BENCHMARK WORKSHOP ON GREENLAND HALIBUT AND REDFISH STOCKS (WKBNORTH)

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Contents

i Executive summary

The objective of this benchmark process was to propose and evaluate assessment methods and the data upon which they depend for the four stocks: 1) Greenland halibut in subareas 1 and 2; 2) Greenland halibut in subareas 5, 6, 12, and 14; 3) golden redfish in subareas 5, 6, 12, and 14; and 4) beaked redfish in Subarea 14 and Division 5.a. Greenland halibut in subareas 1 and 2 was previously assessed by the AFWG-Arctic Fisheries Working Group (Greenland halibut in subareas 1 and 2) using a Gadget model, while the others were assessed by the NWWG-Northwest Working Group using either a surplus production model (Greenland halibut in subareas 5, 6, 12, and 14), a Gadget model (golden redfish), or an ICES category 3 assessment method (beaked redfish).

For both Greenland halibut stocks, age data were sparse and diverse data sources were compiled to fit Gadget length- and age-based models, which was also sex dependent for Greenland halibut in subareas 1 and 2 due to sex-dependent life history variation. Both Gadget models were improvements from previous assessment methods, although the lack of age data creates high uncertainty. A SAM model was proposed for golden redfish, which was tuned using survey data from Iceland, Greenland, and the Faroe Islands. The SAM model showed better diagnostic results and resulted in higher current biomass levels than the previous model, but also confirms the previous view that recruitment has been consistently poor in recent years. Beaked redfish has sparse age data and was also assessed using the Gadget framework, tuned to surveys in Icelandic Waters, and indicates that the stock is below B_{lim} and shows consistently low recruitment in recent years. It is recommended that migration and stock mixing be evaluated in future and that efforts be made to increase age data availability.

Reference points were calculated according to the ICES category 1 methods. Harvest control rules proposed and evaluated were based on the ICES MSY advice rule. The current harvest control rule used for golden redfish was considered precautionary.

ii Expert group information

Expert group name	Benchmark workshop on Greenland halibut and redfish stocks (WKBNORTH)
Expert group cycle	Annual
Year cycle started	2022
Reporting year in cycle	1/1
Chairs	Pamela Woods, Iceland (MFRI)
	Vladlena Gertseva, USA (NOAA)
Meeting venues and dates	28 November–02 December 2022, Hafnarfjörður, Iceland (19 participants)
	13–17 February 2023, Hafnarfjörður, Iceland (23 participants)

1 Description of the benchmark process

This benchmark process covers four stocks that are assessed during regular cycles of the Northwest Working Group (NWWG, three stocks) and Arctic Fisheries Working Group (AFWG, one stock) and have relatively wide distributions for demersal species, due to high mobility and distant migrations. These stocks include Greenland halibut (*Reinhardtius hippoglossoides*) in subareas 1 and 2 (Northeast Arctic, ghl.27.1-2), Greenland halibut (*Reinhardtius hippoglossoides*) in subareas 5, 6, 12, and 14 (Iceland and Faroes grounds, West of Scotland, North of Azores, East of Greenland, ghl.27.561214), Golden redfish (*Sebastes norvegicus*) in subareas 5, 6, 12, and 14 (Iceland and Faroes grounds, West of Scotland, North of Azores, East of Greenland, reg.27.561214), and Beaked redfish (*Sebastes mentella*) in Subarea 14 and Division 5.a, Icelandic slope stock (Iceland grounds, reb.27.5a14). At a previous NWWG meeting (ICES, 2021c), exploratory assessments for beaked redfish were presented to begin the process of benchmark planning. A data evaluation workshop was held in Hafnarfjörður, Iceland, with a hybrid online format on 28 November–2. December 2022 to analyse data availability and quality, consider methods for treating limited age data, and consider possible assessment methods. At least one stock coordinator for each stock attended in person, as well as others working on the stock or contributing data or methods (7 participants present, 14 contributing remotely). Because these stocks are relatively wide-ranging (except beaked redfish), the data evaluation was used to compile and discuss the treatment of several survey indices. The key issues raised at the data evaluation workshop included availability and quality of age readings in Greenland halibut stocks, the relatively short time-series of data considering the long lifespan of redfish stocks, and the tendency for dense hauls to overly influence the survey indices in all stocks. The main stock assessment frameworks being considered were the length- and age-based modelling framework Gadget (Begley and Howell, 2004; Begley 2005; Elvarsson, *et al.*, 2018) and state-space age-based models using SAM (Nielsen and Berg, 2014; Berg and Nielsen, 2016; Nielsen *et al.*, 2020). Before the benchmark, all stocks except beaked redfish were assessed using category 1 framework using either a surplus production model (Greenland halibut subareas 5, 6, 12, and 14) or Gadget models (Greenland halibut in subareas 1 and 2 and golden redfish). Icelandic slope beaked redfish was assessed using a category 3 framework. To evaluate whether category 1 assessment methods could be used, the benchmark meeting took place on 13–17 February 2023, in Hafnarfjörður Iceland, with a hybrid-online format, along with a preparatory online meeting on 18 January 2023. The benchmark meeting with 25 participants, including 2 external reviewers, an ICES facilitator, 8 participants in person, and 14 people that attended remotely for various portions of the benchmark. The main outcomes of the benchmark meeting included a reconfiguration of data sources and improvements to the model structure used for Greenland halibut in subareas 1 and 2; evaluation of available data and a change in modelling framework for Greenland halibut in subareas 5, 6, 12, and 14; the calculation and usage of several survey indices combined so assess golden redfish in subareas 5, 6, 12, and 14 in a new modelling framework; and an update from a category 3 assessment framework to a category 1 assessment framework for beaked redfish. In all cases, ICES category 1 frameworks were proposed, and reference points were calculated based on corresponding ICES guidelines (ICES, 2021b).

2 Northeast Arctic Greenland halibut

ghl.27.1-2 – *Reinhardtius hippoglossoides* in subareas 1 and 2

2.1 Stock description and issues

The Northeast Arctic Greenland halibut stock (NEA G. halibut) is defined within ICES areas 1 and 2, with the continental slope between the Barents Sea and the Norwegian Sea as its most important area (Figure 2.1). It is also found in wider range of the northern Kara Sea, Barents Sea and Norwegian Sea at different life stages (Benzik *et al.*, 2022). Spawning area is at the slope between Norway and Svalbard. Egg and larvae drift northwards and the main nursery area is north and east of Svalbard towards Franz Josef Land. There are growing evidence that the stock might extend further south and west (Albert and Vollen, 2015; Westgaard *et al.*, 2016), but ongoing work on stock structure is not at the stage to be issue for the current benchmark.

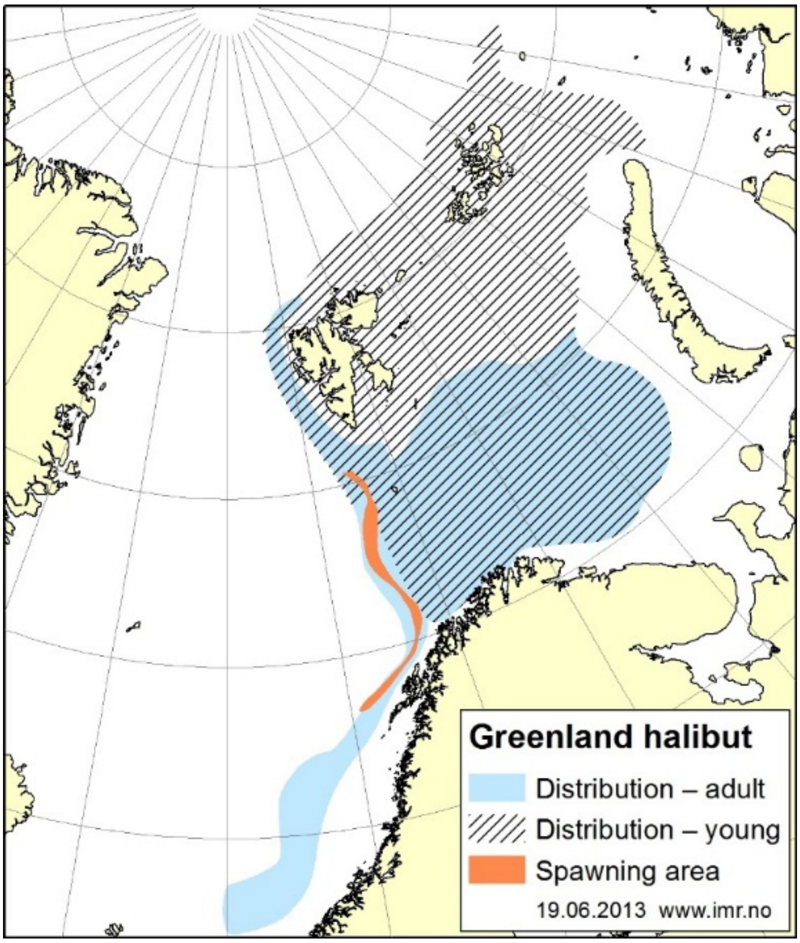

Figure 2.1. Distribution of G. halibut in ICES areas 1 and 2, also showing the spawning area[1].

NEA G. halibut supports fisheries of substantial commercial value. The stock is harvested mainly by Norway and Russia in trawl, gillnets and longline fisheries, with in comparison minor catches in other gears and/or by other countries (Figure 2.2).

[1] https://www.hi.no/hi/temasider/arter/nordostarktisk-blakveite/

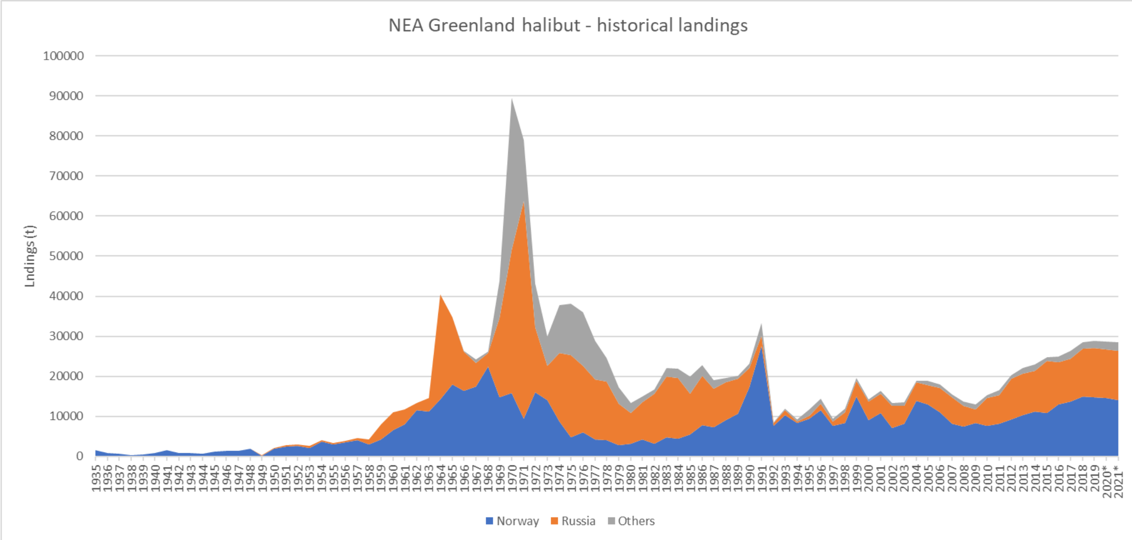

Figure 2.2. NEA Greenland historical halibut landings (Nedreaas and Smirnov, 2004; ICES, 2022).

Bulk of the aimed catches are taken at the slope (Figure 2.3) overlapping with the spawning grounds where males dominate in numbers in the size range up to around 55 cm, before they start to die out. Then gradually females become mature (L50 ≈ 61 cm) and dominate in numbers in the larger sizes at the spawning grounds, and consequently also in the catches.

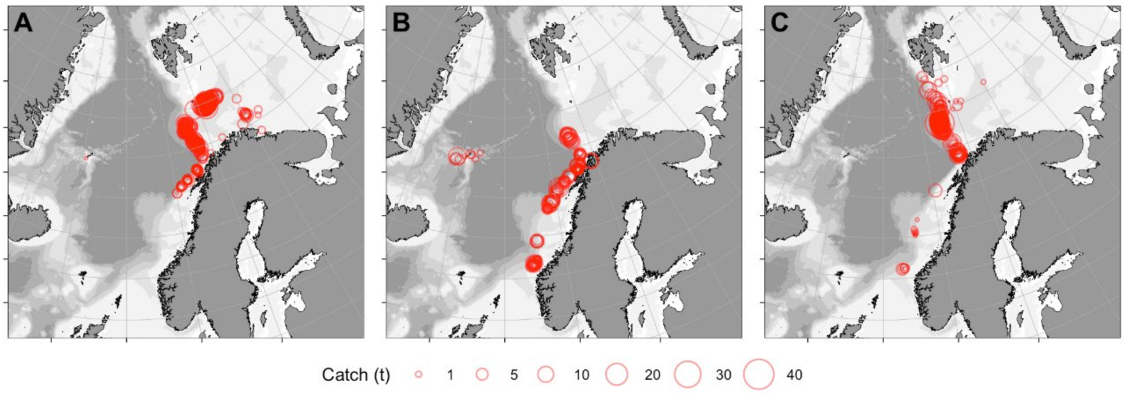

Figure 2.3. Spatial distribution of Norwegian catches where Greenland halibut was the dominant part of the total catch, according to logbooks from 2021. Bubble area is proportional to the size of single catches expressed in metric tonnes. The panels show longline (A), gillnet (B) and trawl (C) catches (ICES, 2022).

Table 2.1 shows advice, TAC and catches of NEA G. halibut. For the years 2010 to 2021, catches exceeded ICES advice in the range of 2229 to 9748 t (17–65%).

Table 2.1. NEA G. halibut in subareas 1 and 2. ICES advice and official catches 2010 and onwards. All weights are in tonnes (table from ICES advice sheet 2021, modified and updated).

Year	ICES advice	Catch corre-sponding to ad-vice	Agreed TAC – Norway/JNRFC	TAC to Norway – EU zone in ICES subareas 2 and 6 ^	Official catches
2010	Same advice as previous year	< 13000	15000*	350	15229
2011	Same advice as previous year	< 13000	15000*	350	16606
2012	No increase in catches	< 15000	18000*	350	20288

Year	ICES advice	Catch corre-sponding to ad-vice	Agreed TAC – Norway/JNRFC	TAC to Norway – EU zone in ICES subareas 2 and 6 ^	Official catches
2013	No increase in catches	< 15000	19000*	824	22167
2014	No new advice, same as for 2013	< 15000	19000*	1000	23025
2015	Same as for 2014	< 15000	19000*	1000	24748
2016	Precautionary approach	< 19800	22000*	1100	24948
2017	Same advice as previous year	< 19800	24000*	1100	26380
2018	Precautionary approach	< 23000	27000*	1100	28438
2019	Same advice as previous year	< 23000	27000*	1250	28832
2020	Precautionary considerations	< 23000	27000*	1250	28713
2021	Same advice as previous year	< 23000	27000*	1800	28431
2022	Precautionary approach	≤ 19094	25000*		
2023	Precautionary approach	≤ 18494	25000*		

*** Set by the Joint Norwegian–Russian Fisheries Commission (JNRFC).**

^ UK after 2020

The NEA G. halibut assessment covers the G. halibut stock in ICES areas 1 and 2. The NEA G. halibut stock in the majority of areas 1 and 2 is managed by the Joint Norwegian-Russian fisheries commission that sets a TAC which then is divided 51% to Norway, 45% to Russia and 4% to other nations. In the south, ICES Area 2.a includes part of the UK EEZ and in 2022 a TAC of 2751 t was set by UK/EU for ICES areas 6; UK and Union waters of 4; UK waters of 2.a; UK and international waters of 5.b[2]. Out of this TAC 600 t were allocated to Norway catching mainly in UK part of 2.a.

Catches in the UK EEZ part of ICES 2.a are included in the stock assessment of NEA G. halibut and it is not possible to separate out these catches in the historical catch data. The total advised catches, therefore, include both those in the area managed by the JNRFC and those in UK waters in 2a. It is recommended that in the ICES advice sheets, managers are made aware that when setting TACs they need to consider that catches from this assessment occur in two different jurisdictions.

Main aims for the benchmark are to upgrade the Gadget model used for assessment since the 2015 ICES Inter Benchmark Process (IBHALI), which is age–length based but tuned only to length data. The revised model is extended further back in time, and available age readings are added, among other improvements. In addition to improved analysis of stock dynamics, the goal is to get better-defined reference points and to establish basis for a harvest control rules (HCL). The upgrade is a recoded model which is run in the renewed Gadget3 framework (Lentin *et al.*, 2022).

[2] https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32022R0515&qid=1650982320384&from=en,last accessed 27. March 2023.

2.2 Multispecies, mixed-fisheries issues, and ecosystem drivers

NEA G. halibut is mostly fished in direct fisheries with minor bycatch of other species. It is to some extend taken as bycatch in other fisheries in the Barents Sea, and bycatch regulations are in place. It is a valuable species and discards are considered negligible.

Greenland halibut is a large fish predator that occurs over a wide range of depths (from 20 to 2200 m) and temperatures (from −1.5 to 10˚C; Vihtakari *et al.*, 2021). Food composition of the Greenland halibut in the Barents Sea includes more than 40 prey species (Haug and Gulliksen, 1982; Michalsen *et al.*, 1998; Dolgov and Smirnov, 2001; Hovde *et al.*, 2002; Vollen *et al.*, 2004). Investigations over a wide area of the continental slope up to Novaya Zemlya show that the main food source of Greenland halibut consists of fish, mostly capelin (*Mallotus villosus villosus*), polar cod (*Boreogadus saida*) and herring (*Clupea harengus*), and cephalopods and shrimp (*Pandalus borealis*). During the 1990s an important component of the diet was waste products from fisheries for other species (heads, guts, etc.). Ontogenetic shift in prey preference was clear with decreasing proportion of small prey (shrimps and small capelin) and increasing proportion of larger fish with increasing predator length. The largest Greenland halibut (length more than 65–70 cm) had a rather big portion of cod and haddock in the diet.

Given a Greenland halibut stock of nearly 100 000 tonnes, the total food consumption of the NEA stock was estimated to be about 280 000 tonnes (Dolgov and Smirnov, 2001). The biomass of commercial species consumed (shrimp, capelin, herring, polar cod, cod, haddock, redfish (*Sebastes* sp.), long rough dab (*Hippoglossoides platessoides*) did not exceed 5000–10 000 tonnes per species. The effect of Greenland halibut as predator on other commercial species in the Barents Sea may thus be minor.

According to Russian data (Dolgov and Smirnov, 2001), among the variety of fish, seabirds and marine mammals investigated, Greenland halibut were found in the diet of three species; Greenland shark (*Somniosus microcephalus*), cod (*Gadus morhua morhua*) and Greenland halibut itself. Additionally, killer whale (*Orcinus orca*), grey seal (*Halichoerus grypus*) and narwhal (*Monodon monoceros*) are potential predators. However, the presence of Greenland halibut in the diet of the above species was minor. Predators fed mainly on juvenile Greenland halibut up to 30–40 cm long.

The mean annual percentage of Greenland halibut in cod diet in 1984–1999 constituted 0.01–0.35% by weight (0.05% on average; Dolgov and Smirnov, 2001). Cannibalism was highest in 1960s (up to 1.2% in frequency of occurrence) according to Russian stomach content data. During the 1980s frequency of occurrence of juveniles in the stomachs did not exceed 0.1%. During the 1990s, the portion of juveniles (by weight) was at the level of 0.6–1.3%. Low levels of consumption of juveniles are related to the distribution pattern of juvenile Greenland halibut. Young Greenland halibut occur mostly in the northeastern Barents Sea (Spitsbergen archipelago and further east to Franz Josef Land and Northern Kara Sea; Albert *et al.*, 2001; Ådlandsvik, 2004; Benzik *et al.*, 2022) where the presence of adult Greenland halibut and other main predators appear minimal in most years. Therefore, the observed variability of recruitment may be driven mainly by environmental factors. However, in some years predation might affect recruitment, and the resent northward extension in distribution of potential predators such as cod, and high abundance of cod, is a concern in that respect (Fossheim *et al.*, 2015). Predation on eggs and larvae is unknown, and a future research topic.

2.3 Data

All input data, both commercial and fisheries independent, have been scrutinised and indices are recalculated, as presented to the WKBNORTH data workshop. Detailed information on data, and data revision, can be found in WD2 and WD3.

Due to sexual dimorphism the assessment model is constructed to account for differences for sexes, and data divided by sex when possible.

2.4 Commercial data

Available commercial data consist of catch data and different sampling strategies for biology and live history data.

The catch data originate from national institutes but through the years they have been collected in different manner, either reported to ICES by countries' official and preliminary ICES statistics[3], uploaded to ICES InterCatch database[4] or reported to the AFWG by group members. In the new model approach Norwegian catches are obtained from the IMR databases through a fully transparent process for those working within the institute and show very minor discrepancy compared to the Norwegian catch data used in previous assessments (WD2).

Five aggregated fleets are defined in the assessment (WD2).

1. TrawlNor: Norwegian trawl catches (bottom trawls).
2. TrawlRus: Russian Trawl (bottom trawls).
3. OtherNor: Norwegian catches other than in bottom trawls (mainly gillnets and longlines, some purse-seine and Danish seine).
4. OtherRus: Russian catches other than in trawl (gillnets and longlines).
5. Internat: International, i.e. catches from other countries than Norway and Russia (bottom trawls).

Russian and Norwegian CPUE series for NEA G. halibut were scrutinised at the last benchmark, and it was concluded that they were consistent for years until strong regulations were implemented in 1992 (Nedreaas, 2013). A standardized version of the Russian trawl fleet CPUE was provided by Kovalev and Tretyakov (2015), and it shows clear similarity in trends to the independently derived Norwegian trawl fleet CPUE series in years when they overlap (Figure 2.4). The Russian CPUE series in years 1980 (start of the model) to 1991 was included in trial runs in the revised assessment, but the conclusion was that it was not clear that it improved the model and due to time constraints at the benchmark it was therefore excluded from the final model. This series might come in use if the model were to be extended even further back in time.

[3] https://www.ices.dk/data/dataset-collections/Pages/Fish-catch-and-stock-assessment.aspx

[4] https://www.ices.dk/data/data-portals/Pages/InterCatch.aspx

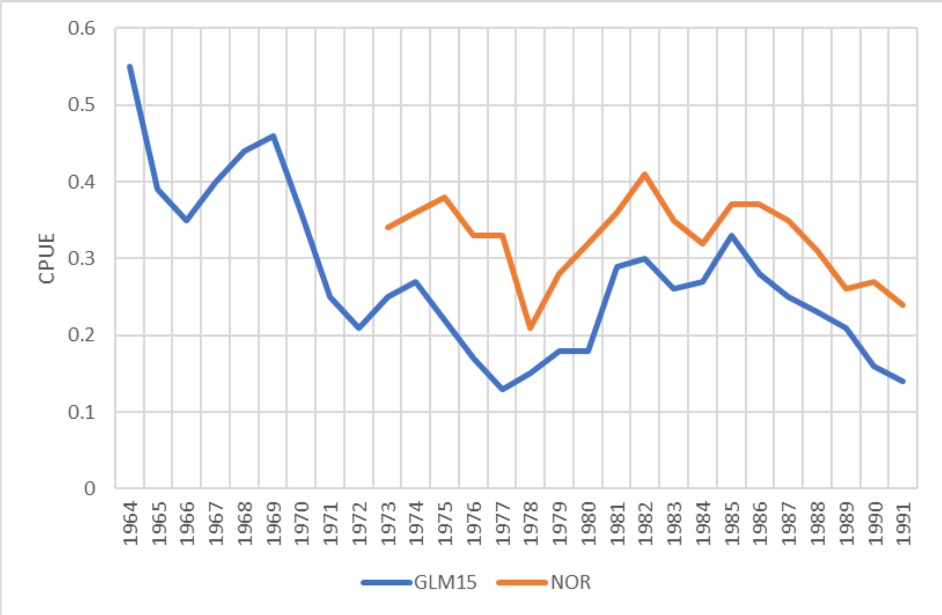

Figure 2.4. Russian (GLM15) and Norwegian CPUE series for NEA G. halibut, from before the partial moratorium regulation in 1992.

2.4.1 Survey data

No survey covers the whole stock distribution area. In the previous assessment data from three surveys were applied, and these are also used in the revived assessment model (also see WD2 and WD3):

- EggaN: Norwegian Sea continental slope survey in autumn (G1165). Yearly 1996–2009, biennially since then, along the continental slope approx. 68–80°N, depths 400–1500 m (but only 500–1000 m used in the index).
- RussianS: Russian autumn bottom-trawl survey in the Barents Sea (G5348). 1984–2020, slope approx. 71–80°N and central Barents Sea, depths down to 900 m.
- EcoS: Joint Russian-Norwegian ecosystem autumn survey in the Barents Sea and adjacent waters (A5216). 2003–present, Barents Sea, depths down to 500 m. As this survey covers the nursery area it is divided into two indices by length < 35 cm that is not split by sex (approximately represents juveniles) and > 35 cm split by sex.

Additional two surveys were examined that are not used in the previous assessment:

- WinterS: Joint Russian-Norwegian ecosystem spring survey in the Barents Sea (A6996). 1986–present, ice-free Barents Sea (west of Svalbard included 2014 and since), mainly 100–500 m. Split by sex. Due to varying coverage throughout the time-series consistent strata had limited overlap with G. halibut distribution and the biomass index from the survey was rejected. More advanced analyses, like VAST, might improve the index estimations but due to time constraints at the benchmark this option was not examined further. However, in the revised model length distributions from this survey are included.
- EggaS: Norwegian Sea continental slope survey in spring (G5678). 2009, 2012 and biennially since then, along the continental slope approx. 62–74°N, depths 400–1500 m (but only 500–1000 m used in the index). This survey was included in trial runs in the revised assessment, but it was not clear that it improved the model and due to time constraints at the benchmark the biomass index was therefore excluded from the final model. This is a short time-series, and it might come into use with added years in future. However, in the revised model length distributions from this survey are included.

More detailed information on Norwegian and the joint Norwegian-Russian surveys, and the re-calculations of these, can be found in WD2, and in Russkikh *et al.* (ICES, 2021a; WD12) for the Russian slope survey.

2.4.2 Age data

Aging of Greenland halibut is not trivial and there will be some differences between age readers and a variation in the results (WD2). Two workshops on age reading of Greenland halibut have been held by ICES (ICES, 2011; ICES, 2017; WD3 of this document), with aim to develop and validate new age reading methods. The latter (WKARGH2) had in its recommendations that "While it is recognized that some ageing issues remain to be resolved, the WKARGH2 recommends that either the frozen whole right otolith or thin-section method can be used to provide age estimates for stock assessments.", and further "Recognizing some bias and low precision in methods, the WKARGH2 recommends that an ageing error matrix or growth curve with error be provided for use in future stock assessments.".

At IMR the "frozen whole right otolith method" was implemented in mid-2000s and a previously used method abandoned. Not all otoliths collected by new sampling protocol for the new aging method have been aged, and as the otoliths need to be kept frozen from when they are collected to age reading it is not possible to age old dry otoliths with this new method. Table 2.2 gives an overview of age readings that are currently available, but as numbers aged are most consistent for the EggaN survey only age from this survey was used in the assessment.

Table 2.2. Number of aged otoliths available to the revived assessment, by year, survey, and from catch sampling (for survey names abbreviations see section 2.3.2).

Year	EggaN	EggaS	EcoS	WinterS	Other surv.	Total surv.	Catch	SUM
2001	200					200		200
2006			499			499		499
2007	316					316		316
2008	502		393			895		895
2009			124			124		124
2011	1159		369			1528		1528
2013	996		70			1066		1066
2014		351	74			425		425
2015	1906		48		13	1967	894	2861
2016		570	68		86	724	1101	1825
2017	770		114	228		1112	135	1247
2018		777	302			1079	604	1683
2019	2058		58	185		2301	712	3013
SUM	7907	1698	2119	413	99	12236	3446	15682

Age estimation by modes in length distributions from the nursery area are possible for at least age groups one and two (Albert *et al.*, 2009). It is therefore possible to distinguish these age groups in the nursery area in northern Barents Sea (Figure 2.5). Based on these length distributions length range for 1 and 2 years old in the data are approximated L1=0–17 and L2=18–27 to construct a juvenile biomass index (WD2). Specimens less than approximately 10 cm are few in the data due to gear selectivity, and they are insignificant in terms of biomass in the assessment.

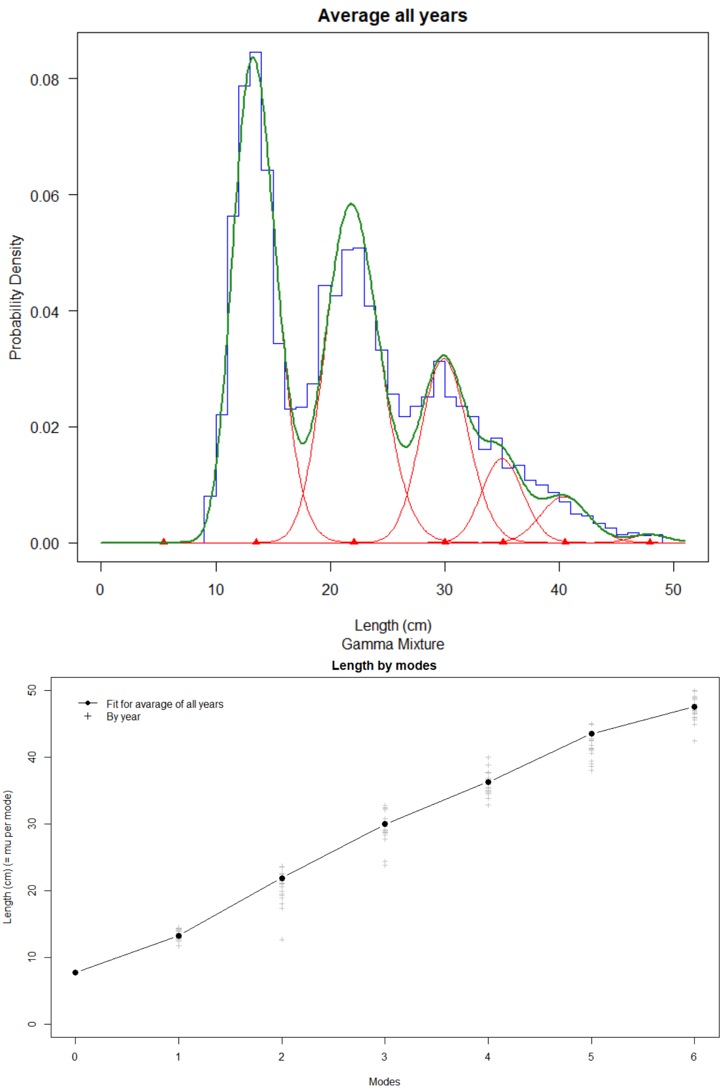

Figure 2.5. Length distribution (upper panel) from surveys 1996–2018 in the nursery area (defined as Barents Sea north of 76.5 °N), and average length (lover panel) for each mode in the distribution (Hallfredsson and Vollen, 2015, updated).

2.5 Conclusions from data evaluation workshop

Revised survey indices and catch data were presented to the data evaluation workshop (WD2). Several topics were discussed regarding survey index data including whether changes in depth and location restrictions in the definition of survey indices were appropriate, and what form of survey index calculations should be included given the current restrictions in data availability from Russian surveys. It was decided that 1 recruitment index and five adult indices were appropriate to examine in the model. With regards to Russian data availability, the original indices available from the 1980s but calculated in 5 cm intervals would be better to use than a shorter revised time-series (1992–2020) with a higher resolution of 1 cm intervals, as other surveys do not extend as far back in time.

Age data were also discussed as being available only since early 2000s and for selected surveys and catches. However, the change in ageing methodology could affect the ability to detect changes in growth over time, as well as natural mortality estimates. Growth and longevity also differed greatly by sex. Estimations of natural mortality using data-limited methods were presented to the data evaluation workshop (WD1). It was decided that the proposed method for setting M, which relied more heavily on using growth life history information rather than longevity information, was sufficient when set by sex, but that it would be a good idea to explore its effect on the model through sensitivity analyses and to consider other longevity-based methods for estimating M, both of which were done before the final model configuration being chosen.

The possibility of extending age data back in time was also considered, either by calculating a conversion based on data read using each method by the same person or by comparing readings within a short window of time to avoid biases due to time-varying growth. However, this possibility was abandoned after further exploration suggested relatively poor data quality available for this purpose.

