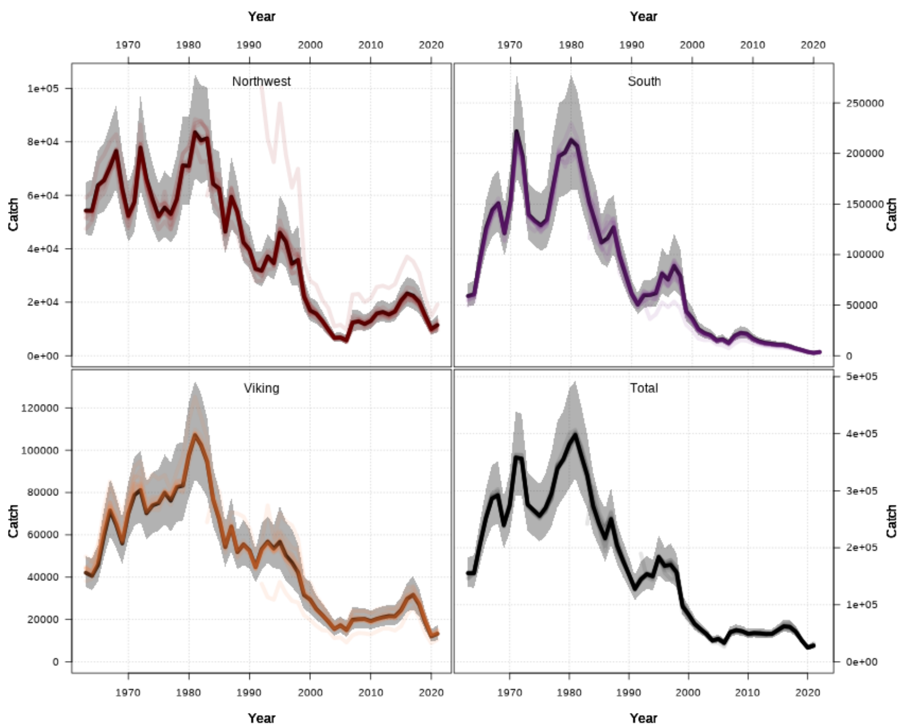


Figure 43: Estimated catch from sensitivity runs for recruitment

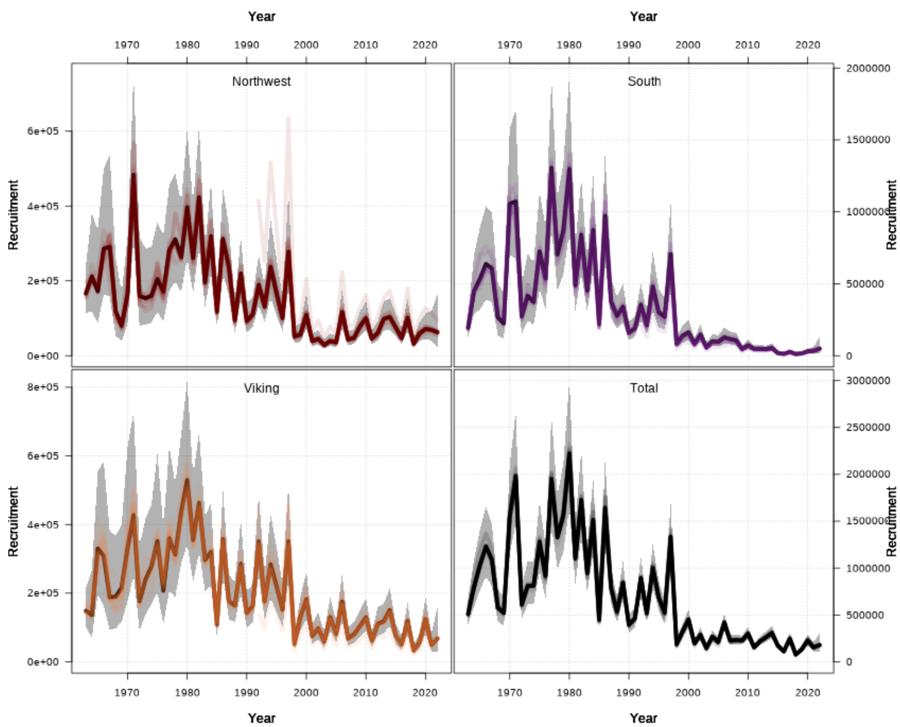

Year
1970 1980 1990 2000 2010 2020
Northwest
South
Viking
Total
SSB
200000
150000
100000
50000
0
6e+05
5e+05
4e+05
3e+05
2e+05
1e+05
0e+00
8e+05
6e+05
4e+05
2e+05
0e+00
Year



Year
Northwest
South
Viking
Total
F2-4
Year



Year
1970 1980 1990 2000 2010 2020
Northwest
South
Viking
Total
Catch
1e+05
8e+04
6e+04
4e+04
2e+04
0e+00
250000
200000
150000
100000
50000
0
120000
100000
80000
60000
40000
20000
0
5e+05
4e+05
3e+05
2e+05
1e+05
0e+00


Northwest
South
Viking
Total
Year
Recruitment
1970
1980
1990
2000
2010
2020
0e+00
2e+05
4e+05
6e+05
8e+05
0
500000
1000000
1500000
2000000
2500000
3000000

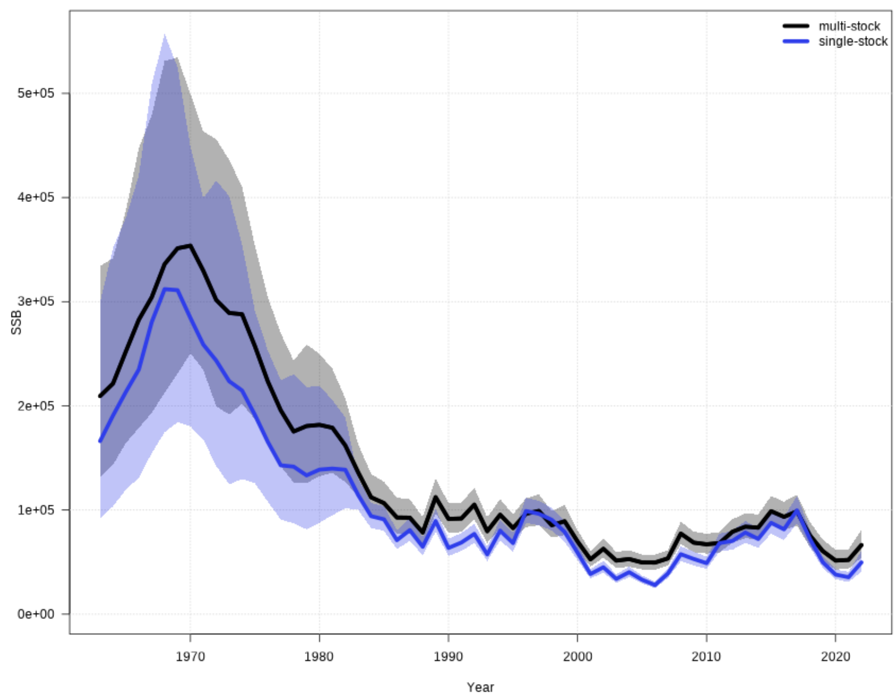


Figure 44: Comparison between estimated SSB trajectories of the multi-stock and single-stock SAM fits.

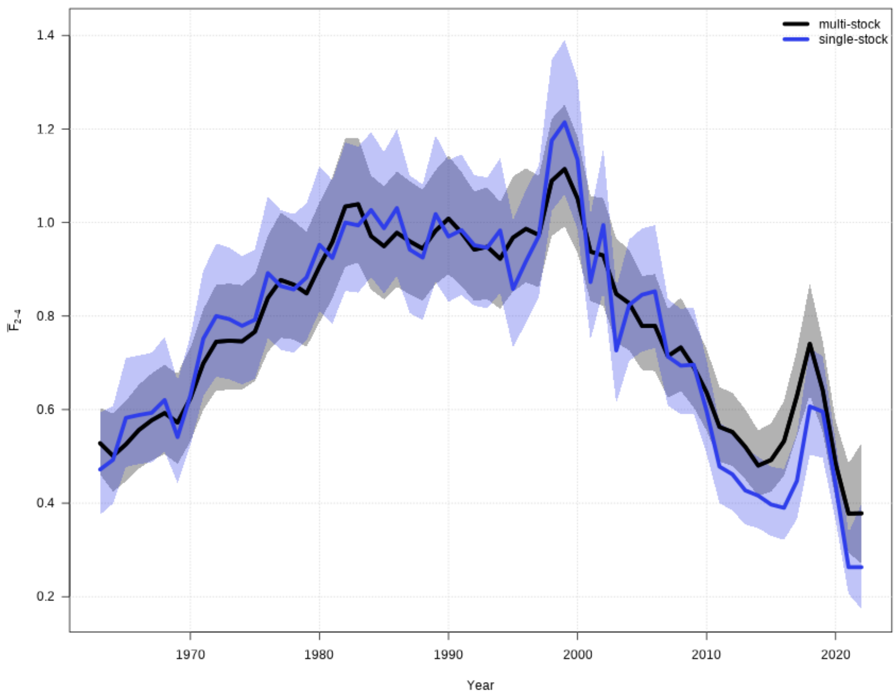


Figure 45: Comparison between estimated average fishing mortality rate trajectories of the multi-stock and single-stock SAM fits.

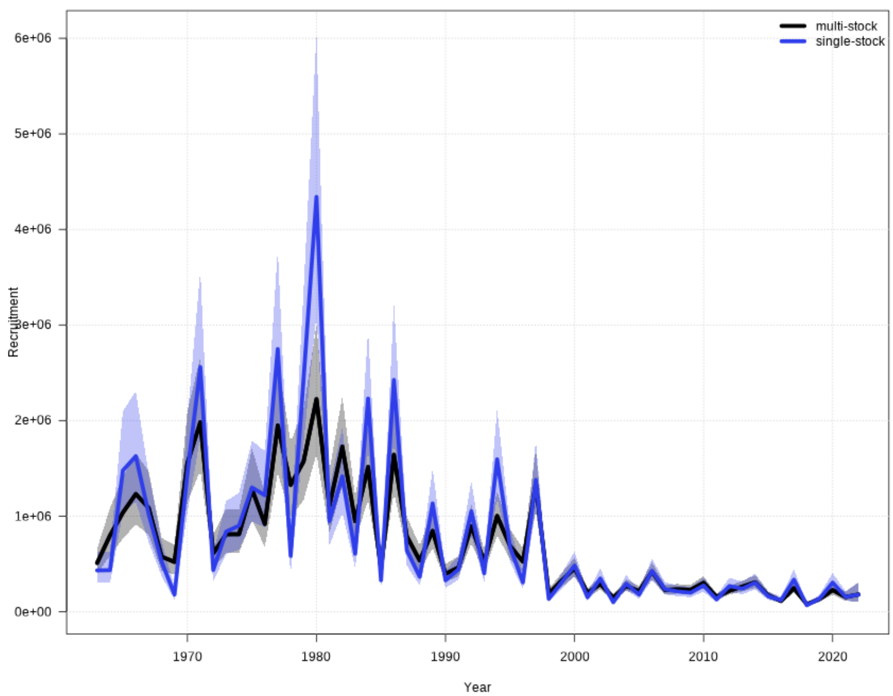


Figure 46: Comparison between estimated recruitment trajectories of the multi-stock and single-stock SAM fits.

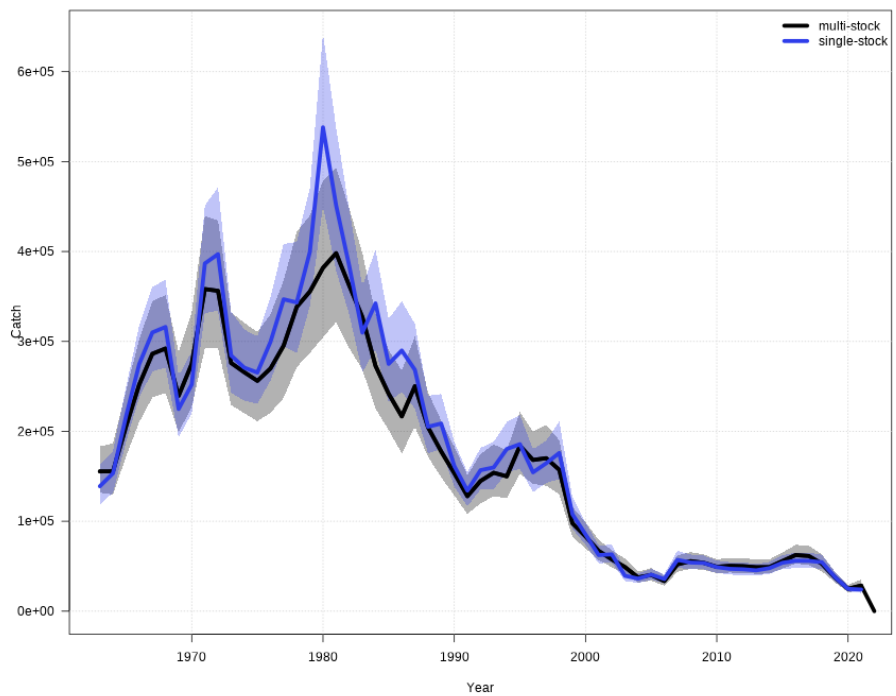


Figure 47: Comparison between estimated catch trajectories of the multi-stock and single-stock SAM fits.

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21.13 Short term forecasts of the Northern Shelf cod stock complex

Short term forecasts of the Northern Shelf cod stock complex

Christoffer Moesgaard Albertsen

1 Introduction

Forecasting catch scenarios is an essential part of scientific advice in fisheries. Both the single-stock and multi-stock SAM models are statistical time-series models. Therefore, the model formulation directly determines how to forecast the modelled system. However, there are different ways to handle the forecast of catch scenarios, including future biological input and recruitment. These options are described below.

2 Forecast functionality in the multiStockassessment package

Both the single-stock and multi-stock SAM R packages includes functions to forecast the assessed system. While the single-stock SAM package includes both a `forecast` and `modelforecast` function, the multi-stock package only includes a `modelforecast` function. Both procedures use the model equations to forecast the system. The modelforecast function can do either simulation based forecasts, or forecasts using the Laplace approximation to give a most likely trajectory into the future. Here, forecasts using the simulation based `modelforecast` functions are described.

With the modelforecast procedure, each simulation corresponds to a hypothetical universe with a hypothetical manager setting a target F for the year to come. Neither the universe nor the manager has any information about other hypothetical universes or managers. That is, each simulation is done in isolation. At the beginning of each year, the hypothetical manager sets a target F for the coming year based on a deterministic forecast of abundance, N, fishing mortality rates, F, and biological input data in the years before. An option is available to do a non-linearity correction, such that the target corresponds to a second order approximation of the log-mean instead of a deterministic forecast of the value. Consequently, when the hypothetical manager sets the target, any simulated value for the affected year is unknown. Further, stochasticity will be added to the target F depending on the settings. As a result, summaries of simulated values will never correspond exactly to the constraints set due to random variability in the simulations.

In summary, the simulation procedure is:

1) Given F and N until year $y-1$, do a deterministic forecast (with optional non-linearity correction) to calculate $\tilde{F}$ corresponding to the target for year y
2) Simulate F for year y with $\log \tilde{F}$ as the log-mean
3) Simulate N for year y
4) Calculate output such as expected catch
5) Continue to year $y+1$

2.1 Target F

Target F for the coming year is set based on input constraints for each stock. The constraints can be set directly on F, on catch, landings, next years SSB, next years TSB, using a harvest control rule, or using the fitted model (see section "Further details on the stockassessment::modelforecast function" below). Each constraint can be given across all ages or for an age range. However, constraints can not currently be used to set selectivity. Therefore, only one constraint can be set per fleet. For fleets without explicit constraints, the ratio between Fs are constrained to be constant. Future versions are expected to allow constraints across stocks in a similar manner. Selectivity can either be fixed or projected by the model.

For the Northern Shelf cod stock complex, the intermediate year F will be constrained by a catch value per stock to be determined by the working group. In the advice year, F will be constrained on a specific target depending on the catch scenario. For the function to return an SSB in the beginning of the year after the advice year, an F target must be given for that year as well. However, the value will not affect the advice.

2.2 Variability in F

Besides the options to determine the log-mean of the projected F process, several options are available to determine the variability in forecasted F values. Four options are available to determine how the variance scales with time. First, F can be set to have zero variability. In practice, the variance is multiplied by 10^{-6}. Note, however, that while the variability in F, given the target value, will be zero for each simulation, there can be variability in F between simulations. The second option is to let the variance in F given the target be constant in time. This will give a stationary F process. Third, the variance can be scaled as a random walk. For a simulation based forecast, the variability given the target is accumulated with this option. Finally, a time-fixed F deviation vector can be used for each simulation.

Further, two options are available to set the process covariance for F. Either the estimated covariance can be used, or the asymptotic normal covariance of the last estimated F vector can be used.

2.3 Recruitment

The `modelforecast` functions allow two options for forecasting recruitment. By default, the estimated recruitment model is used for forecasting. Alternatively, a vector of years can be given. If recruitment years are given, future recruitments are simulated from a log-normal distribution with the same median and log-variance as the recruitment years given.

3 Forecast settings for Northern Shelf cod

Following the discussion at the benchmark workshop, most settings were kept similar to the previous North Sea cod short term forecast. However, F was simulated with a stationary covariance. The covariance was set to the asymptotic normal covariance of the final year estimated F. Further, a non-linearity correction was used when determining F corresponding to target values in the simulations. Finally, landing fraction must be averaged over the same year range as other inputs, when calculated within the forecast. Therefore, a three-year average was used.

Table 1: Suggested settings to be used for short term forecasts

Model component/option	Setting
Method	Simulation based with 1000 replicates
Base year	Last year with catch data
Re-sample first year	Yes, N and F in base year are re-sampled from asymptotic normal distribution of the corresponding estimates
Maturity	Forecasted according to GMRF process
Natural mortality	Forecasted according to GMRF process
Stock weights	Forecasted according to GMRF process
Catch/landing/discard weights	Average of final three years (before intermediate year)
Landing fraction	Average of final three years (before intermediate year)
F and M before spawning	Average of final three years (before intermediate year)
Recruitment	Simulated from a log-normal with the same median and log-variance as recruitment from 1998 onward
Selectivity	Forecasted according to the SAM F process
F covariance	Stationary using asymptotic normal of estimates
Non-linearity correction	Yes

Model component/option	Setting
Intermediate year assumption	Determined by working group based on the best knowledge of the fishery at the time

4 Short term forecast example

To illustrate the forecasting functionality, catch scenarios were forecasted using the settings above. Preliminary reference points were used for the scenarios (table 2). Catch scenarios resembled the catch scenarios used for the advice on fishing opportunities on North Sea cod given in 2022. However, since total allowable catch for the assessment area cannot be directly related to the stocks, scenarios based on the 2022 TAC were changed to scenarios based on the 2022 intermediate year catch assumption. Finally, scenarios using the ICES advice rule applied a harvest control rule in each simulated trajectory. The shape of the harvest control rule is similar to the ICES advice rule, however, SSB below Blim always resulted in $F = 0$ (fig. 1). The working group should follow the ICES procedure.

Table 2: Preliminary reference points used for the short term forecast example. In this example, the reference points are used for catch. Selectivity is stanardized by average F over ages 2 to 4.

Reference point	Northwest	South	Viking
F_{MSY}	0.222	0.193	0.239
$F_{MSY\ lower}$	0.136	0.115	0.155
MSY $B_{trigger}$	28 571	15 099	19 787
B_{lim}	21 964	10 374	13 504
F_{pa}	0.692	0.442	0.635
F_{lim}	0.8328181	0.5014057	0.8508905

4.1 Intermediate year assumption

For illustration, the intermediate year assumption was based on the total allowable catch (TAC) for 2022 within the area as given by “COUNCIL REGULATION (EU) 2022/109 of 27 January 2022 fixing for 2022 the fishing opportunities for certain fish stocks and groups of fish stocks applicable in Union waters and for Union fishing vessels in certain non-Union waters”. It was assumed that the TAC for COD/5BE6A (320 tonnes) would only be fishing on the Northwestern stock, the TAC for COD/07D (772 tonnes) would only be fishing on the Southern stock, and the TAC for COD/03AN (1893 tonnes) and COD/4N-S62 (382 tonnes) would only be fishing on the Viking stock. The TAC for COD/2A3AX4 (13246 tonnes) was split to substocks by assuming that stocks were uniformly

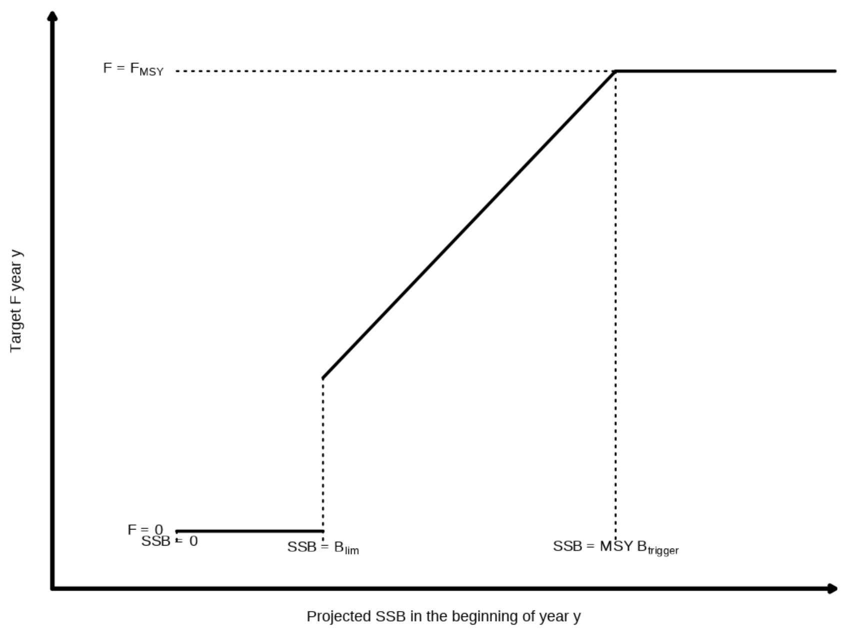

Figure 1: Shape of the harvest control rule used in the short term forecast example. The shape is similar to the ICES advice rule, but always gives $F = 0$ if the projected SSB is below B_{lim}.

distributed in the areas they are present (Northwest: 6a, 4a, 4b; South: 7d, 4c, 4b; Viking: 3a20, 4a, 4b), and calculating the proportion of each stock in 4a-c. In turn, the stock composition in areas 4a-c could be calculated. Finally, the stock composition was used to split the TAC for COD/2A3AX4 to stocks. As a result, the catch targets in 2022 were 8717 for the Northwestern stock, 2896 for the Southern stock, and 5000 for the Viking stock. For future forecasts, the intermediate year assumptions should be determined by the working group based on the best available knowledge of the fishery.

4.2 Results

The results of the short term forecast example is presented in the tables and figures below.

Table 3: Example catch scenarios for the Northwest stock using stochastic F with non-linearity correction and using the asymptotic normal covariance of final year F estimates in the forecast with 1000 replicates. In the first two scenarios, the ICES advice rule is followed in each simulated trajectory.

Basis	Total catch (2023)	Projected landings (2023)	Projected discards (2023)	F_{total} (ages 2 - 4) (2023)	$F_{landings}$ (ages 2 - 4) (2023)	$F_{discard}$ (ages 2 - 4) (2023)	SSB (2024)	% SSB change	% Catch change	% probability of falling below Blim in 2024
MSY approach: F_{MSY} x SSB (2023) / MSY $B_{trigger}$	22691 (14249 - 35998)	20687 (12771 - 33411)	2004 (1478 - 2587)	0.222 (0.163 - 0.301)	0.182 (0.133 - 0.251)	0.040 (0.030 - 0.050)	97077 (61452 - 144875)	31.8 % (-7.8 % - 82.8 %)	160.3 % (63.5 % - 2727993.6 %)	0.0 %
F = F~MSY lower~ x SSB (2023) / MSY $B_{trigger}$	14711 (8978 - 23190)	13414 (8163 - 21495)	1297 (815 - 1695)	0.137 (0.100 - 0.180)	0.112 (0.083 - 0.151)	0.025 (0.017 - 0.029)	105873 (69713 - 157816)	42.2 % (2.3 % - 105.9 %)	68.8 % (3.0 % - 1447193.6 %)	0.0 %
F = 0	0 (0 - 0)	0 (0 - 0)	0 (0 - 0)	0.000 (0.000 - 0.000)	0.000 (0.000 - 0.000)	0.000 (0.000 - 0.000)	125328 (82580 - 191776)	70.3 % (25.4 % - 139.8 %)	-100.0 % (-100.0 % - -871806.4 %)	0.0 %
F = F_{pa}	54628 (36357 - 83015)	48945 (31964 - 75156)	5683 (4393 - 7859)	0.690 (0.514 - 0.942)	0.566 (0.419 - 0.789)	0.124 (0.095 - 0.153)	54572 (34397 - 91279)	-25.6 % (-54.1 % - 16.6 %)	526.7 % (317.1 % - 7429693.6 %)	0.0 %
F = F_{lim}	61131 (41174 - 90941)	54410 (36598 - 82366)	6721 (4576 - 8575)	0.840 (0.608 - 1.141)	0.685 (0.494 - 0.942)	0.155 (0.114 - 0.199)	47184 (27053 - 79055)	-35.0 % (-61.0 % - 5.7 %)	601.3 % (372.3 % - 8222293.6 %)	0.4 %
SSB (2024) = B_{lim}	83825 (52582 - 129872)	73899 (46887 - 114147)	9926 (5695 - 15725)	1.577 (1.037 - 2.445)	1.295 (0.848 - 2.051)	0.282 (0.189 - 0.394)	22196 (13067 - 36333)	-69.5 % (-84.6 % - -44.6 %)	861.6 % (503.2 % - 12115393.6 %)	48.2 %
SSB (2024) = MSY $B_{trigger}$	78111 (46291 - 123687)	68969 (40857 - 107628)	9142 (5434 - 16059)	1.324 (0.819 - 2.010)	1.082 (0.659 - 1.689)	0.242 (0.160 - 0.321)	28594 (17696 - 45351)	-61.1 % (-79.8 % - -30.8 %)	796.1 % (431.0 % - 11496893.6 %)	13.5 %
Catch (2022) - 20%	7111 (4428 - 11166)	6483 (4057 - 10414)	628 (371 - 752)	0.063 (0.037 - 0.107)	0.052 (0.030 - 0.086)	0.011 (0.007 - 0.021)	117559 (77626 - 187171)	58.3 % (14.9 % - 119.9 %)	-18.4 % (-49.2 % - 244793.6 %)	0.0 %

Basis	Total catch (2023)	Projected landings (2023)	Projected discards (2023)	F_{total} (ages 2 - 4) (2023)	$F_{landings}$ (ages 2 - 4) (2023)	$F_{discard}$ (ages 2 - 4) (2023)	SSB (2024)	% SSB change	% Catch change	% probability of falling below Blim in 2024
Catch (2022) - 15%	7339 (4816 - 11752)	6699 (4335 - 10908)	640 (481 - 844)	0.064 (0.037 - 0.113)	0.053 (0.030 - 0.095)	0.011 (0.007 - 0.018)	115937 (75986 - 182569)	57.8 % (12.8 % - 125.6 %)	-15.8 % (-44.8 % - 303393.6 %)	0.0 %
Catch (2022) - 10%	7845 (5119 - 12068)	7161 (4621 - 11137)	684 (498 - 931)	0.069 (0.041 - 0.128)	0.057 (0.033 - 0.104)	0.012 (0.008 - 0.024)	114119 (72358 - 178756)	55.5 % (12.0 % - 119.8 %)	-10.0 % (-41.3 % - 334993.6 %)	0.0 %
Catch (2022) - 5%	8303 (5252 - 13131)	7559 (4792 - 11863)	744 (460 - 1268)	0.074 (0.043 - 0.129)	0.061 (0.035 - 0.105)	0.013 (0.008 - 0.024)	115042 (71621 - 187014)	54.9 % (13.2 % - 122.6 %)	-4.8 % (-39.8 % - 441293.6 %)	0.0 %
Catch (2022)	8721 (5431 - 13650)	7961 (4993 - 12598)	760 (438 - 1052)	0.078 (0.044 - 0.140)	0.065 (0.036 - 0.115)	0.013 (0.008 - 0.025)	114226 (73718 - 173352)	52.5 % (11.3 % - 110.1 %)	0.0 % (-37.7 % - 493193.6 %)	0.0 %
Catch (2022) + 5%	9189 (5827 - 14399)	8377 (5344 - 13200)	812 (483 - 1199)	0.083 (0.047 - 0.146)	0.068 (0.038 - 0.118)	0.015 (0.009 - 0.028)	112406 (69093 - 173751)	50.5 % (9.1 % - 119.1 %)	5.4 % (-33.2 % - 568093.6 %)	0.0 %
Catch (2022) + 10%	9683 (6127 - 15375)	8842 (5614 - 14179)	841 (513 - 1196)	0.087 (0.049 - 0.154)	0.072 (0.041 - 0.126)	0.015 (0.008 - 0.028)	114070 (71630 - 179183)	53.4 % (11.1 % - 113.7 %)	11.1 % (-29.7 % - 665693.6 %)	0.0 %
Catch (2022) + 15%	10103 (6468 - 15698)	9182 (5864 - 14368)	921 (604 - 1330)	0.089 (0.054 - 0.157)	0.073 (0.043 - 0.128)	0.016 (0.011 - 0.029)	114619 (73689 - 175290)	49.9 % (8.1 % - 112.7 %)	15.9 % (-25.8 % - 697993.6 %)	0.0 %
Catch (2022) + 20%	10265 (6281 - 15858)	9303 (5630 - 14686)	962 (651 - 1172)	0.092 (0.050 - 0.157)	0.076 (0.042 - 0.131)	0.016 (0.008 - 0.026)	111231 (72219 - 176971)	51.7 % (12.3 % - 120.3 %)	17.8 % (-27.9 % - 713993.6 %)	0.0 %
F = F_{2022}	13405 (8375 - 20178)	12161 (7632 - 18547)	1244 (743 - 1631)	0.122 (0.074 - 0.204)	0.099 (0.061 - 0.169)	0.023 (0.013 - 0.035)	108865 (66428 - 168698)	46.0 % (1.8 % - 108.1 %)	53.8 % (-3.9 % - 1145993.6 %)	0.0 %
F = F_{MSY}	22855 (14796 - 35242)	20745 (13068 - 32085)	2110 (1728 - 3157)	0.223 (0.166 - 0.307)	0.183 (0.134 - 0.253)	0.040 (0.032 - 0.054)	94776 (59973 - 146271)	28.6 % (-8.6 % - 83.3 %)	162.2 % (69.7 % - 2652393.6 %)	0.0 %
F = F~MSY lower~	14599 (9033 - 23377)	13338 (8172 - 21439)	1261 (861 - 1938)	0.136 (0.099 - 0.178)	0.112 (0.082 - 0.149)	0.024 (0.017 - 0.029)	106423 (66728 - 161001)	44.8 % (2.6 % - 106.9 %)	67.5 % (3.6 % - 1465893.6 %)	0.0 %

Table 4: Example catch scenarios for the South stock using stochastic F with non-linearity correction and using the asymptotic normal covariance of final year F estimates in the forecast with 1000 replicates. In the first two scenarios, the ICES advice rule is followed in each simulated trajectory.

Basis	Total catch (2023)	Projected landings (2023)	Projected discards (2023)	F_{total} (ages 2 - 4) (2023)	$F_{landings}$ (ages 2 - 4) (2023)	$F_{discard}$ (ages 2 - 4) (2023)	SSB (2024)	% SSB change	% Catch change	% probability of falling below Blim in 2024
MSY approach: F_{MSY} x SSB (2023) / MSY $B_{trigger}$	4257 (0 - 9000)	3425 (0 - 6837)	832 (0 - 2163)	0.187 (0.000 - 0.283)	0.154 (0.000 - 0.238)	0.033 (0.000 - 0.045)	27905 (15578 - 61157)	73.6 % (12.8 % - 206.6 %)	47.0 % (-100.0 % - 610298.3 %)	0.0 %
F = F~MSY lower~ x SSB (2023) / MSY $B_{trigger}$	2642 (0 - 5426)	2149 (0 - 4227)	493 (0 - 1199)	0.112 (0.000 - 0.172)	0.092 (0.000 - 0.142)	0.020 (0.000 - 0.030)	29544 (16556 - 60606)	81.7 % (19.4 % - 220.0 %)	-8.8 % (-100.0 % - 252898.3 %)	0.0 %
F = 0	0 (0 - 0)	0 (0 - 0)	0 (0 - 0)	0.000 (0.000 - 0.000)	0.000 (0.000 - 0.000)	0.000 (0.000 - 0.000)	34127 (17505 - 74918)	104.5 % (37.3 % - 246.3 %)	-100.0 % (-100.0 % - - 289701.7 %)	0.0 %
F = F_{pa}	8798 (4474 - 17380)	7067 (3571 - 12938)	1731 (903 - 4442)	0.442 (0.299 - 0.656)	0.365 (0.246 - 0.545)	0.077 (0.053 - 0.111)	21756 (11629 - 49588)	32.7 % (-19.1 % - 138.4 %)	203.8 % (54.5 % - 1448298.3 %)	0.6 %
F = F_{lim}	9477 (4853 - 19707)	7542 (3785 - 14831)	1935 (1068 - 4876)	0.503 (0.340 - 0.749)	0.412 (0.278 - 0.613)	0.091 (0.062 - 0.136)	20087 (9679 - 47909)	28.3 % (-23.6 % - 152.8 %)	227.2 % (67.6 % - 1680998.3 %)	3.8 %
SSB (2024) = B_{lim}	18839 (6386 - 55428)	14310 (5127 - 36161)	4529 (1259 - 19267)	1.289 (0.561 - 3.249)	1.067 (0.464 - 2.798)	0.222 (0.097 - 0.451)	10414 (6083 - 18119)	-35.5 % (-71.7 % - 34.0 %)	550.5 % (120.5 % - 5253098.3 %)	49.2 %
SSB (2024) = MSY $B_{trigger}$	14239 (2906 - 50432)	11000 (2258 - 32830)	3239 (648 - 17602)	0.835 (0.208 - 2.811)	0.686 (0.163 - 2.327)	0.149 (0.045 - 0.484)	14942 (9274 - 24143)	-5.8 % (-58.0 % - 80.4 %)	391.7 % (0.3 % - 4753498.3 %)	5.9 %
Catch (2022) - 20%	2310 (1284 - 4342)	1877 (1068 - 3318)	433 (216 - 1024)	0.098 (0.046 - 0.199)	0.081 (0.037 - 0.167)	0.017 (0.009 - 0.032)	31369 (15104 - 71905)	86.5 % (19.4 % - 223.5 %)	-20.2 % (-55.7 % - 144498.3 %)	0.0 %
Catch (2022) - 15%	2473 (1345 - 4634)	2003 (1138 - 3382)	470 (207 - 1252)	0.105 (0.053 - 0.221)	0.086 (0.044 - 0.181)	0.019 (0.009 - 0.040)	30412 (15766 - 63233)	82.5 % (20.2 % - 212.6 %)	-14.6 % (-53.6 % - 173698.3 %)	0.1 %
Catch (2022) - 10%	2556 (1437 - 4909)	2094 (1193 - 3656)	462 (244 - 1253)	0.112 (0.054 - 0.234)	0.093 (0.044 - 0.192)	0.019 (0.010 - 0.042)	30024 (14926 - 59559)	79.8 % (22.2 % - 206.5 %)	-11.7 % (-50.4 % - 201198.3 %)	0.3 %
Catch (2022) - 5%	2774 (1512 - 5196)	2230 (1254 - 3744)	544 (258 - 1452)	0.121 (0.054 - 0.261)	0.099 (0.045 - 0.214)	0.022 (0.009 - 0.047)	29334 (14381 - 68341)	80.4 % (21.5 % - 201.7 %)	-4.2 % (-47.8 % - 229898.3 %)	0.3 %
Catch (2022)	2913 (1616 - 5607)	2334 (1284 - 4217)	579 (332 - 1390)	0.129 (0.063 - 0.256)	0.106 (0.052 - 0.215)	0.023 (0.011 - 0.041)	28959 (14188 - 63559)	75.0 % (18.4 % - 204.6 %)	0.6 % (-44.2 % - 270998.3 %)	0.3 %
Catch (2022) + 5%	3054 (1687 - 5955)	2457 (1392 - 4255)	597 (295 - 1700)	0.132 (0.061 - 0.269)	0.108 (0.050 - 0.221)	0.024 (0.011 - 0.048)	29555 (14294 - 69606)	76.9 % (16.7 % - 204.5 %)	5.5 % (-41.7 % - 305798.3 %)	0.2 %

Basis	Total catch (2023)	Projected landings (2023)	Projected discards (2023)	F_{total} (ages 2 - 4) (2023)	$F_{landings}$ (ages 2 - 4) (2023)	$F_{discard}$ (ages 2 - 4) (2023)	SSB (2024)	% SSB change	% Catch change	% probability of falling below Blim in 2024
Catch (2022) + 10%	3162 (1811 - 6046)	2531 (1489 - 4546)	631 (322 - 1500)	0.140 (0.070 - 0.305)	0.116 (0.057 - 0.247)	0.024 (0.013 - 0.058)	28831 (13886 - 64863)	76.6 % (15.4 % - 196.9 %)	9.2 % (-37.5 % - 314898.3 %)	0.4 %
Catch (2022) + 15%	3316 (1908 - 6660)	2686 (1590 - 4704)	630 (318 - 1956)	0.146 (0.072 - 0.301)	0.120 (0.060 - 0.247)	0.026 (0.012 - 0.054)	28848 (14913 - 57976)	72.8 % (14.3 % - 208.7 %)	14.5 % (-34.1 % - 376298.3 %)	0.2 %
Catch (2022) + 20%	3299 (1841 - 5852)	2687 (1479 - 4403)	612 (362 - 1449)	0.145 (0.071 - 0.316)	0.120 (0.058 - 0.260)	0.025 (0.013 - 0.056)	28290 (13921 - 64646)	76.1 % (14.4 % - 205.0 %)	13.9 % (-36.4 % - 295498.3 %)	0.5 %
F = F_{2022}	5270 (2936 - 10601)	4212 (2449 - 7377)	1058 (487 - 3224)	0.243 (0.126 - 0.473)	0.200 (0.103 - 0.405)	0.043 (0.023 - 0.068)	26882 (11712 - 58982)	61.8 % (2.3 % - 168.3 %)	82.0 % (1.4 % - 770398.3 %)	0.9 %
F = F_{MSY}	4298 (2081 - 9097)	3448 (1696 - 6791)	850 (385 - 2306)	0.194 (0.132 - 0.282)	0.160 (0.108 - 0.236)	0.034 (0.024 - 0.046)	27738 (14096 - 59807)	70.1 % (11.6 % - 187.5 %)	48.4 % (-28.1 % - 619998.3 %)	0.5 %
F = F~MSY lower~	2659 (1339 - 5404)	2144 (1091 - 4167)	515 (248 - 1237)	0.116 (0.080 - 0.167)	0.095 (0.065 - 0.139)	0.021 (0.015 - 0.028)	29967 (15736 - 66097)	83.3 % (23.6 % - 232.7 %)	-8.2 % (-53.8 % - 250698.3 %)	0.2 %

Table 5: Example catch scenarios for the Viking stock using stochastic F with non-linearity correction and using the asymptotic normal covariance of final year F estimates in the forecast with 1000 replicates. In the first two scenarios, the ICES advice rule is followed in each simulated trajectory.

Basis	Total catch (2023)	Projected landings (2023)	Projected discards (2023)	F_{total} (ages 2 - 4) (2023)	$F_{landings}$ (ages 2 - 4) (2023)	$F_{discard}$ (ages 2 - 4) (2023)	SSB (2024)	% SSB change	% Catch change	% probability of falling below Blim in 2024
MSY approach: F_{MSY} x SSB (2023) / MSY $B_{trigger}$	10672 (0 - 21613)	10049 (0 - 20942)	623 (0 - 671)	0.233 (0.000 - 0.326)	0.197 (0.000 - 0.277)	0.036 (0.000 - 0.049)	25426 (15073 - 44654)	21.6 % (-21.1 % - 112.8 %)	113.4 % (-100.0 % - 1661208.1 %)	0.3 %
F = F~MSY lower~ x SSB (2023) / MSY $B_{trigger}$	7433 (0 - 13847)	6991 (0 - 13163)	442 (0 - 684)	0.152 (0.000 - 0.216)	0.129 (0.000 - 0.184)	0.023 (0.000 - 0.032)	28324 (15587 - 52486)	37.8 % (-10.0 % - 130.6 %)	48.7 % (-100.0 % - 884608.1 %)	0.6 %
F = 0	0 (0 - 0)	0 (0 - 0)	0 (0 - 0)	0.000 (0.000 - 0.000)	0.000 (0.000 - 0.000)	0.000 (0.000 - 0.000)	35079 (19089 - 67078)	69.8 % (17.3 % - 148.9 %)	-100.0 % (-100.0 % - - 500091.9 %)	0.1 %
F = F_{pa}	22614 (11973 - 40976)	21303 (10989 - 38311)	1311 (984 - 2665)	0.630 (0.447 - 0.871)	0.537 (0.381 - 0.744)	0.093 (0.066 - 0.127)	14739 (7832 - 28705)	-29.9 % (-59.6 % - 16.5 %)	352.3 % (139.5 % - 3597508.1 %)	40.3 %

Basis	Total catch (2023)	Projected landings (2023)	Projected discards (2023)	F_{total} (ages 2 - 4) (2023)	$F_{landings}$ (ages 2 - 4) (2023)	$F_{discard}$ (ages 2 - 4) (2023)	SSB (2024)	% SSB change	% Catch change	% probability of falling below Blim in 2024
F = F_{lim}	26457 (14817 - 45079)	24640 (13382 - 43401)	1817 (1435 - 1678)	0.842 (0.612 - 1.133)	0.718 (0.517 - 0.973)	0.124 (0.095 - 0.160)	11000 (5507 - 21844)	-46.3 % (-69.9 % - -5.2 %)	429.1 % (196.3 % - 4007808.1 %)	72.1 %
SSB (2024) = B_{lim}	23383 (7126 - 51571)	21930 (6667 - 48977)	1453 (459 - 2594)	0.690 (0.264 - 1.258)	0.588 (0.223 - 1.063)	0.102 (0.041 - 0.195)	13666 (8944 - 19576)	-35.3 % (-68.9 % - 23.2 %)	367.7 % (42.5 % - 4657008.1 %)	47.9 %
SSB (2024) = MSY $B_{trigger}$	15690 (0 - 42635)	14795 (0 - 41045)	895 (0 - 1590)	0.377 (0.000 - 0.866)	0.322 (0.000 - 0.740)	0.055 (0.000 - 0.126)	19654 (13969 - 26950)	-2.4 % (-53.6 % - 79.7 %)	213.8 % (-100.0 % - 3763408.1 %)	1.8 %
Catch (2022) - 20%	3984 (2408 - 6387)	3771 (2300 - 6079)	213 (108 - 308)	0.079 (0.037 - 0.165)	0.067 (0.032 - 0.141)	0.012 (0.005 - 0.024)	31556 (16384 - 65096)	50.9 % (2.3 % - 135.5 %)	-20.3 % (-51.8 % - 138608.1 %)	0.9 %
Catch (2022) - 15%	4267 (2655 - 6638)	4026 (2521 - 6286)	241 (134 - 352)	0.086 (0.043 - 0.196)	0.074 (0.036 - 0.164)	0.012 (0.007 - 0.032)	30962 (15175 - 58976)	47.4 % (-1.3 % - 128.1 %)	-14.7 % (-46.9 % - 163708.1 %)	1.6 %
Catch (2022) - 10%	4497 (2854 - 7048)	4251 (2684 - 6765)	246 (170 - 283)	0.091 (0.042 - 0.184)	0.076 (0.036 - 0.158)	0.015 (0.006 - 0.026)	31114 (15644 - 62120)	47.2 % (0.5 % - 128.6 %)	-10.1 % (-42.9 % - 204708.1 %)	0.9 %
Catch (2022) - 5%	4777 (3008 - 7689)	4528 (2801 - 7326)	249 (207 - 363)	0.094 (0.048 - 0.206)	0.080 (0.041 - 0.177)	0.014 (0.007 - 0.029)	31271 (15400 - 61928)	47.2 % (0.4 % - 127.9 %)	-4.5 % (-39.8 % - 268808.1 %)	1.2 %
Catch (2022)	4901 (3158 - 7719)	4634 (2985 - 7289)	267 (173 - 430)	0.102 (0.050 - 0.232)	0.087 (0.042 - 0.195)	0.015 (0.008 - 0.037)	29868 (13944 - 57916)	45.2 % (-1.7 % - 122.0 %)	-2.0 % (-36.8 % - 271808.1 %)	2.3 %
Catch (2022) + 5%	5176 (3340 - 8229)	4899 (3096 - 7805)	277 (244 - 424)	0.108 (0.053 - 0.247)	0.091 (0.044 - 0.205)	0.017 (0.009 - 0.042)	29568 (14227 - 60328)	41.2 % (-4.3 % - 116.8 %)	3.5 % (-33.2 % - 322808.1 %)	1.9 %
Catch (2022) + 10%	5480 (3414 - 8885)	5139 (3217 - 8473)	341 (197 - 412)	0.114 (0.054 - 0.236)	0.097 (0.045 - 0.203)	0.017 (0.009 - 0.033)	29770 (13925 - 60231)	44.4 % (-4.7 % - 116.5 %)	9.6 % (-31.7 % - 388408.1 %)	1.9 %
Catch (2022) + 15%	5852 (3823 - 8860)	5506 (3648 - 8449)	346 (175 - 411)	0.123 (0.056 - 0.261)	0.105 (0.048 - 0.220)	0.018 (0.008 - 0.041)	29029 (13995 - 57297)	39.1 % (-6.7 % - 115.7 %)	17.0 % (-23.5 % - 385908.1 %)	2.3 %
Catch (2022) + 20%	5771 (3677 - 8767)	5453 (3441 - 8243)	318 (236 - 524)	0.116 (0.058 - 0.253)	0.100 (0.050 - 0.213)	0.016 (0.008 - 0.040)	29512 (13826 - 59339)	43.2 % (-6.2 % - 120.8 %)	15.4 % (-26.5 % - 376608.1 %)	2.1 %
F = F_{2022}	6954 (4404 - 10831)	6570 (4093 - 10252)	384 (311 - 579)	0.145 (0.074 - 0.273)	0.123 (0.063 - 0.234)	0.022 (0.011 - 0.039)	28641 (14146 - 57040)	36.5 % (-11.9 % - 104.1 %)	39.1 % (-11.9 % - 583008.1 %)	1.8 %
F = F_{MSY}	10760 (6008 - 19700)	10168 (5642 - 19111)	592 (366 - 589)	0.240 (0.172 - 0.335)	0.203 (0.147 - 0.280)	0.037 (0.025 - 0.055)	24840 (13860 - 48026)	20.6 % (-20.1 % - 82.3 %)	115.2 % (20.2 % - 1469908.1 %)	1.9 %
F = F~MSY lower~	7370 (3817 - 13883)	6991 (3520 - 13250)	379 (297 - 633)	0.155 (0.112 - 0.212)	0.132 (0.095 - 0.181)	0.023 (0.017 - 0.031)	28350 (15527 - 53735)	36.4 % (-8.2 % - 112.6 %)	47.4 % (-23.7 % - 888208.1 %)	0.9 %