2.6 Proposed stock assessment

In ICES NEA G. halibut used to be assessed by XSA but this age-based approach was abounded in 2000s due to concerns that the age readings were not correct, with the growth rate considerably overestimated (Albert *et al.*, 2005). Intermediately the stock was assessed as ICES category 3 stock by trends in two surveys until a Gadget model, only tuned to length data, was accepted at the ICES IBPHALI benchmark in 2015 (ICES, 2015).

Assessments of NEA G. halibut using production models have been presented to ICES on earlier occasions by Bakanev in 2013 (ICES WKBUT 2013, WD4), Mikhaylov in 2016 (ICES AFWG 2016, WD14) with update in 2019 (ICES AFWG 2019, WD21), and a SPiCT approach was presented to the AFWG 2018 meeting by Hallfredsson (ICES AFWG 2018 report). The AFWG has concluded that in principle, a production model could be used in conjunction with the Gadget assessment model to extend the simulations back in time and provide better estimates for Blim. However, the inability of production models to follow variable recruitment, and especially runs of above or below average recruitment, limits their ability to give advice for this stock (ICES AFWG 2019 report).

Advice for the stock is given biennially, where last advice applies for 2022 and 2023, and this practice is proposed to be continued.

An updated Gadget (Begley and Howell, 2004; Begley, 2005) age- and length-based model in the new Gadget 3 framework (Lentin *et al.*, 2022) was considered as most appropriate to the stock.

Model structure:

- Model used: Gadget 3.
- Start year 1980.
- One year time-step.
- Single area model, with variable distributions handled through fleet selectivity (“fleets as areas” approach)
- Two sexes, split into mature and immature stock components
- Logistic maturity estimated for each sex
- 1 cm length classes and 1-year age classes

  - Lengths: females; immature 1–100 cm, mature 1–120 cm - males; immature 1–65 cm, mature 1–90 cm
  - Age: immature 1–25+, mature 3–25+
- Von Bertanlanffy growth estimated separately for males and females, with Linf for males fixed to 68 cm. Length-at-age one fixed.
- Natural mortality set to 0.12 for females and 0.16 for males
- Initial size of recruits fixed at 14 cm (model has proved unable to estimate this)
- Recruitment modelled as annual numbers, no relationship with SSB (estimated directly), assumed equal recruitment of male and female
- Initial population follows a simplifying assumption of constant recruitment, M and F, giving an exponential decay by age. A fixed maturity ogive is used to split immature and mature proportions. S.d. of lengths-at-age is externally fixed.
- Fisheries and surveys are modelled with fixed catch in tonnes per fleet, and sex-specific selectivity estimated using length distribution data and sex-at-length data.
- Five aggregated commercial fleets (as described above), each with sex-specific logistic selectivity
- Five aggregated commercial fleets (as described above), each with sex-specific logistic selectivity
- Three surveys used for indices (EcoS, EggaN and RussianS), with logistic selectivity (but with a min:max length range to avoid bias in indices on fish suspected to be poorly selected)
- Only length distributions used from Winter and EggaS surveys

More detailed model description, as well as outputs and diagnostics are shown in WD17.

2.7 Short-term forecast methods

Five-year projections conducted using the Gadget 3 assessment model under the following assumptions:

- Split between fleets are assumed to remain unchanged from the average of the previous two years;
- Fishing intensity in the current year assumed to be the average of the intensity in previous two years;
- Two years of forecast will be used to give two years of catch advice using reference points below
- Results are presented for 1 January the following year.

These procedures are preliminary. As the harvest control rule has not been finalized, short-term projection methods will also be finalized later.

2.8 Reference points

Trends and biomass levels in stock dynamics are stable in the revised assessment. Therefore, the suggested reference points are for ICES category 1 stock (ICES, 2021b).

2.8.1 B_{pa}/B_{lim}

The stock–recruitment relationship was considered to resemble an ICES Stock Type 5 pattern (ICES, 2021b), characterized as having no sign of recruitment failure but also no clear relationship between stock size and number of recruits. At the meeting it was agreed that the biomass to be used in this calculation is the mature female biomass, given that females mature later and live longer than males. B_{lim} was therefore considered to be the lowest observed female mature stock size (25 031 in 1992), and B_{pa} was calculated as B_{lim}*1.4 , or 35 043 t.

2.8.2 Fishing pressure

A Management Strategy Evaluation (MSE) was conducted for Greenland halibut in subareas 1 and 2 (WD17). The evaluation followed ICES procedures using the ICES advice rule (ICES, 2021b). Simulations were based on fleet selectivities set to be the same as estimated by the model with catch proportions by fleet fixed to the average of last 4 years. Advice error in the simulations was implemented as autocorrelated lognormal variations in F, with a CV of 0.212 and ρ of 0.423. From these simulations, reference points were calculated for the stock according to ICES category 1 guidelines (ICES 2021).

The fishing pressure reference points, defined in terms of harvest rate applied to an estimated reference biomass of all Greenland halibut greater than or equal to 45 cm length ($B_{\geq 45}$) as proxy for fishable biomass, were estimated in accordance with the ICES guidelines. Recruitment was drawn from historical estimates between 1990 and 2017 using a 7-year block-bootstrap to account for autocorrelation. The recruitment had a breakpoint as a hockey-stick function set to B_{lim} from which it decreased linearly to zero. This resulted in an estimate of HR_{lim} of 0.190, HR_{PA} of 0.162 and HR_{msy} of 0.154. Using the ICES advice rule for Greenland halibut in subareas 1 and 2, based on a harvest rate HR_{mgt} of 0.154 applied to $B_{\geq 45}$, modified by the ratio SSB_y /MGT $B_{trigger}$ when SSB_y < MGT $B_{trigger}$, maintains a high yield while being precautionary as it results in lower than 5% probability of SSB < B_{lim} in the medium and long term.

In short, the HR_{target} is set to HR_{msy} which equals 0.154. The fishable biomass is taken to be the > 45 cm biomass. The $B_{trygger}$ in the ICES Advice Rule is set to be B_{pa}, which equals 34 043 t. B_{msy} has not been calculated.

2.9 Comments to the assessment

An overview of model exploration before, and at, the benchmark is given in WD 17.

Between the end of the physical benchmark meeting and completion of the final model the following adjustments were made: Recalculation of data weighting, and flat top selectivity applied to all fleets.

Within the fisheries in the Barents Sea and associated slope, fish tend to move to the slope as they mature. This means that fisheries on the shelf tend to fewer of the large mature fish. The Barents Sea Greenland halibut Gadget model was designed to be a "fleets as areas model", where fleet selectivity would take care of the issue of the larger fish moving out of the areas covered by some fleets and surveys. However, the dome shaped selectivity required for this was problematic. The model employing the dome shaped selectivity was unstable, with a large pattern in the jitter analysis indicating that the model was unable to converge to a single solution. The reasons for this are unclear, but it was clear that the dome-shaped selectivity model cannot be used at present as the basis for advice. The model presented here therefore uses exponential ("flat topped", "S-shaped") selectivity curves for all fleets and surveys. The ecosystem survey index is expected to be affected by this issue, and the survey index has been computed over a range of sizes (28–65cm) to avoid this and ensure that the movement of fish does not cause undue bias. It is clear in the data, that the trawl fleets catch fewer large fish than the other gears (which are more concentrated along the slope) and there is therefore a slight mis-match here between model and data. The fits to the length distributions are otherwise good for these fleets, and the issue of dome shaped selectivity is therefore a research recommendation for future improvements in the model.

2.10 Future research and data requirements

Efforts to improve stock assessment in future should include:

- Develop a harvest control rule.
- Gather age data over more years.
- Further examine consequences of using of dome-shaped vs. logistic selectivity in the Gadget model.
- Examine further Norwegian and joint Norwegian/Russian survey indices using VAST or similar statistical analysis.
- Implement a revised Russian survey index.
- Review stock structure for Greenland halibut in the North Atlantic, reflecting the results from an ongoing international project (NORSUTAIN).

3 Greenland halibut in Iceland and Faroes grounds, West of Scotland, North of Azores, and East of Greenland

ghl.27.561214 – *Reinhardtius hippoglossoides in subareas 5, 6, 12, and 14*

3.1 Stock description and issues

The primary motivation for the benchmarking of the stock was the recent availability of age disaggregated information. Until last year the assessment was a biomass production model based on annual catch and survey data. Since around 2000, age readings ceased due to conflicting perception of the readings. The annual otoliths sampling in the field has however been kept. In recent years new methods of otolith reading have been agreed among institutes in the North Atlantic and an effort to read historic samples are initiated in most institutes. Additional motivations for the benchmark include re-evaluation of the catch-per-unit-effort series used as the basis for the assessment, and the inclusion of catch composition data from the whole of fishery operations in assessment.

Greenland halibut in ICES Subareas 5, 6, 12 and 14 (Iceland and Faroes grounds, West of Scotland, North of Azores, East of Greenland) are assessed as one stock.

In Icelandic Waters, it is found on the continental shelf around Iceland with the highest abundance west, north and east off the coast in deeper and colder waters. It is mainly found on a muddy substratum at depths ranging from 200–1500 m. The main spawning grounds are located west off the coast at around 1000 m depth and eggs and larvae drift mainly between Iceland and the east coast of Greenland until juveniles seek bottom post metamorphosis. After spawning, Greenland halibut migrates further north and east to their main feeding grounds. No juvenile grounds are known within the assessment area, and substantial migration is known to occur with adjacent management units (Vihtakari *et al.*, 2022).

In the waters of East Greenland it mainly found at depths between 600 m and 1400 m along the steep continental slope from whereas in the Faroes it is mainly found North and East of the islands at 200 to 600 m.

The stock unit has historically been questioned; spawning grounds have not been well documented and major nursery grounds have never been observed within the stock area as defined by ICES. Under a project, NORSUSTAIN, funded by the Council of Nordic Ministers a recent published study using a compilation of historic tag-recapture data from the entire North Atlantic show a migratory behaviour between the stocks defined by ICES and NAFO. Also, genetic studies reveal continuous patterns along an east-west gradient suggesting less strict stock definition. More approaches on studies of the stock structure are ongoing and will be collectively concluded in near future. Until then the stock in subareas 5, 6, 12, and 14 is considered a stock unit.

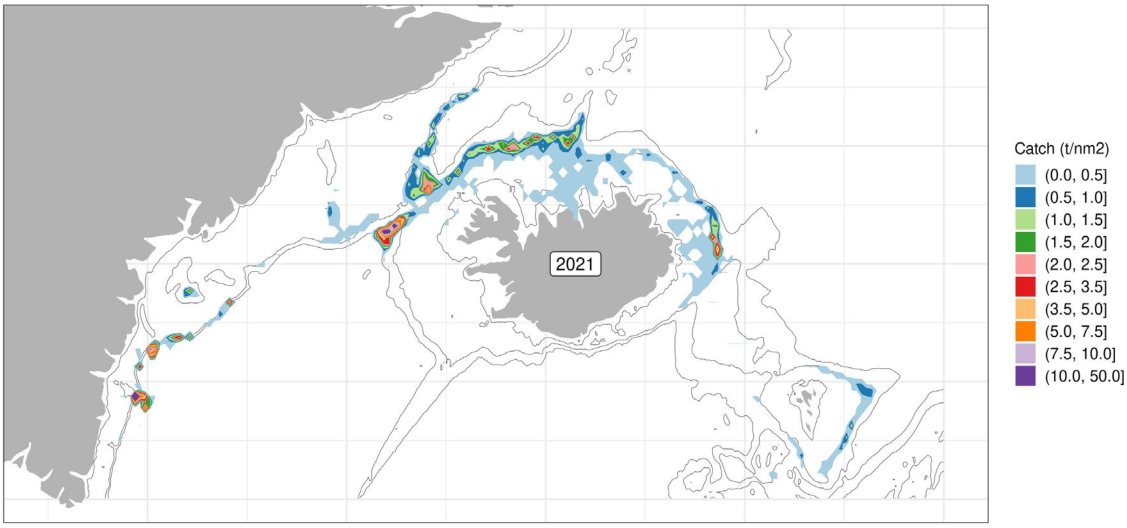

Figure 3.1. Greenland halibut. Catch distribution in 2021.

3.2 Multispecies, mixed-fisheries issues, and ecosystem drivers

The fishery in Icelandic Waters started in the 1960s, and it is believed to be fairly targeted and seasonal at the beginning. Changes in the fishing practices in recent years in Icelandic Waters has led to an effort that is more evenly distributed through the year while remaining targeted towards Greenland halibut. The main bycatch species are cod and deep-water redfish. In Greenland waters along the East Greenland shelf and slope an international fishery started in 1962. Information on bycatch in Greenland and Faroese waters are not available, but the catch composition is not believed to be substantially different from that observed in Icelandic Waters.

A recent study of the deep-sea fish community in East Greenland (Emblemsvåg *et al.*, 2022) observed a change over the past decades for more boreal fish species and a loss in species diversity due to sea warming. It is suggested that such development may affect the ecosystem to be less resilient to pressures such as fishery and a more precautionary approach to fishery management is advocated for.

3.3 Data

3.3.1 Commercial data

Overview of the available commercial data are available in WD4 and WD15. Main features, catch composition is available from all fishing grounds, while sampling effort in Icelandic Waters has been highest. Sampling has improved on other fishing grounds in recent years. Age information from commercial samples is only available from Icelandic Waters, while aging has started both in Greenland and Faroe Islands and will become available in the coming years.

Landings data were revised during the benchmark, and now based on ICES catch statistics.

3.3.2 Survey data

Scientific surveys are conducted in the three areas, namely East Greenland, Iceland and the Faroes. The East Greenland survey was ceased since 2017 but has resumed in 2022 with a new research vessel. The trawl gear has changed from the gear used up to 2016 and calibration analyses are currently being conducted.

Only the Icelandic and Greenlandic surveys are used for the analytical assessment as the design of the Faroese survey is not compatible with the other two.

Age data are currently only available from the Icelandic autumn survey.

3.4 Proposed stock assessment

Past assessment was based on a Bayesian stock production model that synthesized three data sources, commercial CPUE from the Icelandic trawler fleet, a combined autumn survey and total catches. The representativeness of the CPUE series had diminished over the years as the proportion of the catch taken by the Icelandic trawlers had decreased substantially and with the increased gillnet effort towards Greenland halibut north of Iceland the area available to trawling decreased.

The development of new assessments for Greenland halibut focused mainly on including the new age data into the assessment (see Section 3.1). Two approaches were considered, an age-based model in the SAM framework and an age- and length-based model developed in the Gadget3 framework.

The SAM model, discussed in WD5 and WD15, was not taken forward as it relied heavily on assumptions on constant ALK for observations prior to 2015 which may not be representative for the data that is expected to be used by the model in the coming years. The assumption of constant ALK did result in catch and survey matrices with no internal consistency in following cohorts. Development of this model will however continue with addition of new age data.

An age- and length-based model was considered most appropriate to the assessment of the stock (Gadget, Lentin et. al, 2023, Begley and Howell, 2004, Begley 2005). The model estimates are based on a synthesis of key commercial size composition data and survey age and size compositions. The model was fit to total biomass series from the combined autumn survey assuming a non-linear relationship (WD6 and WD9). Key model features included:

- Start year 1985
- Two time-steps, equal in length, within the year
- Age range: 1 to 20+
- Size range: 4–100 cm, 1 cm length groups
- Growth:
    - Length based von Bertalanffy size update (k, $L\infty$)
    - Beta-binomial size dispersal with a maximum length group growth set as 15 cm (β)
    - Length–weight relationship estimated externally
- Natural mortality set as 0.15
- Initial population and recruitment
    - Annual recruitment occurs in the first time-step, one parameter per year Ry .
    - Mean length and standard deviation at recruitment is estimated
    - Initial population set to represent a realistic distribution according to natural mortality and fishing mortality
    - Initial mean length-at-age is defined using the Von B growth curve, and initial numbers at length are dispersed assuming a normal distribution around the mean length with a fixed CV.
- Fishing split by fleet:
    - 6 fleets, 1 survey, 3 bottom trawls (Greenland, Iceland and Faroese), gillnet and longlines in Iceland

   - Logit selectivity for each fleet (α_f , $l_{50,f}$)
- Maturity at length estimated externally based on autumn survey samples
- Likelihood functions:
   - Survey indices are fit assuming a linear or power relationship.
   - Composition data are assumed randomly sampled and fit using sums of squares of proportions
- Uncertainties are estimated using a spatial bootstrap for the composition data and simulated survey indices based on estimated survey CV.

3.5 Short-term forecast methods

Short-term forecasts for Greenland halibut in subareas 5, 6, 12, and 14 will be conducted using the settings described below.

- Model used: Age–length forward projection using Gadget software
- Initial stock size: abundance-at-age and length for all ages
- Maturity: Estimated outside the model, based on a fixed maturity ogive by length
- F and M before spawning: NA
- Weight-at-age in the stock: Gadget uses a weight–length relationship and von Bertalanffy growth (no weights-at-age are supplied to Gadget)
- Weight-at-age in the catch: Gadget uses a weight–length relationship and von Bertalanffy growth (no weights-at-age are supplied to Gadget)
- Exploitation pattern:
   - Landings: logistic selection-at-length by fleet, with parameters estimated within Gadget. No discards assumed.
   - Proportion of harvest rates allocated to fleets are based on three-year average.
   - Intermediate year assumptions: Catch is set equal to the TAC during the fishing season and projections for the following year run at a selected harvest rate that corresponds to the selected fishing mortality.
- Stock–recruitment model used: Fixed hockey-stick recruitment function, with geometric mean recruitment set as the asymptote.

3.6 Reference points

A Management Strategy Evaluation (MSE) was conducted for Greenland halibut in subareas 5, 6, 12, and 14 (WD6). Simulations were based fitting the model to spatially bootstrapped compositional data and survey indices with randomly generated lognormal error. This series of operating models were used to generates the "true" future populations with simulations to account for observation error and estimate processes such as maturity, growth, and length-weight relationships used in the forecast. Similarly, fleet selectivities are the same as estimated by the model with catch proportions by fleet fixed to the average of last 5 years. Advice error in the simulations was implemented as autocorrelated lognormal variations in F, with a CV of 0.212 and ρ of 0.423. Recruitment was drawn from historical estimates after 1995 using a 7-year block-bootstrap from the bootstrap model estimates in the whole reliable time-series (after 1995) to account for autocorrelation. The recruitment had a breakpoint as a hockey-stick function set to B_{lim} from which it decreased linearly to zero.

From these simulations, reference points were calculated for the stock according to ICES category 1 guidelines (ICES 2021). This resulted in B_{lim} of 15 700 t, based on the lowest estimate of SSB observed (1994), and $B_{pa} = B_{lim}e^{1.645\sigma_B}$ of 21 000 t, with σ_B being set to 0.19. The fishing pressure reference points, defined in terms of fishing mortality applied to ages from 9–14, were estimated in accordance with the ICES guidelines. This resulted in an estimate of F_{lim} of 0.5, F_{PA} of

0.38 and F_{msy} of 0.24. Using the ICES advice rule for Greenland halibut in subareas 5, 6, 12, and 14, based on a fishing mortality F_{mgt} of 0.24 applied to age 9–14 modified by the ratio SSB_y /MGT $B_{trigger}$ when SSB_y < MGT $B_{trigger}$, maintains a high yield while being precautionary as it results in lower than 5% probability of SSB < B_{lim} in the medium and long term.

3.7 Future research and data requirements

Efforts to improve stock assessment in future should include:

- Review stock structure for Greenland halibut in the North Atlantic, reflecting the results from an ongoing project (NORSUTAIN).
- Improve sampling: biological and fishery data are required from Division 5b and Subarea 14.
- Find methods for and conduct ageing of historic samples of otoliths to improve the age–length-keys currently used for the stock. This is especially important for Division 5b and Subarea 14.
- Evaluate the 'new' survey in 14 conducted by the RV Tarajoq with regards to catchability and selectivity compared with the old survey series for that area.

4 Golden redfish in Iceland and Faroes grounds, West of Scotland, North of Azores, and East of Greenland

reg.27.561214 – *Sebastes norvegicus* in subareas 5, 6, 12, and 14

4.1 Stock description and issues

Golden redfish (*Sebastes norvegicus*) in ICES division 5.a (Iceland), 5.b (Faroe Islands) and subareas 12 and 14 (East Greenland) have been considered as one management unit (reg.27.561214). Catches in ICES Subarea 6 have traditionally been included in the NWWG report but not used in the assessment. Data from ICES Subarea 6 are, however, not used in the assessment, as catches are very low. Like other *Sebastes* species, golden redfish is slow growing, long-lived, and late-maturing, and display various kind of pelagic and demersal behaviour during their lifespan.

This stock has been assessed previously using a Gadget model with annual advice provided in accordance with the ICES framework (Category 1). For more information on stock description and issues, refer to WD7 and WD12.

4.2 Multispecies, mixed-fisheries issues, and ecosystem drivers

For more information on multispecies, mixed-fisheries and ecosystem drivers, refer to WD7 and WD12.

4.3 Data

For more information on data available, refer to WD7 and WD12.

4.3.1 Conclusions from data evaluation workshop

At the data evaluation workshop, discussion surrounding golden redfish approached topics including 1) the decision to exclude area 6 from survey indices as little fishing is observed there and the connection between other areas are unknown 2) the difficulty in specifying *M* in long-lived species, which could be approached using a profile likelihood profile or by tracking specific cohorts through time where they are visible in length distributions, 3) whether survey indices could be treated to avoid being overly influenced by dense hauls using Winsorization, means over stations, T-distribution methods, means over stations, or VAST modelling, whether different error structures should be implemented for different surveys using VAST, and 5) whether it would be helpful to implement different growth parameters for different periods.

4.4 Proposed stock assessment

The current assessment, which is based on a Gadget model, has shown a historical retro and progressively worse fits to survey length distribution data over time. Since its development, a longer series of age data have become available so that comparisons with age-structured models could be performed. Early explorations of improved Gadget models indicated greater difficulty than the age-based model SAM in tracking changes in growth of both smaller and larger golden redfish over the past decade, as well as changes in selectivity of the commercial fleet. Therefore, the Gadget model development was discontinued for the time being in favour of development of the SAM model for annual assessment. The assessment model proposed at WKBNORTH 2023 is therefore an age-based SAM model (Berg and Nielsen, 2014; Nielsen and Berg, 2016; Nielsen *et al.*, 2020). Key model features include (WD11 and WD14):

- Year range of 1966–2022, and age range of 6–25+
- Input data included:
    - Catch-at-age data in years 1966, 1972, and 1995–2021. The two earlier years of data are likely to be inaccurate but stabilize model optimization.
    - Total catch series where catch-at-age data are not available, which is equivalent to landings due to a discard ban, for years 1967–1971 and 1973–1994.
    - Autumn survey numbers-at-age 1996–2021, based on age data from Icelandic surveys applied to numbers combined across surveys conducted in Icelandic, Faroese and Greenlandic waters.
    - A total biomass spring survey index series, combined across surveys conducted in Icelandic, Faroese and Greenlandic waters.
    - Maturity-at-age, calculated from a static length-based maturity ogive applied to length distributions observed within years and averaged by age.
- Recruitment is estimated directly as annual numbers-at-age 6.
- Autoregressive parameters (lag1) were estimated in residuals of the autumn survey numbers-at-age data.
- Autumn survey catchabilities were estimated by age except for ages 15–25+, which were estimated by a single parameter. All catchabilities were estimated as linear relationships.
- Observation variances were estimated within certain groups of ages for autumn survey numbers-at-age and catch-at-age data.
- Breaks in the recruitment series, which is modelled as a random walk, were inserted at years 1994, 2001, and 2014, to allow for shifts in the mean recruitment through time.
- Natural mortality was assumed 0.05 for all ages except the plus group, which was set to 0.1.

During the workshop and the exchanges between the Icelandic scientists and the reviewers, the main discussion points included 1) whether Winsorization was appropriate treatment of the data, 2) whether it was appropriate to apply age–length keys from the autumn survey to both the spring and autumn survey numbers-at-length series and fit the model with two survey-at-age series, and 3) whether survey catchabilities of older fish should be fixed to the same parameter value. It was concluded that 1) Winsorization does not appear necessary at this time, and could instead remove informative data, 2) using the same age–length keys twice to create survey input data could inaccurately reduce uncertainty, and 3) fixing catchabilities of older fish to the same value is likely to be biological realistic and avoid some possible problems related to overestimation of biomass levels. Another important topic considered was whether recent low recruitment is indicative of a productivity shift, and it was decided that for a long-lived species such as golden redfish, the time-series of low recruitment must be longer to indicate a long-term productivity shift.

The final assessment showed that total biomass peaked 2013–2015 and has since then declined. Trends in spawning-stock biomass indicate a slightly later peak and decline because of changes in growth, and consequently maturity, over the past decade (WD8). This recent peak is the result of a period of high recruitment spanning 2002–2012. However, recruitment levels over the past 8 years have been consistently lower than any recruitment values observed in the rest of the time-series, indicating that the stock will continually decline roughly over the next decade, likely surpassing B_{lim}, unless strong recruitment will be observed.

4.5 Short-term forecast methods

Short-term projections are performed using the standard procedure in SAM using the forecast function. Three-year averages are used for stock and catch weights, and maturity. From this projection the advice is derived. The advice is based on the Icelandic fishing year starting in September each year. This causes a mismatch between the assessment model, which is based on the calendar year. To provide advice for the fishing year, the standard calculating of fishing mortality used in the projection procedure in SAM is adapted (WD8). As recruitment over the past 8 years has been consistently lower than historical values, the stock is projected as the mean recruitment over the previous 5 years, continuing current practice from recent years.

4.6 Reference points

A Management Strategy Evaluation (MSE) was conducted for golden redfish in subareas 5, 6, 12, and 14 (WD8). The operating model, which generates the "true" future populations in the simulations, was based on equilibrium simulations (eqsim). Selection, maturity and stock weights were based on the resampling of estimates by age from previous 20 years. Recruitment was projected using a mean value equal to the mean of estimated recruits in the whole reliable time-series (after 1989) and a multiplicative lognormal error based on the CV and autocorrelations estimated by the assessment model. However, as the estimated CV of recruitment was unrealistically large using this procedure, recruitment variation was truncated to fall close to the range of recruitment estimates observed in the past. The recruitment had a breakpoint in B_{lim} from which it decreased linearly to zero. Advice error in the simulations was implemented as autocorrelated lognormal variations in F, with a CV of 0.212 and ρ of 0.423.

From these simulations, reference points were calculated for the stock according to ICES category 1 guidelines (ICES, 2021b). This resulted in B_{lim} of 111 000 t, based on the lowest estimate of SSB observed (1994), and $B_{pa} = B_{lim}e^{1.645\sigma_B}$ of 154 000 t, with σ_B being set to the ICES default of 0.2. The fishing pressure reference points, defined in terms of fishing mortality applied to ages from 9 to 19, were estimated in accordance with the ICES guidelines. This resulted in an estimate of F_{lim} of 0.167, F_{PA} of 0.114 and F_{msy} of 0.112.

There is no accepted current harvest control rule for golden redfish. The previous harvest control rule used has the same functional structure as the ICES advice rule, which sets a TAC for the fishing year y/y+1 based on a fishing mortality F_{mgt} of 0.097 applied to ages 9 to 19 modified by the ratio SSB_y /MGT $B_{trigger}$ when SSB_y < MGT $B_{trigger}$. $B_{trigger}$ is set to 220 000 t. As F_{mgt} is less than the F_{msy} reference point used in the ICES advice rule and a $B_{trigger}$ of 220 000 t exceeds MSY $B_{trigger}$ (see Section 4.6), then the previous harvest control rule, as well as the ICES advice rule, can be considered to maintain high yield while being precautionary as it results in lower than 5% probability of SSB < B_{lim} in the medium and long term.

4.7 Future research and data requirements

Efforts to improve stock assessment in future should include:

- Studies aimed at understanding causes of apparent changes in growth for both younger and older golden redfish.
- A more detailed comparison of autumn and spring survey data to understand why they indicate diverging trends in biomass over the past decade.

- Determine whether using alternative methods (e.g. VAST) would be useful in creating survey indices.
- Monitoring of changes in selectivity-at-age.
- Studies on natural mortality.
- Continued and/or greater sampling of otoliths.

5 Beaked redfish East of Greenland and Iceland grounds (Icelandic slope stock)

reb.27.5a14 – *Sebastes mentella* in Subarea 14 and Division 5.a

5.1 Stock description and issues

Icelandic slope beaked redfish *Sebastes mentella* (reb.27.5a14) is a redfish species which is similar in appearance to golden redfish (*Sebastes norvegicus*). There are some characteristic features that distinguish those two species apart, and the depth is one of them, with Icelandic slope beaked redfish inhabiting deeper waters (>400 m). Around Iceland the species is mainly found in the warmer waters in the western, southern, and southeastern parts of continental slope. Beaked redfish is a slow growing, long-lived, and late maturing. Mainly fish larger than 30 cm are found in Icelandic Waters, whereas the East Greenland shelf is most likely the main nursery area.

The Icelandic slope beaked redfish in 5a and 14 has been considered a data-limited stock with annual advice provided in accordance with the ICES framework (Category 3.2). For more information on stock description and issues, refer to WD10 and WD11.

5.2 Multispecies, mixed-fisheries issues, and ecosystem drivers

For more information on mixed-fisheries issues and ecosystem drivers, refer to WD10 and WD11.

5.3 Data

For more information data available, refer to WD10 and WD11.

5.3.1 Conclusions from data evaluation workshop

At the data evaluation workshop, discussion surrounding beaked redfish approached topics including 1) the decision to start the model from 1976 instead of 1970 to avoid problems regarding changes in the fleet when the Icelandic EEZ was implemented in 1976, 2) if there were any thoughts regarding what stock–recruitment relationship would be implemented, 3) generally how different sources of data contribute to model fitting.

5.4 Proposed stock assessment

The current assessment, which is based on survey trends, is not considered to capture the true state of the stock. The assessment model proposed at WKBNORTH 2023 is a statistical age- and length-based model implemented using the Gadget modelling framework (Lentin *et al.*, 2023; Begley and Howell, 2004; Begley, 2005; Elvarsson *et al.*, 2018). Key model features include (WD11 and WD14):

- Year range of 1975–2021 with a biannual time-step.
- Immature and mature substocks, with age ranges of 3–20 and 5–50, respectively.

- Movement from the immature component to the mature component via maturation (a length-based ogive) and ageing (knife-edged movement from age 20).
- Fitting to the following datasets: length- and age–length distributions from commercial catches and the autumn survey; 5 length-disaggregated survey indices (Autumn survey); maturation data (Autumn survey).
- Recruitment is estimated directly as annual numbers-at-age 3.
- Growth is estimated through a von Bertalanffy function, length at recruitment, and various parameters implementing variability.
- Commercial landings encompassing the period are assumed known to the model and removed without error.
- Selectivity is estimated as a logistic curves individual to commercial and survey fleets.
- Catchability is estimated as a power relationship for the survey index that represent the smallest length group fish, and a linear relationship for each of the three larger length-group indices.
- Natural mortality was assumed 0.05 for all ages.

During the workshop and the exchanges between the Icelandic scientists and the reviewers, the main discussion points included (1) boundary issues during the estimation process, and (2) assumptions regarding key parameter values (natural mortality). Regarding the former point, an alternative simplified configuration for the initial conditions (numbers-at-age) was tested. This greatly reduced the number of estimable parameters for the initial conditions, and whereas it also reduced the flexibility of the model, differences in the output between the two configurations was negligible. Convergence with the updated configuration was also improved and thus it was deemed preferable for the assessment model. Regarding the parameter assumptions, a likelihood profile was run testing a suite of values for natural mortality. This showed little variation in the likelihood scores for natural mortality values and therefore the value of 0.05 was maintained.

The final assessment showed that the spawning-stock biomass has continually declined from the early 1990s to present and is currently at its lowest point in the time-series. Since a recruitment spike in 2003, annual recruitment has also steadily declined, and furthermore, since 2010 recruitment has remained at exceptionally low values resulting in a declining total stock size and a stock composition that is increasingly dominated by older, mature fish.

5.5 Short-term forecast methods

Short-term forecasts for Greenland halibut in subareas 5, 6, 12, and 14 will be conducted using the settings described below.