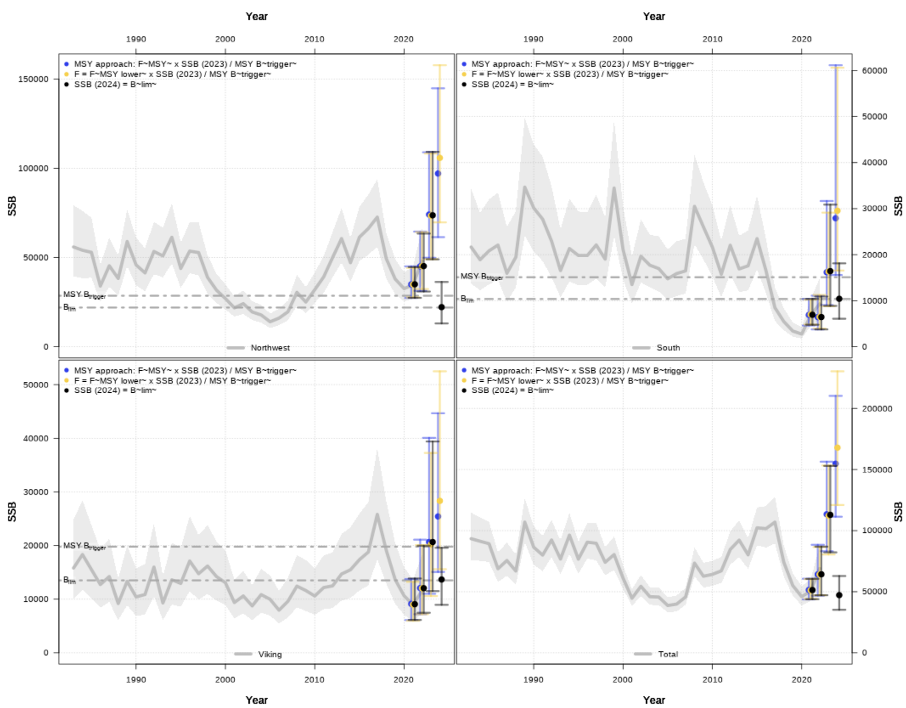

Illustration of forecasted SSB for three catch scenarios.

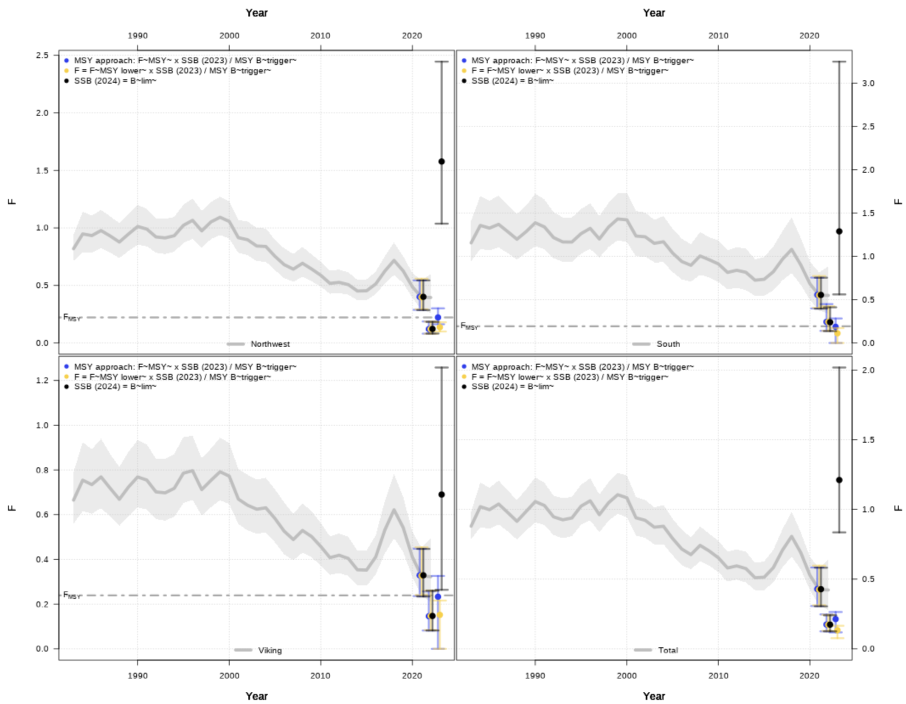

Illustration of forecasted F for three catch scenarios. For the total forecasted F, a naive average of the stock-wise F is presented. Note that this is different from the full-year-one-stock-equivalent F presented for the estimated period.

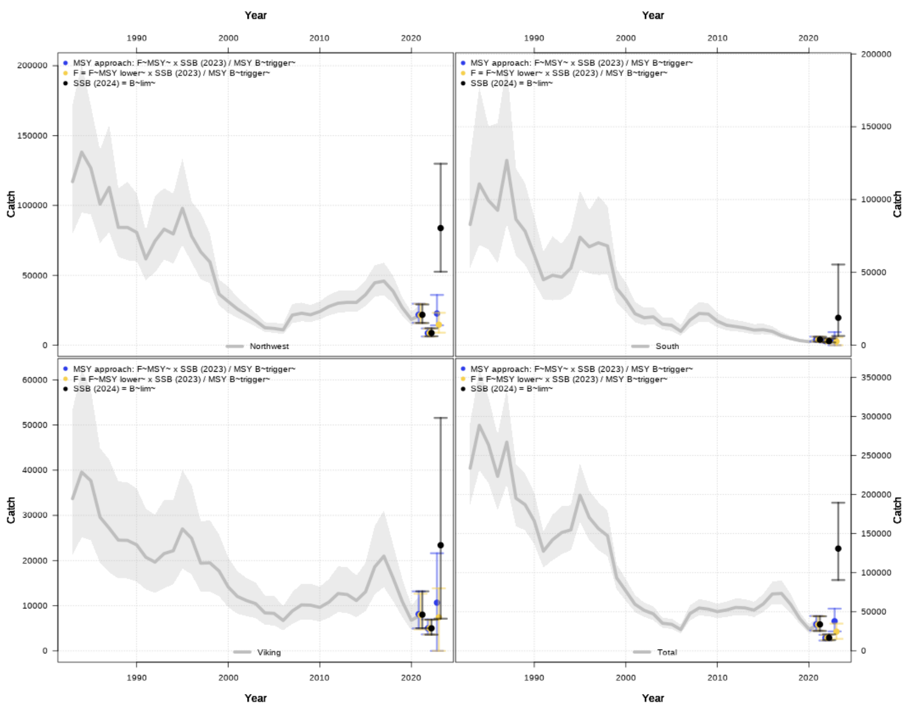

Illustration of forecasted catch for three catch scenarios.

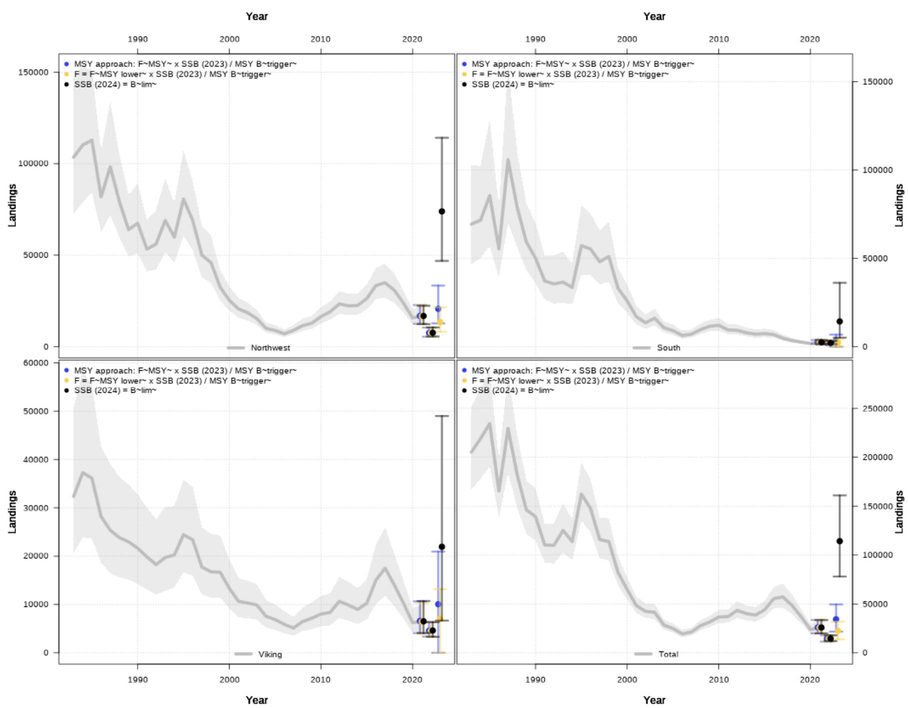

Illustration of forecasted landings for three catch scenarios.

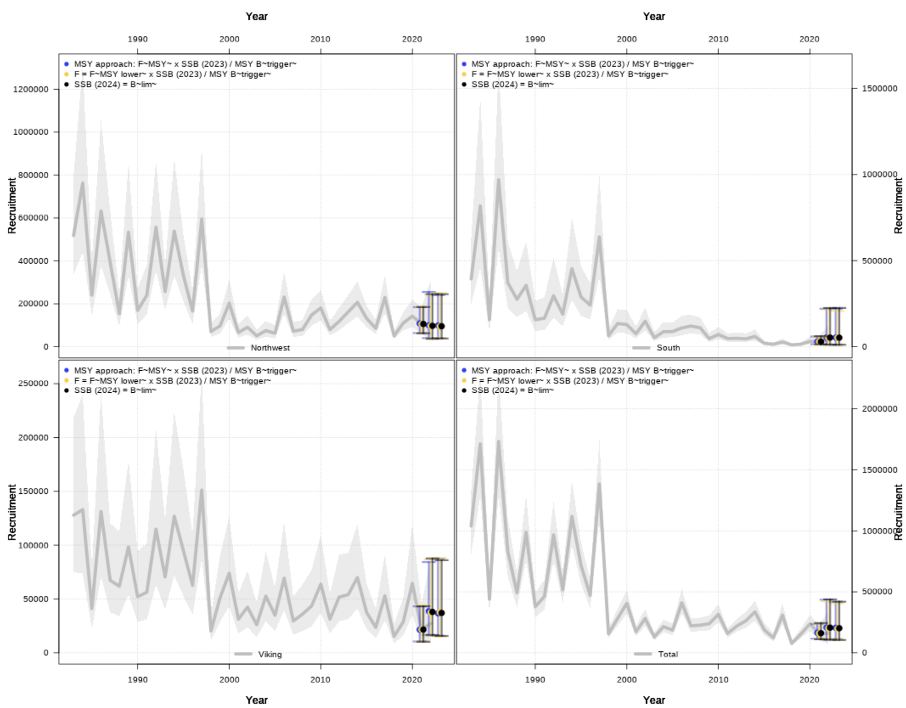

Illustration of forecasted F for three catch scenarios.

5 Documentation of the stockassessment::modelforecast function

The forecast function (modelforecast.msam) in the multiStockassessment package makes use of the modelforecast function from the stockassessment package. For convenience, and further details, the documentation of that function is included below.

5.1 `modelforecast`

Model based forecast function

5.1.1 Description

Model based forecast function

5.1.2 Usage

```
modelforecast(fit, ...)
modelforecast.sam(
  fit,
  constraints = NULL,
  fscale = NULL,
  catchval = NULL,
  fval = NULL,
  nextssb = NULL,
  landval = NULL,
  nosim = 0,
  year.base = max(fit$data$years),
  ave.years = max(fit$data$years) + (-9:0),
  overwriteBioModel = FALSE,
  rec.years = c(),
  label = NULL,
  overwriteSelYears = NULL,
  deterministicF = FALSE,
  processNoiseF = FALSE,
  fixedFdeviation = FALSE,
  useFHessian = FALSE,
  resampleFirst = !is.null(nosim) && nosim > 0,
  customSel = NULL,
  lagR = FALSE,
  splitLD = FALSE,
  addTSB = FALSE,
  biasCorrect = FALSE,
  returnAllYears = FALSE,
  returnObj = FALSE,
```

```
  progress = TRUE,
  estimate = median,
  silent = TRUE,
  newton_config = NULL,
  custom_pl = NULL,
  useNonLinearityCorrection = (nosim > 0 && !deterministicF),
  ncores = 1,
  ...
)
```

5.1.3 Arguments

Argument	Description
`fit`	SAM model fit
`...`	other variables used by the methods
`constraints`	a character vector of forecast constraint specifications
`fscale`	a vector of f-scales. See details.
`catchval`	a vector of target catches. See details “old specification”.
`fval`	a vector of target f values. See details “old specification”.
`nextssb`	a vector target SSB values the following year. See details “old specification”.
`landval`	a vector of target catches. See details “old specification”.
`nosim`	number of simulations. If 0, the Laplace approximation is used for forecasting.
`year.base`	starting year default last year in assessment. Currently it is only supported to use last assessment year or the year before
`ave.years`	vector of years to average for weights, maturity, M and such
`overwriteBioModel`	Overwrite GMRF models with ave.years?
`rec.years`	vector of years to use to resample recruitment from. If the vector is empty, the stock recruitment model is used.
`label`	optional label to appear in short table
`overwriteSelYears`	if a vector of years is specified, then the average selectivity of those years is used (not recommended)
`deterministicF`	option to set F variance to (almost) zero (not recommended)
`processNoiseF`	option to turn off process noise in F

Argument	Description
`fixedFdeviation`	Use a fixed F deviation from target?
`useFHessian`	Use the covariance of F estimates instead of the estimated process covariance for forecasting?
`resampleFirst`	Resample base year when nosim > 0?
`customSel`	supply a custom selection vector that will then be used as fixed selection in all years after the final assessment year (not recommended)
`lagR`	if the second youngest age should be reported as recruits
`splitLD`	if TRUE the result is split in landing and discards
`addTSB`	if TRUE the total stock biomass (TSB) is added
`biasCorrect`	Do bias correction of reported variables. Can be turned off to reduce running time (not recommended).
`returnAllYears`	If TRUE, all years are bias corrected. Otherwise, only forecast years are corrected.
`returnObj`	Only return TMB object?
`progress`	Show progress bar for simulations?
`estimate`	the summary function used (typically mean or median) for simulations
`silent`	Passed to MakeADFun. Should the TMB object be silent?
`newton_config`	Configuration for newton optimizer to find F values. See ?TMB::newton for details. Use NULL for TMB defaults.
`custom_pl`	Parameter list. By default, the parameter list from fit is used.
`useNonLinearityCorrection`	Should a non linearity correction be added to transformation of logF? See Details - Non-linearity correction.

5.1.4 Details

Function to forecast the model under specified catch constraints. In the forecast, catch constraints are used to set the mean of the $log(F)$ process for each simulation. Therefore, catch constraints are not matched exactly in individual simulations. Likewise, the summary of a specific set of simulations will not match exactly due to random variability. By default, recruitment is forecasted using the estimated recruitment model. If a vector of recruitment years is given, recruitment is forecasted using a log-normal distribution with the same mean and variance as the recruitment in the years given. This is different from the forecast function, which samples from the recruitment estimates. Catch scenarios are specified by a vector of target constraints. The first value determines F in the year after the base year.

5.1.5 Value

an object of type samforecast

5.1.6 Forecast constraints

5.1.6.1 F based constraints Forecasts for F values are specified by the format `F[f,a0-a1]=x` where f is the residual catch fleet and a0-a1 is an age range. For example, `F[2,2-4]=0.3` specifies that the average F for the second fleet over ages 2-4 should be 0.3. If an `*` is added to the target value, the target will be relative to the year before. For example, `F[2,2-4]=0.9*` specifies that the average F for the second fleet over ages 2-4 should be 90% of the year before. Further, the target for a fleet can be relative to the total by adding `*F` or to another fleet by adding `*F[f]` where f is the fleet number. The same age range will always be used. If the fleet is omitted (e.g., `F[2-4]`), the target is for the total F. If the age range is omitted (e.g., `F[2]`), the fbar range of the model is used. Likewise, both fleet and age range can be omited (e.g., F=0.3) to specify a value for total F with the range used in the model.

For example:

`F=0.2` Will set the median average total fishing mortality rate to 0.2

`F[1]=0.2` Will set the median average fishing mortality rate of the first fleet to 0.2

`F[2-4]=0.2` Will set the median average total fishing mortality rate over ages 2 to 4 to 0.2

`F[3,2-4]=0.2` Will set the median average fishing mortality rate over ages 2 to 4 for the third fleet to 0.2

5.1.6.2 Catch/Landing based constraints Forecasts for catch and landing values are specified by the format `C[f,a0-a1]=x` for catch and `L[f,a0-a1]` for landings. If the age range is omitted, all modelled ages are used. Otherwise, the format is similar to F based scenarios. If an `*` is added to the target value, the target will be relative to the year before. Further, the catch target for a fleet can be relative to the total by adding `*C` or to another fleet by adding `*C[f]` where f is the fleet number. The same age range will always be used. Likewise, relative landing targets can be specified using `*`, `*L`, or `*L[f]` for targets relative to last year, the total, or fleet f, respectively.

For example:

`C=100000` Will scale F such that the total predicted catch is 100000

`C[1]=100000` Will scale F such that the predicted catch of the first fleet is 100000

`C[2-4]=100000` Will scale F such that the total predicted catch for ages 2 to 4 is 100000

`C[3,2-4]=100000` Will scale F such that the predicted catch for ages 2 to 4 in the third fleet is 100000

`L=100000` Will scale F such that the total predicted landing is 100000

`L[1]=100000` Will scale F such that the predicted landing of the first fleet is 100000 `L[2-4]=100000`
Will scale F such that the total predicted landing for ages 2 to 4 is 100000

`L[3,2-4]=100000` Will scale F such that the predicted landing for ages 2 to 4 in the third fleet is 100000

5.1.6.3 Next year's SSB/TSB based constraints: Forecasts for spawning stock biomass (SSB) and total stock biomass (TSB) values are specified by the format `SSB[a0-a1]=x` for SSB and `TSB[a0-a1]` for TSB. For setting F in year y, the relevant biomass for year y+1 is predicted for the constraint. If spawning is not at the beginning of the year, F is assumed to be the same for year y and y+1 in the prediction. The format is similar to catch/landing based scenarios. However, fleets have no effect. If an age range is omitted, the full age range of the model is used. If an `*` is added to the target value, the target will be relative to the year before. That is, when setting F in year y, the predicted biomass in year y+1 will be relative to the biomass in year y-1. Note that since SSB and TSB used for catch constraints are predicted, the input constraint will differ from the output SSB and TSB estimates due to process variability.

For example:

`SSB=200000` Will scale F such that the predicted SSB at the beginning of the next year is 200000}

`SSB[3-9]=200000` Will scale F such that the predicted SSB for ages 3 to 9 at the beginning of the next year is 200000

`TSB=200000` Will scale F such that the predicted TSB at the beginning of the next year is 200000

`TSB[3-9]=200000` Will scale F such that the predicted TSB for ages 3 to 9 at the beginning of the next year is 200000

5.1.6.4 Harvest control rule based constraints Harvest control rules can be specified for forecasts using the format `HCR=x~y` where x is the target and y is the biomass trigger (see ?hcr for full details on the form of the harvest control rule). Further, the target can be specified as an F target (`HCR=xF~y`), catch target (`HCR=xC~y`), or landing target (`HCR=xL~y`). Likewise the trigger can either be for SSB (`HCR=x~ySSB`) or TSB (`HCR=x~yTSB`). Age ranges can be set for both triggers and targets and a fleet can be set for the target. The notation and defaults are similar to the F based and SSB/TSB based constraints, respectively. When setting F in year y, the projected biomass in year y is used by default. To use the (at this time known) biomass in a previous year, a time lag can be specified. To specify a time lag of, e.g., 1 year for SSB the format is `HCR=x~ySSB-1`. Finally, the origin and cap for the HCR can be set using `HCR[FO=a,FC=b,BO=d,BC=e]=x~y`, where FO is the F (or catch or landing) value at origin, BO is the biomass at origin, FC is the F (or catch or landing) value when the HCR is capped and BC is the biomass at which the HCR is capped. See ?hcr for further details on the shape of the HCR. For a HCR similar to the ICES advice rule, the specification is on the form `HCR[BC=Blim] = fmsy~MSYBtrigger`. Note that, unlike an ICES advice rule, the HCR does not do a forecast to determine if fishing can continue below Blim.

For example:

`HCR=0.9~100000` Will apply a harvest control rule with an F target of 0.9 and a biomass trigger of 100000 on SSB

`HCR=10000C~100000` Will apply a harvest control rule with a catch target of 10000 and a biomass trigger of 100000 on SSB

`HCR=0.9~100000SSB` Will apply a harvest control rule with an F target of 0.9 and a biomass trigger of 100000 on SSB

`HCR=0.9F[1,2-4]~100000SSB` Will apply a harvest control rule with an F target on the first fleet ages 2-4 of 0.9 and a biomass trigger of 100000 on SSB

`HCR=0.9~100000TSB[0-4]` Will apply a harvest control rule with an F target of 0.9 and a biomass trigger of 100000 on TSB for ages 0 to 4

`HCR[FC=1e-9,BC=20000]=0.9~100000` Will apply a harvest control rule with an F target of 0.9 and a biomass trigger of 100000 on SSB where biomass values below 20000 will give an F of 1e-9

`HCR[FO=0,BO=30000]=0.9~100000` Will apply a harvest control rule with an F target of 0.9 and a biomass trigger of 100000 on SSB where the slope on which F is reduced goes to zero F at a biomass of 30000

5.1.6.5 Combining constraints Constraints for different fleets can be combined by `&`. For example, `F[2-4]=0.5 & C[2]=10000` specifies that total Fbar over ages 2-4 should be 0.5 while the catch for the second residual catch fleet should be 10,000t. The constraints cannot affect within-fleet selectivity. Therefore, a fleet can at most have one constraint per year, and the total number of constraints cannot exceed the number of catch fleets. That is, if a constraint is given for the sum of fleets, there must be at least one fleet without any constraints. For fleets where no constraints are given, a constraint is set to keep their relative Fs constant.

5.1.6.6 Values relative to previous year Catch constraints specified as specific values are inherently different from catch constraints specified as relative values, even if they lead to the same F. Catch constraints specified as relative values will propagate the uncertainty in, e.g, F from previous years whereas constraints specified as specific values will not. This is different from the `forecast` function where, for example, a forecast using fval is the same as a forecast using fscale, if they lead to the same F.

5.1.6.7 Process variability In the forecast, constraints are used to set the predicted F value in year y based on information available until year y-1. Therefore, constraints using predicted values for year y, such as catch, will not be matched exactly by the realized catch due to process variability in F, N, biological processes and catch itself.

5.1.7 Non-linearity correction

In the model forecasts, constraints are calculated to set the mean of the log(F) process, corresponding to the median F-at-ages. Typically, the constraints are non-linear functions of log(F)-at-age. Therefore, when stochasticity is added to log(F) (i.e., `deterministicF=FALSE`), target values will correspond to a transformation of the median, and not the median of the transformation. For example, a target for the average fishing mortality (Fbar) will correspond to the average of the median F at age, which will be different from the median Fbar.

The `useNonLinearityCorrection` argument can be used to shift the target from a function of the mean log(F) (median F) towards the log-mean of the function of log(F), which is approximately the median of the function of log(F). }

5.1.8 Old specification

It is also possible to specify forecast constraints in a way similar to the `forecast` function. There are four ways to specify a scenario. If e.g. four F values are specified (e.g. fval=c(.1,.2,.3,4)), then the first value is used in the year after the last assessment year (base.year + 1), and the three following in the three following years. Alternatively F's can be specified by a scale, or a target catch. Only one option can be used per year. So for instance to set a catch in the first year and an F-scale in the following one would write `catchval=c(10000,NA,NA,NA)`, `fscale=c(NA,1,1,1)`. If only NA's are specified in a year, the F model is used for forecasting. The length of the vector specifies how many years forward the scenarios run. Unlike the forecast function, no value should be given for the base year. Internally, the old specification is translated such that `fval=x` becomes `F=x`, `fscale=x` becomes `F=x*`, `catchval=x` becomes `C=x`, `nextssb=x` becomes `SSB=x`, and `landval=x` becomes `L=x`.

5.1.9 Forecasts using Laplace approximation or simulations

Forecasts can be made using either a Laplace approximation projection (nosim=0) or simulations (nosim > 0). When using the Laplace approximation, the most likely projected trajectory of the processes along with a confidence interval is returned. In contrast, simulation based forecasts will return individual simulated trajectories and summarize using the function given as the estimate argument along with an interval covering 95% of the simulations.

5.1.10 Warnings

Long term forecasts with random walk recruitment can lead to unstable behaviour and difficulties finding suitable F values for the constraints. If no suitable F value can be found, an error message will be shown, and F values will be NA or NaN. Likewise, forecasts leading to high F values in some years (or large changes from one year to another) may cause problems for the optimization as they will be used as starting values for the next years. Since the model works on log space, all target values should be strictly positive. Values too close to zero may cause problems.

5.1.11 See also

forecast

21.14 Working Document on Reference Points for Northern Shelf cod substocks

Alex Holdgate, Nicola Walker, José De Oliveira

ICES provides guidelines for estimating precautionary approach (PA) and maximum sustainable yield (MSY) reference points for category 1 stocks (ICES ref pts cat 1-2). There are a number of steps, but key to estimating B_{lim} is the following.

1) Identifying appropriate stock-recruitment (SR) pairs
2) Identifying stock type from the stock-recruit pairs
3) Estimating biomass limit reference points

An analysis of the SR pairs output by multiSAM is carried out to identify the appropriate time-series and determine the stock type for each of the three substocks. All subsequent analyses to model the SR relationship and estimate PA and MSY reference points were conducted with the ICES proprietary software EqSim in accordance with ICES guidelines.

21.14.1 Stock-recruitment relationship

ICES recommends that the full time series of SR pairs should be used to estimate reference points unless there is very strong evidence to truncate (e.g., regime shift or change in productivity). A decision to truncate the Northern Shelf cod multiSAM assessment to start in 1983 was made at the benchmark workshop, primarily due to a lack of data and appropriate assumptions suitable for estimating substock level status in the historical period. Given the new multiSAM modelling framework can produce SR pairs at the substock level, the SR pairs for each substock were evaluated before a decision on truncating the time series beyond 1983 was made. We only considered segmented regression (similar to previous benchmarks).

21.14.2 ICES stock-types

ICES defines six stock types, each with specific characteristics and subsequent actions to take when defining reference points. In general, stock type depends on: the SR relationship (i.e. how recruitment changes as a function of SSB), the estimated range of SSB, and whether there is evidence of recruitment impairment and/or a stock depletion. Determining stock type is a difficult process that relies heavily on expert judgment, and can be argued to be subjective as a result. For example, this proved to be difficult for the Viking substock, and no agreement on stock type was reached for this substock (although a proposal was put forward). An examination of the development in fishing pressure, SSB and recruitment is often required to help determine the most appropriate stock type for each substock.

21.14.3 Fishing pressure

Fishing pressure has been relatively high for all three substocks over the time period. Generally speaking, fishing pressure increased throughout the 1990s and fell through the 2000s and 2010s, albeit with a surge observed from 2015 to 2020. It is worth noting that the estimated fishing pressure in 2021 is the lowest of the time-series for all three substocks.

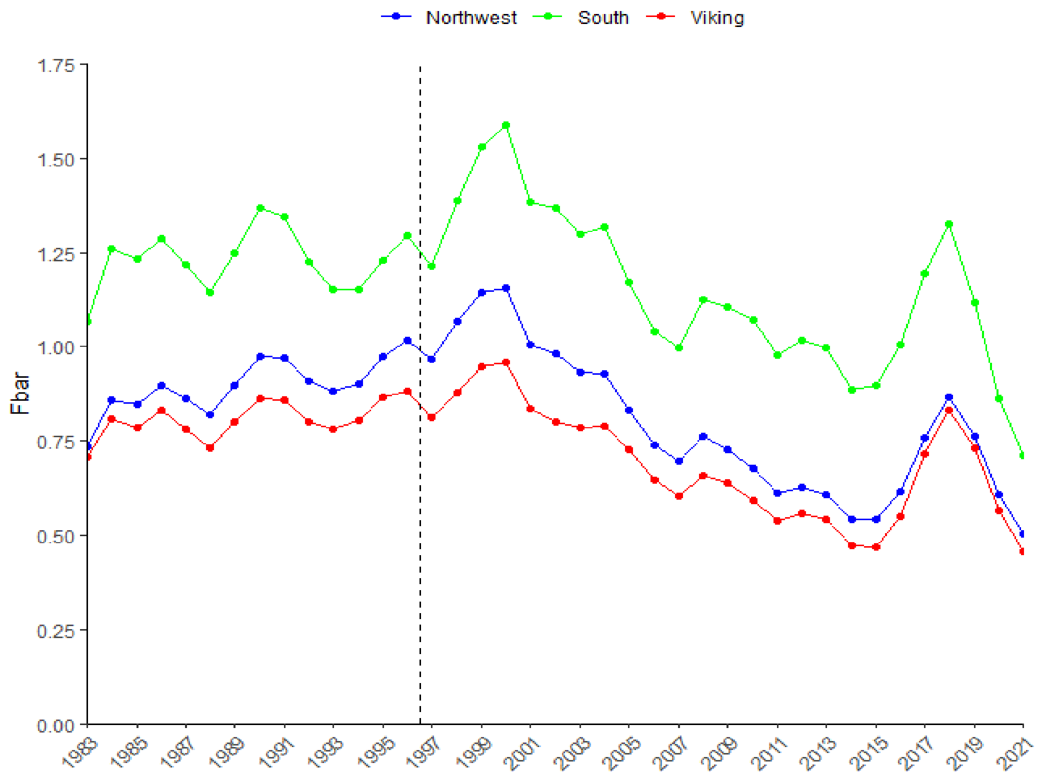

Figure 21.4. F_{bar} (ages 2–4) over time for the three substocks. The vertical dashed line indicates the delineation of a potential regime shift.

21.14.4 Productivity and recruitment regimes

The development in recruits-per-spawner of the three substocks provides strong evidence for the southern substock of two distinct recruitment regimes: one prior to 1997 (SSB year; recruitment one year later), and the other 1997+. The evidence for the remaining two substocks is less clear. Given these trends and the evidence of different productivity and recruitment regimes, we determined the stock-type and fit SR models to either (1) the full time series of SR pairs as estimated by multiSAM or (2) a truncated time series of SR pairs related to SSB in 1997 onwards for each substock.

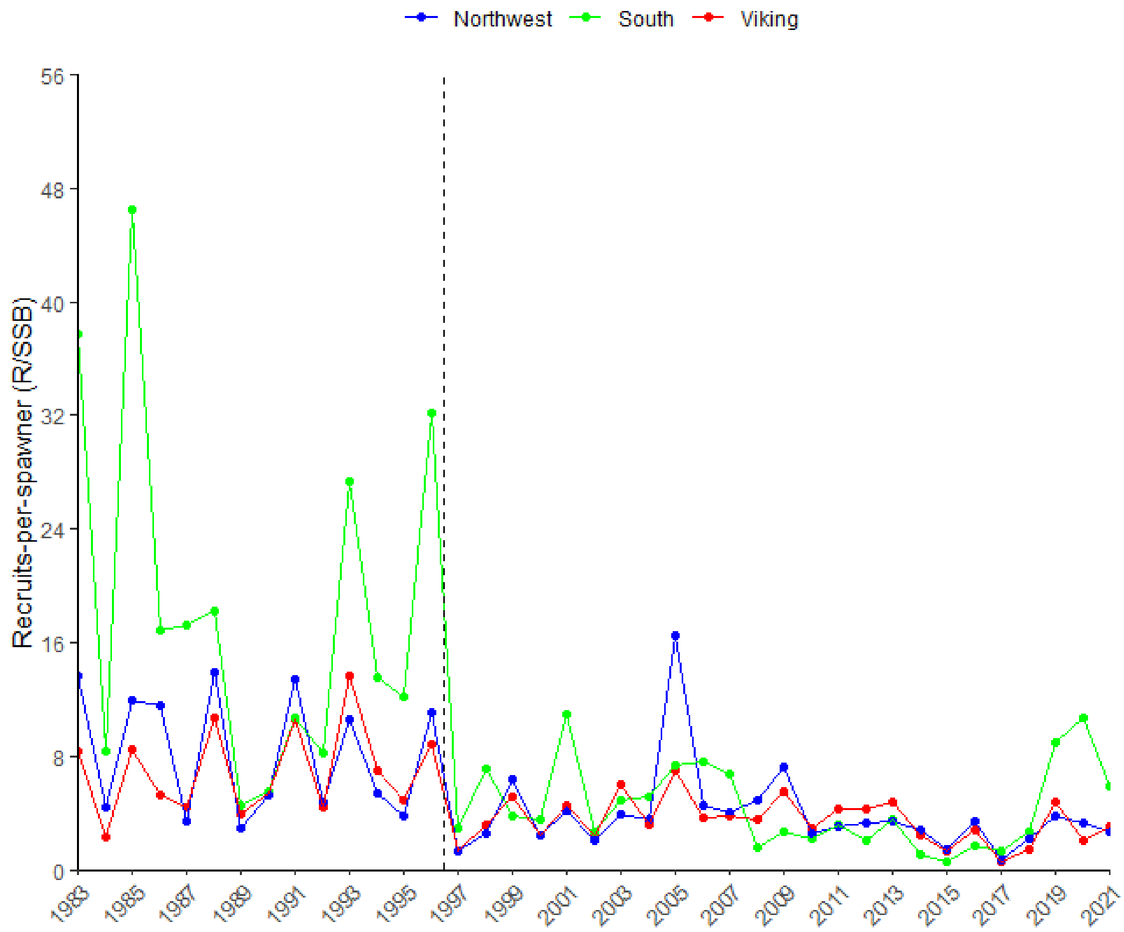

Figure 21.5. Recruits-per-spawner for the three substocks (year indicates the SSB year). The vertical dashed line indicates the delineation of a potential regime shift.

21.14.5 Natural mortality

Estimates of natural mortality from the latest SMS key-run are used for all three substocks, presented here.

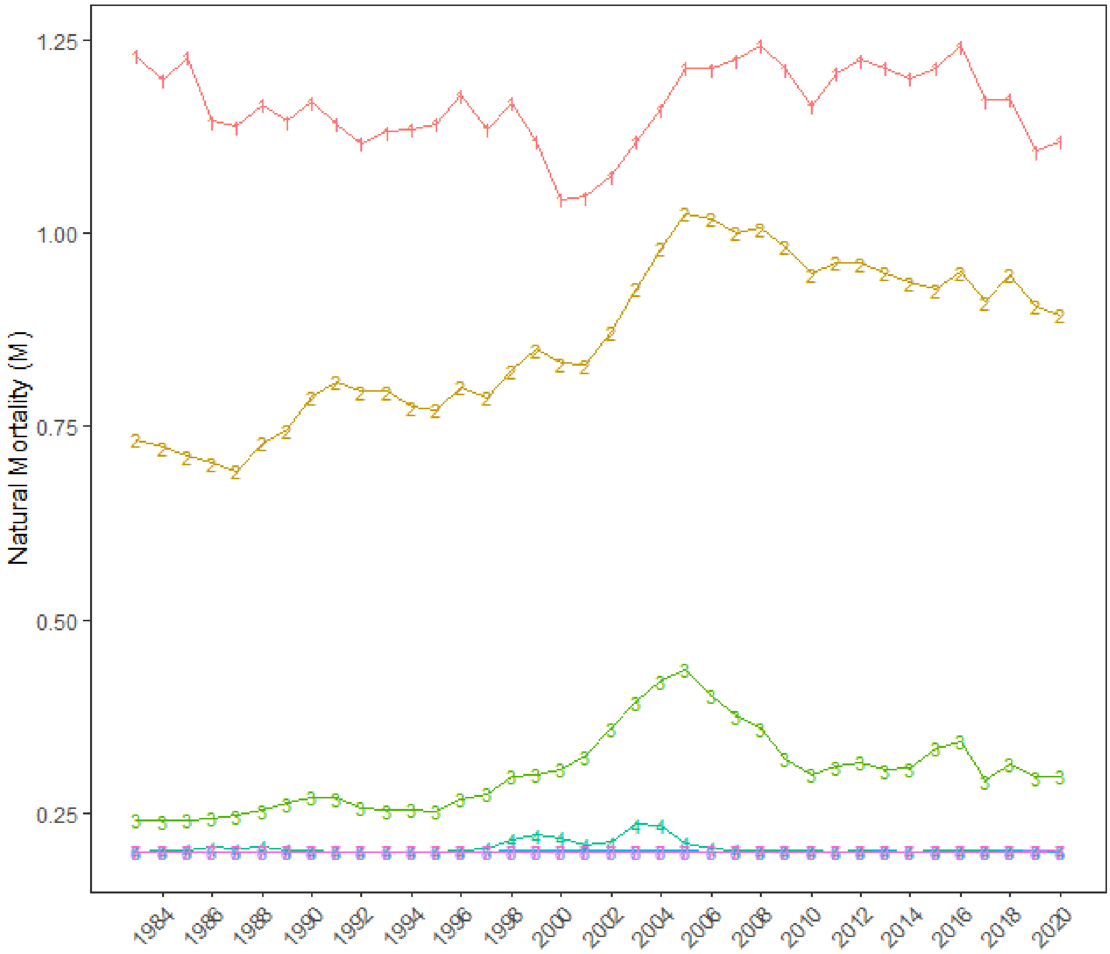

Figure 21.6. Natural mortality estimates from the latest SMS key run (2020).

21.14.6 Northwestern SR relationship

Analysing the SR pairs from 1983+ led to a Type 2 stock definition, characterised by a wide dynamic range of SSB and evidence of recruitment impairment which is apparent when considering the SR pairs from 1983+ (blue points) in comparison to the SR pairs from 1997+ (red points). Truncating the time series to 1997+ also led to a Type 2 stock definition. Some members of the group argued for a type 5 definition for this substock, characterised by no clear relationship between SSB and R and no evidence of recruitment impairment. However, there was broad consensus that, apart from the high recruitment at low SSB estimated in 2005, R seems to decrease at lower SSBs, highlighted by the cluster of SR pairs around the 14000 – 25000 SSB and 60000 – 90000 R marks. Following the ICES guidelines for Type 2 stocks, the SR relationship is modelled as a segmented regression with the breakpoint (B_{lim}) estimated in EqSim.

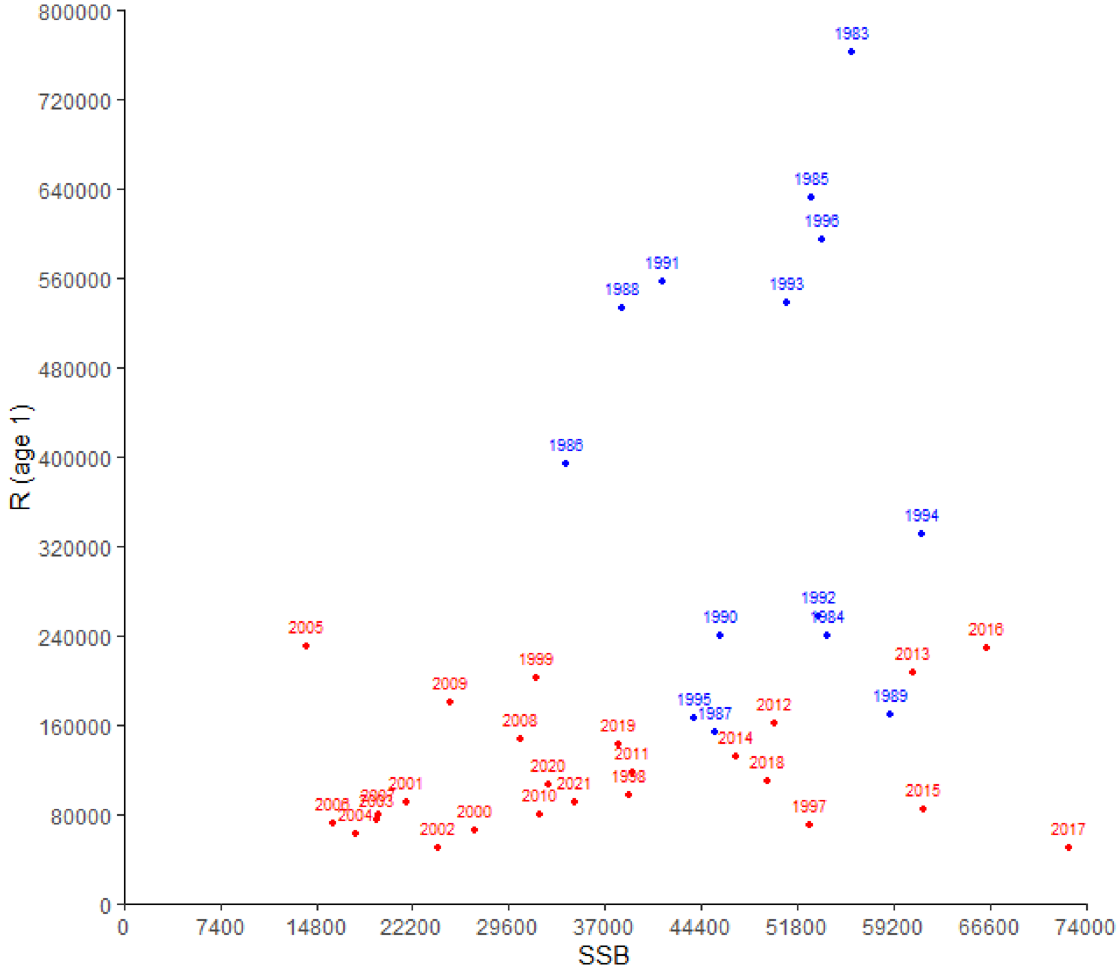

Figure 21.7. Northwestern substock stock-recruitment pairs from 1983+ (SSB in y and R in y+1). Blue indicates pairs prior to 1997.

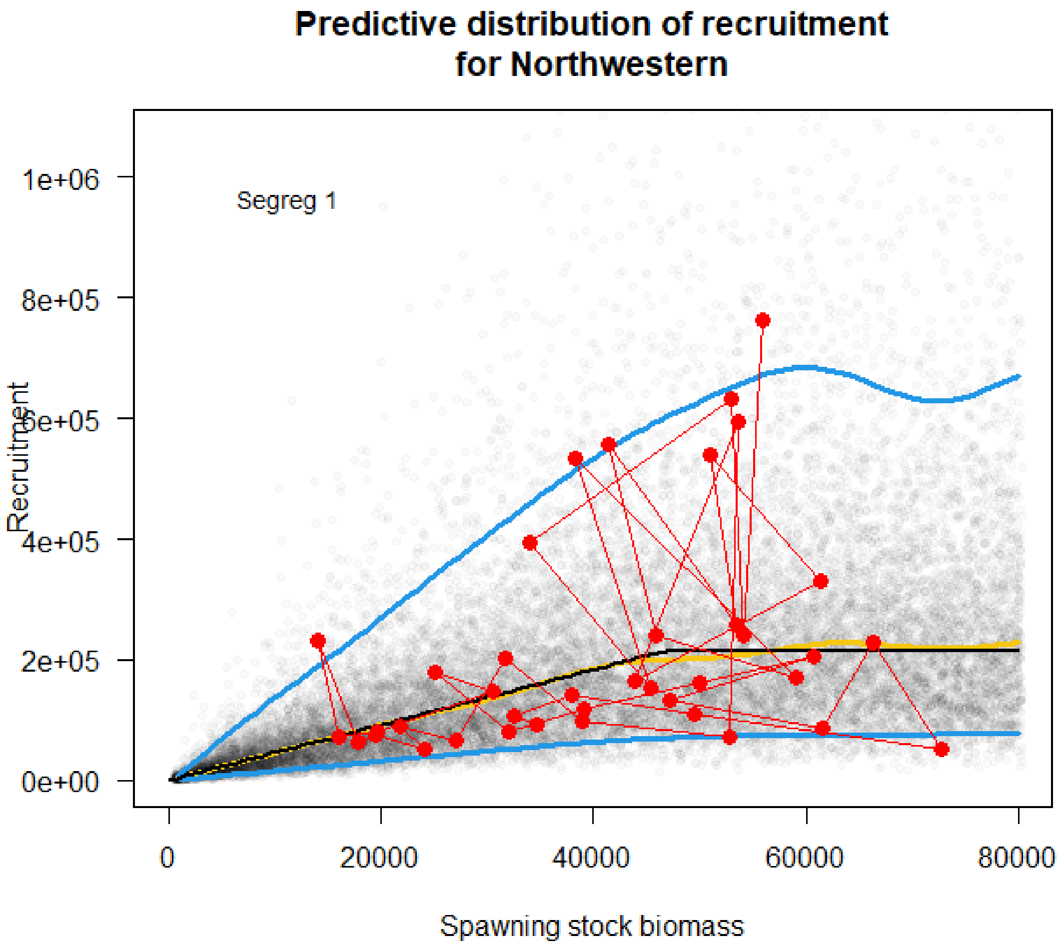

Figure 21.8. Northwestern substock segmented regression to 1983+, assuming Type 2.