- Model used: Age–length forward projection using Gadget software.
- Initial stock size: abundance-at-age and length for all ages.
- Maturity: Estimated outside the model, based on a fixed maturity ogive by length.
- F and M before spawning: NA.
- Weight-at-age in the stock: Gadget uses a weight–length relationship and von Bertalanffy growth (no weights-at-age are supplied to Gadget).
- Weight-at-age in the catch: Gadget uses a weight–length relationship and von Bertalanffy growth (no weights-at-age are supplied to Gadget).
- Exploitation pattern:
    - Landings: logistic selection-at-length by fleet, with parameters estimated within Gadget. No discards assumed.
    - Proportion of harvest rates allocated to fleets are based on three-year average.

- Intermediate year assumptions: Catch is set equal to the TAC during the fishing season and projections for the following year run at a selected harvest rate that corresponds to the selected fishing mortality.
- Stock–recruitment model used: Fixed hockey-stick recruitment function, with geometric mean recruitment set as the asymptote.

5.6 Reference points

A Management Strategy Evaluation (MSE) was conducted for beaked redfish in Division 5a and Subarea 14 (WD11). Simulations were based fitting the model to spatially bootstrapped compositional data and survey indices with randomly generated lognormal error. This series of operating models were used to generates the "true" future populations with simulations to account for observation error and estimate processes such as maturity, growth, and length-weight relationships used in the forecast. Similarly, fleet selectivity is the same as estimated by the model with catch proportions by fleet fixed to the average of last 5 years. Advice error in the simulations was implemented as autocorrelated lognormal variations in F, with a CV of 0.212 and ρ of 0.423. Recruitment was e drawn from historical estimates after 1995 using a 7-year block-bootstrap from the bootstrap model estimates in the whole reliable time-series (after 1995) to account for autocorrelation. The recruitment had a breakpoint as a hockey-stick function set to B_{lim} from which it decreased linearly to zero.

From these simulations, reference points were calculated for the stock according to ICES category 1 guidelines (ICES, 2021b). From the stock–recruitment relationship, there appears evidence that recruitment is impaired (Stock Type 2). Attempts at statistically fitting a segmented regression failed, so B_{lim} was set to 138 000 t by based on taking the mean SSB over 2000–2005, a period of low but stable biomass levels. From B_{lim}, B_{pa} was set as $B_{pa} = B_{lim}e^{1.645\sigma_B}$ = 192 000 t, with σB being set to 0.20. The fishing pressure reference points, defined in terms of fishing mortality applied to the max age (50+), were estimated in accordance with the ICES guidelines. This resulted in an estimate of F_{lim} of 0.110, F_{PA} of 0.061, limiting F_{msy} to 0.061. If biomass levels return to levels above B_{lim}, using the ICES advice rule for beaked redfish in subareas 5, 6, 12, and 14, based on a fishing mortality F_{mgt} of 0.061 modified by the ratio SSB_y/MGT $B_{trigger}$ when $SSBy$ < MGT $B_{trigger}$, would maintain a high yield while being precautionary as it results in lower than 5% probability of SSB < B_{lim} in the medium and long term.

5.7 Future research and data requirements

Efforts to improve stock assessment in future should include:

- Exploration of the VAST model to construct survey index. Increasing age data availability.
- Explore effects of extending survey areas.
- Determine whether it is possible to use the length distribution from the early years of the survey (1996–1999 which did not cover the whole distribution area of the stock).

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Annex 2: Resolutions

Benchmark workshop on Greenland halibut and redfish stocks

Approved on the Resolutions Forum in October 2022

2022/2/FRSG46 A **Benchmark workshop on Greenland halibut and redfish stocks** (WKBNORTH), chaired by ICES Chair, Pamela Woods* (Iceland) and Vladlena Gertseva* (External Chair, USA), and attended by invited external experts Daniel Hennen (USA) and Paul Regular (Canada), will be established. WKNORTH will meet on 28 November to 2 December 2022 for a data evaluation workshop (DEWK), and on 13–17 February 2023 for the final benchmark workshop. Both meetings will take place at MFRI in Iceland (with hybrid access). If additional time is needed to agree to reference points and the short-term forecast, the benchmark can agree to additional meeting days. WKBNORTH will work to:

a) As part of the data evaluation workshop:
   i) Consider the quality of data proposed for use in the assessment;
   ii) Consider stock identity and migration issues;
   iii) Make a proposal to the benchmark on the use and treatment of data for each assessment, including discards, surveys, life history, etc; and
   iv) Stakeholders are invited to contribute data in advance of the data evaluation workshop (including data from non-traditional sources) and to contribute to data preparation and evaluation of data quality.
b) In preparation for the assessment methods workshop:
   i) Following the DEWK, produce working documents to be reviewed during the Benchmark assessment meeting at least 14 days prior to the meeting.
c) As part of the assessment methods workshop, agree to and thoroughly document the most appropriate, data, methods and assumptions for:
   i) Obtaining population abundance and exploitation level estimates (conducting the stock assessment);
   ii) Estimating fisheries and biomass reference points that are in line with ICES guidelines (see Technical document on reference points);
      (1) If additional time is needed to conduct the work and agree to reference points, a short additional reference point workshop could be scheduled to conduct this work.
   iii) Conducting the short-term forecast.
d) As part of the assessment methods workshop, a full suite of diagnostics (regarding for e.g. data, retrospective behaviour, model fit, predictive power etc.) should be examined as a whole to evaluate the appropriateness of any model developed and proposed for use in generating advice.
e) If no analytical assessment method can be agreed, then an alternative method (the former method, or following the ICES data-limited stock approach see WKLIFE X (https://doi.org/10.17895/ices.pub.5985) should be put forward by the benchmark;
f) Update the stock annex as appropriate; and
g) Develop recommendations for future improvements of the assessment methodology and data collection.

The benchmark workshop will report by 17 March 2023 for the attention of ACOM.

Annex 3: Working documents

List of working documents

ICES WKBNORTH 2023 WD-1: NEA Greenland halibut natural mortality estimations

Elvar H. Hallfredsson

ICES WKBNORTH 2023 WD-2: Data revision for the Northeast Atlantic Greenland halibut

Windsland K., Vihtakari M., Hallfredsson E. H., Howell D.

ICES WKBNORTH 2023 WD-3: Strata and survey indices for the new AFWG GHL Gadget*

Mikko Vihtakari, Kristin Windsland, Elvar H. Hallfredsson

ICES WKBNORTH 2023 WD-4: Stock ID and sub-stock structure for NWWG GHL

ICES WKBNORTH 2023 WD-5: Greenland halibut in 5, 6, 12 and 14 Assessment using SAM

ICES WKBNORTH 2023 WD-6: Greenland halibut in 5, 6, 12 and 14 Assessment using Gadget

Bjarki Þór Elvarsson

ICES WKBNORTH 2023 WD-7: Golden redfish - Data Compilation*

Kristján Kristinsson

ICES WKBNORTH 2023 WD-8: SAM assessment of Golden redfish

Pamela Woods

ICES WKBNORTH 2023 WD-9: NWWG GHL gadget model*

ICES WKBNORTH 2023 WD-10: Icelandic slope beaked redfish - Data Compilation*

Kristján Kristinsson

ICES WKBNORTH 2023 WD-11: Beaked redfish data gadget

Kristján Kristinsson and William Butler

ICES WKBNORTH 2023 WD-12: Golden redfish survey indices

Kristján Kristinsson

ICES WKBNORTH 2023 WD-13: GHL otolith exchange*

Lise Heggebakken (IMR) and Kristin Windsland (IMR)

ICES WKBNORTH 2023 WD-14: Beaked redfish gadget model output*

ICES WKBNORTH 2023 WD-15: NWWG GHL exploratory SAM run

ICES WKBNORTH 2023 WD-16: GHL 1-2 model output figures*

ICES WKBNORTH 2023 WD-17: Assessment model for the Northeast Atlantic GHL

Mikko Vihtakari, Will Butler, Daniel Howell, Elvar H. Hallfredsson, Kristin Windsland, Bjarki Elvarsson

**Only available online.*

NEA Greenland halibut natural mortality estimations

Elvar H. Hallfredsson

Introduction

Natural mortality (M), defined as all mortality except by fisheries, in fish stocks is important in most fisheries assessment models but has shown to be difficult to estimate. Several data limited approaches have been suggested based on relation between M and longevity and/or other life history parameters. Mannini al. (2020) and Maunder et al. (2023) give a comprehensive review of different M estimation methods.

Here M is estimated for Greenland halibut in ICES areas 1 and 2 (NEA G. halibut; in Barents and Norwegian Seas) by several different life history based methods, in relation to the ongoing revision of the stock assessment, to provide estimates that are independent of the assessment model.

Material and methods

Life history parameters

The approach chosen to examine M was to use the Natural Mortality Tool (NMT) Shiny app ([The Natural Mortality Tool: Empirical Estimators of Natural Mortality (M) (noaa.gov)] (Cope and Hamel 2022). The app provides M estimates by different methods given available input parameters (Table 1). Table T1 and T2 in appendix lists up the different methods in NMT and which inputs they use, as well as reference to each of the methods.

Due to dimorphism in G. halibut between sexes, in traits like age at maturity, growth rate and longevity, the estimations are made separately for females and males.

Table 1. Live history parameters for G. halibut in ICES areas 1 and 2.

Sex	Female	Male		
Parameter	Value	Value	Unit	Source
Max age	28	23	yr	IMR database
Max age -average 5 oldest.	26	22.2	yr	IMR database
A50	13.8	6.6	yr	Derived from L50 and VBGF
VBGF Linf	92.3	63.2	cm	IMR slope survey
VBGF K	0.071	0.153	yr^{-1}	IMR slope survey
VBGF t0	-1.856	-0.904	yr	IMR slope survey
VBGF Winf	12015	2290	G	IMR slope survey
VBGF kw	0.058	0.167	yr^{-1}	IMR slope survey
Age Chen-Wat	13.8	6.6	yr	Same as A50 used
Length Gislason	61.9	42.4	cm	Same as L50 used
Total wet weight	12015	2290	G	VBGF Winf used
User M	0.1	0.15	yr^{-1}	Guesstimate, stock coordinator

The parameter estimates in VBGF and observed maximum age is based on IMR data (Windsland et al 2022). Age reading for this species is difficult and different methods are applied at different institutes. Age in the IMR data is achieved using the frozen whole right otolith age reading method (Albert et al. 2009, ICES 2011, ICES 2017).

As a preliminary approach age at maturity (A50) was derived from length at maturity (L50) (females = 61.9 cm, males=42.4 cm) and applying von Bertalanffy's growth function (VBGF).

For the inputs "Age Chen-Wat"and "Length Gislason" it was decided to use values corresponding to the L50 length, and for "Total wet weight" values corresponding to VBGF Winf.

Results

Table 2, figure 1 and figure 2 show the estimated M values by the different methods. There is a considerable difference between the estimates, where methods that use longevity give noticeably higher estimates.

Table 2. M (yr^{-1}) estimates with different methods in NMT. (NA = use inputs that are not provided).

	Method	Females	Males
1	FishLife	0.10	0.10
2	Then_nls	0.23	0.28
3	Then_lm	0.19	0.23
4	Hamel_Amax	0.19	0.23
5	Chen-Wat	0.08	0.22
6	ZM_AC_pel	0.20	0.20
7	ZM_AC_dem	0.12	0.10
8	Then_VBGF	0.13	0.27
9	Hamel_k	0.11	0.24
10	Jensen_k 1	0.11	0.23
11	Jensen_k 2	0.11	0.24
12	Gislason	0.11	0.25
13	Charnov	0.13	0.28
14	Pauly_lt	0.09	0.17
15	Roff	0.13	0.26
16	Jensen_Amat	0.12	0.25
17	Ri_Ef_Amat	0.07	0.23
18	Pauly_wt	0.08	0.18
19	McC&Gil	NA	NA
20	PnW	NA	NA
21	Lorenzen	0.20	0.32
22	GSI	NA	NA
23	User input	0.10	0.15

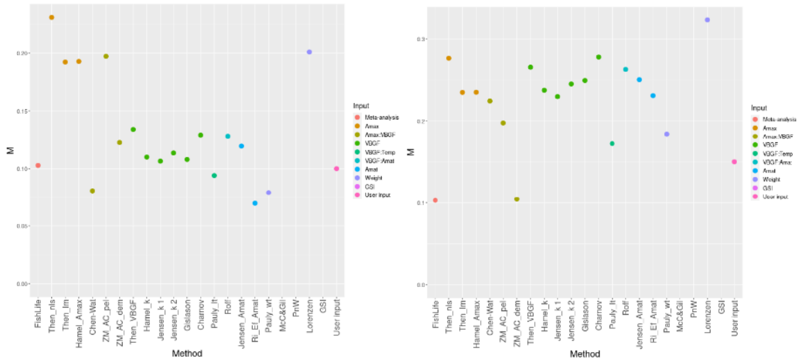

Figure 1. M estimates for G. halibut. Left panel females, right panel males.

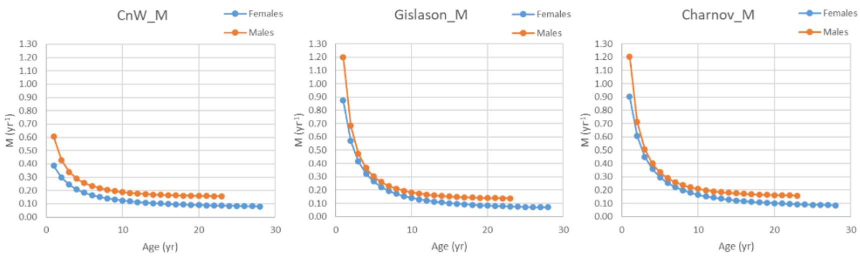

Figure 2. Natural mortality by age (se also table T3 in appendix).

In NMT it is possible to add CV in M and choose error type. This option has not been followed fully through here except for in the composite plots in figure 3 and 4 where CV = 0.85 was chosen in NMT, as suggested by Cope and Hammel (2022) for growth-based estimators, and normal distribution applied. Uncertainty in data limited M estimates is an ongoing research topic, and to pursue this further was considered out of scope for this working document.

Figure 3 and figure 4 additionally show, for females and males respectively, the mean and median M estimates over the used methods.

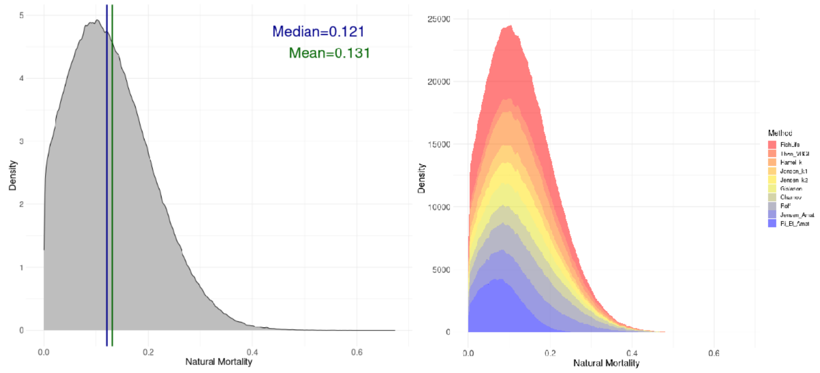

Figure 3. "Composite natural mortality" (left panel) and "Method density and weights" (right panel) plots from NMT with 0.85 as CV in M, for females. Methods with longevity and temperature as inputs, and Lorenzen method, were excluded (i.e. given weight = 0).

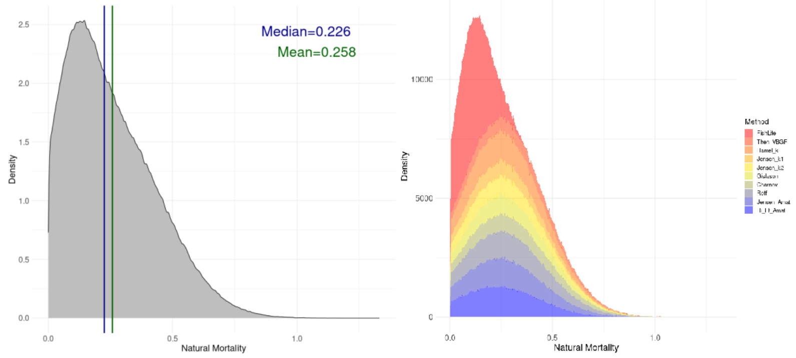

Figure 4. "Composite natural mortality" (left panel) and "Method density and weights" (right panel) plots from NMT with 0.85 as CV in M, for males. Methods with longevity and temperature as inputs, and Lorenzen method, were excluded (i.e. given weight = 0).

Discussion

The NMT app provides a comprehensive way to study M with different data limited approaches. Still, the methods are in most cases based on regression of several stocks and each of the has limitations. Additionally, estimates are depending on quality of the inputs. Therefor it is necessary to examine assumptions behind the different methods as well as how well different inputs are defined, when considering if estimates of M are adequate for the stock in question.

Comparison with G. halibut stocks in other areas

For the Bering Sea estimated maximum age for G. halibut in NOAA data from 1990-2021 was 53 years (length 87 cm) and average for five oldest observations is 48.8 years (https://apps-afsc.fisheries.noaa.gov/refm/age/stats/max_age.htm, Brogan et al. 2021). In the NW Atlantic Dwyer et al. (2016) estimated maximum age to be 33 years for females and 17 for males, with mean lengths 109 and 68 cm respectively, in their data. In both cases ages were estimated using the thin-sectioned left otolith method (Gregg et al. 2006, ICES 2011, ICES 2017). The table below shows M values based on these maximum ages as inputs, for M methods in the NMT app that rely solely on longevity for Bering Sea and NW Atlantic, and additionally for methods based on VBGF parameters for NW Atlantic (Dwyer 2016: males Linf= 90, K = 0.09, t0 =–0.05), females; Linf = 109, K = 0.09, t0 =–0.05).

Table 3. M (yr^{-1}) estimated in the NMT app for G. halibut in NW Atlantic and the Bering Sea. For Bering Sea Females1 is maximum registered age, and Female2 is average of five oldest registered G. halibut.

		NW Atlantic		Bering Sea	
		Females	Males	Females 1	Females 2
	Max age	33 (109 cm)	17 (70 cm)	53	49
Base on Maximum age	Then_nls	0.2	0.37	0.13	0.14
	Then_lm	0.16	0.32	0.1	0.11
	Hamel_Amax	0.16	0.32	0.1	0.11
Based on maximum age and VBGF parameters	ZM_AC_pel	0.18	0.45		
	ZM_AC_dem	0.1	0.28		
Based only on VBGF parameters	Then_VBGF	0.15	0.16		
	Hamel_k	0.14	0.14		
	Jensen_k 1	0.14	0.14		
	Jensen_k 2	0.14	0.14		

There is considerable difference in M estimates for the Bering Sea and the NW Atlantic, compared to the estimates for the Barents Sea. Noticeably in NW Atlantic there is less difference in M between sexes for methods solely based on VBGF, and somewhat higher values in M for females, while the difference is less for methods that include longevity. Expectedly, as maximum age is much higher, the estimates based on longevity in the Bering Sea give lower values of M than same methods give for NW Atlantic and the Barents Sea. Greenland halibut might be slower growing in Bering Sea, but it is also possible that the maximum age is drawn from larger dataset which would increase the probability to find odd old specimens. It is also possible that the age reading methods are not in agreement for the oldest ages as suggested by Brogan et al. (2022).

It should be noted that this comparison is based limited search in the literature for NW Atlantic and Bering Sea, a thorough scrutiny would imply much better access to data and cooperation with scientists in these areas.

Barents Sea

There are no obvious quantitative ways to choose between methods for a given stock. In NMT an option is provided to combine the different methods (composite M). Another option is to use average, or similar way to find joint estimate, based on methods that utilize inputs that are considered most reliably estimated for the stock.

That natural mortality relates to maximum longevity is intuitive, still estimating M based on longevity is often uncertain as maximum age is poorly known (Maunder et al 2022). For NEA G. halibut limited number of age readings and uncertainty in aging, especially for the oldest specimens, makes it difficult to achieve reliable estimates of maximum age. Methods to estimate M that depend on maximum age can be biased, and too low estimates of maximum age will lead to overestimation of M. Thus, methods in NMT to estimate M based on longevity (Table T1 in appendix) might be less reliable, especially for females as they have longer lifespan.

For the NEA G.halibut maximum age in the IMR age data and average of five oldest observations were examined, but the difference in estimates of M were minor, so only calculations with maximum age were presented.

Temperature of 4°C is used as NMT input. This is a guesstimate within the temperature range that is commonly seen at the continental slope and might not be representative for this species, that migrates both vertically and horizontally. This is an extra uncertainty in estimates based on methods that include temperature as input.

The Lorenzen method gives considerably higher M estimates than most other methods. This method has been updated (Lorenzen et al. 2022), but the update is not presently implemented into NMT. Lorenzen et al. (2022) suggest that mortality at asymptotic length (MLinf) characterizes late adult mortality and is related to the constant M traditionally used in fisheries assessments. They conclude that the best predictor for Minf in their analysis is lnMLinf=a + c K, where Minf is M at lengt Linf, K is the VBGF K, a = 0.42 and c = 0.93 (model 6 in table 3 in Lorenzen et al 2022).

For NEA G. halibut this becomes lnMLinf = 0.42 + 0.93 · 0.071 = -2.03 and MLinf = 0.13 for females, and lnLMinf = 0.42 + 0.93 · 0.153 = -2.03 and MLinf = 0.26 for males.

They further argue that the best general estimate for MLinf is at 0.85 of a growth-based predictor of M, and such estimates are given in table T3 in appendix. However, their best fit model for M by length (model 7) was lnM = a + b ln(L/Linf) + c lnK where a = 0.28, b = -1.30 and c = 1.08. Figure 5 shows M at length for the NEA G. halibut based on this model.

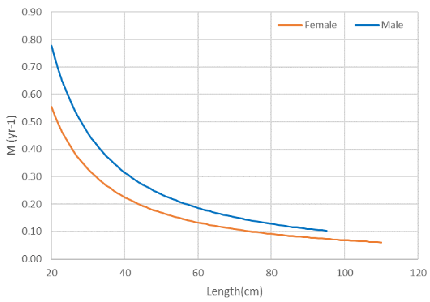

Figure 5. M at length based on the best fit model from Lorenzen et al. 2022 (see also table T5 in Appendix).

Methods in NMT that do not relay on longevity or temperature, and excluding Lorenzen (i.e. keep: Then_VBGF, Hamel_k, Jensen_k 1, Jensen_k 2, Gislason, Charnov, Pauly_lt, Roff, Jensen_Amat, Ri_Ef_Amat, Pauly_wt), give relatively consistent estimates of M for both females (range 0.07-0.13, mean = 0.11, median = 0.11) and males (range 0.17-0.28, mean = 0.24, median = 0.25).

The composite option in NMT, with weighting of methods as suggested by the program (figures 3 and 4), provides mean (females = 0.121, males = 0.226) and median (females = 0.131, males = 0.258) values for M estimates (figure 3 and 4).

Recommendations

Based on the M estimates from the different methods, and the considerations above, a recommendation for NEA Greenland halibut could be M = 0.12 for females and M = 0.24 for males.

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Appendix

T1. From Cope and Hamel (2022).

List of empirical M estimators and the inputs needed to apply the method. A link to references for each method is found in the NMT app.

Method	Inputs
FishLife	Scientific name
Then_nls	longevity
Then_lm	longevity
Hamel_Amax	longevity
ZM_CA_pel	longevity, k, t_0
ZM_CA_dem	longevity, k, t_0
Chen-Wat	Age, k, t_0
Then_VBGF	L_∞, k
Hamel_k	k
Jensen_k 1	k
Jensen_k 2	k
Gislason	L_∞, k, length
Charnov	L_∞, k, length
Pauly_lt	L_∞, k, Temp
Roff	k, age at maturity
Jensen_Amat	age at maturity
Ri_Ef_Amat	age at maturity
Pauly_wt	W_∞, k_w, Temp
McC&Gil	dry weight, Temp
PnW	dry weight
Lorenzen	wet weight
GSI	GSI

T2. References for each method in the NMT app (https://connect.fisheries.noaa.gov/natural-mortality-tool/_w_e99b4282/References_M.html).

FishLife

Thorson, J.T., Munch, S.B., Cope, J.M., Gao, J., 2017. Predicting life history parameters for all fishes worldwide. Ecol Appl 27, 2262-2276. https://doi.org/10.1002/eap.1606

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Then_nls, Then_lm, Then_VBGF

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Hamel_Amax, Hamel_k

Hamel, O.S., 2015. A method for calculating a meta-analytical prior for the natural mortality rate using multiple life history correlates. ICES Journal of Marine Science 72, 62-69. https://doi.org/10.1093/icesjms/fsu131

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Chen-Wat

Chen, S. and S. Watanabe. 1989. Age Dependence of Natural Mortality Coefficient in Fish Population Dynamics. Nippn Suisan Gakkaishi 55(2): 205-208.

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Gislason

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Charnov

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Roff, D. A. 1984. The evolution of life history parameters in teleosts. Can. J. Fish. Aquat. Sci. 41: 989-1000.

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Rikhter, V.A., Efanov, V.N., 1976. On one of the approaches to estimation of natural mortality of fish populations. ICNAF Res. Doc. 79/VI/8, 12.

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PnW

Peterson, I. and J. S. Wroblewski. 1984. Mortality rate of fishes in the pelagic ecosystem. Can. J. Fish. Aquat. Sci. 41: 1117-1120.

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GSI

Gunderson, D. R. and P. H. Dygert. 1988. Reproductive effort as a predictor of natural mortality rate. J. Cons. Int. Explor. Mer 44: 200-209.

Hamel, O.S. 2015. A method for calculating a meta-analytical prior for the natural mortality rate using multiple life history correlates. ICES Journal of Marine Science 72, 62-69.

T3. Natural mortality by age for methods in NMT that allow for age specific M.

	CnW_M		Gislason_M		Charnov_M	
Age	Females	Males	Females	Males	Females	Males
1	0.39	0.61	0.87	1.20	0.90	1.20
2	0.30	0.43	0.57	0.68	0.61	0.71
3	0.24	0.34	0.42	0.47	0.45	0.51
4	0.21	0.29	0.32	0.37	0.36	0.40
5	0.18	0.26	0.27	0.30	0.30	0.33
6	0.17	0.23	0.22	0.26	0.25	0.29
7	0.15	0.22	0.19	0.23	0.22	0.26
8	0.14	0.21	0.17	0.21	0.20	0.24
9	0.13	0.20	0.16	0.20	0.18	0.22
10	0.12	0.19	0.14	0.18	0.17	0.21
11	0.12	0.18	0.13	0.17	0.15	0.20
12	0.11	0.18	0.12	0.17	0.14	0.19
13	0.11	0.17	0.11	0.16	0.14	0.19
14	0.11	0.17	0.11	0.16	0.13	0.18
15	0.10	0.17	0.10	0.15	0.12	0.18
16	0.10	0.17	0.10	0.15	0.12	0.17
17	0.10	0.16	0.09	0.15	0.11	0.17
18	0.09	0.16	0.09	0.14	0.11	0.17
19	0.09	0.16	0.09	0.14	0.11	0.17
20	0.09	0.16	0.08	0.14	0.10	0.16
21	0.09	0.16	0.08	0.14	0.10	0.16
22	0.09	0.16	0.08	0.14	0.10	0.16
23	0.09	0.16	0.08	0.14	0.09	0.16
24	0.08		0.08		0.09	
25	0.08		0.07		0.09	
26	0.08		0.07		0.09	
27	0.08		0.07		0.09	
28	0.08		0.07		0.09	

T4. M and MLinf for NEA G. halibut. Mlinf calculated as 0.85M (Lorenzen et al. 2022)

	M		MLinf	
	Female	Male	Female	Male
Then_VBGF	0.13	0.27	0.11	0.23
Hamel_k	0.11	0.24	0.09	0.20
Jensen_k 1	0.11	0.23	0.09	0.20
Jensen_k 2	0.11	0.24	0.10	0.21
Gislason	0.11	0.25	0.09	0.21
Charnov	0.13	0.28	0.11	0.24
Pauly_lt	0.09	0.17	0.08	0.15
Roff	0.13	0.26	0.11	0.22
Jensen_Amat	0.12	0.25	0.10	0.21
Ri_Ef_Amat	0.07	0.23	0.06	0.20
Average	0.11	0.24	0.09	0.21
median	0.11	0.25	0.10	0.21
max	0.13	0.28	0.11	0.24
min	0.07	0.17	0.06	0.15

T5. M at length (in cm) based on the best fit model from Lorenzen et al. 2022.

	Female	Male		Female	Male		Female	Male
Length	M	M	Length	M	M	Length	M	M
1	27.27	38.19	41	0.22	0.31	81	0.09	0.13
2	11.08	15.51	42	0.21	0.30	82	0.09	0.12
3	6.54	9.16	43	0.21	0.29	83	0.09	0.12
4	4.50	6.30	44	0.20	0.28	84	0.09	0.12
5	3.37	4.71	45	0.19	0.27	85	0.08	0.12
6	2.66	3.72	46	0.19	0.26	86	0.08	0.12
7	2.17	3.04	47	0.18	0.26	87	0.08	0.11
8	1.83	2.56	48	0.18	0.25	88	0.08	0.11
9	1.57	2.20	49	0.17	0.24	89	0.08	0.11
10	1.37	1.91	50	0.17	0.24	90	0.08	0.11
11	1.21	1.69	51	0.16	0.23	91	0.08	0.11
12	1.08	1.51	52	0.16	0.22	92	0.08	0.11
13	0.97	1.36	53	0.16	0.22	93	0.08	0.11
14	0.88	1.24	54	0.15	0.21	94	0.07	0.10
15	0.81	1.13	55	0.15	0.21	95	0.07	0.10
16	0.74	1.04	56	0.15	0.20	96	0.07	0.10
17	0.69	0.96	57	0.14	0.20	97	0.07	0.10
18	0.64	0.89	58	0.14	0.19	98	0.07	0.10
19	0.59	0.83	59	0.14	0.19	99	0.07	0.10
20	0.56	0.78	60	0.13	0.19	100	0.07	0.10
21	0.52	0.73	61	0.13	0.18	101	0.07	0.09
22	0.49	0.69	62	0.13	0.18	102	0.07	0.09
23	0.46	0.65	63	0.12	0.17	103	0.07	0.09
24	0.44	0.61	64	0.12	0.17	104	0.07	0.09
25	0.42	0.58	65	0.12	0.17	105	0.06	0.09
26	0.39	0.55	66	0.12	0.16	106	0.06	0.09
27	0.38	0.53	67	0.12	0.16	107	0.06	0.09
28	0.36	0.50	68	0.11	0.16	108	0.06	0.09
29	0.34	0.48	69	0.11	0.16	109	0.06	0.09
30	0.33	0.46	70	0.11	0.15	110	0.06	0.08
31	0.31	0.44	71	0.11	0.15			
32	0.30	0.42	72	0.11	0.15			
33	0.29	0.41	73	0.10	0.14			
34	0.28	0.39	74	0.10	0.14			
35	0.27	0.38	75	0.10	0.14			
36	0.26	0.36	76	0.10	0.14			
37	0.25	0.35	77	0.10	0.13			
38	0.24	0.34	78	0.09	0.13			
39	0.23	0.33	79	0.09	0.13			
40	0.23	0.32	80	0.09	0.13			

ICES WKBNORTH WD2: Data revision for the Northeast Atlantic Greenland halibut stock (ghl.27.1-2)

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2023-05-05

Contents

1 Introduction

The assessment of the Northeast Atlantic (NEA) Greenland halibut stock (ghl.27.1-2) at Arctic Fisheries Working Group (AFWG) will be revised in 2023. The Globally applicable Area Disaggregated General Ecosystem Toolbox version 2 (Gadget) is currently used as an assessment model for NEA Greenland halibut. We aim to upgrade the model engine to use gadget3, which is superior in performance compared to the older versions of the model. During the revision process, we revisited most input data from Norwegian surveys and fisheries. Reproducibility and transparency were important goals in the new approach, in addition to quality control and improvements to the input data. Here we document suggested changes to the input data and assessment model, and explain decisions behind the new approaches.

2 General data concepts

The gadget2 and gadget3 frameworks use a data storing and query system called MareFrame DataBase or MFDB in short. The use of MFDB enables a structured way of shipping data with the model and export of data in the right format to Gadget. It also allows the use of bootstrapping functions build into the new Gadget versions to estimate uncertainty. We therefore export all data to an MFDB and use the database to serve Gadget and assessment report. Consequently all data used in the assessment will be shipped together with it. Instructions on how to do the export in general can be found here. However, the use of MFDB is not mandatory for Gadget 3 assessments, and the use of the database might be abandoned in future assessments of the stock.