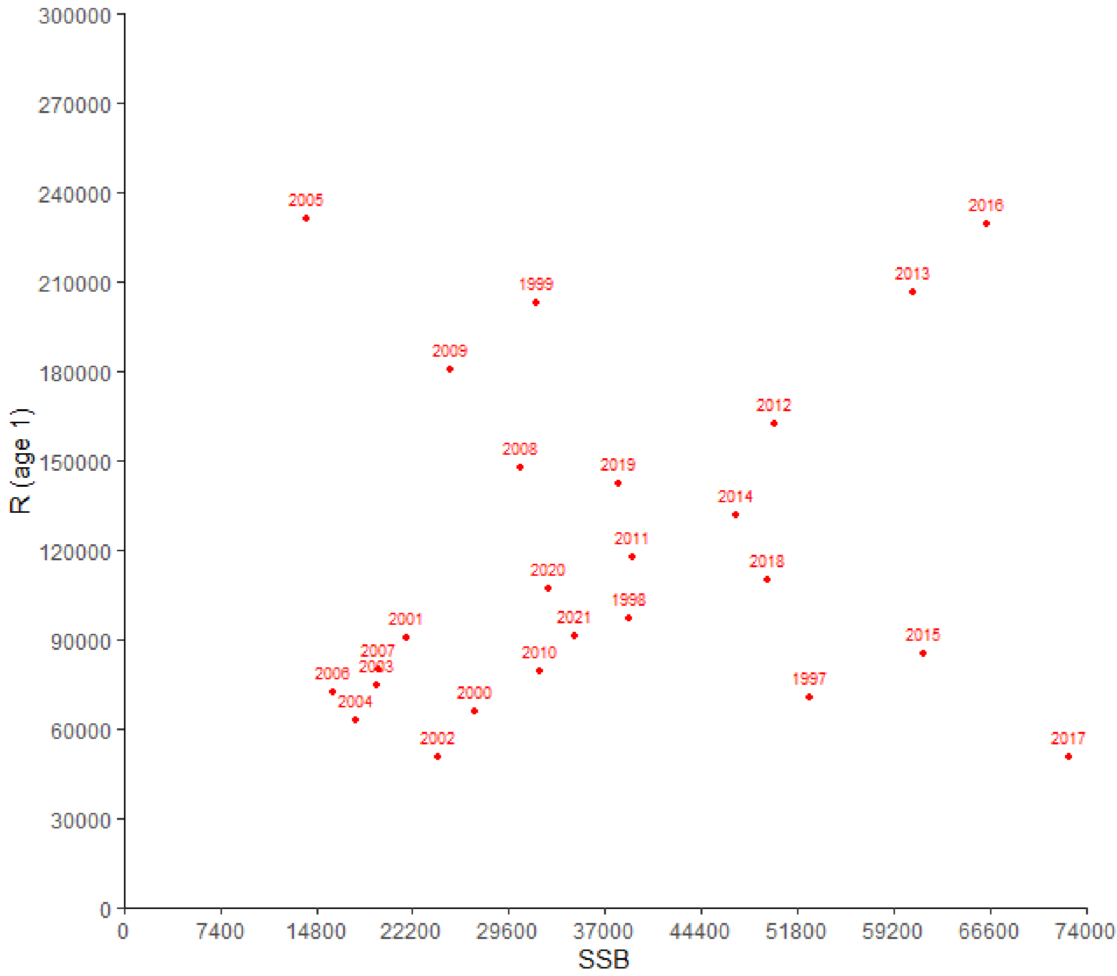

Figure 21.9. Northwestern substock stock-recruitment pairs from 1997+ (SSB in y and R in y+1).

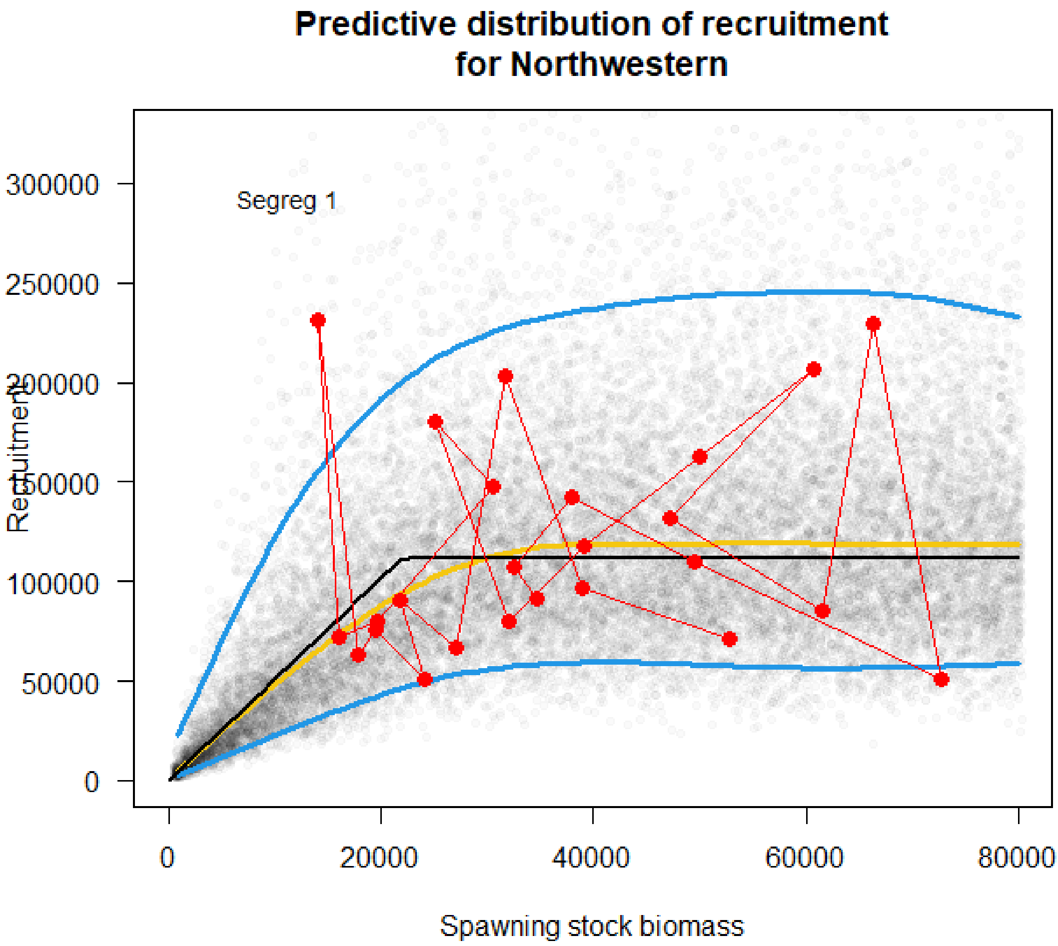

Figure 21.10. Northwestern substock segmented regression to 1997+, assuming Type 2.

21.14.7 Northwestern biological and selectivity data

The most recent 3 years of selectivity estimates were selected from which to resample for the simulations due to trends in the selectivity pattern for the Northwestern substock (i.e. increasing F-at-age for ages 5+ and a decreasing F-at-age for ages 3-). An analysis of biological parameters (i.e. mean weights, proportion mature and natural mortality) showed minimal trends in general and so the previous 10 years of data were selected to resample future biological data in the simulations.

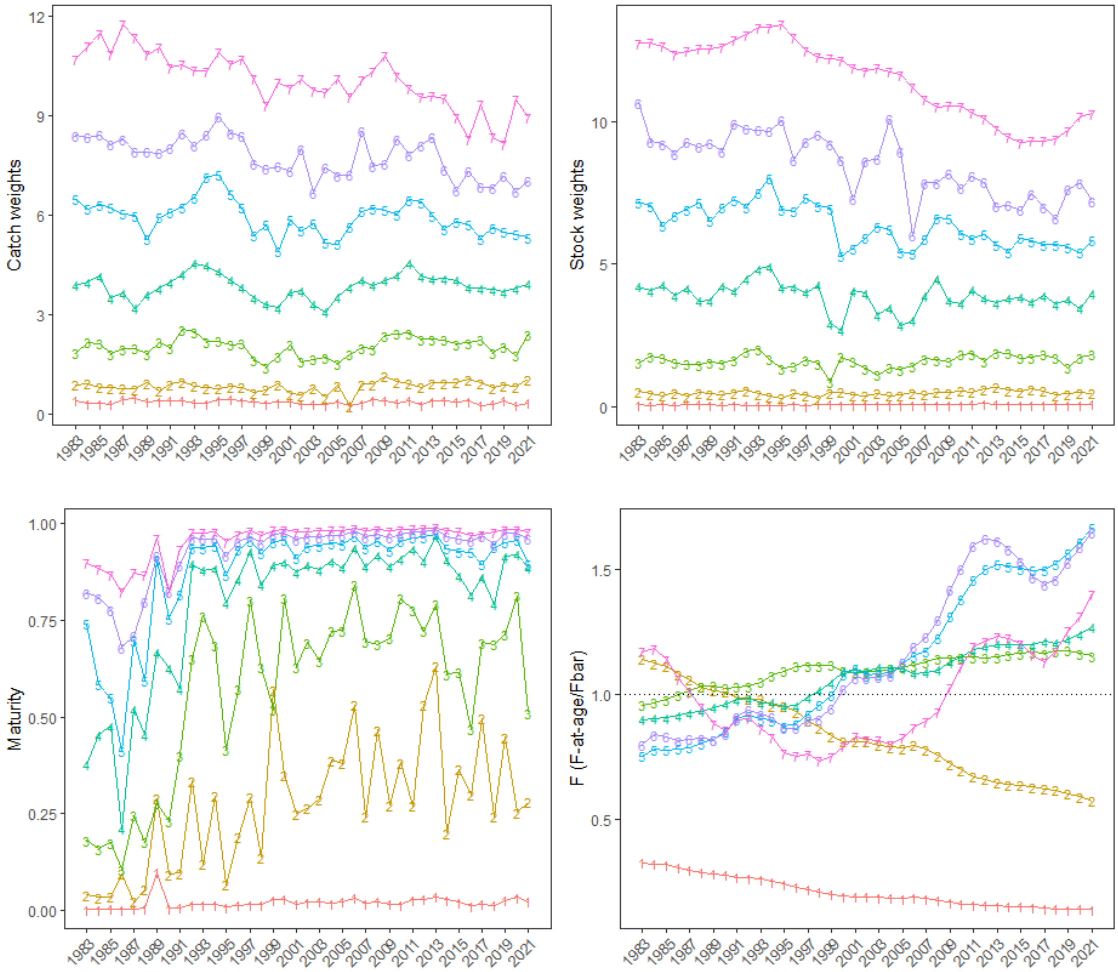

Figure 21.11. Northwestern biological and selectivity data-at-age 1983+.

21.14.8 Viking SR relationship

There was no consensus on stock-type definition when considering the ICES guidelines for the Viking substock, both for the full time series (1983+) or the truncated time series (1997+) of SR pairs. Generally, the SSB range for both sets of SR pairs was considered relatively narrow, discounting the high SSB and low R estimated in 2017. Some members of the group argued for evidence of recruitment impairment characterised by the cluster of SR pairs around the 8000 – 11000 SSB and 20000 – 40000 R marks. However, given the lack of consensus in the group, a proposal was made to set B_{lim} as the mean SSB in the lower 50th percentile producing above average recruitment, which was generally well received by the group. This approach is consistent with the method used to define B_{lim} during the benchmark for Western Baltic cod (WKBALTCOD2 2019). Consequently, the SR relationship is modelled as a segmented regression with the breakpoint fixed at B_{lim} as calculated above.

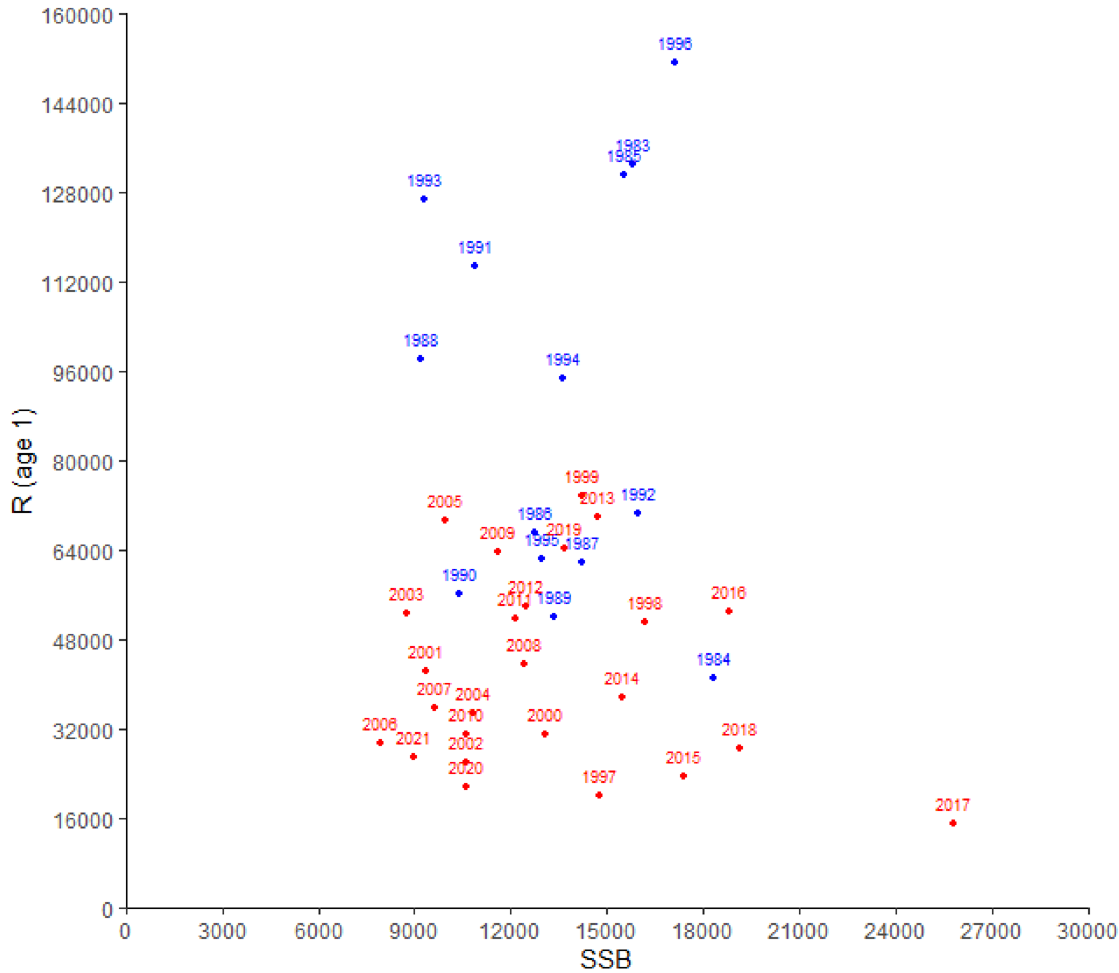

Figure 21.12. Viking substock stock-recruitment pairs from 1983+ (SSB in y and R in y+1). Blue indicates pairs prior to 1997.

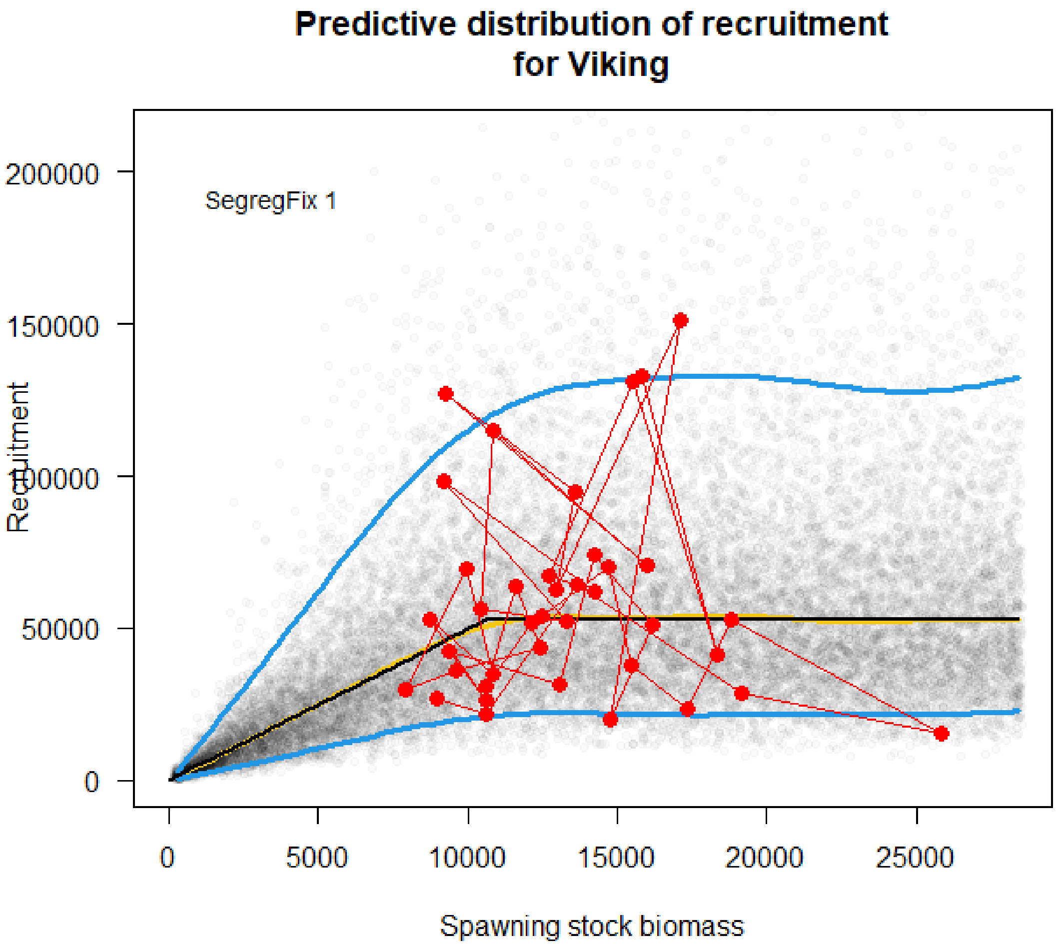

Figure 21.13. Viking substock segmented regression to 1983+, with the breakpoint set at the mean SSB in the lower 50th percentile producing above average recruitment.

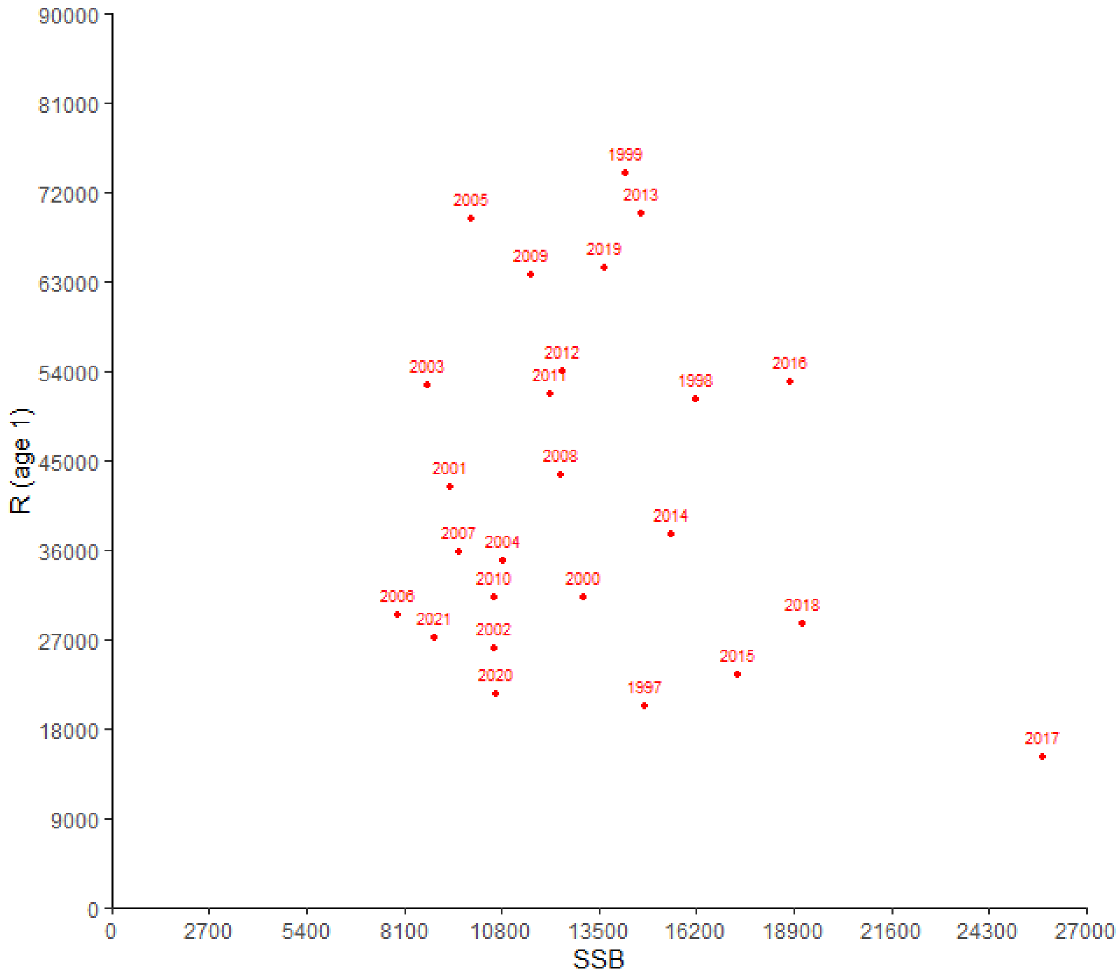

Figure 21.14. Viking substock stock-recruitment pairs from 1997+ (SSB in y and R in y+1).