The database export/import routine is error-prone. Sufficient tests must be developed together with a focus on the data accuracy going into the assessment model during the peer-review. Numbers in this document, and in the AFWG tables, will be peer-reviewed and can be used as a basis for tests and data comparisons. Data export and import is documented in the R scripts section.

3 Survey data

Three scientific surveys are used in the NEA Greenland halibut assessment, and additional two were considered for use in the assessment revision:

Norwegian Sea continental slope survey in autumn (G1165) (Harbitz et al. 2011) (hereafter EggaN).

- Conducted every year from 1994 in autumn, split on sex since 1996. Biennial since 2009.
- Sampling by commercially sized bottom trawl (Alfredo)
- Covers the Norwegian Sea eastern continental slope from 68 to 80N. Includes the main spawning area.
- Spatially and depth stratified, with majority of stations in strata between 500 m and 1000 m depth since 2009.
- Depths 400 to 1500 m north of 70.50N, and 400—1000 m south of this latitude.

Joint Russian-Norwegian ecosystem autumn survey in the Barents Sea and adjacent waters (A5216, hereafter Ecosystem survey or EcoS) (Eriksen et al. 2018).

- Conducted 2004 and yearly onward, in autumn.
- Sampling by Campelen scientific trawl.
- Covers entire ice-free Barents Sea, including the nursery area in northern part.
- Stations distributed in a 35×35 nautical mile regular grid. Around Svalbard additional depth stratified bottom trawl hauls are carried out.
- Depths from 100 m and mainly down to 500 m.

Russian autumn bottom trawl survey in the Barents Sea (G5348, hereafter RussianS).

- Conducted yearly 1984-2020, in autumn.
- Sampling by Russian bottom trawl
- Covers eastern Norwegian Sea continental slope from 71N to 80N and central Barents Sea.

- Stations spatially and depth stratified.
- Depths from 100-900 m.
- Revised for 1992 - 2020 at ICES AFWG 2021 (**russkikh2021?**).

Joint Russian-Norwegian ecosystem spring survey in the Barents Sea (A6996) (**fall2022?**) (hereafter WinterS).

- Conducted yearly 1986 to present, in February/March.
- Sampling by Campelen scientific bottom trawl
- Covers ice-free Barents Sea. West of Svalbard included 2014 and since.
- Stations spatially stratified, and by densities of main target species (cod, capelin).
- Depths mainly from 100-500 m.
- Was evaluated for use in NEA Greenland halibut assessment at the WKNORTH revision.Due to varying coverage throughout the time series consistent strata had limited overlap with G. halibut distribution and the biomass index from the survey was rejected. However, in the revised model length distributions from this survey are included.

Norwegian Sea continental slope survey in spring (G5678, hereafter EggaS) (Harbitz et al. 2011).

- Conducted in 2009, 2012 and biennially since then, in March/April.
- Sampling by commercially sized bottom trawl (Alfredo).
- Covers the eastern Norwegian Sea continental slope from 62 to 74.5N.
- Stations spatially and depth stratified.
- Depths 400 to 1500 m, with majority of stations in strata between 500 m and 1000 m.
- Was evaluated for use in NEA Greenland halibut assessment at the WKNORTH revision. This survey was included in trial runs in the revised assessment, but it was not clear that it improved the model and due to time constraints at the benchmark the biomass index was therefore excluded from the final model. This is a short time series and it might come in use with added years in the future. In the revised model only length distributions from this survey are included.

4 Survey indices

4.1 Introduction

All indices used in the revised assessment are recalculated with a new approach, except the index based on the Russian autumn survey at the slope. Here the new proposed indices are presented first, and then compared to the old approach. Finally, indices from two surveys that potentially can be added to the assessment are presented. All indices are swept area trawl indices and are calculated using a new strata system (WD3).

4.2 Methods

The revised indices are all calculated using the StoX program (Johnsen et al. 2019). The EggaN survey index is split by sex and used as is from the Stox output. Two indices are derived from the EcoS, one index that represents juveniles, and one for bigger individuals. Data from this survey cannot be split by sex in StoX due to variations in the sampling procedure during the time series, resulting in lack of data for sex split. This is not a concern for the juvenile index (fish below 35 cm) because the sex ratio can be assumed 50/50 (Vollen et al. 2019). The adult index for fish more than 35 cm is divided by sex applying the sex splitkey as used in the previous assessment (**vollen2019b?**) to the StoX output data.

4.3 New Survey indices

4.3.1 EggaN survey index

Indices based on the EggaN survey (figure 1) are shown in figure 2. The indices, separately for males and females, are presented with 95% CI as estimated by bootstrapping in StoX. Since 2009 the survey also covers the Bear Island Trench, but this area is not included in the index. The survey covers depths from 400-1500 m, but only strata between 500 and 1000 m are used for the index as these are the depths where G. halibut is mainly found in this area. Additionally, station density in the deepest and shallowest strata has been varying through the years, and very low in some year.

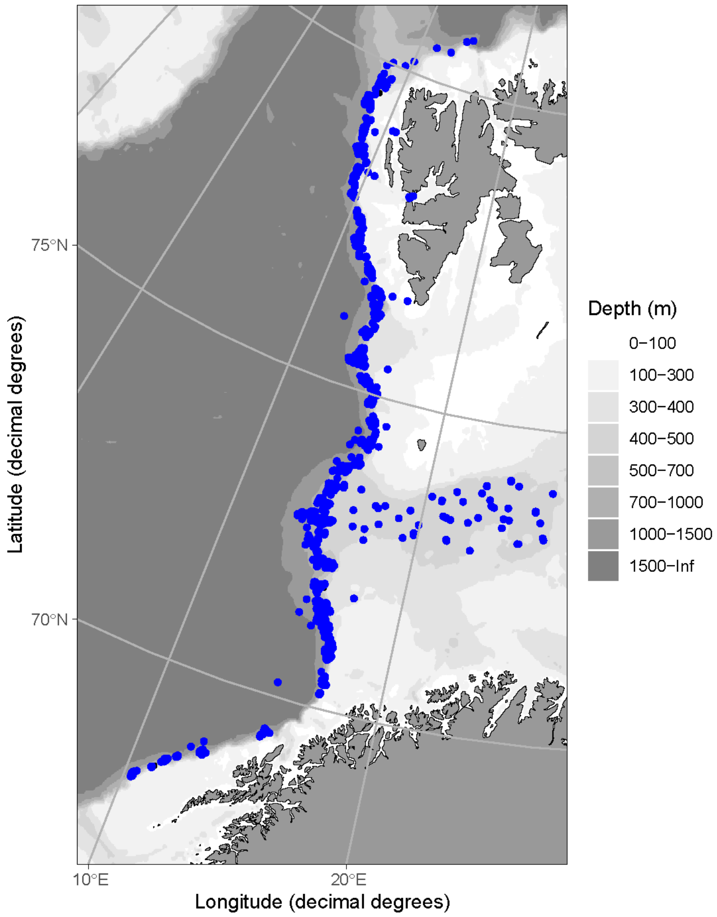

Figure 1: EggaN survey, bottom trawl stations gathered for the whole timeseries. Stations in blue and black are with and without G.halibut catches, respectively.

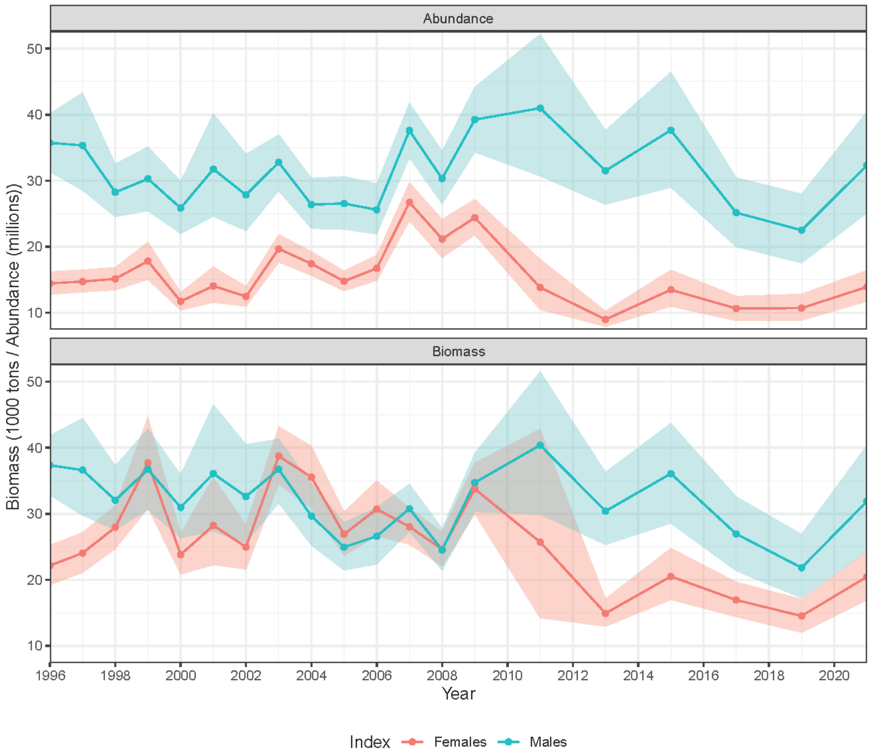

Figure 2: New EggaN survey indices, for males and females, with 95 % CI.

4.3.2 EcoS (adults)

The EcoS indices consists of data on fish above 35 cm from the Ecosystem survey (figure 3). The indices, separately for males and females, are presented with 95% CI as estimated by bootstrapping in StoX (figure 4).

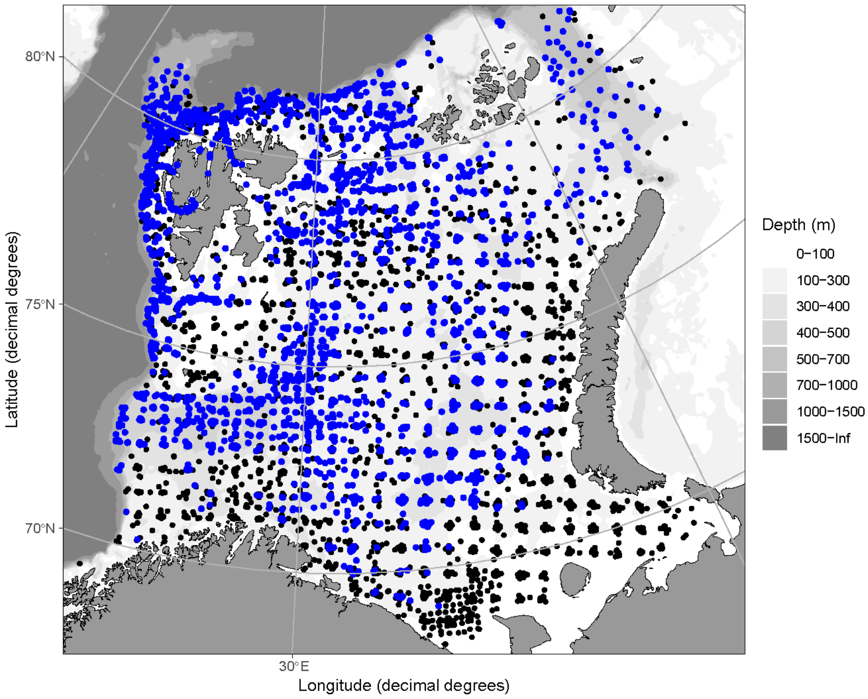

Figure 3: Ecosystem survey bottom trawl stations gathered for the whole timeseries. Stations in blue and black are with and without G. halibut in the catches, respectively.

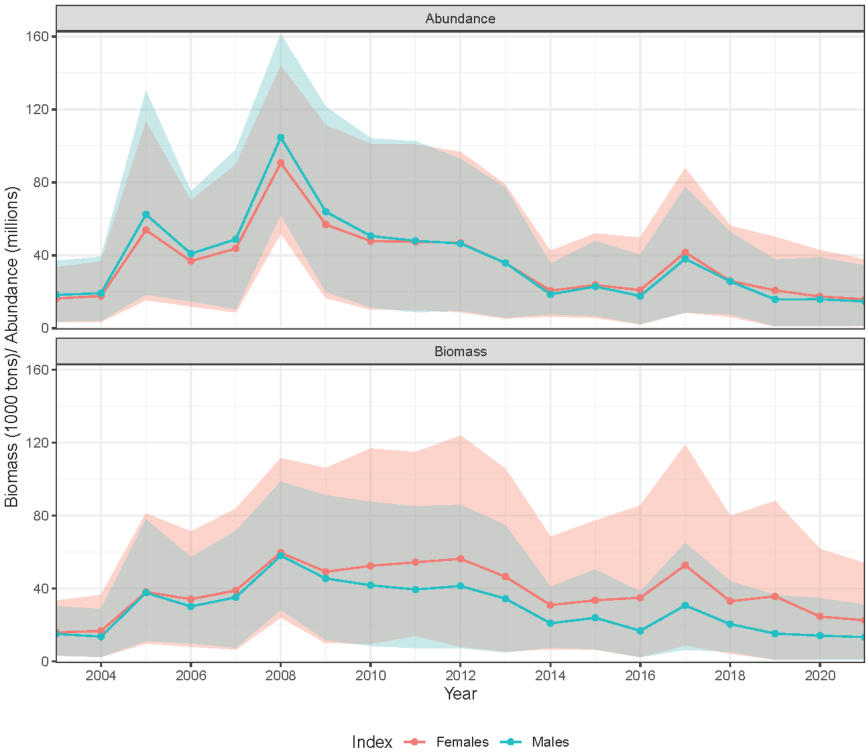

Figure 4: New EcoS survey indices for adult males and females, with 95 % CI.

4.3.3 Juvenile index

These indices consists of data on fish under 35 cm from the Ecosystem survey (figure 5), an annual time series since 2003. The indices, separately for three different length intervals, are presented with 95% CI as estimated by bootstrapping in StoX (figure 6). The length intervals L1, L2 and L3 roughly represent age 1, 2 and 3, respectively (Albert et al. 2008). Specimens less than approximately 10 cm are few in the data due to gear selectivity, and they are insignificant in terms of biomass in the assessment.

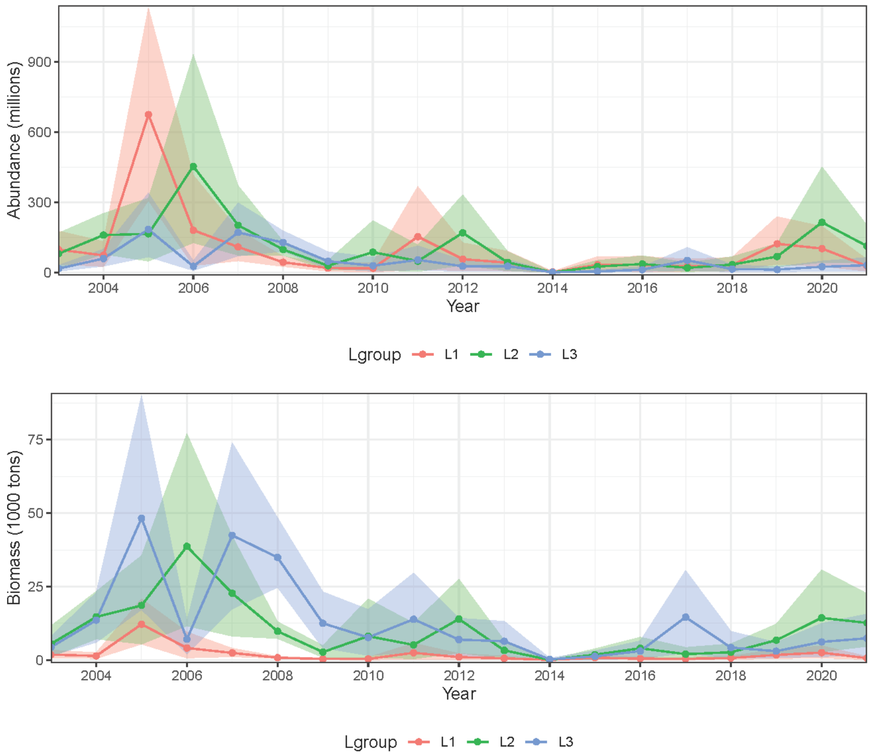

Figure 5: Juvenile indices for different lenght groups in the Ecosystem survey (L1=0-17, L2=18-27, L3=28-35, with 95 % CI.

4.4 Comparing new and old survey indices

4.4.1 EggaN survey

The new EggaN indices match approximately the trends of the old indices, but with lower biomass and abundance (figure 6). In the new index, only strata with depths between 500-700 and 700-1000 are used. The old index was calculated on strata with depths 400-500, 500-700, 700-1000 and 1000-1500. By excluding the deepest and most shallow strata from the old index, levels of biomass and abundance are more similar (figure 7). The remaining differences are likely caused by differences in the strata area.

Figure 6: Comparison of old and new EggaN survey indices.

Figure 7: Comparison of subset of old EggaN survey indices (only depths 500-1000) and the new EggaN survey indices.

4.4.2 EcoS

There is a large difference between the new and old EcoS survey index for adults (figure 8). The difference is mostly explained by a difference in which data goes into the index. The old adult indices were created by including data on fish of all lengths, but excludes a defined juvenile area (north of 76.5°North). This geographical division was an approximation since the majority of juveniles are found in the northern part. However, there can be considerable amounts of adults in the previously defined juvenile area, and vice versa. The new adult index is based on data from the entire survey, but excluding fish below 35 cm. By filtering the new index to match the old data selection, most of the differences disappear (figure 9). The spike in the new index for 2005 is probably due to a large number of smaller individuals being placed in a stratum with a bigger area than in the old index. The reason for the spike in the old index in 2018 needs further investigation.

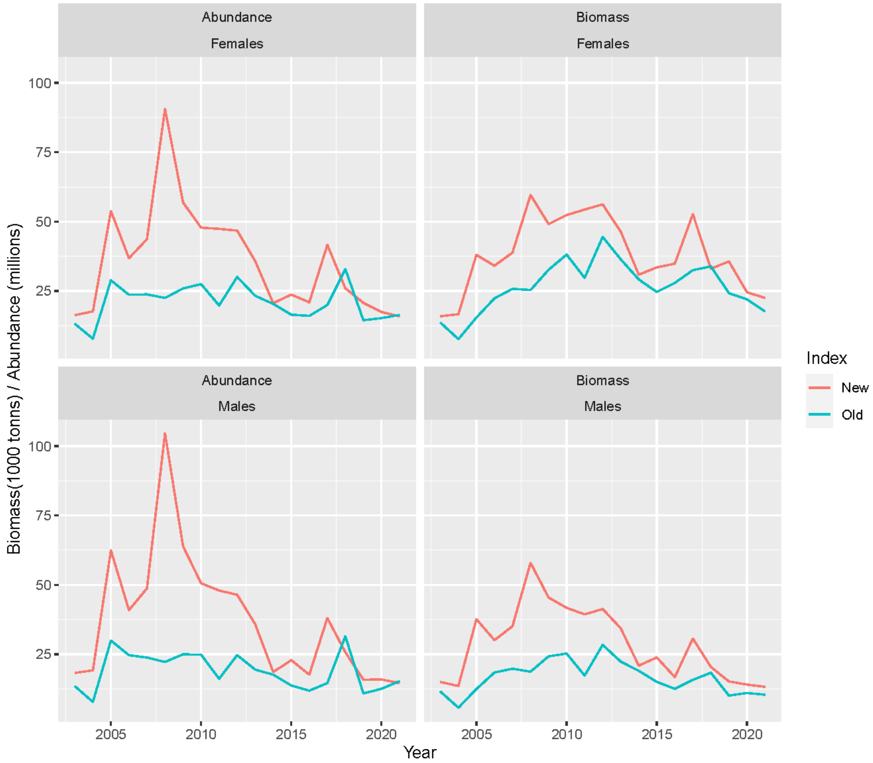

Figure 8: Comparison of old and new adult Ecosystem survey indices.

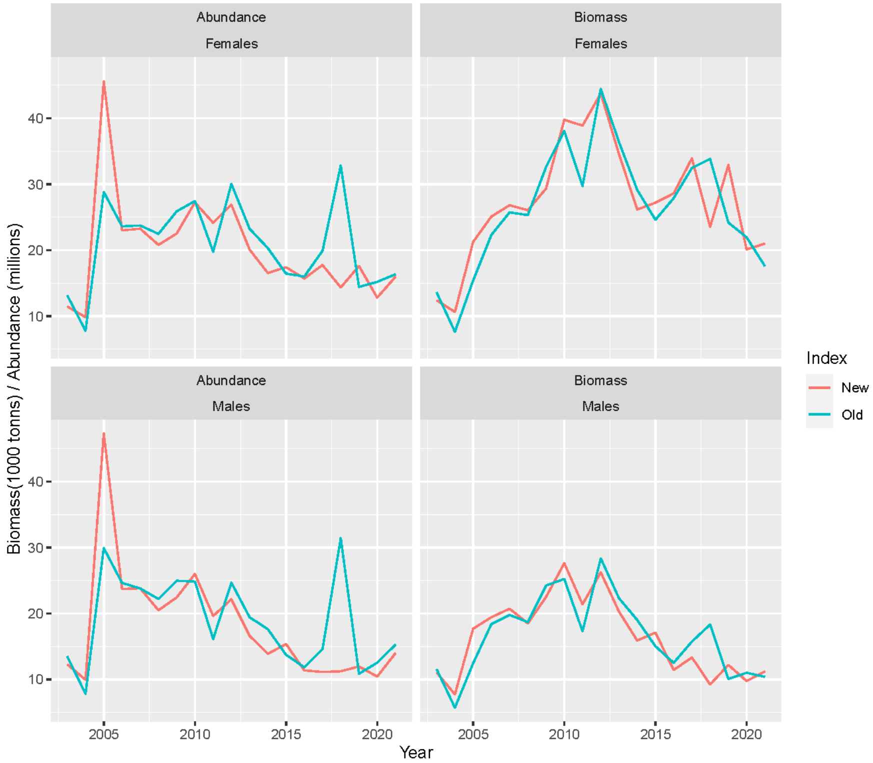

Figure 9: Comparison of old adult Ecosystem survey indices and subset of new Ecosystem survey indices.

4.4.3 Juvenile index

The differences between the new and the old juvenile index were relatively minor for most years (figure 10), except 2005. Filtering the data to get matching data selections gives similar results (figure 11). The differences may be caused by a station with a big catch being placed in a stratum with a bigger area. Another possible reason may be that a large number of 1-year olds in 2005 are proportionately more dominant in the new index, as the old index included more of the large fish in the defined juvenile area than the new index being defined by fish length.

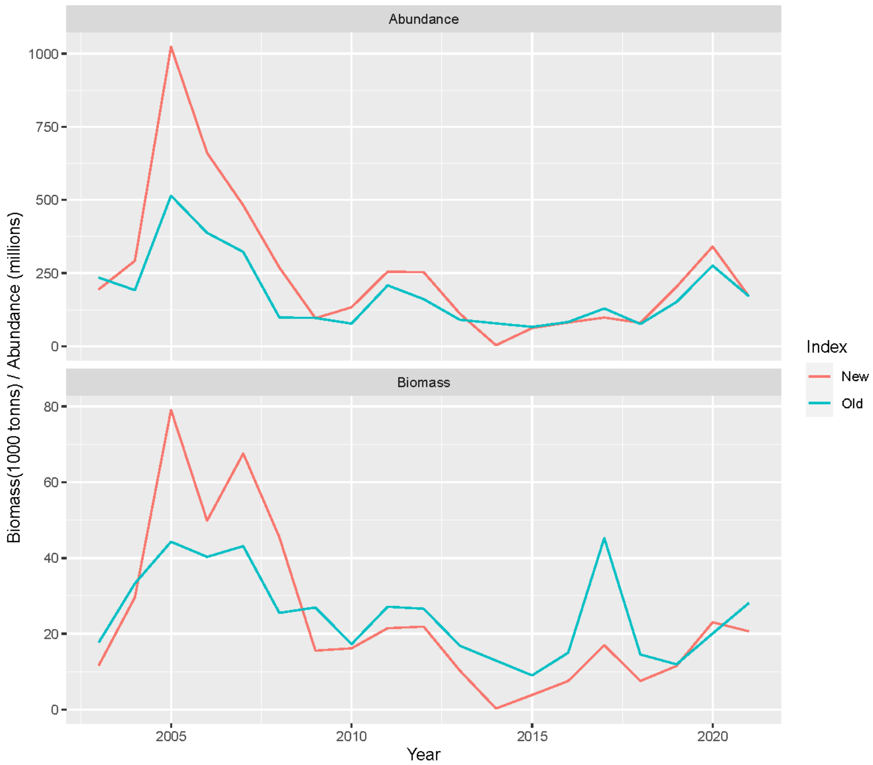

Figure 10: Comparison of old and new Juvenile survey indices.

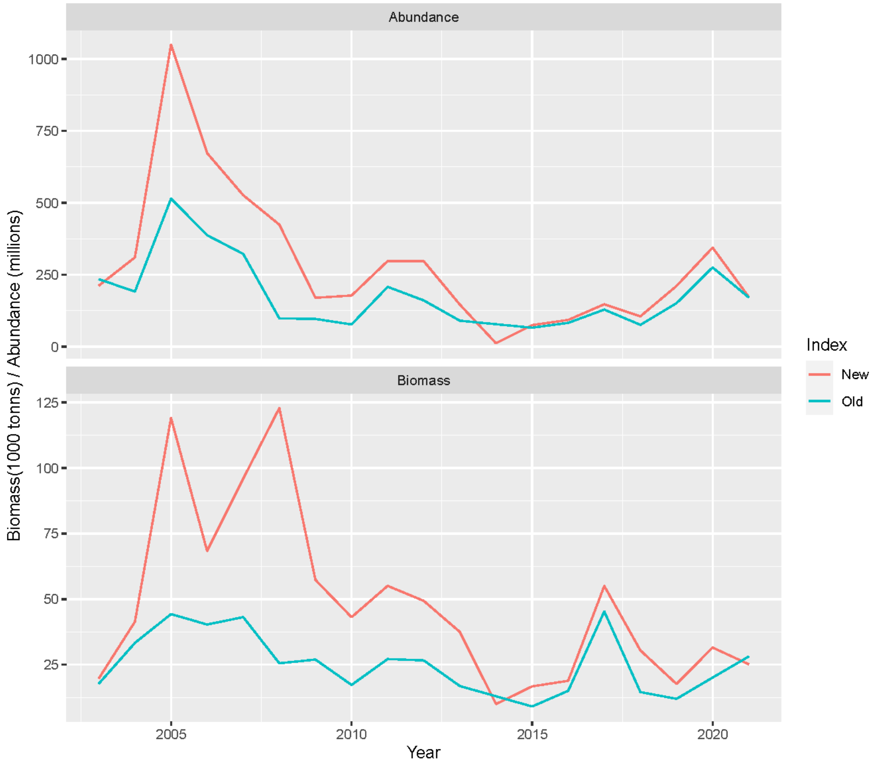

Figure 11: Comparison of old and subset of new Juvenile survey indices.

4.5 Survey indices to be considered

4.5.1 WinterS

The WinterS survey has been running annually in the Barents Sea since 1994, constantly covering the central and southern Barents Sea (figure 12). The coverage of the central Barents Sea has varied through the years due to ice coverage and, since 2014,the coverage has been extended to include the area west and north of Svalbard. These issues need to be sorted out before considering adding the survey to the assessment. A preliminary index is shown in figure 13.

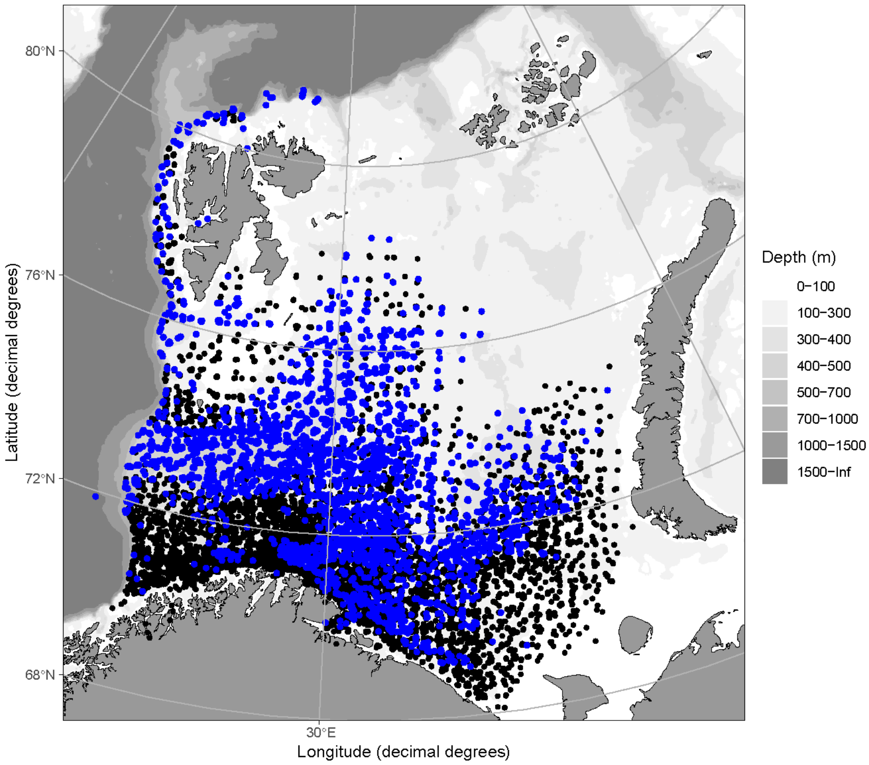

Figure 12: Joined Russian-Norwegian ecosystem spring survey in the Barents Sea bottom trawl stations gathered for the whole time-series. Stations in blue and black are with and without G. halibut in the catches, respectively.

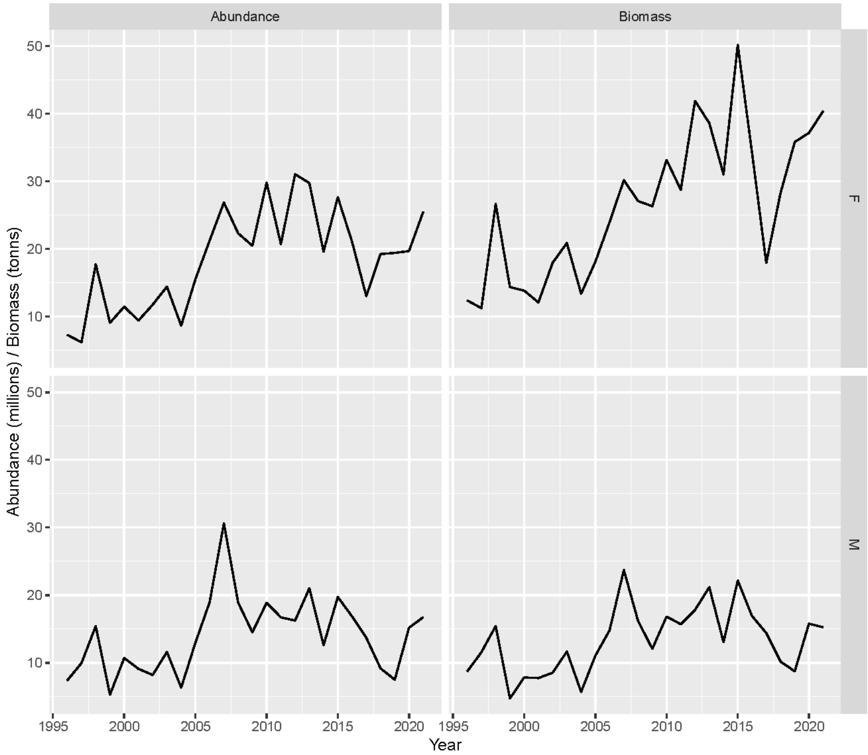

Figure 13: WinterS indices, for males and females.

4.5.2 EggaS

The EggaS time series (figure 14) is currently short, conducted in 2009 and 2012, and biennially since then. A preliminary index is shown in figure 15.