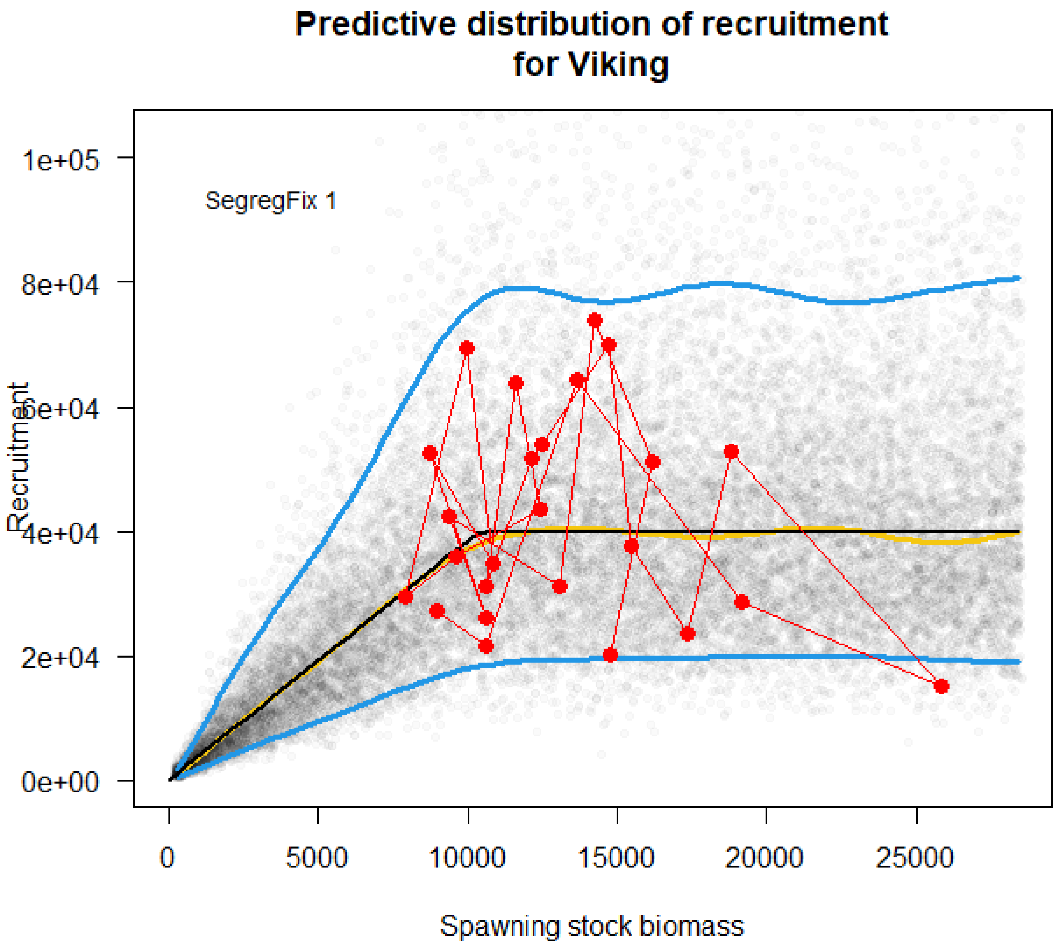

Figure 21.15. Viking substock segmented regression to 1997+, with the breakpoint set at the mean SSB in the lower 50th percentile producing above average recruitment.

21.14.9 Viking biological and selectivity data

The most recent 3 years of estimates were selected to resample future selectivity data in the simulations due to trends in the selectivity pattern for the Viking substock i.e. increasing F-at-age for ages 5+ and a decreasing F-at-age for ages 3-. An analysis of biological parameters (i.e. mean weights, proportion mature and natural mortality) showed minimal trends and so the previous 10 years of data were selected to resample future biological data in the simulations.

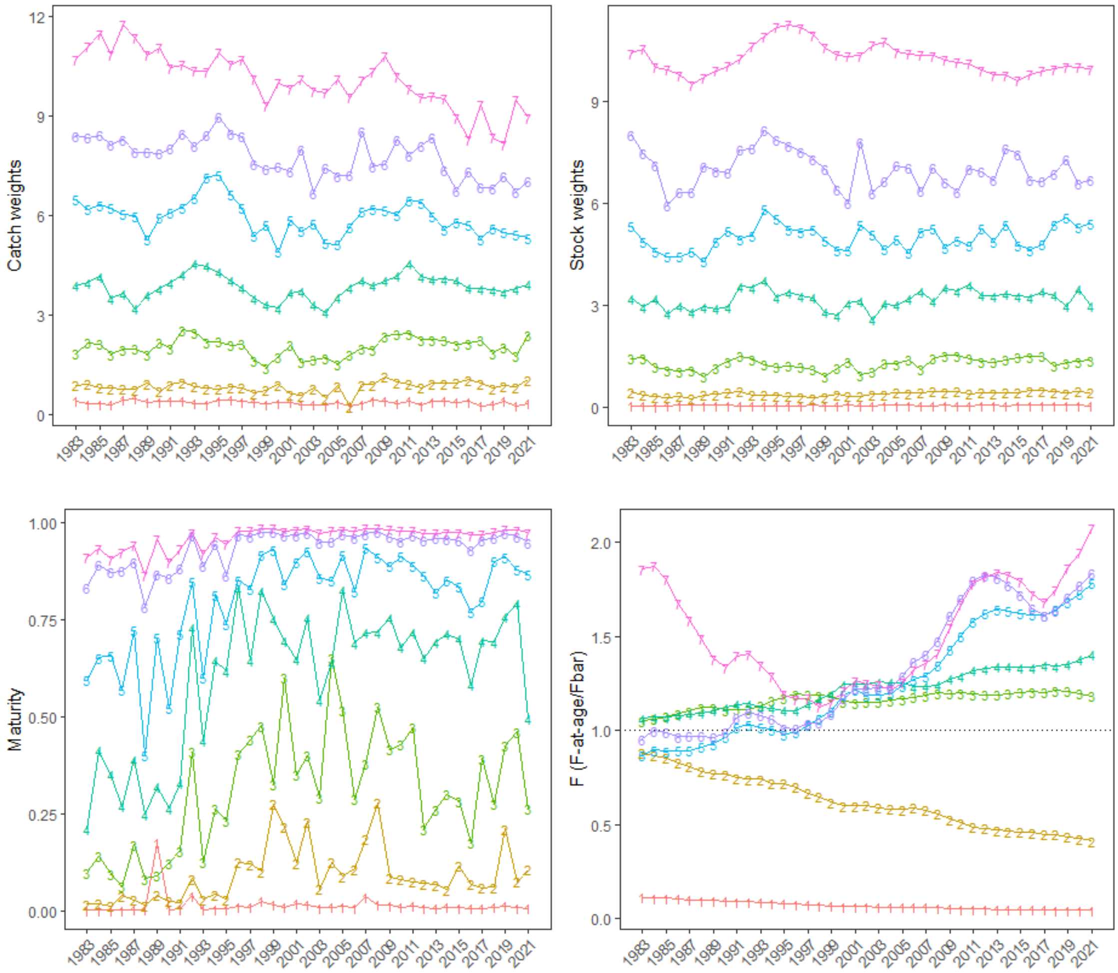

Figure 21.16. Viking biological and selectivity data-at-age 1983+.

21.14.10 Southern SR relationship

The group decided there was enough evidence of a different recruitment regime prior to 1997 to warrant truncating the Southern SR estimates. This is backed up in the literature (see e.g. Weijerman *et al*., 2005; Alvarez-Fernandez *et al*., 2012; Beaugrand *et al*., 2014). Analysing the SR pairs for the truncated time series led to a Type 2 stock definition, with strong evidence of recruitment impairment observed in the cluster of the most recent SR estimates towards the axes' origins. Following the ICES guidelines for Type 2 stocks, the SR relationship is modelled as a segmented regression with the breakpoint (B_{lim}) estimated in EqSim.

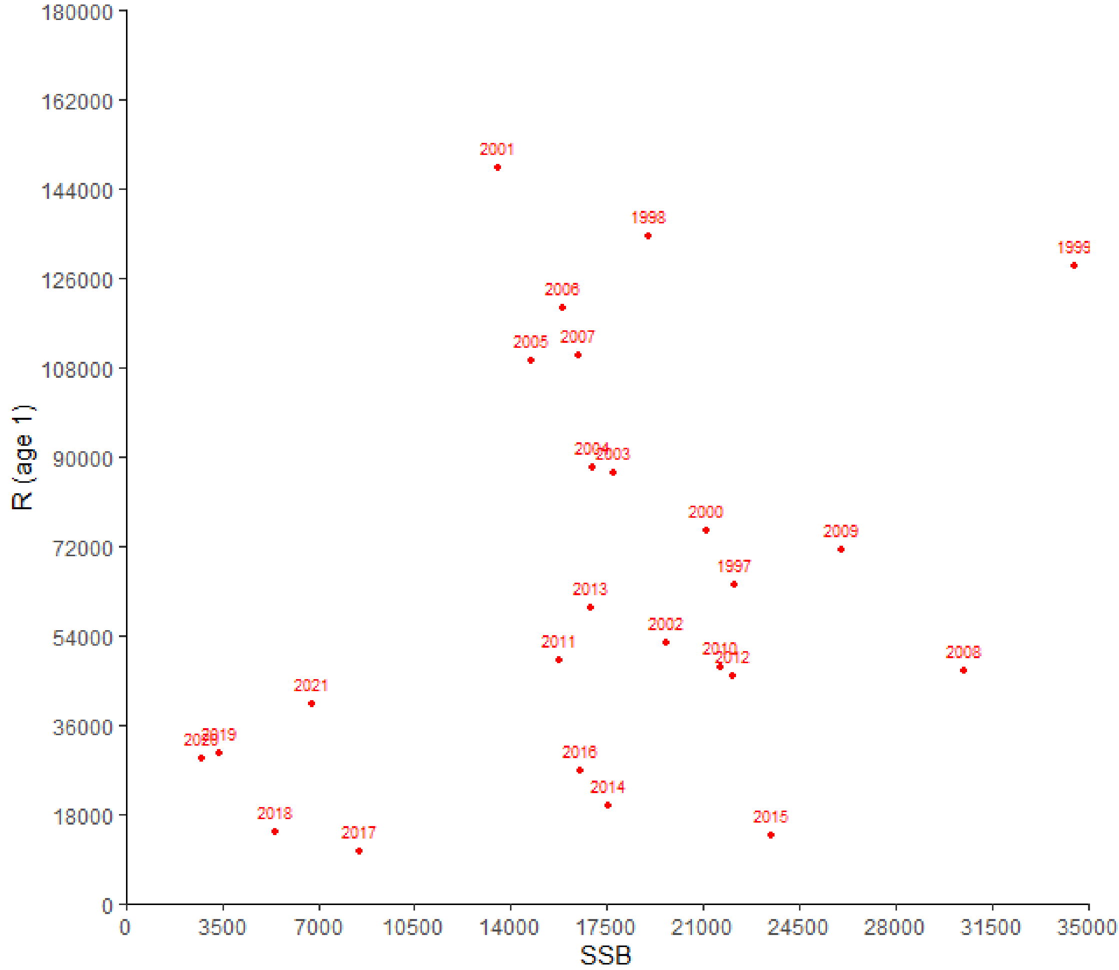

Figure 21.17. Southern substock stock-recruitment pairs from 1997+ (SSB in y and R in y+1).

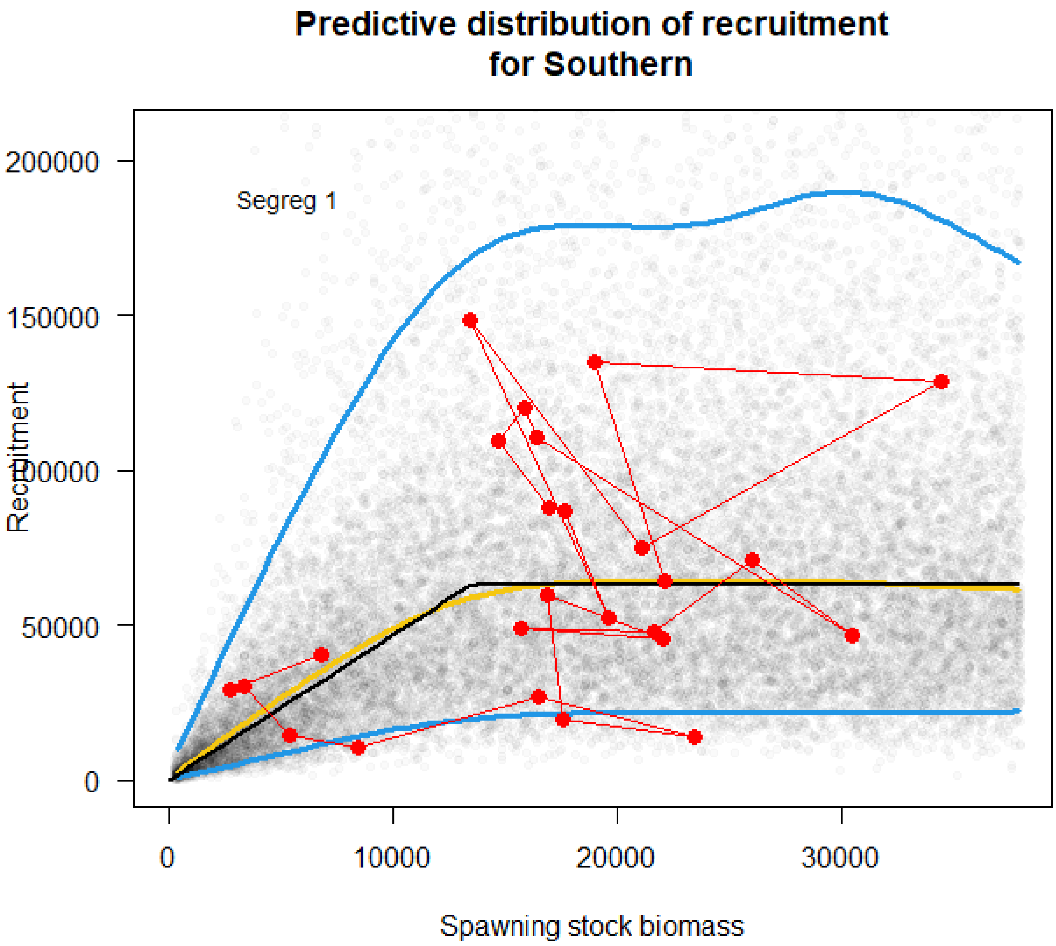

Figure 21.18. Southern substock segmented regression to 1997+, assuming Type 2.

21.14.11 Southern biological and selectivity data

The previous 3 years of data were selected to resample future selectivity data in the simulations due to observed trends in the selectivity pattern for the Southern substock i.e. increasing F-at-age for ages 5+ and a decreasing F-at-age for ages 3-. A sensitivity analysis using either the previous 10 years or 5 years of biological data was carried out for the Southern substock due to observed trends in the stock weights (decreasing for ages 4+) and the maturity (decreasing for ages 3 and 4, and potentially increasing for age 2). This exercise is to help determine which year-range to use in the final simulations.

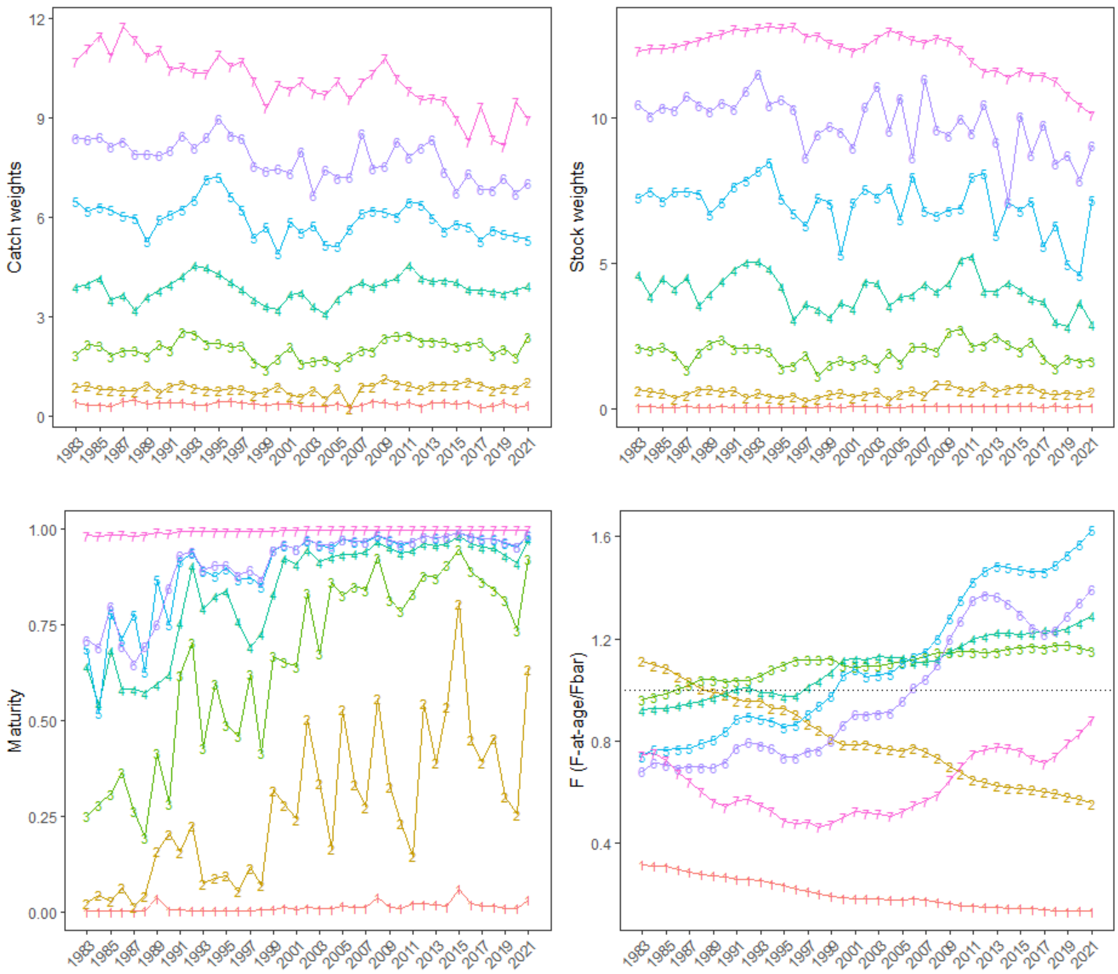

Figure 21.19. Southern biological and selectivity data-at-age 1983+.

21.14.12 Reference points

Below are the reference points estimated according to the ICES guidelines for each scenario outlined above for each substock of the Northern Shelf cod meta-population. B_{lim} follows from the definition of stock type, and B_{pa} is derived based on the usual formula (see Appendix). Initially, MSY $B_{trigger}$ is set equal to B_{pa}, and potentially updated by comparing the F_{bar} (Figure 21.4) to F_{msy}, following the guidelines. Once F_{MSY} is estimated (the peak of the median yield curve), the F_{MSY} range is calculated as those F values associated with median yield that is 95% of the peak of the median yield curve. $F_{p.05} = F_{pa}$ is the F value associated with a 5% risk upon application of the ICES MSY advice rule and F_{lim} is the F value associated with a 50% probability of SSB being above or below B_{lim}. F_{lim} is calculated from EqSim runs applying a fixed F harvest strategy without assessment or advice error (F_{cv} and $F_{phi} = 0$) and with the point of inflection of the stock–recruitment relationship forced at B_{lim} (see Appendix in Section 21.14.19).

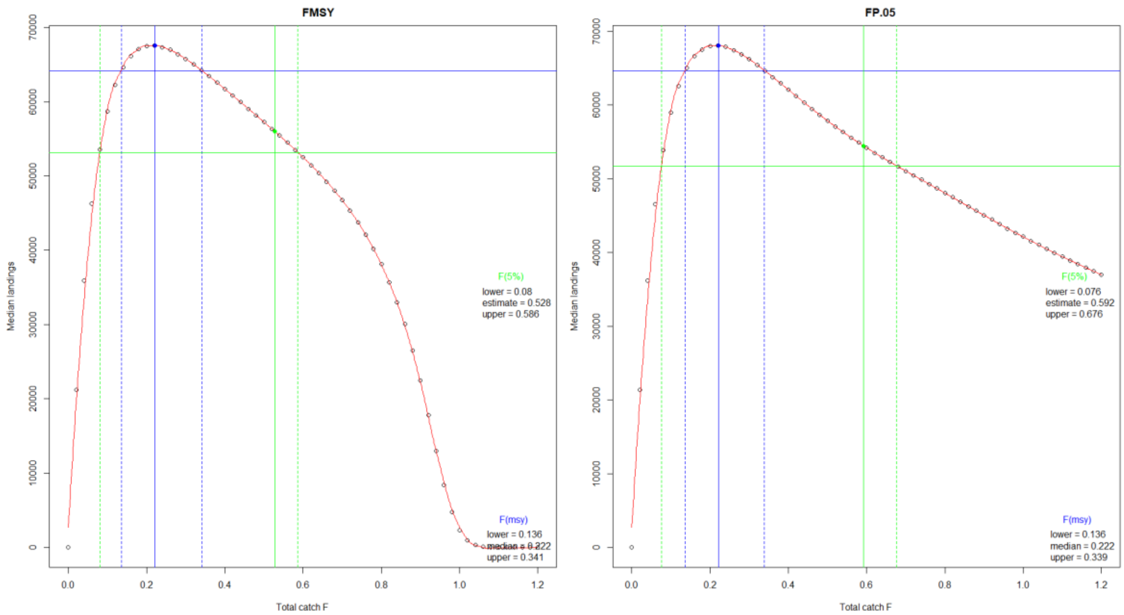

Figure 21.20. Northwestern substock for the period 1983+: estimation of F_{msy} (left) and $F_{p.05}$ (right)

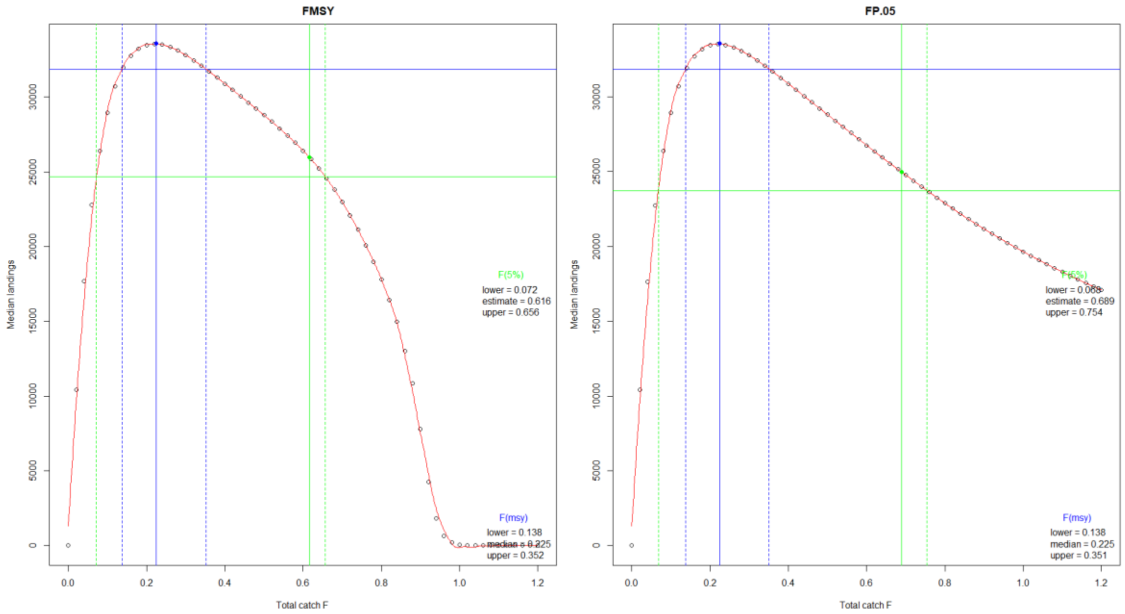

Figure 21.21. Northwestern substock for the period 1997+: estimation of F_{msy} (left) and $F_{p.05}$ (right)