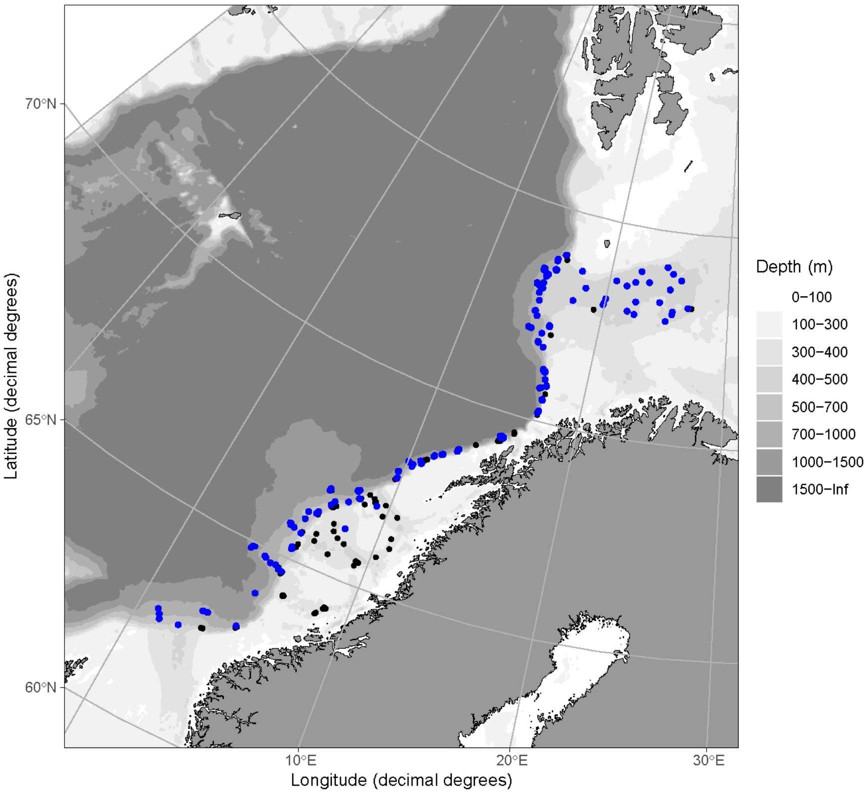

Figure 14: Norwegian Sea continental slope survey in spring. Stations in blue and black are with and without G. halibut in the catches, respectively.

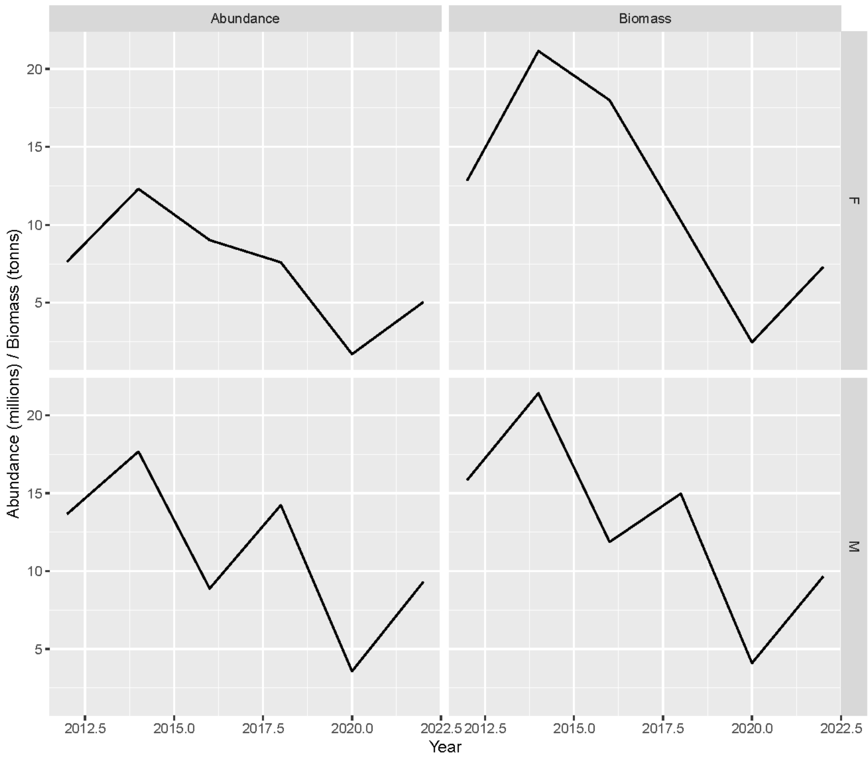

Figure 15: EggaS survey indices, for males and females.

5 Life history parameters

See the R scripts section for filtering and extraction of data used for life history parameters.

5.1 Length-weight

Greenland halibut lengths are measured as total lengths rounded down to the closest centimeter during IMR surveys. Length-weight parameters were calculated using all Norwegian and joint Norwegian-Russian survey data (EggaN, EggaS, EcoS and WinterS) and non-linear least-squares estimation, which produced a better visual fit to data than the linearization method through log-transformation of both axes (Figure 16). Since juvenile fish are rarely sex determined on IMR surveys, we randomly allocated all <25 cm fish with missing sex to males and females. This increased the number of observations for small sizes and improved the length-weight regressions. The function in R used for the calculations (plot_lw) is documented in the ggFishPlots package.

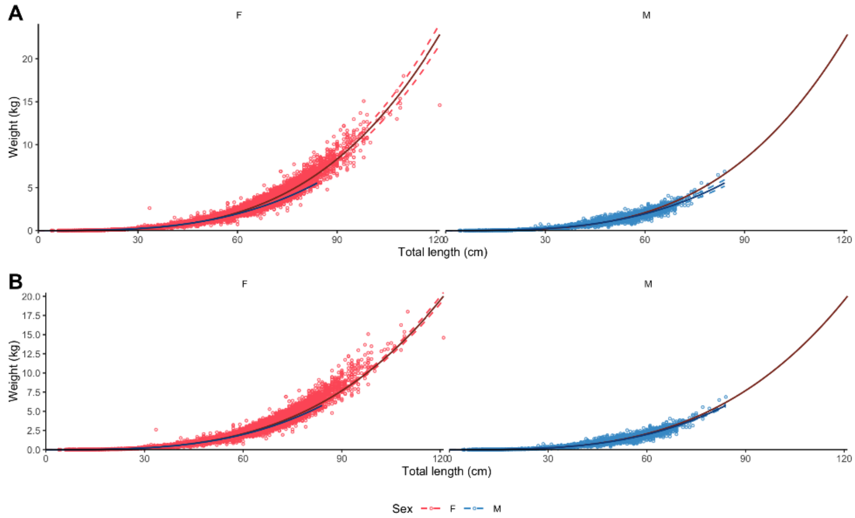

Figure 16: Length-weight relationship for female (F, red color, left panels) and male (M, blue color, right panels) Greenland halibut using nonlinear least squares (A) and linearized regression after log-log transformation (B). Dashed lines represent 95% confidence intervals for the regressions. Additional blue and red lines indicate regressions for males and females in left and right panels, respectively, and have been added for comparison.

The estimated length-weight parameters were comparable to those on FishBase (Figure 17). The nonlinear least squares regression caused more spread to the parameters between sexes compared to the linear logarithm transformed regression.

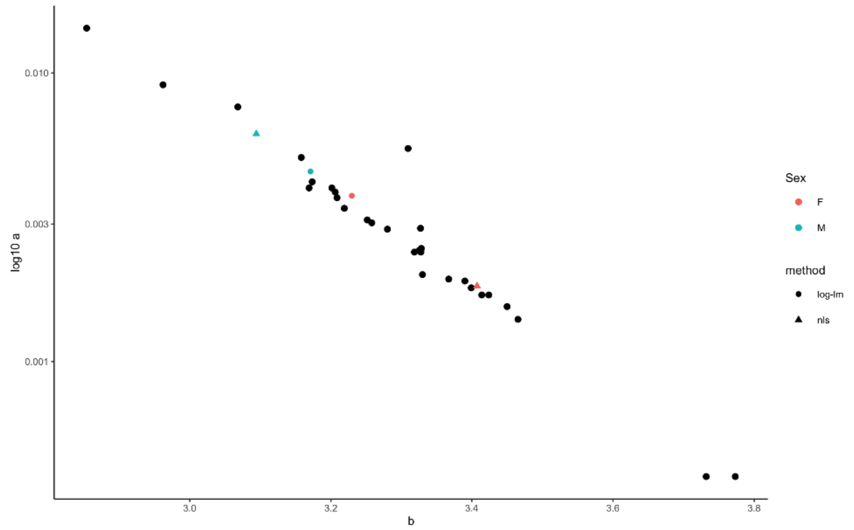

Figure 17: Logarithm transformed length-weight intercept (a) against the slope (b). Black dots indicate values reported on FishBase. Colored symbols represent parameters calculated using IMR survey data. Red indicates females, blue males. Symbol shape is related to the calculation method (nls = nonlinear least squares regression, log-lm = log-log transformed linear regression).

The new gadget3 model for Greenland halibut uses centimetres as length units and kilograms as weight units. Hence the intercept, a, has to be multiplied by 1000 to be comparable to those reported in FishBase (Table 1).

Table 1: Suggested length-weight parameters for female (F) and male (M) Greenland halibut to be used in the new assessment model with centimetres as length units and kilograms as weight units.

sex	term	estimate	std.error	p.value	conf.low	conf.high
F	a	1.827e-06	0.000	0	1.781e-06	1.873e-06
F	b	3.4074	0.003	0	3.4015	3.4133
M	a	6.155e-06	0.000	0	5.962e-06	6.353e-06
M	b	3.0942	0.004	0	3.0862	3.1022

5.2 Growth

Growth parameters were estimated using nonlinear least squares fitting of Von Bertalanffy growth curves using the nls function and fishmethods package (Figure 18, Table 2). The routine is documented in the plot_growth function in the ggFishPlots package.

See the Rscripts section on how the data were extracted from the IMR database. We used data from EggaN, EggaS, EcoS and WinterS surveys to calculate the growth curves. Age determination was done by four experienced readers using a new recommended age reading method of Greenland halibut (Albert et al. 2008). Since juveniles are rarely sex determined on IMR surveys, we randomly allocated all <25 cm fish with missing sex to females and males. This increased the number of observations for small sizes, and did not bias the growth curves because growth between males and females begin to diverge after aproximately 10 years. Only otoliths with high (IMR code 1, ICES code AQ1) or moderate (IMR code 2, ICES code AQ2) readability were included to the analysis.

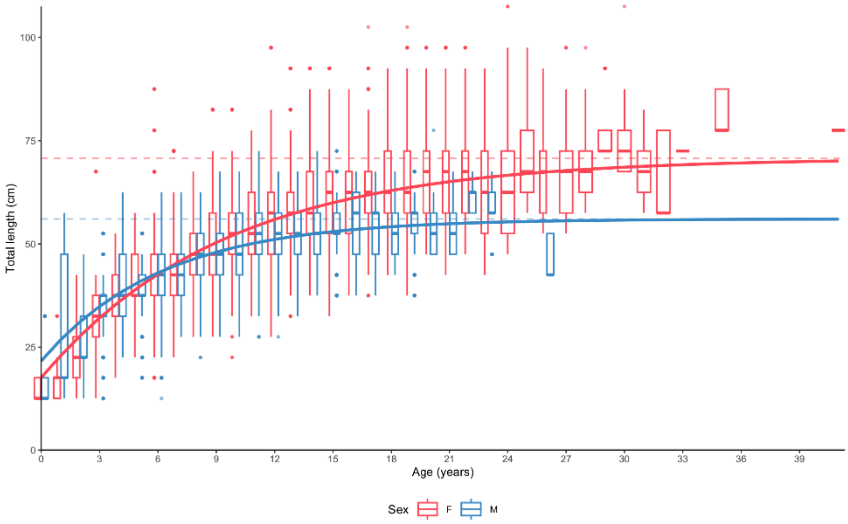

Figure 18: Von Bertalanffy growth curves for male and female Greenland halibut

Table 2: Von Bertalanffy growth function parameters for female (F) and male (M) Greenland halibut.

sex	term	estimate	std.error	statistic	p.value	conf.low	conf.high
F	Linf	70.753	0.150	472.677	0	70.462	71.052
F	K	0.106	0.001	106.894	0	0.105	0.108
F	t0	-2.673	0.058	-45.855	0	-2.789	-2.559
M	Linf	56.038	0.128	436.818	0	55.795	56.289
M	K	0.162	0.002	72.789	0	0.157	0.166
M	t0	-3.023	0.077	-39.261	0	-3.174	-2.877

5.3 Maturity

We used survey data from EggaN and Ecosystem surveys to estimate maturity ogives for Greenland halibut. Maturity readings from Russian surveys were filtered out from the dataset due to inconsistency in maturity scales. We used the IMR general scale for males (Table 3), IMR special Greenland halibut scale for females (Table 4), and converted the values to a general scale used in MFDB (Table 5). Males higher than IMR scale value 1 and females higher than special scale value 2 were considered mature, respectively (Núñez, Hallfredsson, and Falk-Petersen 2015). On the MFDB scale, values higher than 2 were considered mature.

Maturity ogives were calculated for male and female Greenland halibut using binomial general linear models (glm function in R). The calculus is documented in the plot_maturity function in ggFishMaps package.

Table 3: General IMR maturity stage conversion to MFDB maturity scale used for male Greenland halibut.

IMR maturation stage	Description	Convert to MDFB scale
1	Immature	1
2	Maturing	4
3	Spawning	5
4	Spawned/resting	5
5	Uncertain (between 1 and 4)	NA

Table 4: Special IMR maturity stage conversion to MFDB maturity scale used for female Greenland halibut.

IMR special stage	Description	Convert to MDFB scale
1	Immature. Ovaries very small. Eggs not visible with bare eyes.	1
2	Maturing. Eggs visible with bare eyes.	2
3	Maturing. Egg diameter 1-2 mm	3
4	Maturing. Egg diameter 2-4 mm. Eggs transparent with a colored dot.	4
5	Spawning. Eggs transparent, clear, and large (4-5 mm). Runny.	5
6	Spawned. Overies red and soft. Possibly residual transparent or opaque residual eggs.	5
7	Uncertain (between 1 and 6)	NA

Table 5: MFDB maturity scale for both sexes of Greenland halibut used in the assessment. MFDB maturity stage > 2 are considered mature.

MFDB maturity stage	Description
1	Immature. Small tests and ovaries.
2	Immature. For females only. Eggs visible with bare eyes.
3	Mature. For females only. Egg diameter 1-2 mm.
4	Mature. Maturing. Cabable of spawning that year.
5	Mature. Currently spawning or spawned already.

5.3.1 Maturity by length

The maturity ogive by length suggested approximately 20 cm lower L50 values for males compared to females (Figure 19, Table 6).

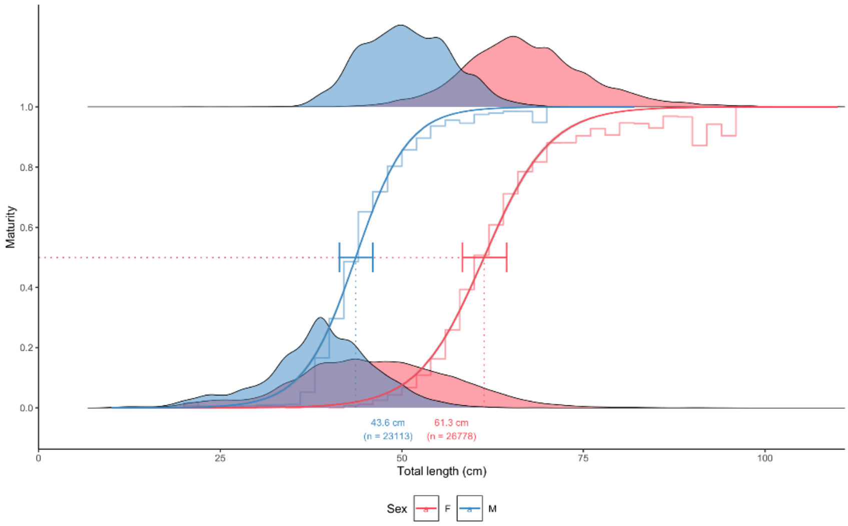

Figure 19: Maturity ogives by length for male and female Greenland halibut estimated using binomial general linear models. Lengths at 50% mature (L50) values together with number of observations used to calcualte the estimates are shown using colored letters for each sex. Density occurrences of mature and immature part of population, on top and bottom of the curve, respectively. Step-wise lines indicate average values for 2 cm length bins.

Table 6: Maturity parameters by length for male and female Greenland halibut. Mean refers to the estimated length when 50% are mature.

mean	ci.min	ci.max	sex	intercept	slope	n
43.629	41.381	45.998	M	-12.108	0.278	23113
61.340	58.360	64.473	F	-13.563	0.221	26778

5.3.2 Maturity by age

Uncertainty in age reading influenced the maturity ogives by age (Figure 20). Addition of 0 years old immature males increased the A50 estimates for males, but did not influence females (Figure 21), indicating that the dataset did not contain enough small males to estimate maturity by age. The A50 estimate was two times higher for females than males (Table 7). These estimates were used as initial values.

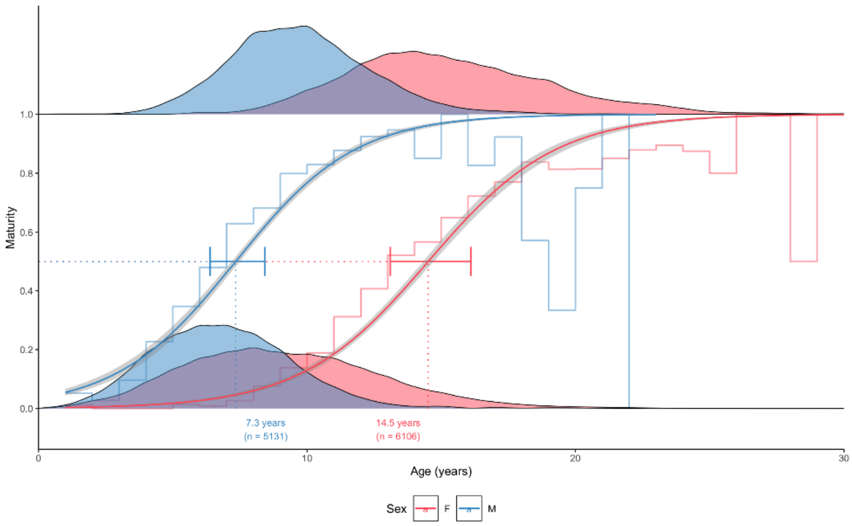

Figure 20: Maturity ogives by age for male and female Greenland halibut estimated using binomial general linear models. Ages at 50% mature (L50) values together with number of observations used to calcualte the estimates are shown using colored letters for each sex. Density occurrences of mature and immature part of population, on top and bottom of the curve, respectively. Step-wise lines indicate average values for 2 cm length bins.

Table 7: Maturity parameters by age for male and female Greenland halibut. Mean refers to the estimated age when 50% are mature.

mean	ci.min	ci.max	sex	intercept	slope	n
14.520	13.096	16.106	F	-6.112	0.421	6106
7.341	6.391	8.423	M	-3.299	0.449	5131

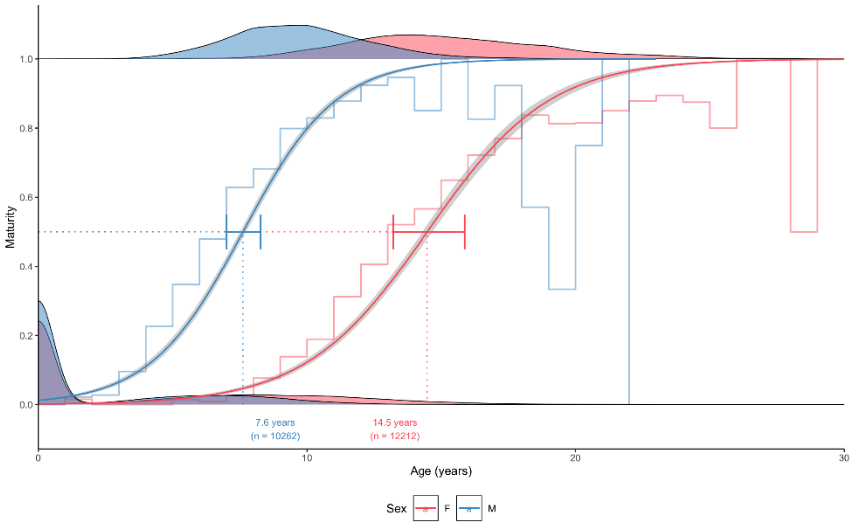

Figure 21: Maturity ogives by age for male and female after adding 100% immature 0-age juveniles. See the figure above for detailed caption.

5.4 Total mortality

Catch curves were used to study the age data and compare total mortalities (Z) to the model estimates, but these values were not used in the model itself. We used the `plot_catchcurve` function from the ggFishPlots package (Vihtakari 2023) to calculate the instantaneous total mortality (Z) estimates. The year 2007 was a clear outlier and these age data were removed from the model (Figure 22). Annual Z varied between 0.19 in 2009 and 0.56 in 2015 for females, and between 0.29 and 0.69 for males. These annual Z values did not seem stable and were depending on the number of otoliths read per year. Hence we aggregated all years for this back-of-the-envelope total mortality calculation.

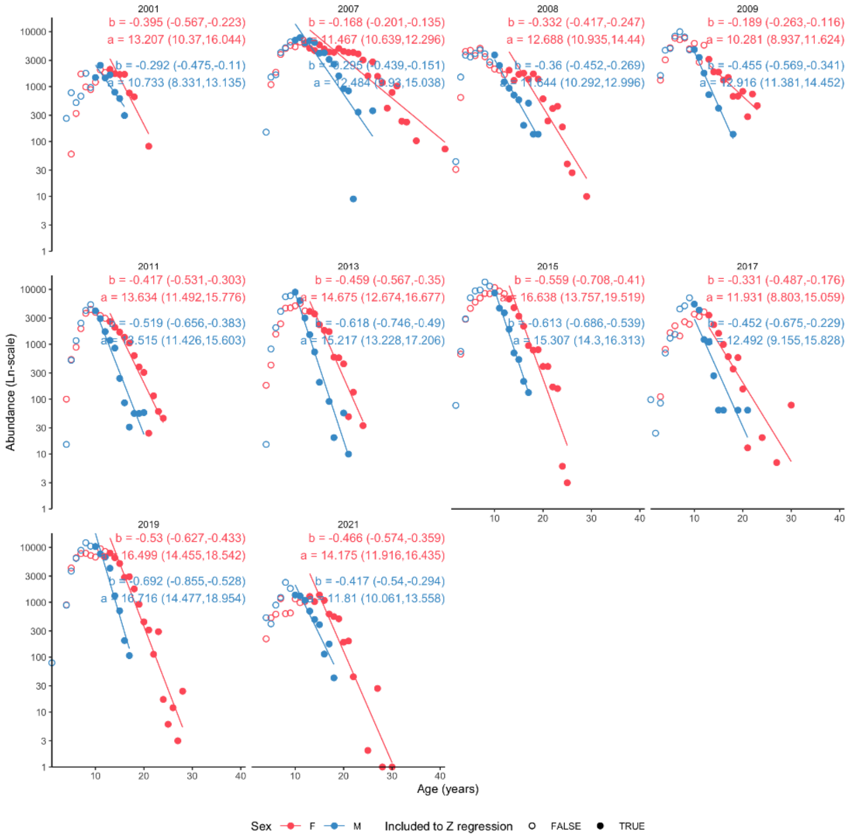

Figure 22: Catch curves to estimate annual total mortality for Greenland halibut using only EggaN data with age readings done by four experienced readers and the new recommended age reading method.

Aggregated catch curves indicated three mortality stages for females: zero mortality from age 8 to 12, a medium slope from age 12 to 23, and a steep slope from age 23 to 30 (Figure 23). We picked the medium slope but total mortality estimate for females could be drastically different had we used different ages. For males, the catch curve slope was less dependent on selected ages than for females.

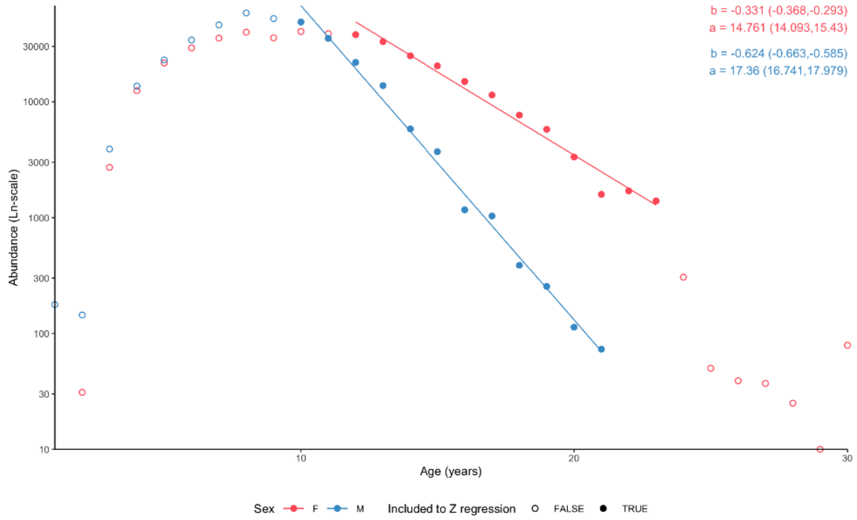

Figure 23: Catch curve with age data aggregated over all years (except 2007) for Greenland halibut using only EggaN data with age readings done by four experienced readers and the new recommended age reading method. Solid points indicate the ages used to estimate total mortalities (Z).

The resulting Z estimates for sexes should be taken as indicative only (see the R output under). There were 613 and 9527 % more 0 age females and males, respectively, than other ages according to the catch curves.

Instantenous total mortality (Z) estimated using a catch curve and
age range for females and for males.

Females:
Z = 0.331 (0.293-0.368 95% CIs)
N at age 0 = 2575351 (1319197-5027628 95% CIs)
Longevity = 44.7 years (38.3 - 52.7 95% CIs)

Males:
Z = 0.624 (0.585-0.663 95% CIs)
N at age 0 = 34619571 (18636512-64310034 95% CIs)
Longevity = 27.8 years (25.2 - 30.7 95% CIs)

6 Catch data

NEA G. halibut fisheries are by several different gears, but by predominantly bottom trawl, longlines and gillnets. The fishereis are conducted by Norway, Russia, and, to lesser extend, other countries. In the previous model the catches are aggregated to four fleets, each separated by sex. All reported Greenland halibut catches are assumed landed (ICES 2021). Hence, we may use the terms "landings" and "catches" interchangeably.

6.1 Material and methods

The suggested approach aims to as much transparency, reproducibility, and automation as possible. Consequently, the data routine has been overhauled and is called "the new approach" here. Summary of catch data used in the previous assessment can be found in the Excel file AFWG_2022_tables.xlsx on the ICES AFWG SharePoint. We compare the data for the new approach with the numbers in the Excel sheet and numbers pulled directly out from the previous assessment model for NEA Greenland halibut (`data/in/landings/catch.in.kg`; called "the old approach" in figures and text). Historic catches in tab 8.7 in the AFWG report 2022 are used as a baseline in the comparison (Figure 24). The data are read directly from the Excel using a script shown in the R scripts section.

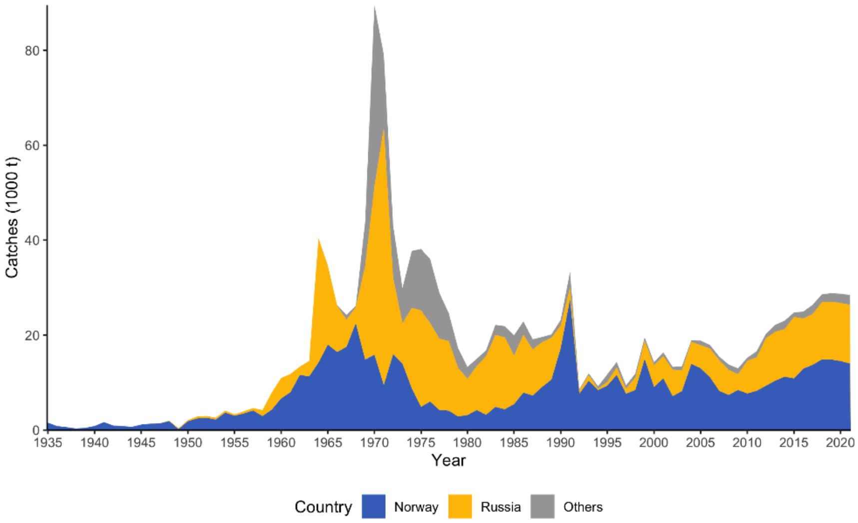

Figure 24: Historical catches according to Table 8.7 in AFWG (2022)

6.1.1 Catches in the previous Gadget model

The previous NEA Greenland halibut assessment model uses data on catches acquired from a range of sources. The data originate from national institutes but through the years they have been collected in different manner, either reported to ICES by countries' official and preliminary ICES statistics, uploaded to ICES InterCatch database or reported to the AFWG by group members. The data acquisition for these sources is largely undocumented, yet a peer-controlled process, leading to annually aggregated catches. Discards are regarded as negligible.

In the previous Gadget model, the catch data are used as one of the likelihood datasets for comparison during the parameter estimation process. The model uses one fleet effort parameter for each year, in combination with parameters governing the length selectivity of the fleet. The effort parameter estimation is weighted by a scaling factor (annual catch by a fleet / annual total catches). The effort parameters are tuned during estimation using catch data as likelihood components to estimate catch levels. In the new model, catches will be used directly as "predation" data of fleets on stocks.

6.1.2 New ways of acquiring data

Gadget3 offers superior processing efficiency compared to previous versions of the model making it feasible to bootstrap data for multiple iteration runs of the model to estimate uncertainty. Consequently, data should be supplied at as low level as possible, preferably as single landing events from individual vessels. While it is not possible to acquire such data from all countries, Norway maintains a standardized database from which landings can be acquired.

Norwegian catch data are openly available online on the Norwegian Directorate of Fisheries internet site. We do not use those data here because IMR has a more direct way of obtaining data, but they should produce similar results. A new suggested way of acquiring Norwegian catches uses two sources: 1) the standardized Norwegian Marine Database (NMD) for data after 2004, and 2) data from IMR servers aggregated by Norwegian fisheries main area and month for years when NMD data are not available (1977-2004). The NMD data (1) contain single landing events and are acquired using the `RstoxUtils::downloadLandings` function for R. The aggregated data (2) are read and processed from Excel files on IMR servers using the `RstoxUtils::readSluttseddelXLS` function. Both datasets are filtered to contain Norwegian Fisheries directorate statistical areas 0, 1, 2, 3, 4, 5, 6, 7, 10, 11, 12, 13, 14, 15, 16, 17, 18, 20, 21, 22, 23, 24, 25, 26, 27, 30, 34, 35, 36, 37, 38, 39, 50 (Figure 25). Accessing both sources requires IMR intranet connection, which is only granted for people associated with the institute. The entire data acquisition is documented in in the R scripts section. These data use codes made by the Norwegian Directorate of Fisheries. These codes are currently only in Norwegian, but are converted to English during the MFDB export phase.

The official catches used in the previous NEA Greenland halibut model have been acquired from the same source but processed differently leading to discrepancies in the "old" and "new" landings statistics from Norway. Below we compare these approaches highlighting the discrepancies and reasons for them.

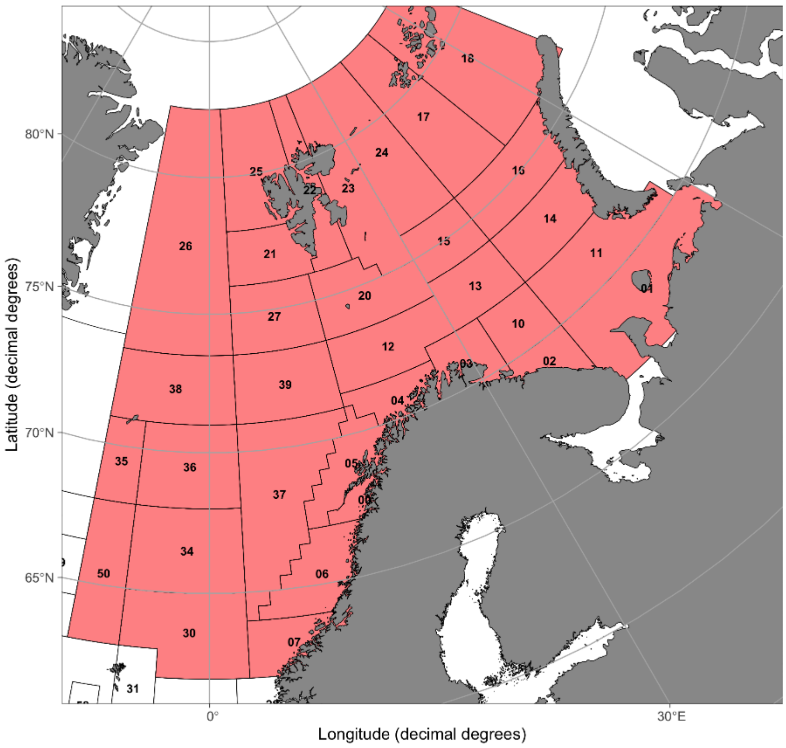

Figure 25: Norwegian Fisheries directorate statistical areas where the catches originate from (red polygons). The red area approximates ICES areas 1 and 2 south of 82.5°N. .

6.1.3 Russian catches

Russian total catches are reported to ICES, while more detailed catch data are delivered to stock coordinator by email on an Excel sheet. This Excel sheet is converted to a csv file. See the R scripts section on how the data are read.

6.1.4 International catches

International catches are downloaded on from www.ices.dk. See the R scripts section on how the data are read.

6.2 Results

6.2.1 Norwegian catches

Although trawls used to provide most Greenland halibut catches for Norwegian vessels in the past, longlines have been the most important gear since the late 1990s (Figure 26). The last two years (2019-2021), longlines and other hooked gear contributed 44.8% to total Norwegian reported landings, followed by 26.8% of trawls, 21.3% of gillnets and 7% of seines. Note that these figures do not apply for all countries as AFWG estimates similar percentages for the entire stock in Subareas 1 and 2 in 2020-2021 to be 61% for trawls, 25% for longlines, 10% for gillnets and 3% for seines (calculated from tab 8.5 in AFWG 2022 tables.xlsx).

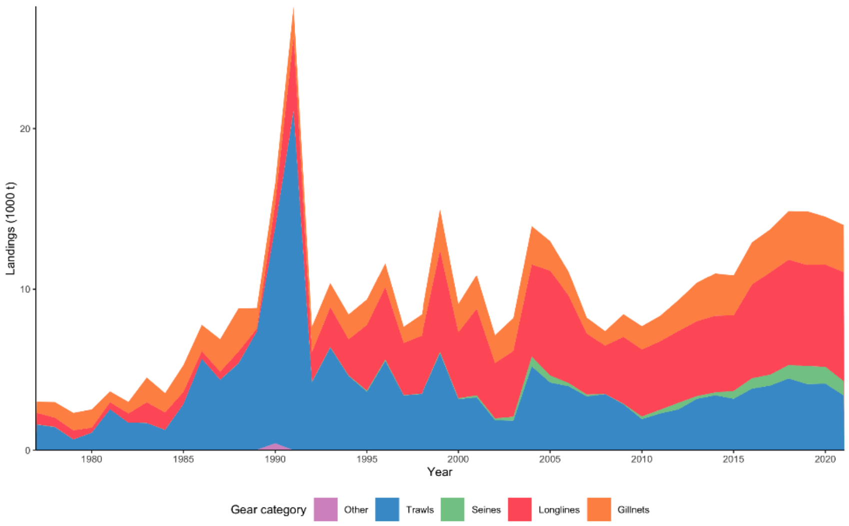

Figure 26: Developement of Norwegian catches by gear category through time.

The "new" catches downloaded directly from the database had similar trends but did not match exactly to those used in the previous assessment model ("Old") or in the catch time-series ("Historical") (Figure 27). The discrepancy between the previous assessment model ("Old") and "Historical" catches could be explained by the inclusion of international catches to *trawl_no* (norwegian trawl) in the "Old" approach. In the new approach international catches are separated into a fleet of it own. The "new" catches have been almost equal to the "historical" since 1991. Discrepancies in 2011 and 2014 were found to be mistakes in the old data routine. Consequently these estimates are more accurate for the "new" method. The discrepancy in 2019 was minor (22 tons), but unknown. Discrepancies before 1991 were larger (up to 1785 tons) and difficult to trace, as information on how the historical catch data were collected is limited.

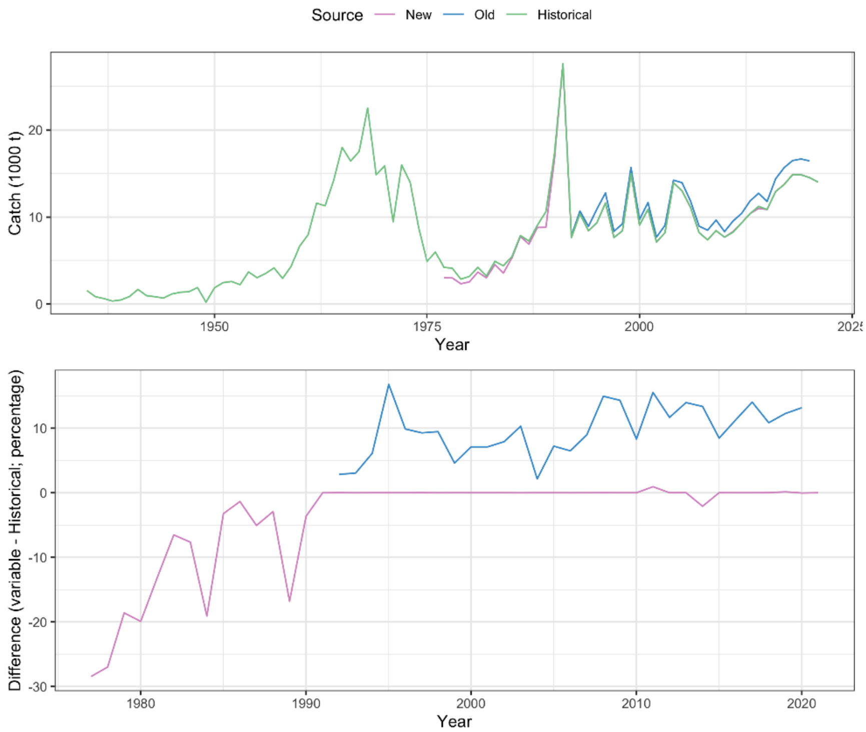

Figure 27: Norwegian catches according to direct downloads from IMR database ("New"), those used in the previous assessment model ("Old"), and the AFWG Table 8.7 Historical catches.

6.2.1.1 trawl_no: trawl, seine and international The Norwegian trawl and seine landings were mostly caught with bottom trawl (Table 8). The catches used in the previous assessment model are the sum of Norwegian trawl and seine catches together with landings from other countries than Norway and Russia as reported to ICES. While the sum reproduced catches before 2011, the new approach did not fully reproduce the *trawl_no* catches in the previous assessment model since 2011 (Figure 28). This discrepancy was up to 7 % of Norwegian catches and only influences the allocation between fleets.

Table 8: Summed catches by gear name in the Norwegian trawl and seine fleet.The Norwegian gear names translate in order as they appear in the "Gear name" column to: Bottom trawl, Danish seine, shrimp trawl, undefined trawl, pelagic trawl, double trawl, undefined seine, purse seine/ring net, pair trawling.

Gear name	Summed catch (t)	Percentage of total
Bunntrål	176 620	91.9
Snurrevad	9 331	4.9
Reketrål	4 364	2.3
Udefinert trål	1 631	0.8
Flytetrål	146	0.1
Dobbeltrål	39	0.0
Udefinert not	24	0.0
Snurpenot/ringnot	22	0.0
Bunntrål par	16	0.0

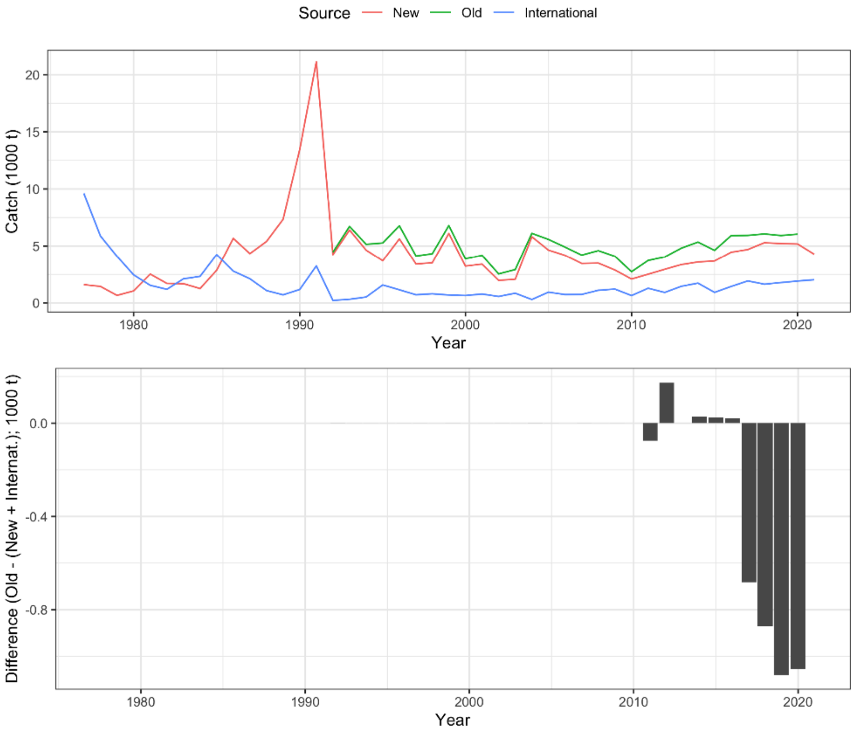

Figure 28: Trawl and seine catches by Norwegian vessels in ICES subareas 1 and 2. New indicates catches acquired from the IMR databases and contains only Norwegian landings. Old indicates the catches used in the previous AFWG assessement model and contain Norway as well as other countries except Russia. International indicates historical catches from countries other than Russia and Norway acquired from the AFWG tables.

6.2.1.2 gil_no: longline and gillnet The catches used in the assessment model are a sum of all Norwegian landings except trawls and seines. The annual sums were almost identical between the new and old method except for 2014, 2015, 2017 and 2018 (Figure 29). The large differences in 2017 and 2018 could be explained by wrong recording of catch between trawl_no and gil_no fleets by the old approach.

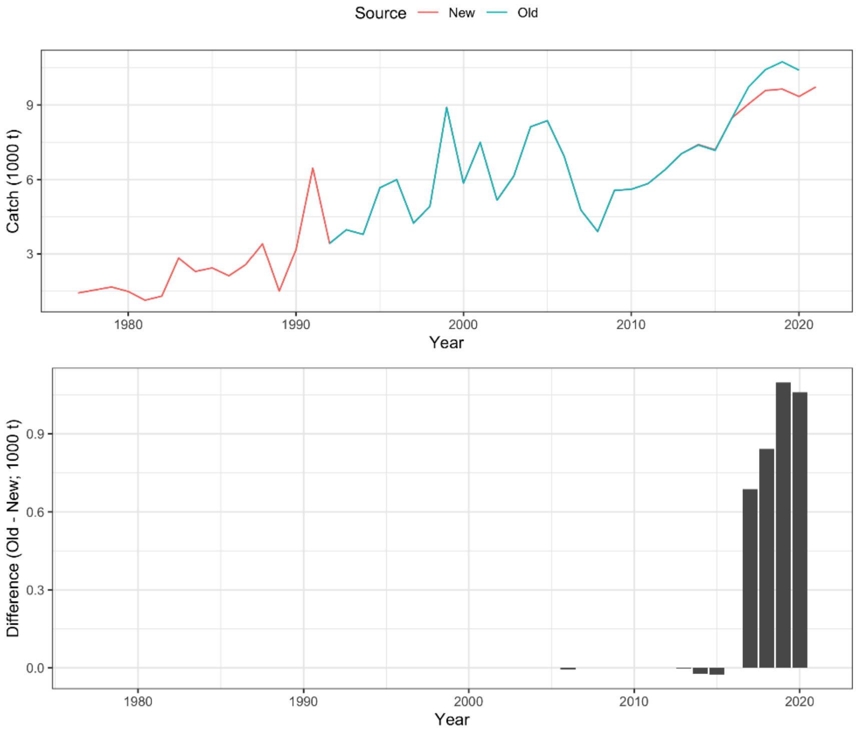

Figure 29: Other catches than trawl by Norwegian vessels in ICES subareas 1 and 2. New indicates catches acquired from the IMR databases. Old indicates the landings used in the previous AFWG assessement model.

Floating longlines, autolines, and other longlines contributed 65% of total catch within the fleet, while gillnets contributed 34% (Table 9).

Table 9: Summed catches by gear name in the Norwegian longline and gillnet fleet. The Norwegian gear names translate in order as they appear in the "Gear name" column to: Floating longline, set net, autoline, other lines, drift nets, undefined gill-nets, hand line/jig, other gears, undefined hook gears, inshore/coastal pots, shell dredge, trolling line/handline/vertical line, traps, deep sea pots

Gear name	Summed catch (t)	Percentage of total
Flyteline	54 772	23.4
Settegarn	53 086	22.7
Autoline	51 187	21.9
Andre liner	46 347	19.8
Drivgarn	15 227	6.5
Udefinert garn	11 615	5.0
Juksa/pilk	831	0.4
Annet	559	0.2
Udefinert krokredskap	146	0.1
Teiner	13	0.0
Skjellskrape	7	0.0
Dorg/harp/snik	2	0.0
Ruser	1	0.0
Havteiner	0	0.0

6.2.2 Russian catches

The sum of trawl_ru and gil_ru in the `data/in/catches/Russian catches 1984-2021.csv` file equaled to those of historical catches in the AFWG 2022 tables except for year 1989 for which catch data was missing (Figure 30). The Russian catches in the IMR database were only a fraction of these data, because they only contain catches by Russian vessels delivered to Norwegian harbors, and cannot be used to estimate total Russian landings.

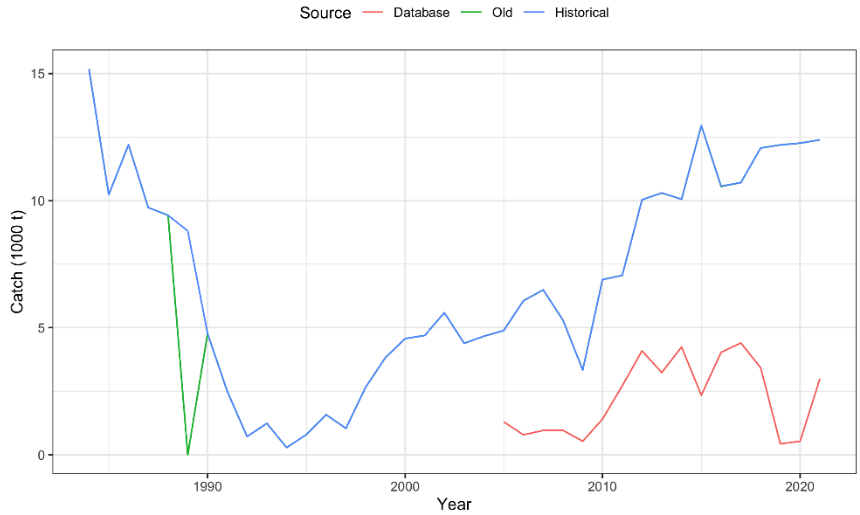

Figure 30: Russian catches over time. The sum of trawl_ru and gil_ru ("Old"), AFWG table 8.7 catches ("Historical") and Greenland halibut catches delivered to Norwegian harbors by Russian vessels ("Database").

6.2.2.1 Split by gear Unlike the Norwegian catches, the Russian landings were reported to be caught mostly with trawl (Figure 31). The AFWG tables did not contain allocation to gear. Catches in the .csv file were split to gear (trawls vs long lines) from 1991 onward. Before 1991, all catches were reported to trawls.

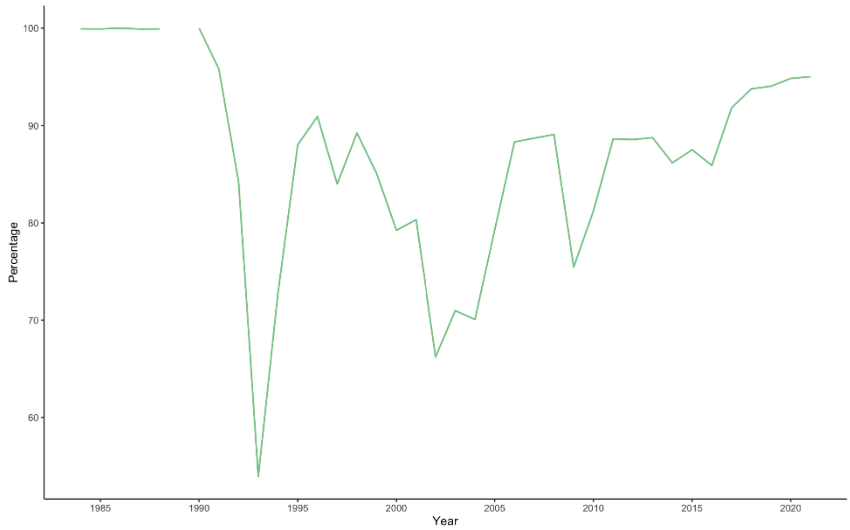

Figure 31: Percentage of trawl catches in Russian catches calculated from Russian catches 1984-2021.csv.

6.2.3 International catches

Similarly to Russian catches, it was not possible to reproduce the historical international landings purely by using catches delivered to Norwegian harbors (Figure 32). It should be examined whether these information can be extracted from an ICES database in a transparent and automated manner. The international data were not split by gear.

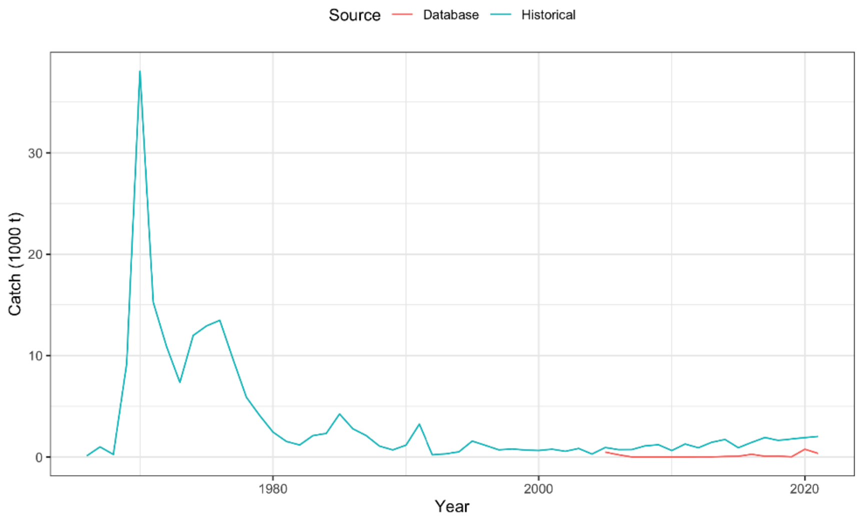

Figure 32: International catches over time. AFWG table 8.7 catches ("Historical") and Greenland halibut catches delivered to Norwegian harbors by non-Russian and Norwegian vessels ("Database")

6.3 Suggested fleets and their data sources in the new Gadget model

We suggest formulating the fleets for the new assessment model based on separate data sources: Norwegian trawlers (TrawlNor), other Norwegian vessels (OtherNor), Russian trawlers (TrawlRus), other Russian vessels (OtherRus), and all international vessels (Internat). Since the Norwegian and Russian data are not split by gear before 1977 and 1991, respectively, we suggest using average proportion of the last 10 years in both datasets to allocate the historic AFWG table catches to the corresponding fleets (Figure 33, Table 10). In theory, this would allow starting the assessment model as early as 1935, or 1946 when reporting of Russian catches begun. However, we do not suggest starting the assessment model that early due to potential inaccuracies in historic data, and are currently aiming to start from 1980. Further, we suggest not to allocate catches to sex as we lack these data for most years and fleets. Sex distribution is suggested to be handled using likelihood similarly to length distributions of fish from each fleet.

The recipe to acquire and manipulate data for the suggested fleets is given below in separate sections. Sources/fleets may be modified if all data will be available from ICES databases eventually.

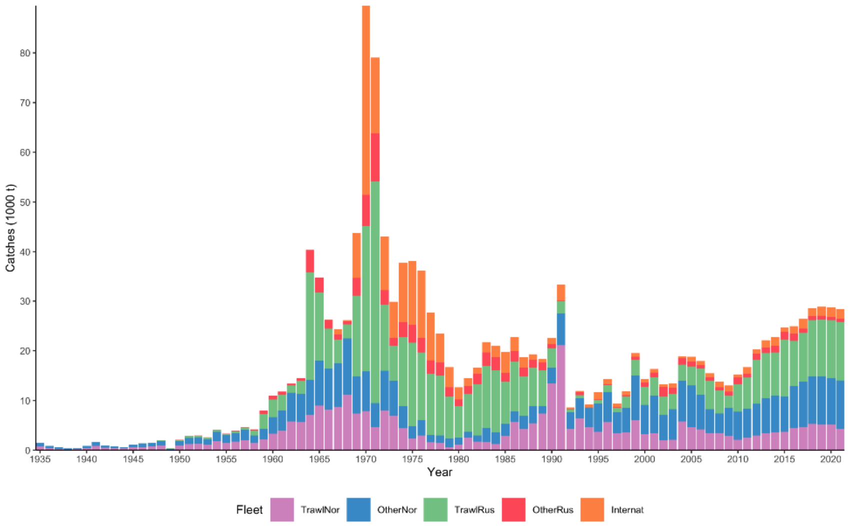

Figure 33: Summarized Greenland halibut catches in ICES Subareas 1 and 2 split by the suggested fleets shown as stacked bar plot.

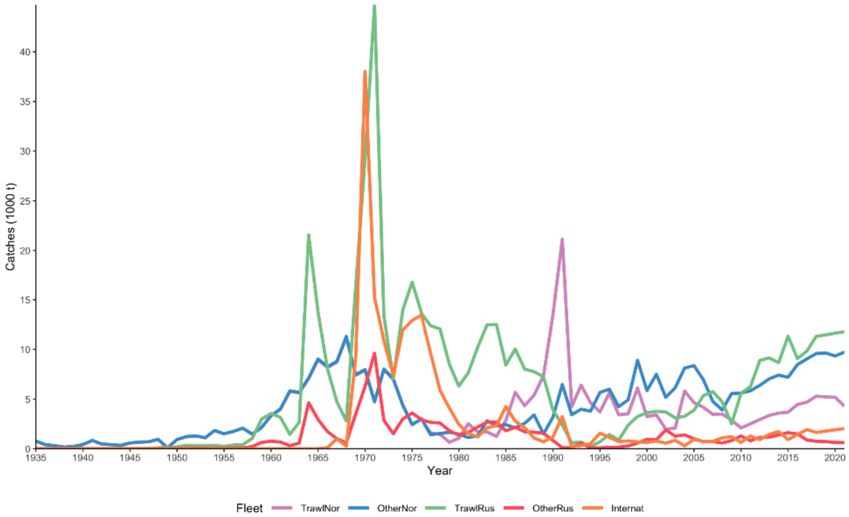

Figure 34: Summarized Greenland halibut catches in ICES Subareas 1 and 2 split by the suggested fleets shown as unstacked lines.

6.3.1 TrawlNor

Obtained from the IMR databases through a fully transparent process for those working within the institute. Contains data from trawls and seines (gear code "^1\\d|^5\\d|61"). The data are aggregated by month and Norwegian main area for 1977-2004 and by landing event from 2005. Data before 1977 are split from historic catches in AFWG table 8.7 using average proportion between TrawlNor and OtherNor in 1977-1986. Data after 2004 can be used for bootstrapping. Differs from trawl_no in the previous assessment by removal of international catches from the fleet and extension of the dataset back to 1935. The acquisition is explained in Material and methods. Data manipulation for >1976 as follows:

```
## Annually aggregated TrawlNor catches in kilograms
TrawlNor <- readr::read_rds("data/out/Catches from IMR database.rds") %>%
  filter(nation == "NOR" & grepl("^1\\d|^5\\d|61", gear_id)) %>%
  group_by(year) %>%
  summarise(TrawlNor = sum(mass))
```

6.3.2 OtherNor

Obtained similarly to TrawlNor but contains the catches not included in TrawlNor, mostly longline and gillnet (Table 9). The acquisition is explained in Material and methods. Data manipulation for >1976 as follows:

```
## Annually aggregated OtherNor catches in kilograms
OtherNor <- readr::read_rds("data/out/Catches from IMR database.rds") %>%
  filter(nation == "NOR" & !grepl("^1\\d|^5\\d|61", gear_id)) %>%
  group_by(year) %>%
  summarise(OtherNor = sum(mass))
```

6.3.3 Splitting of historic Norwegian catches

Covers years 1935-1977. Acquired from the AFWG table 8.7 and is aggregated annually. Splitting using average proportion between TrawlNor and OtherNor in 1977-1986. These data do not contain length or sex distributions. Reading of the Excel sheet is explained in Material and methods.

```
## Split factor
split_fac <- full_join(TrawlNor, OtherNor, by = "year") %>%
  filter(year < 1987) %>%
  mutate(prop = OtherNor/(TrawlNor+OtherNor)) %>%
  pull(prop) %>%
  mean()
## Annually aggregated HistNor catches in kilograms
HistNor <- hist_land %>%
  rename(year = Year, value = Norway) %>%
  filter(year < 1977) %>%
  mutate(TrawlNor = (1-split_fac)*value*1e3,
         OtherNor = split_fac*value*1e3) %>%
  dplyr::select(year, TrawlNor, OtherNor)
```

6.3.4 TrawlRus

Obtained from Russia, previously through AFWG and ICES, at the time of writing through direct contact between stock coordinator and Russian scientists. Contains quarterly aggregated information allocated to three separate ICES areas (1, 2a and 2b). Allocated to gear (trawl and long lines) from 1991 onward. Missing data from 1986. Same information as trawl_ru in the previous AFWG model. Length distributions delivered together with catch data. Reading of the file demonstrated in Material and methods. Data manipulation for >1990 as follows:

```
## Annually aggregated TrawlRus catches in kilograms
TrawlRus <- catch_rus %>%
  filter(gear == "trawl",
         year > 1990) %>% # filtering year because not split to gear before
  group_by(year) %>%
  summarise(TrawlRus = sum(value)*1e3)
```

6.3.5 OtherRus

Same as TrawlRus, but using "long line" data instead of "trawl". Data manipulation for >1990 as follows:

```
## Annually aggregated OtherRus catches in kilograms
OtherRus <- catch_rus %>%
  filter(gear == "long line",
         year > 1990) %>% # filtering year because not split to gear before
  group_by(year) %>%
  summarise(OtherRus = sum(value)*1e3)
```

6.3.6 Splitting of historic Russian catches

Covers years 1946-1990. Splitting using average proportion between TrawlRus and OtherRus in 1991-2000. Length distributions available back to 1984. No sex distributions. Reading of the Excel sheet is explained in Material and methods.

```
## Split factor
split_fac <- full_join(TrawlRus, OtherRus, by = "year") %>%
  filter(year < 2001) %>%
  mutate(prop = OtherRus/(TrawlRus+OtherRus)) %>%
```

```
  pull(prop) %>%
  mean()
## Annually aggregated HistRus catches in kilograms
HistRus <- hist_land %>%
  rename(year = Year, value = Russia) %>%
  filter(year < 1991) %>%
  mutate(TrawlRus = (1-split_fac)*value*1e3,
         OtherRus = split_fac*value*1e3) %>%
  dplyr::select(year, TrawlRus, OtherRus) %>%
  na.omit()
```

6.3.7 Internat

If data from ICES are not available in a transparent way, acquired from the AFWG table 8.7 "Others" column. Aggregated annually. Starts from 1966. Preferably a similar automated way of acquiring data than described for the Norwegian landings should be made. Reading of the Excel sheet is explained in Material and methods.

```
## Annually aggregated Internat landings in kilograms
Internat <- hist_land %>%
  rename(year = Year) %>%
  mutate(HistInt = 1e3*Others) %>%
  select(-Norway, -Russia, -Others, -Total) %>%
  na.omit()
```

6.3.8 Catch reference table

Table 10: Suggested NEA Greenland halibut catches in 1000 metric tons (million kg)

Year	TrawlNor	OtherNor	TrawlRus	OtherRus	Internat
1935	0.76	0.77			
1936	0.41	0.42			
1937	0.31	0.31			
1938	0.16	0.17			
1939	0.23	0.23			
1940	0.42	0.43			
1941	0.83	0.84			
1942	0.48	0.48			
1943	0.41	0.41			
1944	0.34	0.34			
1945	0.57	0.58			
1946	0.67	0.67	0.02	0.00	
1947	0.70	0.71	0.02	0.00	
1948	0.93	0.94	0.09	0.02	
1949	0.10	0.10	0.15	0.03	
1950	0.92	0.93	0.18	0.04	
1951	1.21	1.22	0.35	0.07	
1952	1.28	1.29	0.31	0.07	
1953	1.10	1.11	0.32	0.07	
1954	1.83	1.85	0.34	0.07	
1955	1.50	1.51	0.24	0.05	
1956	1.74	1.75	0.37	0.08	
1957	2.06	2.07	0.42	0.09	
1958	1.46	1.47	1.04	0.22	

1959	2.14	2.16	2.99	0.64	
1960	3.32	3.35	3.54	0.76	
1961	3.97	4.01	3.16	0.68	
1962	5.77	5.83	1.45	0.31	
1963	5.62	5.68	2.67	0.57	
1964	7.07	7.13	21.56	4.63	
1965	8.96	9.04	13.73	2.95	
1966	8.18	8.26	8.04	1.73	0.12
1967	8.72	8.81	4.72	1.01	1.00
1968	11.20	11.31	2.80	0.60	0.26
1969	7.39	7.46	16.27	3.49	9.17
1970	7.90	7.97	29.29	6.29	38.03
1971	4.71	4.76	44.74	9.60	15.23
1972	7.95	8.03	13.33	2.86	10.87
1973	6.96	7.03	7.05	1.51	7.35
1974	4.37	4.42	13.96	3.00	11.97
1975	2.42	2.44	16.77	3.60	12.91
1976	2.99	3.02	13.65	2.93	13.47
1977	1.60	1.42	12.39	2.66	9.61
1978	1.44	1.54	12.06	2.59	5.88
1979	0.66	1.66	8.49	1.82	4.09
1980	1.05	1.48	6.31	1.36	2.46
1981	2.52	1.12	7.64	1.64	1.54
1982	1.71	1.29	10.20	2.19	1.19
1983	1.69	2.82	12.48	2.68	2.11
1984	1.26	2.28	12.50	2.68	2.33
1985	2.86	2.43	8.43	1.81	4.24
1986	5.68	2.11	10.04	2.16	2.79
1987	4.33	2.56	8.01	1.72	2.12
1988	5.40	3.41	7.76	1.67	1.08
1989	7.34	1.49	7.26	1.56	0.70
1990	13.44	3.17	3.92	0.84	1.18
1991	21.12	6.46	2.39	0.10	3.24
1992	4.24	3.43	0.60	0.11	0.22
1993	6.40	3.98	0.67	0.57	0.32
1994	4.64	3.79	0.21	0.08	0.52
1995	3.70	5.67	0.70	0.10	1.57
1996	5.63	5.99	1.43	0.14	1.15
1997	3.42	4.25	0.87	0.17	0.71
1998	3.51	4.92	2.37	0.29	0.80
1999	6.10	8.90	3.25	0.57	0.69
2000	3.23	5.86	3.62	0.95	0.65
2001	3.40	7.49	3.77	0.92	0.78
2002	1.97	5.17	3.70	1.89	0.57
2003	2.08	6.14	3.11	1.27	0.85
2004	5.82	8.12	3.27	1.40	0.30
2005	4.64	8.37	3.87	1.01	0.94
2006	4.18	6.94	5.35	0.71	0.73
2007	3.46	4.77	5.75	0.73	0.74
2008	3.49	3.90	4.72	0.58	1.10
2009	2.88	5.56	2.52	0.82	1.21

2010	2.09	5.61	5.60	1.29	0.64
2011	2.51	5.84	6.25	0.80	1.28
2012	2.94	6.39	8.89	1.15	0.92
2013	3.36	7.04	9.15	1.16	1.45
2014	3.59	7.41	8.67	1.39	1.73
2015	3.68	7.20	11.34	1.62	0.92
2016	4.45	8.48	9.07	1.49	1.44
2017	4.69	9.05	9.84	0.88	1.93
2018	5.29	9.58	11.32	0.75	1.64
2019	5.22	9.64	11.47	0.73	1.78
2020	5.18	9.34	11.63	0.63	1.91
2021	4.28	9.73	11.78	0.62	2.03

7 Age reading data

7.1 Introduction

In the new assessment, we wish to include age data. During Workshop on Age Reading of Greenland Halibut (WKARGH) in 2011 (ICES 2011), several age reading methods for Greenland halibut were described and evaluated. The different methods can be classified into two groups: A) Those that produce age-length relationships that broadly compare with the traditional methods described by the joint NAFO-ICES workshop in 1996 (ICES 2017), typically indicating age around 10-12 years for 70 cm fish; and B) Several recently developed techniques that provide much higher longevity and approximately half the growth rate from 40-50 cm on wards compared to the traditional method. These typically produce age estimates of around 20 years or more for 70 cm fish. All available validation and corroboration results, both several published and a few unpublished, were in favor of group B methods.