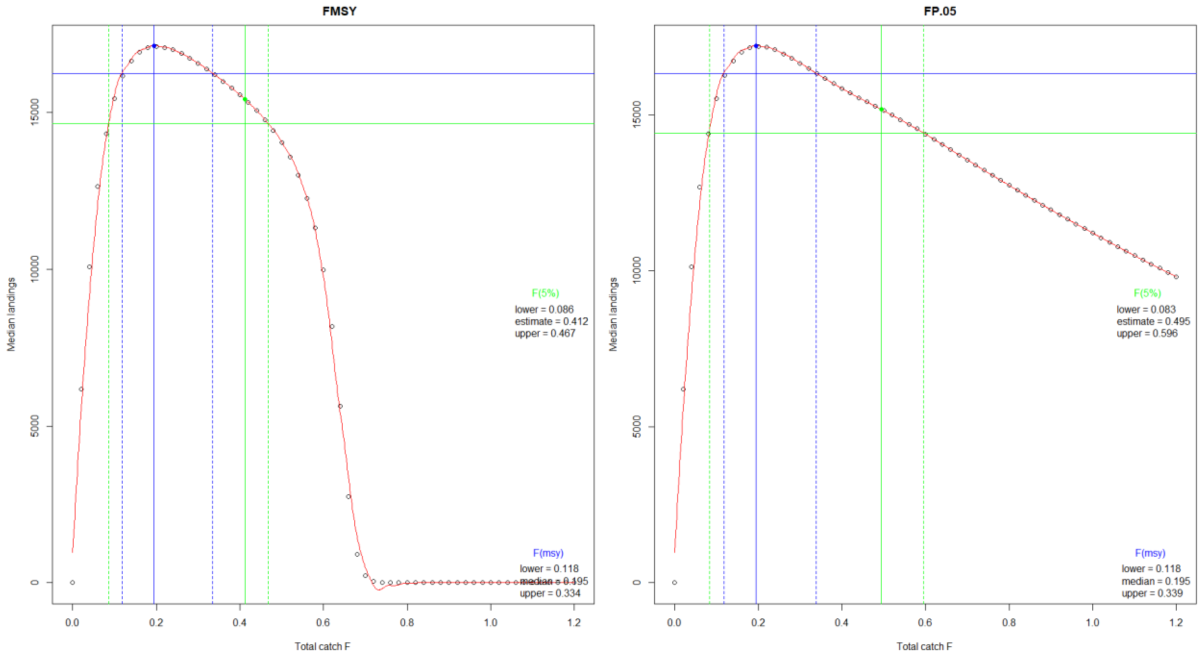

Figure 21.22. Viking substock for the period 1983+: estimation of F_{msy} (left) and $F_{p.05}$ (right)

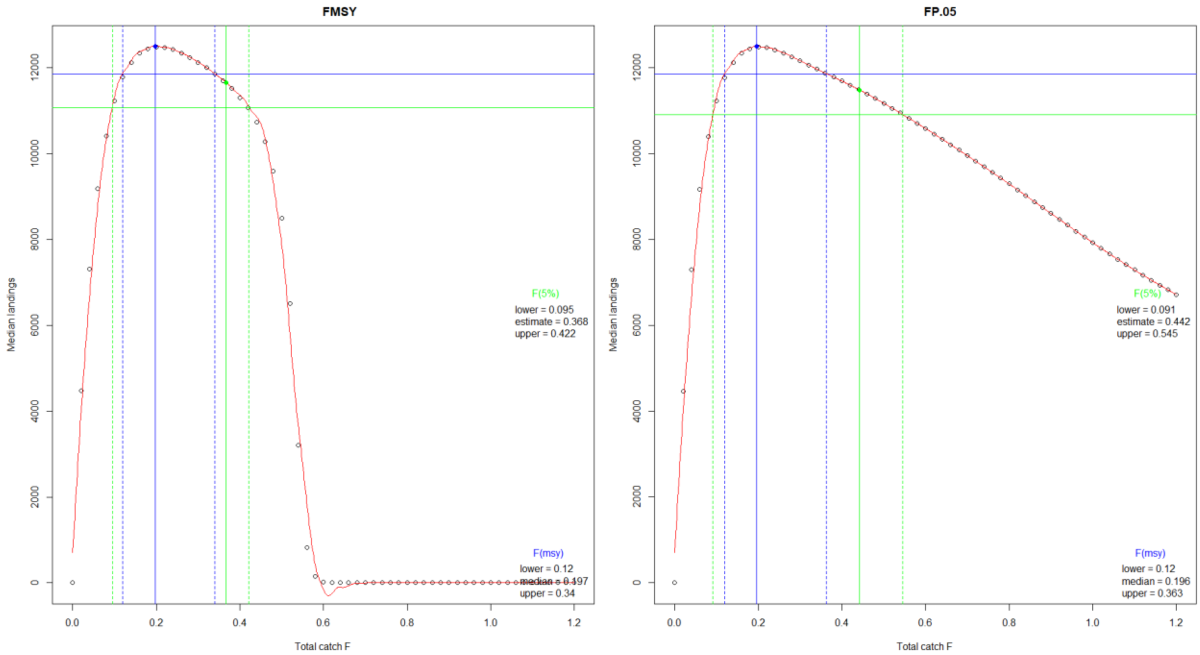

Figure 21.23. Viking substock for the period 1997+: estimation of F_{msy} (left) and $F_{p.05}$ (right)

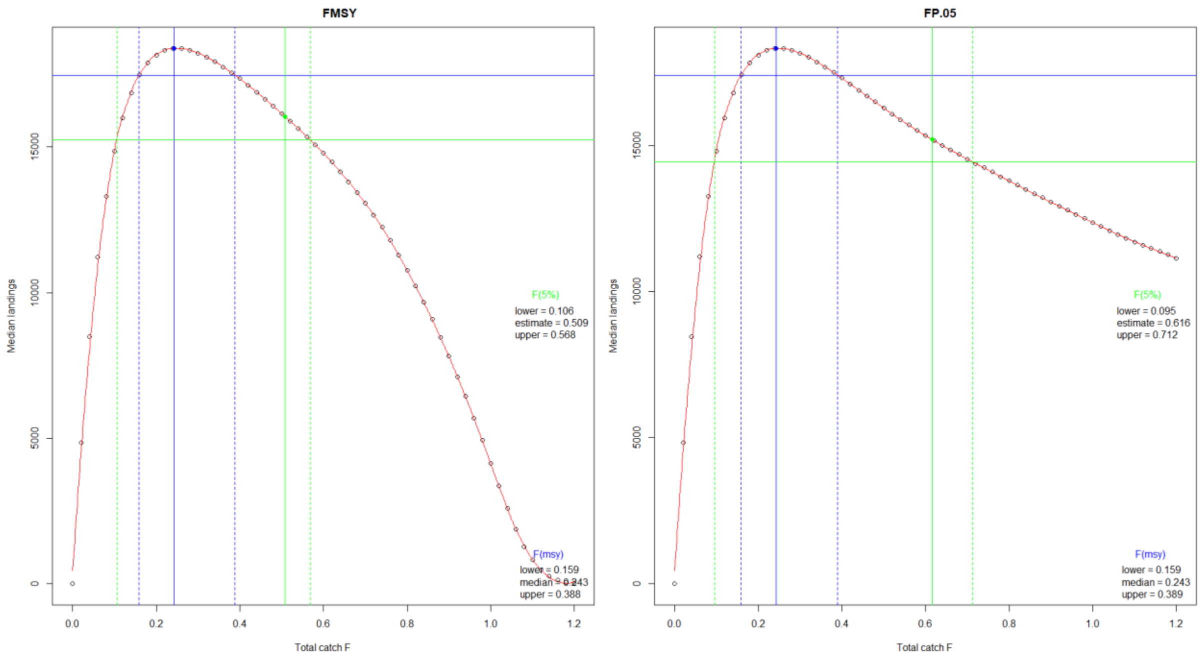

Figure 21.24. Southern substock for the period 1997+ and sampling from the most recent 5 years for biological parameters: estimation of F_{msy} (left) and $F_{p.05}$ (right)

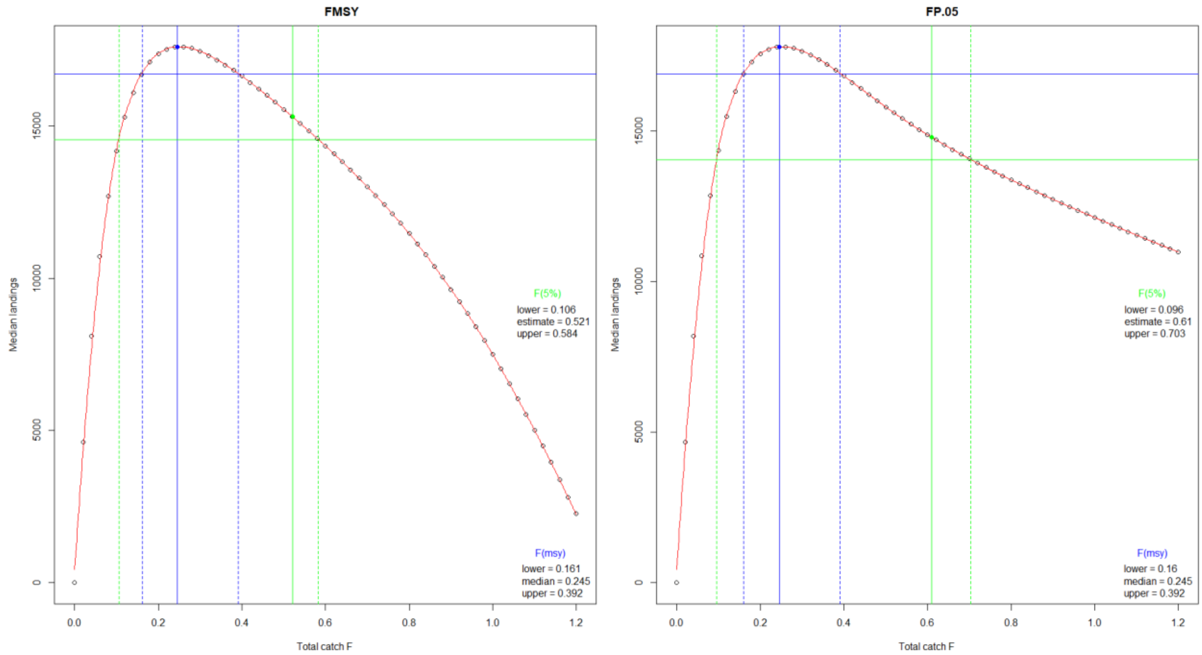

Figure 21.25. Southern substock for the period 1997+ and sampling from the most recent 10 years for biological parameters: estimation of F_{msy} (left) and $F_{p.05}$ (right).

21.14.13 B_{MSY} and B_0

B_{MSY} denotes the expected equilibrium biomass when fishing at F_{MSY} and is estimated as the biomass corresponding to F_{MSY} in the equilibrium curve of fishing pressure (F) vs. stock biomass (median SSB). For each stock, the estimated B_{MSY} under all assumptions of SR type and truncation are much larger than the maximum SSB seen in the SR pairs. B_0 denotes the expected equilibrium biomass of the stock under zero-fishing conditions (i.e. F = 0) and is output by EqSim during equilibrium simulations as the median SSB at $F_{target} = 0$. The values for B_{MSY} and B_0 are presented below.

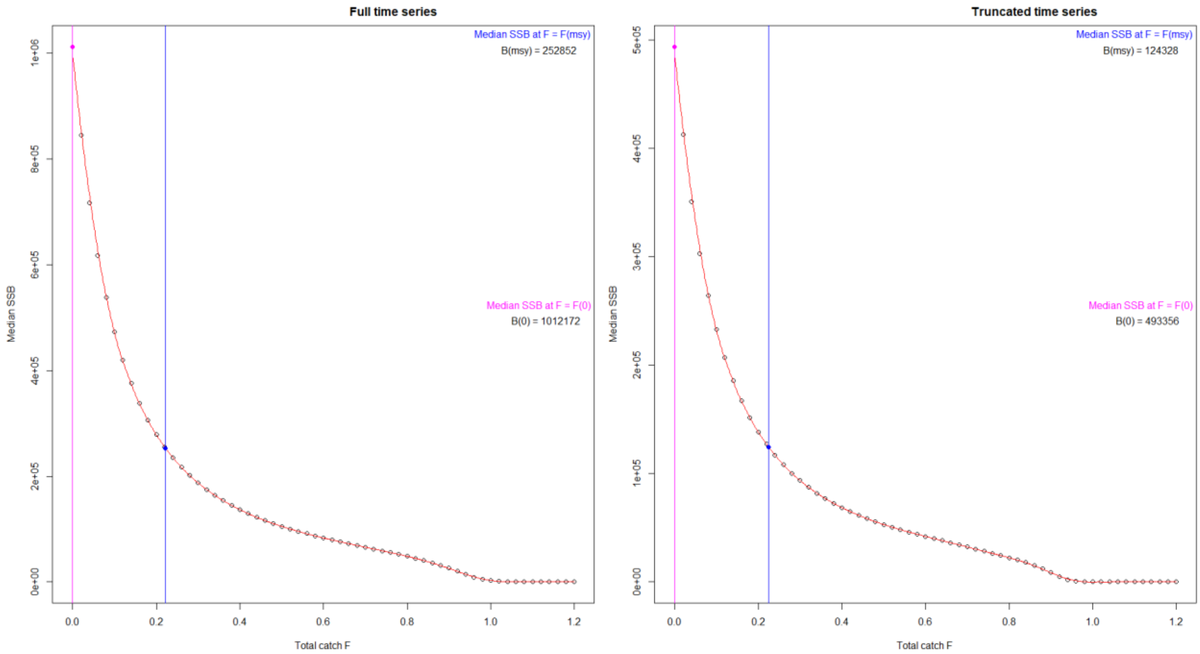

Figure 21.26. Northwestern substock estimation of B_{msy} and B_0 for the full period 1983+ (left) and the truncated period 1997+ (right)

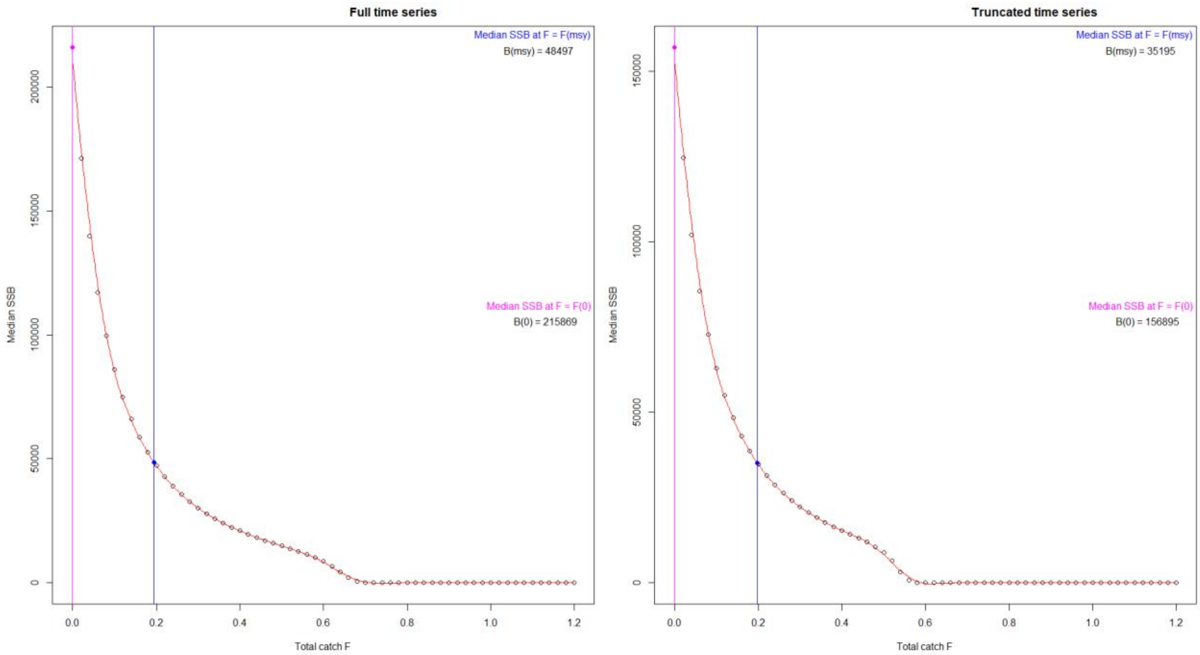

Figure 21.27. Viking substock estimation of B_{msy} and B_0 for the full period 1983+ (left) and the truncated period 1997+ (right)

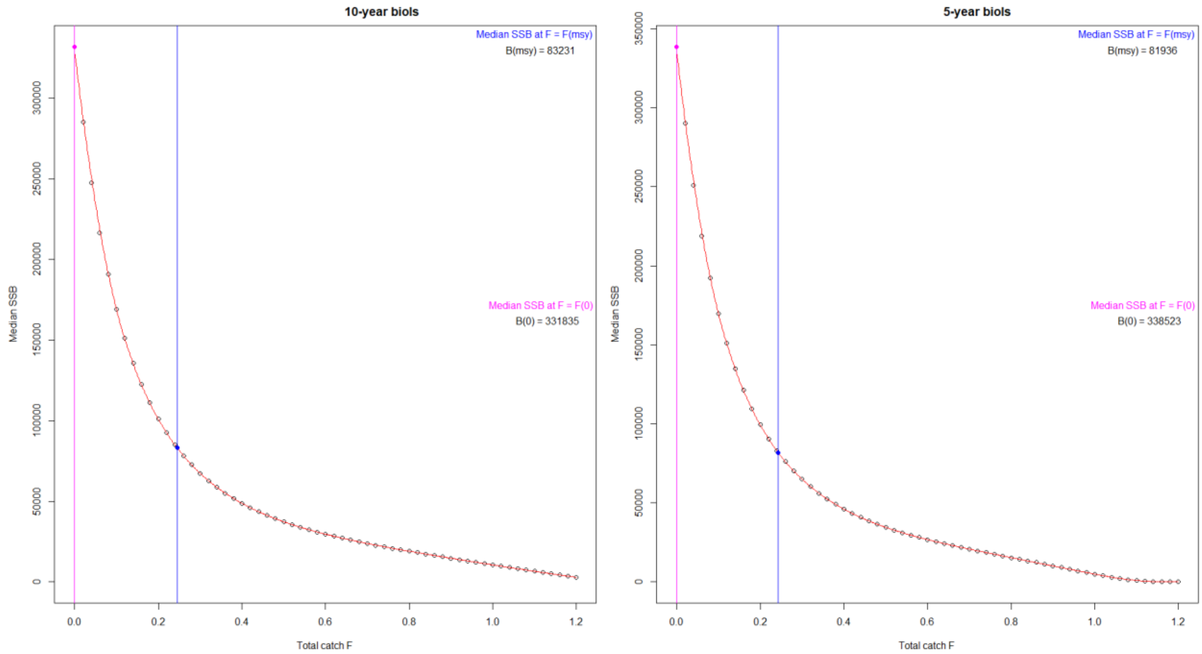

Figure 21.28. Southern substock estimation of B_{msy} and B_0 for the truncated period 1997+ sampling biological parameters from the previous 10 years (left) and the previous 5 years (right).

21.14.14 Autocorrelation in recruitment

Autocorrelation in recruitment residuals is now included as standard in EqSim (rhologRec) and is estimated from the SR model fits. The median value of autocorrelation in recruitment is presented in Table 21.6 below for each substock, stock type and time series scenario.

21.14.15 Reference point table

Table 21.6. Reference points for the three substocks, with two options for each (based on different SR periods for NW and V, and based on different periods for the biological parameters for S).

Northwestern Type 2

Series	$B_{trigger}$	B_{lim}	B_{pa}	F_{MSY}	$F_{MSYupper}$	$F_{MSYlower}$	B_{MSY}	B_0	F_{lim}	$F_{p.05}$	F_{pa}	biol	sel	rhologRec
1983+	60294	46351	60294	0.222	0.341	0.136	252852	1012172	0.836	0.592	0.592	10	3	0.113
1997+	28570	21964	28570	0.225	0.352	0.138	124328	493356	0.839	0.689	0.689	10	3	-0.156

Viking Type M

Series	$B_{trigger}$	B_{lim}	B_{pa}	F_{MSY}	$F_{MSYupper}$	$F_{MSYlower}$	B_{MSY}	B_0	F_{lim}	$F_{p.05}$	F_{pa}	biol	sel	rhologRec
1983+	15444	10611	15444	0.195	0.334	0.118	48497	215869	0.595	0.495	0.495	10	3	0.085
1997+	15098	10374	15098	0.197	0.34	0.12	35195	156895	0.502	0.442	0.442	10	3	-0.217

Southern Type 2

Series	$B_{trigger}$	B_{lim}	B_{pa}	F_{MSY}	$F_{MSYupper}$	$F_{MSYlower}$	B_{MSY}	B_0	F_{lim}	$F_{p.05}$	F_{pa}	biol	sel	rhologRec
1997+	19786	13504	19786	0.245	0.392	0.161	83231	331835	0.948	0.61	0.61	10	3	0.624
1997+	19786	13504	19786	0.243	0.388	0.159	81936	338523	0.852	0.616	0.616	5	3	0.624

21.14.16 Supplementary analysis: follow-up meeting

Recruits-per-spawner

Additional analysis of the recruits-per-spawner for the individual substocks was requested at the final benchmark meeting to assist the decision on truncating the timeseries for the North-western and Viking substocks. A comparison between the average recruits-per-spawner before and after the potential regime shift in 1997 is presented for each substock in the section below.