A second age reading workshop (WKARGH2) in 2016 (ICES 2017) worked on validation and scrutiny of mainly two "type B" methods. The workshop had in its recommendations that "While it is recognized that some ageing issues remain to be resolved, the WKARGH2 recommends that either the frozen whole right otolith or thin-section method can be used to provide age estimates for stock assessments.". At IMR the "frozen whole right otolith method" was implemented in the mid-2000s and the old method (type A) abandoned. Thus IMR age reading data consist of age readings using both types A (hereafter called old) and B (hereafter called new), depending on when the reading was done.

7.2 Saving old age data

There are 78245 Norwegian registrations of age in the IMR database. Of these, 61261 are by using the old method and 16984 are by using the new method. The new method is used on age material from both surveys and commercial sampling. The majority of the age data using the new method is from a Norwegian survey at the continental slope survey in autumn (EggaN).

Boxplots of all age readings show that age data read with the old method only coincide with the new method up to about 4 years and 30-35 cm length (figure 35). A more sophisticated analysis could "translate" between the different reading methods, but this will need to be explored further.

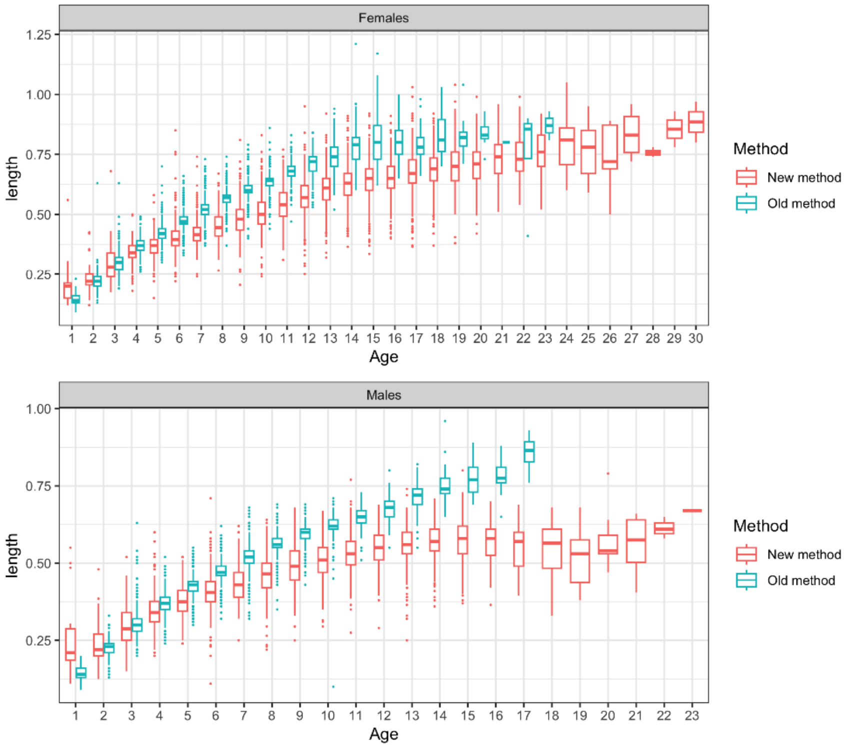

Figure 35: Comparison of different age reading methods using all data available.

7.3 New age reading method

7.3.1 Available data

Table 11 gives an overview of age readings that are currently available with the new method, but as numbers aged are most consistent for the EggaN survey only age from this survey was used in the new assessment.

Table 11: Number of available age readings per year and data source,new age reading method

Year	EggaN	EggaS	Ecosystem	Winter	Other	Survey total	Catch
2 001	200	0	0	0	0	200	0
2 006	0	0	499	0	0	499	0
2 007	316	0	0	0	0	316	0
2 008	502	0	393	0	0	895	0
2 009	0	0	124	0	0	124	0
2 011	1 159	0	369	0	0	1 528	0
2 013	996	0	70	0	0	1 066	0
2 014	0	351	74	0	0	425	0
2 015	1 906	0	48	0	13	1 967	894
2 016	0	570	68	0	86	724	1 101
2 017	770	0	114	228	0	1 112	135
2 018	0	777	302	0	0	1 079	604
2 019	2 058	0	58	185	0	2 301	712

7.3.2 Comparison of age readers

Internal blind comparison between age readers have been conducted in IMR. The differences between the readers using the new method are not big (Figure 36). The differences is larger for the youngest ages and oldest ages. This could be a results of small number of otoliths available.

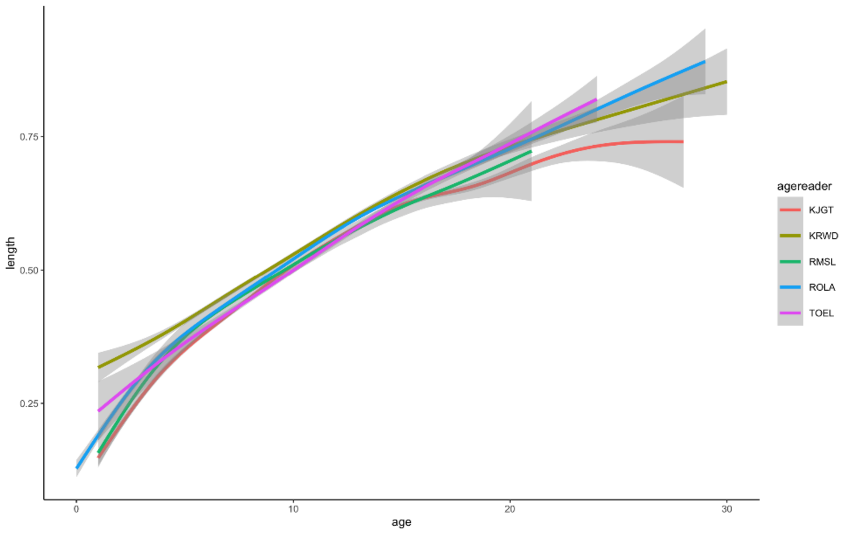

Figure 36: Differences between readers (new method).

7.3.3 Length distribution by estimated age

In order to get an overview over the extent of variation within age, we plotted length distribution by estimated age (Figure 37). The analysis was run on all age readings using the new method.

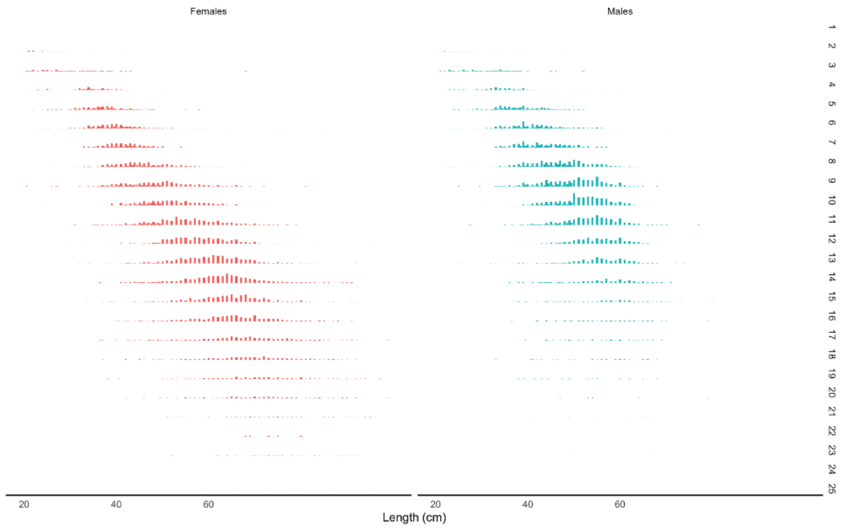

Figure 37: Length distribution by estimated age using the new reading method.

7.3.4 Geographical differences

Greenland halibut collected in the northernmost area, show slower growth than those collected further south (Figure 38). This may be caused by juveniles leaving the nursery area around Svalbard at a specific length rather than age. Hence, the slow-growing individuals may remain in the area for a longer time. This geographical differences were not examined further in the assessment, but are subject to future studies.

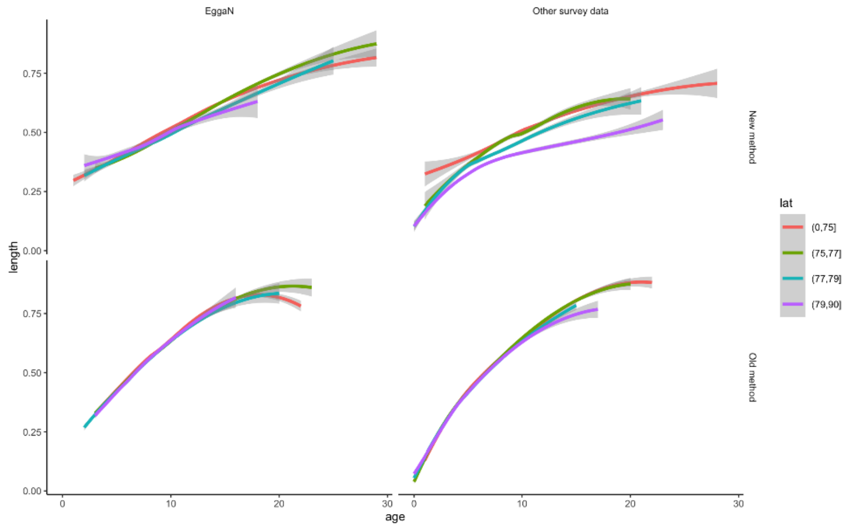

Figure 38: Growth patterns by latitude

7.4 Conclusions on aging

The old age data are only comparable to the new ageing method up to age of around 4 years. The possibility of translating the old ages to new ages needs to be investigated further. The new age reading method produce reasonable age-length relation, but there is wide range in length within age groups. This wide range might be related to individual or geographical differences in growth patterns, and to some extent it might be associated with differences between age readers.

8 References

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9 R scripts

9.1 Run first

Run first script (run at the beginning of each script):

```
### Run first script

### Clear workspace (optional)

if(exists("mdb")) mfdb::mfdb_disconnect(mdb)
if(exists("con_db")) DBI::dbDisconnect(con_db)

rm(list = ls())

###################
#### Libraries ----

# Package names
packages <- c("remotes", "stringi", "tidyverse", "reshape2", "data.table",
              "DBI", "mfdb", "RstoxData", "units", "cowplot", "sf", "knitr")

# Install packages not yet installed
installed_packages <- packages %in% rownames(installed.packages())

if (any(installed_packages == FALSE)) {

  if("remotes" %in% packages[!installed_packages]) {
    install.packages("remotes")
  }

  if("Rgadget" %in% packages[!installed_packages]) {
    remotes::install_github("Hafro/rgadget", upgrade = "never")
  }

  if("infuser" %in% packages[!installed_packages]) {
    remotes::install_version("infuser", "0.2.8")
  }

  if("RstoxUtils" %in% packages[!installed_packages]) {
    remotes::install_github("MikkoVihtakari/RstoxUtils")
  }
```

```
  if("RstoxStrata" %in% packages[!installed_packages]) {
    remotes::install_github("MikkoVihtakari/RstoxStrata")
  }

  installed_packages <- packages %in% rownames(installed.packages())

  install.packages(packages[!installed_packages])
}

# Packages loading
invisible(lapply(packages, library, character.only = TRUE))

rm(packages, installed_packages)

## Dplyr options

options(dplyr.summarise.inform = FALSE)

##########################
## Function shortcuts ----

h <- head

########################
## Custom functions ----

## Intervals for gadged ldist files. From:

create_intervals <- function (prefix, vect) {

  x <- structure(vect[1:(length(vect)-1)],
                 names = paste0(prefix, vect[1:(length(vect)-1)])) %>%
    as.list(.) %>%
    purrr::map(~structure(seq(.,vect[-1][which(vect[1:(length(vect)-1)]==.)],1)[
      -length(seq(.,vect[-1][which(vect[1:(length(vect)-1)]==.)],1))],
                        min = .,
                        max = vect[-1][which(vect[1:(length(vect)-1)]==.)]))

  x[[length(x)]] <- c(x[[length(x)]], attributes(x[[length(x)]])$max) %>%
    structure(.,
              min = min(.),
              max = max(.))


  return(x)
}

#' @title Back-transform predictor variables from a logit model

unlogit <- function(p, model) {
  mean <- unname((log(p/(1 - p)) - coef(model)[1])/coef(model)[2])

  tmp.cis <- suppressMessages(confint(model))
```

```
  ci.max <- unname((log(p/(1 - p)) - tmp.cis[1])/tmp.cis[2])
  ci.min <- unname((log(p/(1 - p)) - tmp.cis[3])/tmp.cis[4])

  data.frame(mean = mean, ci.min = ci.min, ci.max = ci.max)
}


### Read clipboard for Mac

read.clipboard <- function() read.table(pipe("pbpaste"), sep="\t", header=T)

### Standard error of mean

#' @title Standard error of mean
#' @param x numeric vector

se <- function (x){
  sd(x, na.rm = T)/sqrt(sum(!is.na(x)))}

### Column numbers of a data frame

#' @title Column numbers of a data frame
#' @param x data.frame
#' @return retuns a named vector with column names as names and order of columns as elements
#' @author Mikko Vihtakari

coln <- function (x)
{
  y <- rbind(seq(1, ncol(x)))
  colnames(y) <- colnames(x)
  rownames(y) <- "col.number"
  return(y)
}

### Check colors

#' @title Plot color vector to inspect the colors visually
#' @param cols a character vector containing accepted R \link[grDevices]{colors}
#' @return returns a base R plot with the colors given in \code{cols} argument
#' @author Mikko Vihtakari

check_cols <- function(cols) {

  if (is.null(names(cols))) {
    labs <- seq_along(cols)
  } else {
    labs <- paste0(names(cols), "\n[", seq_along(cols), "]")
  }

  mp <- barplot(rep(1, length(cols)), yaxt = "n", col = cols, border = NA,
                names.arg = labs, xlab = "Color sequence",  ylim = c(0,1.2))
  points(mp, rep(1.1, length(cols)), col = cols, pch = 16, cex = 4)
}
```

```r
### Select

#' @title Select an element of each vector from a list
#' @description Selects y'th element of each vector from a list
#' @param x list
#' @param y number of element. Must be integer

select.element <- function(x,y) sapply(x, "[", y)

### round_any

#' @title Round to multiple of any number
#' @param x numeric vector to round
#' @param accuracy number to round to; for POSIXct objects, a number of seconds
#' @param f rounding function: \code{\link{floor}}, \code{\link{ceiling}} or
#'  \code{\link{round}}
#' @keywords internal

round_any <- function(x, accuracy, f = round) {
  f(x / accuracy) * accuracy
}

### Font and line size conversions for ggplot2

#' @title Convert font sizes measured as points to ggplot font sizes
#' @description Converts font sizes measured as points (as given by most programs such as MS Word etc.)
#' @param x numeric vector giving the font sizes in points
#' @return Returns a numeric vector of lenght \code{x} of ggplot font sizes
#' @author Mikko Vihtakari

FS <- function(x) x/2.845276

#' @title Convert line sizes measured as points to ggplot line sizes
#' @description Converts line sizes measured as points (as given by most programs such as Adobe Illustr
#' @param x numeric vector giving the lines sizes in points
#' @return Returns a numeric vector of lenght \code{x} of ggplot line sizes
#' @author Mikko Vihtakari

LS <- function(x) x/2.13

###################
## Definitions ----

MainAreaFilter <- c(0:7, 10:18, 20:27, 30, 34:39, 50) # ICES areas 1 and 2

## Sampling types
### This part is a little hacky and can be improved. The idea was that one could directly map existing 

tmp <- c("ReferanseflatenHav", "ReferanseflatenKyst", "Forskningsfartoy",
         "Leiefartoy", "OvervakningstjenestenKommersieltFiske", "Kystvakt",
         "Provebat", "Moreforskning", "OvervakningstjenestenInnleidFartoy",
         "Landings", "Winter Survey", "Ecosystem Survey", "EggaN Survey",
         "EggaS Survey")
```

```
SamplingTypeList <- data.frame(
  id = c(2:5, 9:13, 99, 105, 106, 1016, 1025),
  name = toupper(abbreviate(tmp, minlength = 3, named = FALSE)),
  description = tmp
)

rm(tmp)

### Sizes and definitions for figures in Frontiers in Marine Science

colwidth <- 85 # mm
pagewidth <- 180 # mm
unit <- "mm"

colwidth_in <- colwidth * 0.0393701
pagewidth_in <- pagewidth * 0.0393701

### ggplot theme

theme_cust <- theme_classic(base_size = 8) %+replace%
  theme(strip.background = element_blank(),
        panel.background = element_blank(),
        plot.background = element_blank(),
        legend.background = element_blank(),
        legend.box.background = element_blank(),
        plot.margin = margin(c(5.5, 10, 5.5, 5.5)))

theme_set(theme_cust) # Set default theme globally for the entire project

####################
## Color themes ----

### Functions to lighten and darken colors, source: https://gist.github.com/Jfortin1/72ef064469d1703c6b

darken <- function(color, factor = 1.2){
  col <- col2rgb(color)
  col <- col/factor
  col <- rgb(t(col), maxColorValue = 255)
  col
}


lighten <- function(color, factor = 1.2){
  col <- col2rgb(color)
  col <- col*factor
  col[col > 255] <- 255
  col <- rgb(t(col), maxColorValue = 255)
  col
}

### Vector of standard colors

cols <- c("#D696C8", "#449BCF", "#82C893", "#FF5F68", "#FF9252", "#FFC95B", "#056A89")
```

```r
# check_cols(cols)

substock_cols <- c("ghl_female_imm" = "tomato1", "ghl_female_mat" = "tomato4",
                   "ghl_male_imm" = "dodgerblue1", "ghl_male_mat" = "dodgerblue4")
## End ----
```

9.2 Survey length, age and maturity data

```r
## ---------------------------
##
## Script name:
##
## Purpose of script: Running this script requires access to BioticExplorerServer
##
## Author: Mikko Vihtakari // Institute of Marine Research, Norway
## Email: mikko.vihtakari@hi.no
##
## Date Created: 2021-06-17
##
## ---------------------------

## Source the run first script

source("0 run first.R")

## ---------------------------

## Load packages

packages <- c("MonetDB.R", "ggOceanMaps")

# Install packages not yet installed
installed_packages <- packages %in% rownames(installed.packages())
if (any(installed_packages == FALSE)) {
  install.packages(packages[!installed_packages])
}

# Packages loading
invisible(lapply(packages, library, character.only = TRUE))

rm(packages)

## ---------------------------

## Source or list custom functions used within the script

split_fun <- function(x) {
  mean(
    c(as.numeric(gsub("[^0-9.-]", "", sapply(strsplit(as.character(x), ","), "[", 1))),
      as.numeric(gsub("[^0-9.-]", "", sapply(strsplit(as.character(x), ","), "[", 2))))
  )
}
```

```
## ---------------------------

## Load data

load("data/out/gearList.rda") # Update by running 3-1 settings.R with reset.model = TRUE
load("data/strata polygons/Ghl strata polygons.rda")

## ---------------------------

## Connect to the database

# system("monetdbd start ~/Desktop/my-dbfarm")

con_db <- DBI::dbConnect(MonetDB.R::MonetDB(), host="localhost", dbname="bioticexplorer", user="monetdb

## Create the data objects

stnall <- dplyr::tbl(con_db, "stnall")
indall <- dplyr::tbl(con_db, "indall")
ageall <- dplyr::tbl(con_db, "ageall")
mission <- dplyr::tbl(con_db, "mission")
updated <- dplyr::tbl(con_db, "metadata") %>% dplyr::pull(timestart) %>% as.Date()
csindex <- dplyr::tbl(con_db, "csindex")

## Cruise series filtering

if(exists("csindex")) {
  csList <- csindex %>%
    collect() %>%
    dplyr::select(cruiseseriescode, name) %>%
    unique() %>%
    arrange(cruiseseriescode)
} else {
  csList <- BioticExplorerServer::cruiseSeries %>%
    dplyr::select(cruiseseriescode, name) %>%
    unique() %>%
    arrange(cruiseseriescode)
}


selCS <- csList[grepl("winter|ecosystem cruise in autumn|continental", csList$name, ignore.case = TRUE)
csFilt <- selCS$cruiseseriescode

## Filter

filtExp <- paste(sapply(csFilt, function(k) {paste0("cruiseseriescode %like% '", k, ",%' | cruiseseries

sel.cols <- c("missiontype", "missionnumber", "cruiseseriescode", "startyear", "platform", "serialnumbe

## Gear overview with door spread
# stnall %>%
#   dplyr::filter(
#     !!!rlang::parse_exprs(filtExp),
```

```
#     commonname == "blåkveite",
#     gearcategory == "Bottom trawls",
#     gearcondition %in% 1:2,
#     samplequality == "1"
#   ) %>%
#   group_by(cruiseseriescode, gearname, startyear, serialnumber) %>%
#   collect() %>%
#   summarise(w = mean(trawldoorspread, na.rm = TRUE)) %>%
#   na.omit() %>%
#   group_by(cruiseseriescode, gearname) %>%
#   summarise(wmean = mean(w), sd = sd(w), n = n()) %>%
#   print(n=100)

## Individual data

x <- indall %>%
  dplyr::filter(
    !!!rlang::parse_exprs(filtExp),
    commonname == "blåkveite",
    !is.na(length),
    gearcategory == "Bottom trawls",
    samplequality == "1"
  ) %>% dplyr::select(all_of(sel.cols)) %>%
  collect() %>%
  filter(
    # area %in% MainAreaFilter,
    gearcondition %in% 1:2,
    !stationtype %in% c("C")
  )

## All age data including double readings. Required to correct a bug in the data

# y <- ageall %>%
#   dplyr::filter(
#     !!!rlang::parse_exprs(filtExp),
#     commonname == "blåkveite",
#     !is.na(length),
#     gearcategory == "Bottom trawls",
#     samplequality == "1"
#   ) %>%
#   dplyr::select(all_of(c(sel.cols, "preferredagereading", "agedeterminationid"))) %>%
#   collect() %>%
#   filter(
#     # area %in% MainAreaFilter,
#     gearcondition %in% 1:2,
#     !stationtype %in% c("C")
#   )

# x %>% filter(cruiseseriescode==6, length > 0.09) %>% mutate(size_group = cut(100*length, c(9, 17, 27,
# x %>% filter(cruiseseriescode==6, length <= 0.35) %>% qmap() + facet_wrap(~startyear)
# ggplot(x %>% mutate(rd = ifelse(is.na(readingdate), "Old", "New")), aes(age, length, color = rd, grou

x$maturationstage[x$nation %in% c(140, 90)] <- NA # Remove Russian maturity readings (they are wrong in
```

```r
x$specialstage[x$nation %in% c(140, 90)] <- NA # Remove Russian maturity readings (they are wrong in so

## Fix a bug in the database data where official readiings are "hiding under" old experimental readings

# rpl_inds <- y %>%
#   filter(preferredagereading != agedeterminationid, !is.na(readingdate)) %>%
#   mutate(id = paste(startyear,platform,serialnumber,catchpartnumber,specimenid)) %>%
#   dplyr::select(id, age, readingdate, agereader, readability)
#
# if(any(duplicated(rpl_inds$id))) stop("Replicated individuals. This hack does not work")
#
# x <- x %>%
#   mutate(id = paste(startyear,platform,serialnumber,catchpartnumber,specimenid))
#
# x[match(rpl_inds$id, x$id),]$age <- rpl_inds$age
# x[match(rpl_inds$id, x$id),]$readingdate <- rpl_inds$readingdate
# x[match(rpl_inds$id, x$id),]$agereader <- rpl_inds$agereader
# x[match(rpl_inds$id, x$id),]$readability <- rpl_inds$readability
#
# x <- x %>% dplyr::select(-id)

## Assign the age reading method

x$readingtype <-
  ifelse(is.na(x$age), NA,
         ifelse(x$agereader %in% c("KJGT","TOEL","KRWD","ROLA"), "new_qualified_reader",
                ifelse(!is.na(x$agereader), "new_other_reader",
                       ifelse(!is.na(x$readingdate), "new_unknown_reader",
                              ifelse(x$startyear >= 2007, "new_no_readingdate",
                                     ifelse(x$startyear < 2000, "old", "in_between"
                                     ))))))

# x$age[x$readability > 2 & !is.na(x$readability)] <- NA # Remove otoliths with readability worse (high
# ggFishPlots::plot_growth(x, female.sex = "1", male.sex = "2", split.by.sex = T)

# x %>% filter(cruiseseriescode == "16") %>% group_by(startyear, catchpartnumber, sex) %>% count()

# Correct maturation stage

matStages <- readxl::read_excel("Data/in/Greenland halibut maturity stages.xlsx")
ms <- na.omit(matStages[c("maturationstage", "maturationstage_becomes")])
ms[,grep("becomes", names(ms))] <- suppressWarnings(as.integer(ms[[grep("becomes", names(ms))]]))
ss <- na.omit(matStages[c("specialstage", "specialstage_becomes")])
ss[,grep("becomes", names(ss))] <- suppressWarnings(as.integer(ss[[grep("becomes", names(ss))]]))

x <- x %>% mutate(
  maturationstage =
    recode(maturationstage, !!!setNames(ms$maturationstage_becomes,
                                        ms$maturationstage)),
  specialstage =
    recode(specialstage, !!!setNames(ss$specialstage_becomes,
                                     ss$specialstage)))
```

```
x[x$maturationstage %in% "1" & is.na(x$specialstage), ]$specialstage <- 1

x[x$sex %in% "1" & !is.na(x$specialstage),]$maturationstage <- x[x$sex %in% "1" & !is.na(x$specialstage

# Find mistakes (immature > 100 cm)

# x %>% group_by(sex, maturationstage, specialstage) %>% count() %>% print(n=50)
# png("test.png", width = pagewidth, height = pagewidth*0.8, res = 300, units = "mm")
# ggplot(x, aes(x = length, y = maturationstage > 3)) + geom_point() + facet_wrap(~sex, ncol = 1)
# dev.off()

saveRDS(x, "data/out/Length raw data for surveys.rds", compress = "xz")

# Modify for MFDB

data(fdir_areas, package = "ggOceanMaps")

# Age data for EggaN, EggaS, and EcoS

aldist_surv <- x %>%
  filter(!is.na(latitudestart), !is.na(longitudestart)) %>%
  st_as_sf(coords = c("longitudestart", "latitudestart"), crs = 4326,
           remove = FALSE) %>%
  rownames_to_column("id") %>%
  st_join(strata$strata %>%
            mutate(population = paste0(geostrata.name, interval))) %>%
  filter(!duplicated(id)) %>%
  st_join(fdir_main_areas %>% mutate(areacell = as.integer(main_area))) %>%
  filter(!duplicated(id)) %>%
  st_set_geometry(NULL) %>%
  mutate(cruiseseriescode = recode(cruiseseriescode, "20,6" = "6")) %>%
  mutate(cruiseseriescode = paste0("10", cruiseseriescode)) %>%
  mutate(
    sampling_type =
      recode(cruiseseriescode,
             !!!setNames(SamplingTypeList$name, SamplingTypeList$id)),
    gear = recode(gear, !!!setNames(gearList$gearcategory, gearList$code)),
    month = ifelse(is.na(stationstartdate),
                   lubridate::month(stationstopdate),
                   lubridate::month(stationstartdate)),
    sex = ifelse(sex > 2, NA, ifelse(sex == 1, "F", "M")),
    length = 100*length + 1e-6) %>% # addition to avoid a floating point issue
  replace_na(list(population = "Outside")) %>%
  filter(!is.na(month))

age_det_surveys <- aldist_surv %>%
  dplyr::filter(!is.na(age)) %>%
  dplyr::filter(grepl("new", readingtype)) %>%
  mutate(cond = paste(sampling_type, cruise, sep = "_")) %>%
  pull(cond) %>% table

aldist_surv <- aldist_surv %>%
  mutate(cond = paste(sampling_type, cruise, sep = "_")) %>%
```

```
  filter(cond %in% names(age_det_surveys)) %>%
  replace_na(list(sex = "U")) %>%
  mutate(length_bin = cut(length, seq(0,115,5)))

# aldist_surv %>%
#   group_by(sampling_type, startyear, cruise, serialnumber, sex) %>%
#   summarise(n = sum(!is.na(length)), a = sum(!is.na(age))) %>%
#   arrange(-a)

aldist_surv <- aldist_surv %>%
  group_by(gear, sampling_type, startyear, month, areacell, population, cruise,
           serialnumber, sex, length_bin) %>%
  summarise(total = n()) %>%
  left_join(
    aldist_surv %>%
      filter(!is.na(age),
             grepl("new", readingtype)) %>%
      group_by(gear, sampling_type, startyear, cruise, sex, age, length_bin) %>%
      count() %>%
      group_by(gear, sampling_type, startyear, cruise, sex, length_bin) %>%
      mutate(aged = sum(n), pr = n/aged),
    multiple = "all"
  ) %>%
  ungroup() %>%
  mutate(est_n = ifelse(is.na(pr), total, pr * total)) %>%
  rename(year = startyear) %>%
  mutate(length = sapply(length_bin, split_fun), .before = length_bin) # this line takes 20 s

# aldist_surv <- aldist_surv %>%
#   filter(!is.na(age)) %>%
#   group_by(gear, sampling_type, startyear, month, areacell, population, cruise,
#            serialnumber, sex, readingtype, age, length_bin) %>%
#   count() %>%
#   group_by(gear, sampling_type, startyear, month, areacell, population, cruise,
#            serialnumber, sex, length_bin) %>%
#   mutate(aged = sum(n), pr = n/aged) %>%
#   arrange(sampling_type, startyear, cruise, serialnumber, sex, length_bin, age) %>%
#   left_join(
#     aldist_surv %>%
#       group_by(gear, sampling_type, startyear, month, areacell, population, cruise,
#                serialnumber, sex, length_bin) %>%
#       summarise(total = n())
#   ) %>%
#   rename(year = startyear) %>%
#   mutate(est_n = pr * total) %>%
#   mutate(length = sapply(length_bin, split_fun), .before = length_bin)

attributes(aldist_surv)$updated <- updated

saveRDS(aldist_surv, file = "data/out/Age length data for surveys.rds", compress = "xz")

# Length data for all surveys
```

```
ldist_surv <- x %>%
  filter(!is.na(latitudestart), !is.na(longitudestart)) %>%
  st_as_sf(coords = c("longitudestart", "latitudestart"), crs = 4326,
           remove = FALSE) %>%
  rownames_to_column("id") %>%
  st_join(strata$strata %>%
            mutate(population = paste0(geostrata.name, interval))) %>%
  filter(!duplicated(id)) %>%
  st_join(fdir_main_areas %>% mutate(areacell = as.integer(main_area))) %>%
  filter(!duplicated(id)) %>%
  st_set_geometry(NULL) %>%
  mutate(cruiseseriescode = recode(cruiseseriescode, "20,6" = "6")) %>%
  mutate(cruiseseriescode = paste0("10", cruiseseriescode)) %>%
  mutate(
    sampling_type =
      recode(cruiseseriescode,
             !!!setNames(SamplingTypeList$name, SamplingTypeList$id)),
    gear = recode(gear, !!!setNames(gearList$gearcategory, gearList$code)),
    month = ifelse(is.na(stationstartdate),
                   lubridate::month(stationstopdate),
                   lubridate::month(stationstartdate)),
    sex = ifelse(sex > 2, NA, ifelse(sex == 1, "F", "M")),
    length = 100*length + 1e-6) %>% # addition to avoid a floating point issue
  replace_na(list(population = "Outside")) %>%
  filter(!is.na(month)) %>%
  rename(year = startyear, weight = individualweight, maturity_stage = maturationstage) %>%
  select(gear, sampling_type, year, month, areacell, population, age,
         readability, readingtype, sex, maturity_stage, length, weight)

attributes(ldist_surv)$updated <- updated

## Save

saveRDS(ldist_surv, file = "data/out/Length data for surveys.rds", compress = "xz")
```