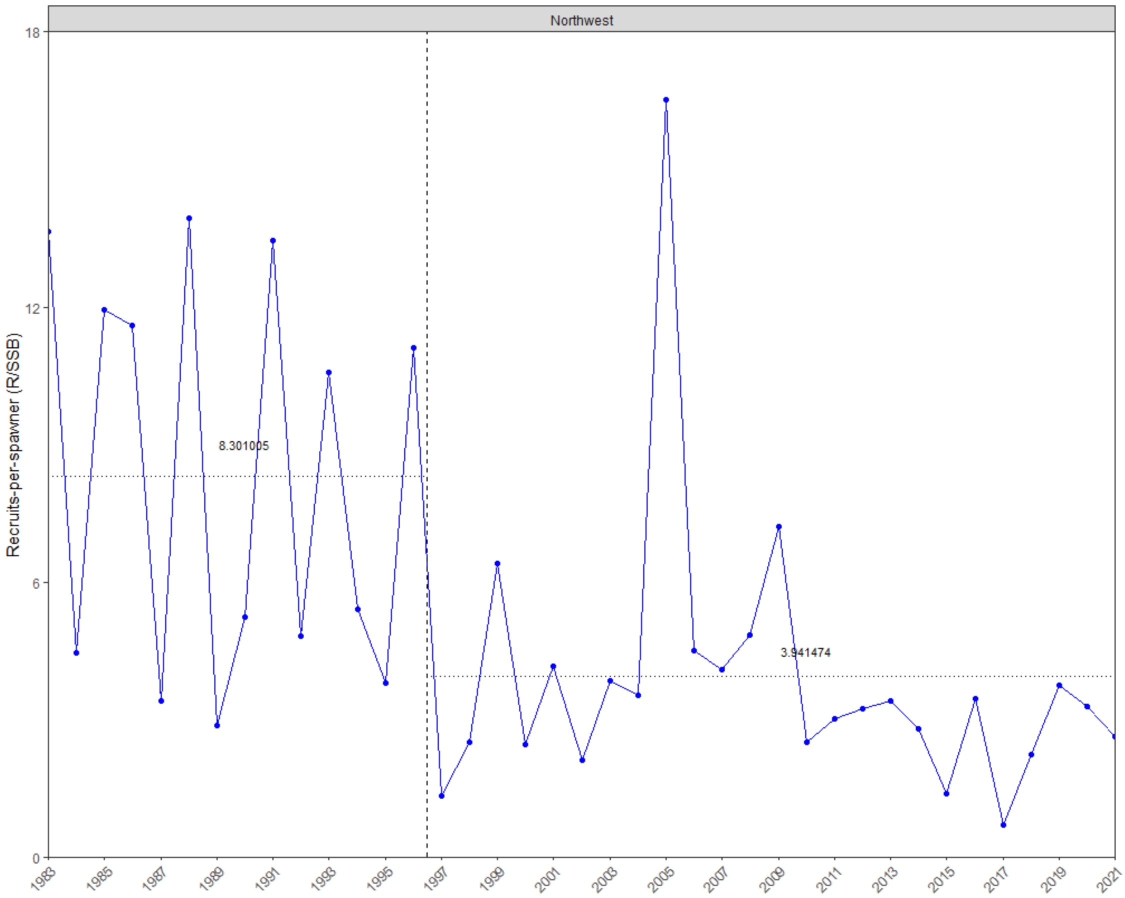

Figure 21.29. Recruits-per-spawner for the Northwestern substock (year indicates the SSB year). The vertical dashed line indicates the delineation of a potential regime shift. The dotted horizontal years show the average recruits-per-spawner for the period pre-1997 (8.301005) and the period post-1997 (3.941474).

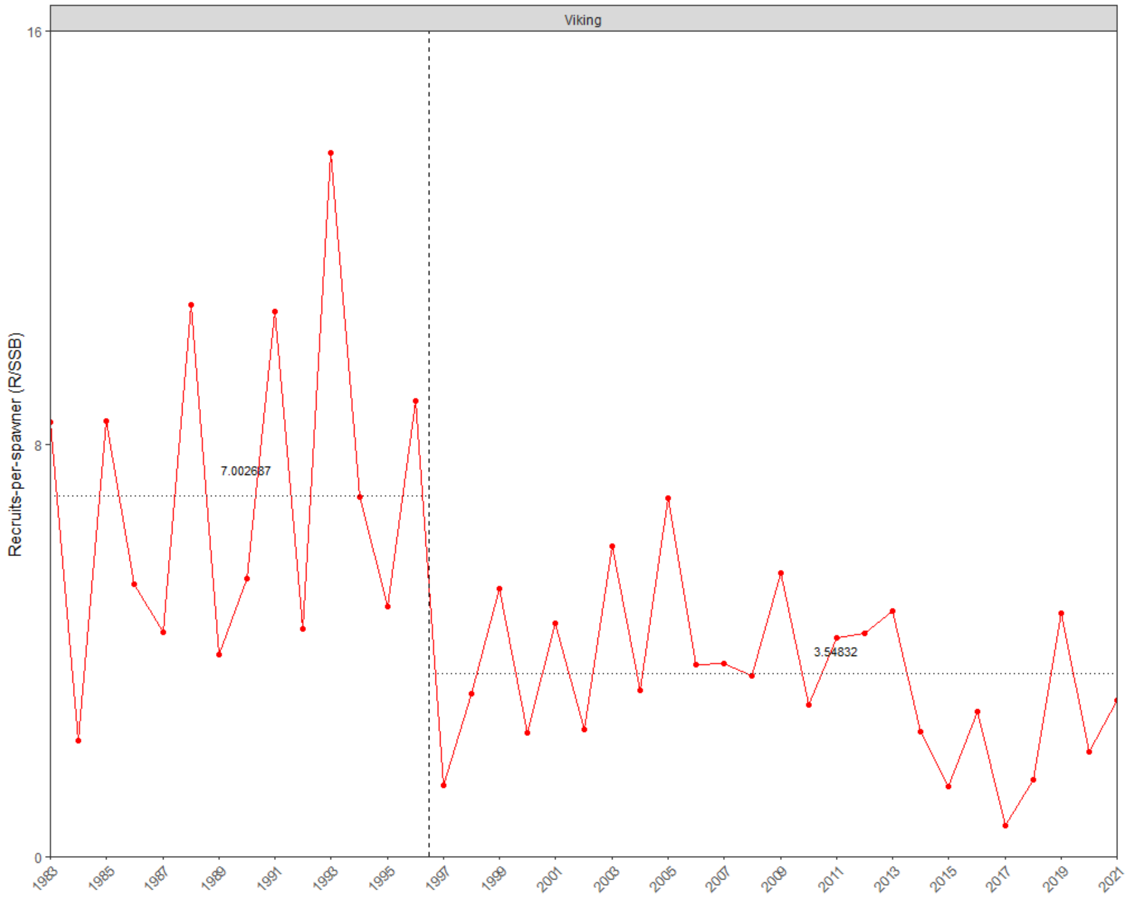

Figure 21.30. Recruits-per-spawner for the Viking substock (year indicates the SSB year). The vertical dashed line indicates the delineation of a potential regime shift. The dotted horizontal years show the average recruits-per-spawner for the period pre-1997 (7.002687) and the period post-1997 (3.54832).

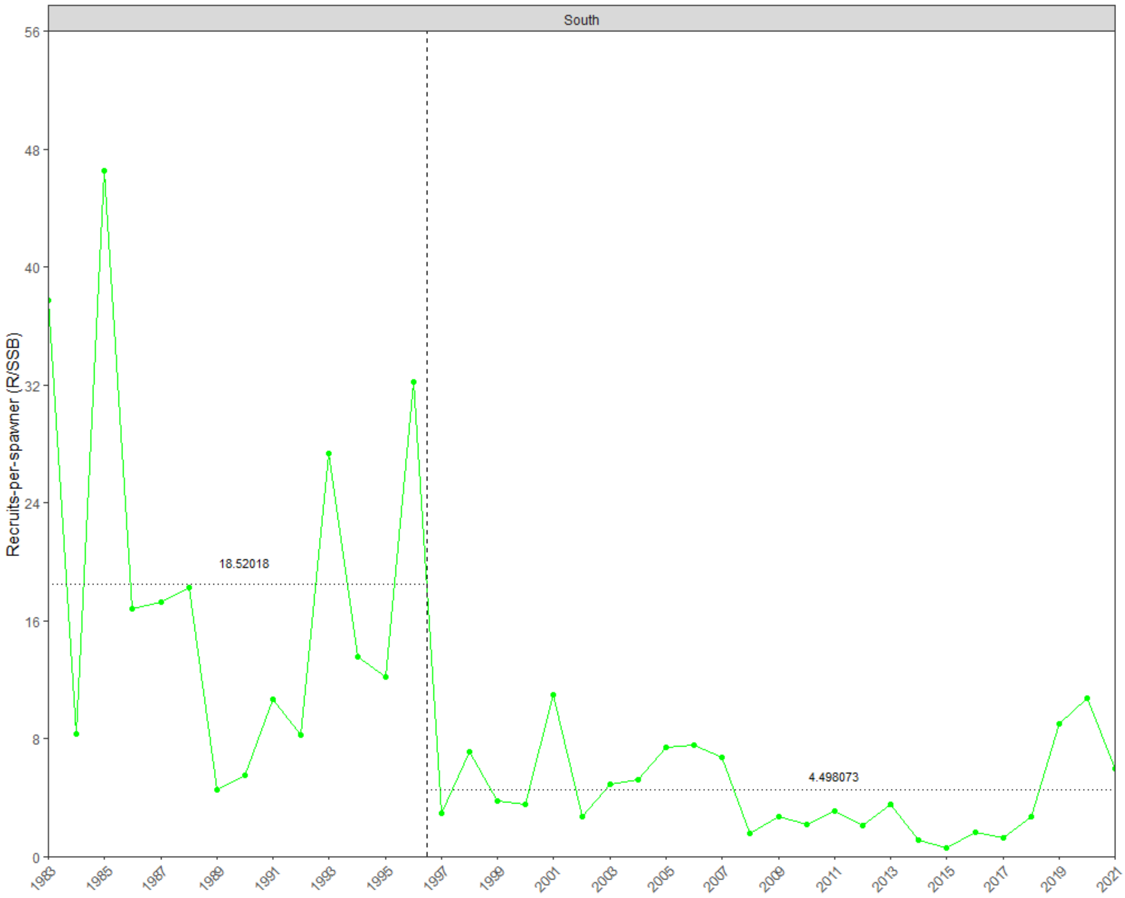

Figure 21.31. Recruits-per-spawner for the Southern substock (year indicates the SSB year). The vertical dashed line indicates the delineation of a potential regime shift. The dotted horizontal years show the average recruits-per-spawner for the period pre-1997 (18.52018) and the period post-1997 (4.498073).

The results in Table 21.7 confirm that the average recruits-per-spawner pre-1997 vs post-1997 are significantly different, providing some support for truncating to consider only 1997+ for all three substocks.

Table 21.7. Results from two-sample t-tests comparing average recruits-per-spawner before and after the potential regime shift (1997) for each substock.

Substock	Avg. RpS 1983 to 1996	Avg. RpS 1997+	*t*	*df*	*p*
Northwestern	8.301005	3.941474	3.3269	20.574	0.003268
Viking	7.002687	3.54832	3.7798	16.542	0.001559
Southern	18.52018	4.498073	4.0378	13.862	0.001245

21.14.17 Autocorrelation in recruitment residuals

Additional simulations without autocorrelation in recruitment residuals ("rhoLogRec = FALSE" in EqSim) were carried out for each substock to check the sensitivity of forcing rhoLogRec to zero on reference point estimates. These sensitivity runs were carried out on the options using the same data and settings as agreed at the final benchmark meeting.

Table 21.8. Reference points for final options (i.e. SR period and biological parameters for S) for each substock with additional sensitivity runs without autocorrelation in recruitment residuals ("rhoLogRec = FALSE" in EqSim).

Northwestern Type 2

Series	$B_{trigger}$	B_{lim}	B_{pa}	F_{MSY}	$F_{MSYupper}$	$F_{MSYlower}$	B_{MSY}	B_0	F_{lim}	$F_{p.05} = F_{pa}$	biol	sel	rhologRec
1997+	28570	21964	28570	0.225	0.352	0.138	124328	493356	0.839	0.689	10	3	-0.156
1997+	28570	21964	28570	0.225	0.35	0.138	124000	492687	0.839	0.678	10	3	N/A

Viking Type M

Series	$B_{trigger}$	B_{lim}	B_{pa}	F_{MSY}	$F_{MSYupper}$	$F_{MSYlower}$	B_{MSY}	B_0	F_{lim}	$F_{p.05} = F_{pa}$	biol	sel	rhologRec
1997+	15098	10374	15098	0.197	0.34	0.12	35195	156895	0.502	0.442	10	3	-0.217
1997+	15098	10374	15098	0.271	0.566	0.125	35203	156727	0.689	0.596	10	3	N/A

Southern Type 2

Series	$B_{trigger}$	B_{lim}	B_{pa}	F_{MSY}	$F_{MSYupper}$	$F_{MSYlower}$	B_{MSY}	B_0	F_{lim}	$F_{p.05} = F_{pa}$	biol	sel	rhologRec
1997+	19786	13504	19786	0.243	0.388	0.159	81936	338523	0.852	0.616	5	3	0.624
1997+	19786	13504	19786	0.261	0.395	0.162	79706	350776	0.957	0.732	5	3	N/A

21.14.18 References

Alvarez-Fernandez, S., Lindeboom, H., and Meesters, E. 2012. Temporal changes in plankton of the North Sea: community shifts and environmental drivers. Marine Ecology Progress Series. 462: 21–38.

Beaugrand, G., Harlay, X., and Edwards, M. 2014. Detecting plankton shifts in the North Sea: a new abrupt ecosystem shift between 1996 and 2003. Marine Ecology Progress Series. 502: 85–104.

Weijerman, M., Lindeboom, H., and Zuur, A.F. 2005. Regime shifts in marine ecosystems in the North Sea and Wadden Sea. Marine Ecology Progress Series. 298: 21–39.

21.14.19 Appendix

General Methods and settings used in EqSim

Assessment error and autocorrelation

The default values for assessment error and autocorrelation in the advisory year (i.e., F_{cv} and F_{phi}) were from WKMSYREF4 were used in simulations for determining F_{MSY} and $F_{p.05}$ i.e., F_{cv} = 0.212 and F_{phi} = 0.423. The multiSAM estimate of the standard deviation of ln(SSB) in the terminal year was also used in the equation linking B_{lim} and B_{pa}:

$$B_{pa} = B_{lim} \times e^{(1.645 \times \sigma)}$$

Where σ is the multiSAM estimate of the standard deviation of ln(SSB) in the terminal year (NW = 0.15987, V = 0.22815, S = 0.23223).

Assumptions and objectives when calculating F reference points

	Include advice rule?	F_{cv}	F_{phi}	Objective (long-term)
F_{lim}	No	0	0	F that results in median SSB = B_{lim}
F_{msy} & range	No	0.212	0.423	F that maximise median yield (95% of maximum median yield for range)
$F_{p.05}$	Yes	0.212	0.423	F that results in 5th percentile SSB = B_{lim}

Using wanted catch to estimate yield curves

Under the landings obligation, all catches over the minimum conservation reference size (MCRS) must be landed. For Northern Shelf cod, all fish aged 3+ are assumed to be above the MCRS and usually be landed and sold, therefore contributing to the "wanted catch" proportion of the fishery. As such, the estimated discards for ages 3+ are added to the landings for each substock before simulating yield curves and estimating the yield-based reference points F_{MSY}, $F_{p.05}$ and F_{lim}.

21.15 Reference points in relation to B_{MSY} and B_0

Alessandro Orio and Massimiliano Cardinale

The WD on the estimation of reference points for Northern Shelf cod substocks (Section 21.14) reports in Table 21.6 the proposed reference points for the different substocks along the estimates of B_{MSY} and B_0 coming from EqSim. In the following table (**Error! Reference source not found.**), we report an extract of the biomass reference points table with the addition of several columns that include ratios between the proposed B_{lim} and B_0, between B_{lim} and B_{MSY}, $B_{trigger}$ and B_0, $B_{trigger}$ and B_{MSY}, and B_{MSY} over B_0. Also added is the value of 50% B_{MSY}.

B_{MSY} is around 22–25% of B_0, which is in line with most of gadoids stocks in the North East Atlantic (ICES 2022a, 2022b) so both B_0 and B_{MSY} are in line with the expected dynamic of ICES assessed cod stocks.

Table 21.9. Biomass reference points for the three substocks, with two options for each (based on different SR periods for NW and V and based on different periods for the biological parameters for S). Ratios between reference points and BMSY and B0 are also reported.

Northwestern Type 2

Series	$B_{trigger}$	B_{lim}	B_{pa}	B_{MSY}	B_0	B_{lim}/B_0	$B_{trigger}/B_0$	B_{lim}/B_{MSY}	$B_{trigger}/B_{MSY}$	B_{MSY}/B_0	50% B_{MSY}
1983+	60294	46351	60294	252852	1012172	0.046	0.060	0.183	0.238	0.250	126426
1997+	28570	21964	28570	124328	493356	0.045	0.058	0.177	0.230	0.252	62164

Viking Type M

Series	$B_{trigger}$	B_{lim}	B_{pa}	B_{MSY}	B_0	B_{lim}/B_0	$B_{trigger}/B_0$	B_{lim}/B_{MSY}	$B_{trigger}/B_{MSY}$	B_{MSY}/B_0	50% B_{MSY}
1983+	15444	10611	15444	48497	215869	0.049	0.072	0.219	0.318	0.225	24249
1997+	15098	10374	15098	35195	156895	0.066	0.096	0.295	0.429	0.224	17598

Southern Type 2

Series	$B_{trigger}$	B_{lim}	B_{pa}	B_{MSY}	B_0	B_{lim}/B_0	$B_{trigger}/B_0$	B_{lim}/B_{MSY}	$B_{trigger}/B_{MSY}$	B_{MSY}/B_0	50% B_{MSY}
1997+	19786	13504	19786	83231	331835	0.041	0.060	0.162	0.238	0.251	41616
1997+	19786	13504	19786	81936	338523	0.040	0.058	0.165	0.241	0.242	40968

Concerning the ratio between B_{lim} and B_0, all values are below 5% except for the Viking when using the short time series, which is nonetheless under 7%. While, regarding the ratio between B_{lim} and B_{MSY}, all values are below 25%. According to the literature and best practice around the world, as summarized by WKREF (ICES 2022a, 2022b), B_{lim} should be set between 10% and 20% of B_0 and/or not be less than 25% B_{MSY}.

Concerning the ratio between $B_{trigger}$ and B_0, all values are below or at 7% except for the Viking when using the short time series. Regarding the ratio between $B_{trigger}$ and B_{MSY}, all values are below 25%, again apart from the Viking when using the short time series. $B_{trigger}$ should be set as minimum at 12.5% B_0 or be set as minimum at 50% B_{MSY}. Setting $B_{trigger}$ as half of B_{MSY} is in line with literature and best practice around the world and with ICES guidelines for SPiCT models (ICES 2022a, 2022b).

When following the current ICES guidelines for this stock, the major issue is on how B_{lim} is set, which in turn affects $B_{trigger}$. Once B_{lim} is set too low, then $B_{trigger}$, which is directly related to it, is also set too low. WKREBUILD pointed out that if B_{lim} and $B_{trigger}$ are too close to each other, small reductions in biomass below $B_{trigger}$ can lead to large changes in F with little time for the stock to adapt/respond (ICES, 2020). Therefore, if you set the trigger too low, F only declines when it is too late, which invalidates the reason for the $B_{trigger}$ existence.

Here we proposed to uncouple B_{lim} and $B_{trigger}$ by setting $B_{trigger}$ at 50% B_{MSY} to be in line with best practice around the world and ICES guidelines for SPiCT models (ICES 2022a, 2022b), and considering the uncertainty related to how the different substocks of cod have been modelled.

In Table 21.10 are reported the final biomass reference point proposed by the cod benchmark, the $B_{trigger}$ reference point proposed in this WD, and the old reference points of NS cod and 6a cod.

It is important to note that the sum of the $B_{trigger}$ and B_{lim} for all substocks proposed by the cod benchmark is about half (i.e. 54%) of the sum of the $B_{trigger}$ and B_{lim} of the North Sea and West of Scotland cod stocks (ICES 2022c, 2022d).

Table 21.10. Biomass reference point proposed by the benchmark, the $B_{trigger}$ reference point proposed in this WD, and the old reference points of NS cod and 6.a cod.

Substock	$B_{trigger}$	B_{lim}	$B_{trigger}$ = 50% B_{MSY}
North-western	28570	21964	62164
Viking	15098	10374	17598
Southern	19786	13504	40968
Sum	63454	45842	120730

Stock	$B_{trigger}$	B_{lim}
NS cod	97777	69841
6.a cod	20126	14376
Sum	117903	84217

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Annex 1: List of participants

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Annex 2: Data call

1. Landings data

The table is designed so it is possible to submit nationally estimated landings by statistical rectangle and Northern Shelf cod population areas, but still giving the user an indication of the underlying assumptions.

An example – Information about statistical rectangle is not known from the official records for the small-scale fleet, but at the national level it is assumed that the fishery is close to the home port, and so the statistical rectangle taken as the position of the home port. This can be indicated in the data table in the following way 'statisticalRectangle' = 'vessel < 12 m and statistical rectangle is assumed to be equal to position of home port'.

Table 1. For commercial landings

Field	Codes	Description
vesselFlagCountry	//vocab.ices.dk/?ref=337	Vessel flag country
year	1995–2021	The year is determined by the landing date
quarter	1–4	The quarter is determined by the landing date.
area	https://vocab.ices.dk/?ref=358	ICES area. Use smallest possible ICES area
areaPopulation	Viking, Northwestern offshore, Northwestern inshore Southern, Unknown	Northern Shelf cod population areas, see appendix 1.
statisticalRectangle	//vocab.ices.dk/?ref=107	ICES statistical rectangle (e.g. 41G9). Use '-9' if unknown
areaPopulationSource	Free text | 'statisticalRectangle'	Source of areaPopulation. If the source is statistical rectangle, then please indicate with ''statisticalRectangle'. If statistical rectangle is estimated, then that can be declared in statisticalRectangleSource. If the population area is estimated by other means at the national level e.g., official areas more detailed than ICES areas, then please describe.
statisticalRectangleSource	Free text | 'Official data'	Source of rectangle If the source is official data (logbooks, VMS, sale notes, monthly journals), then please indicate with 'Official data' If the statistical rectangle is estimated by other means at the national level e.g., position of harbor for the small-scale fleet, then please describe the assumptions
ComLandWeight	0 – 2.000.000.000	Commercial landings (live weight in kg)
UnalloLandWeight	-2.000.000.000 – 2.000.000.000	Unallocated landings, e.g. black landings (Live weight in kg)
AreaMisLandWeight	-2.000.000.000 – 2.000.000.000	Misreporting between areas (Live weight in kg)

Table 2. For recreational catches

vesselFlagCountry	//vocab.ices.dk/?ref=337	Vessel flag country
year		1995–2021. The year is determined by the landing date
area	https://vocab.ices.dk/?ref=358	ICES area. Use smallest possible ICES area
areaPopulation	Viking, Northwestern offshore, North-western inshore Southern, Unknown	Northern Shelf cod population areas, see appendix 1, if this information is availa-ble.
areaPopSource		Etc. assumed that the fishery is close to the home port.
RecrRetainedWeight		Recreational retrained (Live weight in kg)
RecrReleasedWeight		Recreational released (Live weight in kg)
RecrRetainedNum		Recreational retrained (numbers of indi-viduals)
RecrReleasedNum		Recreational released (numbers of indi-viduals)
Survey summary		A short summary of the survey with asso-ciation bias and links to survey reports.

Annex 3: Stock Annex

Please see:

ICES. 2023. Stock Annex: Cod (*Gadus morhua*) in Subarea 4, divisions 6.a and 7.d, and Subdivision 20 (North Sea, West of Scotland, eastern English Channel, Skagerrak). ICES Stock Annex-es. 35 pp. https://doi.org/10.17895/ices.pub.10.17895/ices.pub.22633843