9.3 Catches

Read the AFWG Table 8.7:

```
## ---------------------------
##
## Script name: Read the AFWG table 8.7 from an Excel file
##
## Author: Mikko Vihtakari // Institute of Marine Research, Norway
## Email: mikko.vihtakari@hi.no
##
## ---------------------------

## Source the run first script

source("0 run first.R")

## ---------------------------
```

```
## Process historical data

tmp <- readxl::read_excel("data/in/catches/AFWG_2022_tables.xlsx", "8.7")

colindex <- list(start = which(tmp[1,] == "Year"), end = which(tmp[1,] == "Total"))

out <- lapply(1:2, function(i) {
  dt <- tmp[-1, select.element(colindex, i)[1]:select.element(colindex, i)[2]]
  names(dt) <- as.character(tmp[1, select.element(colindex, i)[1]:select.element(colindex, i)[2]])
  dt
})

out <- do.call(rbind, out)
out <- out[apply(out[2:5], 1, function(x) sum(is.na(x))) != 4,]
out$Year <- as.integer(gsub("\\*", "", out$Year))
out[2:5] <- lapply(out[2:5], as.numeric)
out$Total <- rowSums(out[2:4], na.rm = TRUE)

## Save

saveRDS(out, file = "data/out/AFWG table 8-7 historic catches.rds", compress = "xz")
```

Read Norwegian catches:

```
## ---------------------------
##
## Script name: Download Norwegian catches of NEA Greenland halibut
##
## Purpose of script: Downloads Norwegian catches from the IMR database
##
## Author: Mikko Vihtakari // Institute of Marine Research, Norway
## Email: mikko.vihtakari@hi.no
##
## ---------------------------

## Source the run first script

source("0 run first.R")

## ---------------------------

## Load packages

library(RstoxUtils) # From remotes::install_github("MikkoVihtakari/RstoxUtils")
library(lubridate)

## Gearl list

source("R/gears2MFDB.R")
gearList <- try(gears2MFDB("data/in/Kodeliste_landing_20210326.xlsx"), silent = TRUE)
if(any(class(gearList) == "try-error")) {load("data/out/gearList.rda")}


###########################################
```

```
## Catches (2005->) from the database ####
##########################################

# Untick for a fresh download, takes 10-30 min. Requires intranet connection.
# lnd <- RstoxUtils::downloadLandings("Blåkveite")
# save(lnd, file = paste0("data/in/", as.Date(Sys.time()), " NMD catches.rda"), compress = "xz")

load("data/in/2023-01-11 NMD catches.rda")

x <- lnd$Produkt[, c("Fangstår", "SisteFangstdato", "Redskap_kode",
                     "Hovedområde_kode", "Lokasjon_kode", "Fartøynasjonalitet_kode",
                     "Rundvekt"),
                 with = FALSE]
names(x) <- c("year", "date", "gear_id", "main_area", "sub_area", "nation", "mass")
x$date <- as.Date(x$date, format = "%d.%m.%Y")
x <- x %>%
  add_column(month = lubridate::month(.$date), .before = "date") %>%
  mutate_at(vars(main_area, sub_area), as.integer)
x <- x[!is.na(x$mass) & x$mass > 0,]

#########################
## Catches 1977-2005 ####
#########################

y <- RstoxUtils::readSluttseddelXLS(
  species = "Blåkveite",
  dataDir = "../../../Data/Landings data/sluttseddel_xls_ferdige_År/")
y <- y[y$year < 2005,]

y <- y %>%
  select(-ices_area, -gear_category, -gear) %>%
  add_column(date = NA, .before = "main_area") %>%
  add_column(nation = "NOR", .before = "mass") %>%
  mutate_at(vars(main_area), function(x) as.integer(as.character(x)))

#############
## Merge ####
#############

catchIMR <- rbind(as_tibble(x), as_tibble(y)) %>%
  arrange(year, month, main_area, sub_area, gear_id) %>%
  filter(main_area %in% MainAreaFilter) %>%
  mutate(gear_cat = substr(gear_id, 1, 1),
         gear = recode(gear_id, !!!setNames(gearList$gearcategory, gearList$code))) %>%
  mutate_at(vars(nation), factor)

## Save

saveRDS(catchIMR, file = "data/out/Catches from IMR database.rds", compress = "xz")
```

Read Russian catches:

```
## ---------------------------
##
```

```r
## Script name: Read Russian catches from a csv file
##
## Author: Mikko Vihtakari // Institute of Marine Research, Norway
## Email: mikko.vihtakari@hi.no
##
## ---------------------------

## Source the run first script

source("0 run first.R")

## Read data

dt <- read_csv2("data/in/catches/Russian catches 1984-2021.csv")

## ---------------------------

dt <- dt %>%
  dplyr::select(Year, Quarter, Gear, Total) %>%
  dplyr::rename("year" = "Year", "step" = "Quarter", "gear" = "Gear", "value" = "Total") %>%
  dplyr::mutate(step = as.integer(as.roman(step))) %>%
  dplyr::mutate(area = 1, .before = "value") %>%
  dplyr::arrange(year, step, gear, area)

trawl_ru <- dt %>% filter(gear == "trawl")
other_ru <- dt %>% filter(gear == "long line")

catch_rus <- dt

save(catch_rus, trawl_ru, other_ru, file = "data/out/Russian catches.rda", compress = "xz")
```

Read international catches:

```r
int_landings <-
  read.csv2("data/in/catches/AFWG2022_Int_landings.csv",header=T) %>%
  select(-Norway,-Russia,-Total)
```

9.3.1 To and from MMFDB

The database is set up to a schema called "ghl". The script below documents the current export process.

```r
## ---------------------------
##
## Script name: Export NEA Greenland halibut data to MFDB
##
## Purpose of script: The database contains all data used in the assessment
##
## Author: Mikko Vihtakari // Institute of Marine Research, Norway
## Email: mikko.vihtakari@hi.no
##
## ---------------------------

## Source the run first script

source("0 run first.R")
```

```
## ---------------------------

## Load packages

library("RstoxUtils")

## ---------------------------

## Source or list custom functions used within the script

source("R/gears2MFDB.R")
gearList <- try(gears2MFDB("data/in/Kodeliste_landing_20210326.xlsx"), silent = TRUE)
if(any(class(gearList) == "try-error")) {load("data/out/gearList.rda")}

## ---------------------------

## Read data

ldist_land <- readRDS("data/out/Length data for catches.rds")
ldist_surv <- readRDS("data/out/Length data for surveys.rds")

### Datasets are read close to where they are needed to make it clearer from which file the data come f:

## ---------------------------

## Definitions and checks

year_range <- 1935:2022

## Strata filtering, disabled from here and moved to when reading data
EggaN_strata <- c("C500-700", "C700-1000", "D500-700", "D700-1000","E500-700", "E700-1000", "F500-700",
BESS_strata <- "^0|^X" ## Negate

# Set up the database

# Duckdb:
mfdb(schema_name = "data/mfdb/ghl.duckdb", destroy_schema = TRUE)
mdb <- mfdb("data/mfdb/ghl.duckdb")

# Postgresql:
# mfdb("ghl", destroy_schema = TRUE) # Delete the database for a fresh start
# mdb <- mfdb("ghl")

## Areas

dt <- data.frame(
  id = RstoxUtils::fishingAreasNor@data$FID,
  name = RstoxUtils::fishingAreasNor@data$FID,
  division =
    ifelse(RstoxUtils::fishingAreasNor@data$FID %in% MainAreaFilter, "AFWG", "Out")
)

mfdb_import_area(mdb, dt)
```

```
# tbl(mdb$db,"areacell") %>% collect %>% View

## Sampling types (created in 0 run first.R)

mfdb_import_sampling_type(mdb, SamplingTypeList)

# tbl(mdb$db,"sampling_type") %>% collect %>% View

## Gears

mfdb_empty_taxonomy(mdb, "gear")

# tmp <- RstoxUtils::FDIRcodes$gearCodes[grepl("^\\d0$", RstoxUtils::FDIRcodes$gearCodes$idGear),]
# tmp <- tmp[!duplicated(tmp$gearCategory),]
# tmp <- setNames(tmp$idGear, tmp$gearCategory)
#
# gear_codes <- RstoxUtils::FDIRcodes$gearCodes %>%
#   rename("name" = "idGear", "description" = "gearName", "t_group" = "gearCategory") %>%
#   mutate(t_group = recode(as.factor(.$t_group), !!!tmp))
#
# gear_codes <- tibble(name = 0, description = "Added historical data", t_group = 0) %>%
#   bind_rows(gear_codes)

gear_codes <- gearList %>%
  dplyr::select(gearcategory, majorcategory) %>%
  distinct() %>%
  arrange(majorcategory) %>%
  rename(name = gearcategory, t_group = majorcategory)

tmp <- unique(gear_codes$t_group)[!unique(gear_codes$t_group) %in% gear_codes$name]

gear_codes <- bind_rows(gear_codes, data.frame(name = tmp, t_group = tmp)) %>% arrange(t_group, name)
gear_codes <- bind_rows(tibble::tibble(name = "HistoricalData", t_group = "HistoricalData"), gear_codes

mfdb_import_gear_taxonomy(mdb, gear_codes)

# tbl(mdb$db,"gear") %>% collect %>% print(n=40)
# DBI::dbListTables(mdb$db)

## Strata (called populations because that's the only valid option, see: https://gadget-framework.githu

tmp <- sort(unique(c(ldist_land$population, ldist_surv$population)))

tmp <- tibble(name = tmp,
              description = "IMR Greenland halibut survey strata",
              t_group = ifelse(tmp %in% EggaN_strata, "EggaN & BESS",
                               ifelse(!grepl("(^O|^X)", tmp), "BESS", "None"))
)

mfdb_import_population_taxonomy(mdb, tmp)

rm(tmp)
```

```
## Maturity scales

#################
# Export data ###

#######################################
## Length distribution for landings ###

mfdb_import_survey(
  mdb,
  ldist_land %>% dplyr::select(-readability, -readingtype),
  data_source = "ldist-catches-NOR")

rm(ldist_land)

#######################################
## Length distributions for surveys ###

mfdb_import_survey(
  mdb,
  ldist_surv %>% dplyr::select(-readability, -readingtype),
  data_source = "ldist-surveys-NOR")

rm(ldist_surv)

#####################
## Survey indices ###

## Strata system as "population", https://gadget-framework.github.io/mfdb/articles/population.html
#
# tmp <- tibble(geostrata = LETTERS[1:15]) %>%
#   expand(
#     nesting(geostrata),
#     interval = c("100-300", "300-400", "400-500", "500-700", "700-1000", "1000-1500")) %>%
#   mutate(name = paste0(geostrata, interval))
#
# mfdb_import_population_taxonomy(
#   mdb,
#   data.table(name = tmp$name, description = tmp$name, t_group = "Strata")
# )
#
# rm(tmp)

## EggaN (Norwegian slope survey)

load("data/out/EggaN survey index data.rda")

dt <- data.table::rbindlist(lapply(EggaN, function(k) k$station_length)) %>%
  # filter(Stratum %in% EggaN_strata) %>%
  mutate(areacell = RstoxUtils::pointOnFishingArea(Longitude, Latitude),
         month = 9,
         Biomass = Biomass/1e3) %>% # Biomass index to kg
  rename(weight = Biomass,
```

```
         count = Abundance,
         length = IndividualTotalLength,
         sex = IndividualSex,
         population = Stratum) %>%
  dplyr::select(year, month, areacell, population, sex, length, weight, count)

### Biomass index

mfdb_import_survey(mdb,dt %>% dplyr::select(-count), data_source = "EggaN-index-biomass")

### Abundance index

mfdb_import_survey(mdb,dt %>% dplyr::select(-weight), data_source = "EggaN-index-abundance")

rm(EggaN)

## BESS (Barents Sea Ecosystem Survey)

load("data/out/Ecosystem survey index data.rda")

dt <- data.table::rbindlist(lapply(BESS, function(k) k$station_length)) %>%
  # filter(!grepl(BESS_strata, Stratum)) %>%
  mutate(areacell = RstoxUtils::pointOnFishingArea(Longitude, Latitude),
         month = 9,
         Biomass = Biomass/1e3) %>% # Biomass index to kg
  rename(weight = Biomass,
         count = Abundance,
         length = IndividualTotalLength,
         sex = IndividualSex,
         population = Stratum) %>%
  dplyr::select(year, month, areacell, population, sex, length, weight, count)

### Biomass index

mfdb_import_survey(mdb,dt %>% dplyr::select(-count), data_source = "BESS-index-biomass")

### Abundance index

mfdb_import_survey(mdb,dt %>% dplyr::select(-weight), data_source = "BESS-index-abundance")

rm(BESS)

##############
## Catches ###

### Norwegian catches

landings <- readr::read_rds("data/out/Catches from IMR database.rds")

dt <- landings %>%
  filter(nation == "NOR") %>%
  dplyr::select(-date, -gear_cat, -nation, -sub_area, -gear_cat, -gear_id) %>%
  rename(areacell = main_area, weight_total = mass) %>%
```

```
  mutate(sampling_type = "LND", institute = "NOR")

mfdb_import_survey(mdb, dt, data_source = "catches-NOR")

### Russian catches

load("data/out/Russian catches.rda")

dt <- catch_rus %>%
  filter(gear == "long line") %>%
  mutate(step = recode(step, "1" = "1", "2" = "4", "3" = "7", "4" = "10")) %>%
  rename(areacell = area, weight_total = value, month = step) %>%
  mutate(areacell = 14, gear = "Longlines", sampling_type = "LND", weight_total = weight_total*1e3, ins

mfdb_import_survey(mdb, dt, data_source = "OTH-catches-RUS")

dt <- catch_rus %>%
  filter(gear == "trawl") %>%
  mutate(step = recode(step, "1" = "1", "2" = "4", "3" = "7", "4" = "10")) %>%
  rename(areacell = area, weight_total = value, month = step) %>%
  mutate(areacell = 14, gear = "BottomTrawls", sampling_type = "LND", weight_total = weight_total*1e3,

mfdb_import_survey(mdb, dt, data_source = "TRW-catches-RUS")

### Historical catches

hist_land <- readr::read_rds("data/out/AFWG table 8-7 historic catches.rds")

dt <- hist_land %>%
  rename(year = Year) %>%
  filter(year < 1977) %>%
  mutate(weight_total = 1e3*Norway) %>%
  select(-Norway, -Russia, -Others, -Total) %>%
  mutate(month = 6, areacell = 26, gear = "HistoricalData", sampling_type = "LND", institute = "NOR") %
  na.omit()

mfdb_import_survey(mdb, dt, data_source = "HIST-catches-NOR")

dt <- hist_land %>%
  rename(year = Year) %>%
  filter(year < 1992) %>%
  mutate(weight_total = 1e3*Russia) %>%
  select(-Norway, -Russia, -Others, -Total) %>%
  mutate(month = 6, areacell = 26, gear = "HistoricalData", sampling_type = "LND", institute = "RUS") %
  na.omit()

mfdb_import_survey(mdb, dt, data_source = "HIST-catches-RUS")

dt <- hist_land %>%
  rename(year = Year) %>%
  mutate(weight_total = 1e3*Others) %>%
  select(-Norway, -Russia, -Others, -Total) %>%
  mutate(month = 6, areacell = 26, gear = "HistoricalData", sampling_type = "LND") %>%
```

```
  na.omit()

mfdb_import_survey(mdb, dt, data_source = "HIST-catches-INT")

# tbl(mdb$db,"survey_index") %>% collect()

#############################################
# Check that data are exported correctly ####
#############################################

## The truth table ####

tmp <- hist_land %>%
  rename(year = Year) %>%
  filter(year < 1977) %>%
  mutate(HistNor = 1e3*Norway) %>%
  select(-Norway, -Russia, -Others, -Total)

tmp2 <- landings %>%
  filter(nation == "NOR" & grepl("^1\\d|^5\\d|61", gear_id)) %>%
  group_by(year) %>%
  summarise(TrawlNor = sum(mass))

tmp <- merge(tmp, tmp2, all = TRUE)

tmp2 <- landings %>%
  filter(nation == "NOR" & !grepl("^1\\d|^5\\d|61", gear_id)) %>%
  group_by(year) %>%
  summarise(OtherNor = sum(mass))

tmp <- merge(tmp, tmp2, all = TRUE)

tmp2 <- hist_land %>%
  rename(year = Year) %>%
  filter(year < 1992) %>%
  mutate(HistRus = 1e3*Russia) %>%
  select(-Norway, -Russia, -Others, -Total)

tmp <- merge(tmp, tmp2, all = TRUE)

tmp2 <- other_ru %>%
  group_by(year) %>%
  summarise(OtherRus = sum(value)*1e3)

tmp <- merge(tmp, tmp2, all = TRUE)

tmp2 <- trawl_ru %>%
  group_by(year) %>%
  summarise(TrawlRus = sum(value)*1e3)

tmp <- merge(tmp, tmp2, all = TRUE)

tmp2 <- hist_land %>%
```

```
  rename(year = Year) %>%
  mutate(HistInt = 1e3*Others) %>%
  select(-Norway, -Russia, -Others, -Total)

truth_tab <- merge(tmp, tmp2, all = TRUE)

## MFDB table ####

### HistNor

tmp2 <- mfdb_sample_totalweight(mdb = mdb, cols = NULL,
                                params = list(data_source = "HIST-catches-NOR",
                                              year = year_range
                                )
)

tmp <- data.frame(year = tmp2[[1]]$year, HistNor = tmp2[[1]]$total_weight)

### TrawlNor

tmp2 <- mfdb_sample_totalweight(mdb = mdb, cols = NULL,
                                params = list(gear = c("Trawls", "Seines"),
                                              sampling_type = "LND",
                                              year = year_range,
                                              institute = "NOR"
                                )
)

tmp <- merge(tmp, data.frame(year = tmp2[[1]]$year, TrawlNor = tmp2[[1]]$total_weight), all = TRUE)

### OtherNor

tmp2 <- mfdb_sample_totalweight(mdb = mdb, cols = NULL,
                                params =
                                  list(gear =
                                         grep("Trawls|Seines|Historical",
                                              tbl(mdb$db,"gear") %>% select(name) %>% pull(),
                                              invert = TRUE, value = TRUE),
                                       sampling_type = "LND",
                                       year = year_range,
                                       institute = "NOR"
                                  )
)

tmp <- merge(tmp, data.frame(year = tmp2[[1]]$year, OtherNor = tmp2[[1]]$total_weight), all = TRUE)

### HistRus

tmp2 <- mfdb_sample_totalweight(mdb = mdb, cols = NULL,
                                params = list(data_source = "HIST-catches-RUS",
                                              year = year_range
                                )
)
```

```
tmp <- merge(tmp, data.frame(year = tmp2[[1]]$year, HistRus = tmp2[[1]]$total_weight), all = TRUE)

### TrawlRus

tmp2 <- mfdb_sample_totalweight(mdb = mdb, cols = NULL,
                                params = list(data_source = "TRW-catches-RUS",
                                              sampling_type = "LND",
                                              year = year_range,
                                              institute = "RUS"
                                )
)

tmp <- merge(tmp, data.frame(year = tmp2[[1]]$year, TrawlRus = tmp2[[1]]$total_weight), all = TRUE)

### OtherRus

tmp2 <- mfdb_sample_totalweight(mdb = mdb, cols = NULL,
                                params =
                                  list(data_source = "OTH-catches-RUS",
                                       sampling_type = "LND",
                                       year = year_range,
                                       institute = "RUS"
                                  )
)

tmp <- merge(tmp, data.frame(year = tmp2[[1]]$year, OtherRus = tmp2[[1]]$total_weight), all = TRUE)

### HistInt

tmp2 <- mfdb_sample_totalweight(mdb = mdb, cols = NULL,
                                params = list(data_source = "HIST-catches-INT",
                                              year = year_range
                                )
)

mfdb_tab <- merge(tmp, data.frame(year = tmp2[[1]]$year, HistInt = tmp2[[1]]$total_weight), all = TRUE)

## Compare ####
# i = names(truth_tab)[3]
tmp <- lapply(names(truth_tab), function(i) {
  out <- all.equal(truth_tab[[i]], mfdb_tab[[i]])

  if(!isTRUE(out)) {
    truth_tab[[i]] - mfdb_tab[[i]]
  } else {
    out
  }
})
names(tmp) <- names(truth_tab)

if(all(unlist(tmp))) {
  message("Correct!")
} else {
```

```
  warning("Not so correct. Check!")
}

## Scrap but useful code ####

# mfdb_dplyr_sample(mdb) %>%
#   filter(grepl("^1|^5|61", gear) & sampling_type == "LND") %>%
#   group_by(year) %>%
#   summarise(total_weight = sum(weight)) %>%
#   collect() %>%
#   arrange(year)
#
#
# tmp <- fishingAreasNor[fishingAreasNor@data$FID %in% MainAreaFilter,]
# labels <- sp::SpatialPointsDataFrame(rgeos::gCentroid(tmp, byid=TRUE),
#                                       data = tmp@data)
# labels <- ggspatial::df_spatial(labels)
#
# ggOceanMaps::basemap(limits = raster::extent(tmp)[1:4]) +
#   ggspatial::annotation_spatial(tmp, fill = NA, color = "blue") +
#   ggspatial::geom_spatial_text(data = labels, aes(x = x, y = y, label = FID),
#                                size = FS(8), fontface = 2, color = "blue")
```

Once the data are exported to MFDB, they can be acquired ready to be used when setting up fleets for the Gadget model:

```
## ---------------------------
##
## Script name: Catches
##
## Purpose of script: Load catch data from MFDB
##
## ---------------------------

if(reload_data) {

  ## Source or list custom functions used within the script

  source("R/figure_functions.R")

  ## ---------------------------

  ## Read data

  ## ---------------------------

  # TrawlNor ####

  if(min(model_params$year_range) < 1977) {
    stop("Add splitting historic Norwegian catches to gear. See the Catch data document")
  } else {
    TrawlNor_catches <- mfdb_sample_totalweight(
      mdb = mdb, cols = NULL,
      params = list(gear = c("Trawls", "Seines"),
```

```
                    sampling_type = "LND",
                    year = model_params$year_range,
                    institute = "NOR",
                    timestep = model_params$timestep_fun
    )
  )[[1]]
}

png(file.path(base_dir, "figures/TrawlNor_catches.png"), width = pagewidth, height = pagewidth*0.7, u
print(plot.catches(TrawlNor_catches))
dev.off()

# OtherNor ####

if(min(model_params$year_range) < 1977) {
  stop("Add splitting historic Norwegian catches to gear. See the Catch data document")
} else {
  OtherNor_catches <- mfdb_sample_totalweight(
    mdb = mdb, cols = NULL,
    params =
      list(gear =
             grep("Trawls|Seines|Historical",
                  tbl(mdb$db,"gear") %>% select(name) %>% pull(),
                  invert = TRUE, value = TRUE),
             sampling_type = "LND",
             year = model_params$year_range,
             institute = "NOR",
             timestep = model_params$timestep_fun
      )
  )[[1]]
}

png(file.path(base_dir, "figures/OtherNor_catches.png"), width = pagewidth, height = pagewidth*0.7, u
print(plot.catches(OtherNor_catches))
dev.off()

# TrawlRus ####

if(min(model_params$year_range) < 1991) {

  TrawlRus <- mfdb_sample_totalweight(
    mdb = mdb, cols = NULL,
    params = list(data_source = "TRW-catches-RUS",
                  sampling_type = "LND",
                  year = model_params$year_range,
                  institute = "RUS",
                  timestep = model_params$timestep_fun
    )
  )[[1]]

  OtherRus <- mfdb_sample_totalweight(
    mdb = mdb, cols = NULL,
    params =
```

```
    list(data_source = "OTH-catches-RUS",
         sampling_type = "LND",
         year = model_params$year_range,
         institute = "RUS",
         timestep = model_params$timestep_fun
    )
  )[[1]]

  ## Split factor
  split_fac <- full_join(
    TrawlRus %>% rename("TrawlRus" = "total_weight"),
    OtherRus %>% rename("OtherRus" = "total_weight"),
    by = c("year", "step", "area")) %>%
    filter(year < 2001, year > 1990) %>%
    mutate(prop = OtherRus/(TrawlRus+OtherRus)) %>%
    pull(prop) %>%
    mean()

  # HistRus ####

  HistRus <- mfdb_sample_totalweight(
    mdb = mdb, cols = NULL,
    params = list(data_source = "HIST-catches-RUS",
                  year = model_params$year_range,
                  timestep = model_params$timestep_fun
    )
  )[[1]] %>%
    filter(year < 1991) %>%
    mutate(TrawlRus = (1-split_fac)*total_weight,
           OtherRus = split_fac*total_weight) %>%
    dplyr::select(year, step, area, TrawlRus, OtherRus) %>%
    na.omit()

  # TrawlRus ####

  TrawlRus_catches <- bind_rows(
    HistRus %>% dplyr::select(-OtherRus) %>% rename("total_weight" = "TrawlRus"),
    TrawlRus %>% filter(year > 1990)
  )

  # OtherRus ####

  OtherRus_catches <- bind_rows(
    HistRus %>% dplyr::select(-TrawlRus) %>% rename("total_weight" = "OtherRus"),
    OtherRus %>% filter(year > 1990)
  )

  rm(HistRus, TrawlRus, OtherRus, split_fac)

} else {

  TrawlRus_catches <- mfdb_sample_totalweight(
    mdb = mdb, cols = NULL,
```

```
    params = list(data_source = "TRW-catches-RUS",
                  sampling_type = "LND",
                  year = model_params$year_range,
                  institute = "RUS",
                  timestep = model_params$timestep_fun
    )
  )[[1]]

  # OtherRus ####

  OtherRus_catches <- mfdb_sample_totalweight(
    mdb = mdb, cols = NULL,
    params =
      list(data_source = "OTH-catches-RUS",
           sampling_type = "LND",
           year = model_params$year_range,
           institute = "RUS",
           timestep = model_params$timestep_fun
      )
  )[[1]]
}


png(file.path(base_dir, "figures/TrawlRus_catches.png"), width = pagewidth, height = pagewidth*0.7, u
print(plot.catches(TrawlRus_catches))
dev.off()

png(file.path(base_dir, "figures/OtherRus_catches.png"), width = pagewidth, height = pagewidth*0.7, u
print(plot.catches(OtherRus_catches))
dev.off()

# International catches ####

Internat_catches <- mfdb_sample_totalweight(
  mdb = mdb, cols = NULL,
  params = list(data_source = "HIST-catches-INT",
                year = model_params$year_range,
                timestep = model_params$timestep_fun
  )
)[[1]]

png(file.path(base_dir, "figures/Internat_catches.png"), width = pagewidth, height = pagewidth*0.7, u
print(plot.catches(Internat_catches))
dev.off()

# Survey dummy catches ####

if(!exists("EggaN_ldist")) source("2-3 catch distribution.R")

EggaN_catches <- structure(
  data.frame(
    year = unique(EggaN_ldist$year), step = 1, area = 1, total_weight = 1),
  area_group = mfdb_group(`1` = 1))
```

```
png(file.path(base_dir, "figures/EggaN_catches.png"), width = pagewidth, height = pagewidth*0.7, unit
print(plot.catches(EggaN_catches))
dev.off()

EggaS_catches <- structure(
  data.frame(
    year = unique(EggaS_ldist$year), step = 1, area = 1, total_weight = 1),
  area_group = mfdb_group(`1` = 1))

png(file.path(base_dir, "figures/EggaS_catches.png"), width = pagewidth, height = pagewidth*0.7, unit
print(plot.catches(EggaS_catches))
dev.off()

EcoS_catches <- structure(
  data.frame(
    year = unique(EcoS_ldist$year), step = 1, area = 1, total_weight = 1),
  area_group = mfdb_group(`1` = 1))

png(file.path(base_dir, "figures/EcoS_catches.png"), width = pagewidth, height = pagewidth*0.7, units
print(plot.catches(EcoS_catches))
dev.off()

WinterS_catches <- structure(
  data.frame(
    year = unique(WinterS_ldist$year), step = 1, area = 1, total_weight = 1),
  area_group = mfdb_group(`1` = 1))

png(file.path(base_dir, "figures/WinterS_catches.png"), width = pagewidth, height = pagewidth*0.7, un
print(plot.catches(WinterS_catches))
dev.off()

RussianS_catches <- structure(
  data.frame(
    year = unique(RussianS_ldist$year), step = 1, area = 1, total_weight = 1),
  area_group = mfdb_group(`1` = 1))

png(file.path(base_dir, "figures/RussianS_catches.png"), width = pagewidth, height = pagewidth*0.7, u
print(plot.catches(RussianS_catches))
dev.off()

if(use_cheat_fleet) {
Cheat_catches <- structure(
  data.frame(
    year = unique(Cheat_mat$year), step = 1, area = 1, total_weight = 1),
  area_group = mfdb_group(`1` = 1))

png(file.path(base_dir, "figures/Cheat_catches.png"), width = pagewidth, height = pagewidth*0.7, unit
print(plot.catches(Cheat_catches))
dev.off()
}

## All catches
```

```
  png(file.path(base_dir, "figures/All_catches.png"), width = pagewidth, height = pagewidth*0.7, units =
  print(plot.catches(list("TrawlNor" = TrawlNor_catches,
                          "OtherNor" = OtherNor_catches,
                          "TrawlRus" = TrawlRus_catches,
                          "OtherRus" = OtherRus_catches,
                          "Internat" = Internat_catches)) +
    # ggplot2::guides(fill=ggplot2::guide_legend(nrow=2,byrow=TRUE)) +
    ggplot2::theme(legend.position = "bottom"))
  dev.off()

  # Save

  # save(TrawlNor_catches, OtherNor_catches, TrawlRus_catches, OtherRus_catches, Internat_catches, Egga


  # !reload_data case
} else {
  load(file.path(base_dir, "data/Catches to Gadget.rda"))
}
```

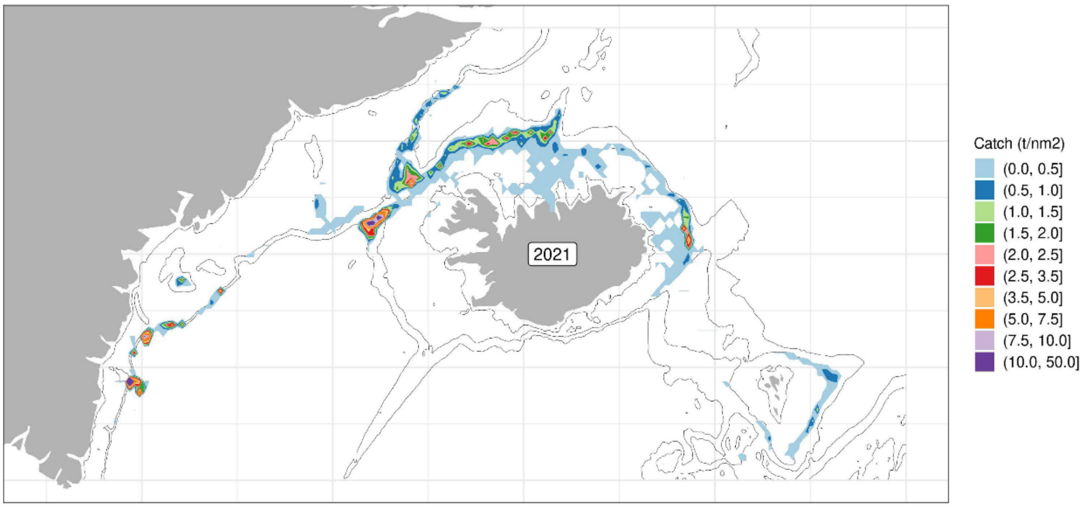
Greenland halibut in 5, 6, 12 and 14: Overview of available data

Stock ID and sub-stock structure

Greenland halibut in ICES Subareas 5, 6, 12 and 14 (East-Greenland, Iceland, Faroe-islands) are assessed as one stock.

In Icelandic waters, it is found on the continental shelf around Iceland with the highest abundance west, north and east off the coast in deeper and colder waters. It is mainly found on a muddy substrate at depths ranging from 200-1500 m. The main spawning grounds are located west off the coast at around 1000 m depth and eggs and larvae drift between Iceland and the east coast of Greenland until juveniles seek bottom post metamorphosis. After spawning, Greenland halibut migrates further north and east to their main feeding grounds. No juvenile grounds are known within the assessment area, and substantial migration is known to occur from adjacent management units (Vihtakari et. al 2022).

In the water East of Greenland it mainly found at depths greater than 600 m on the steep continental slope where as in the Faroes it is mainly found North and East of the islands at 200 to 600 m.



Greenland halibut. Catch distribution in 2021

Issue list

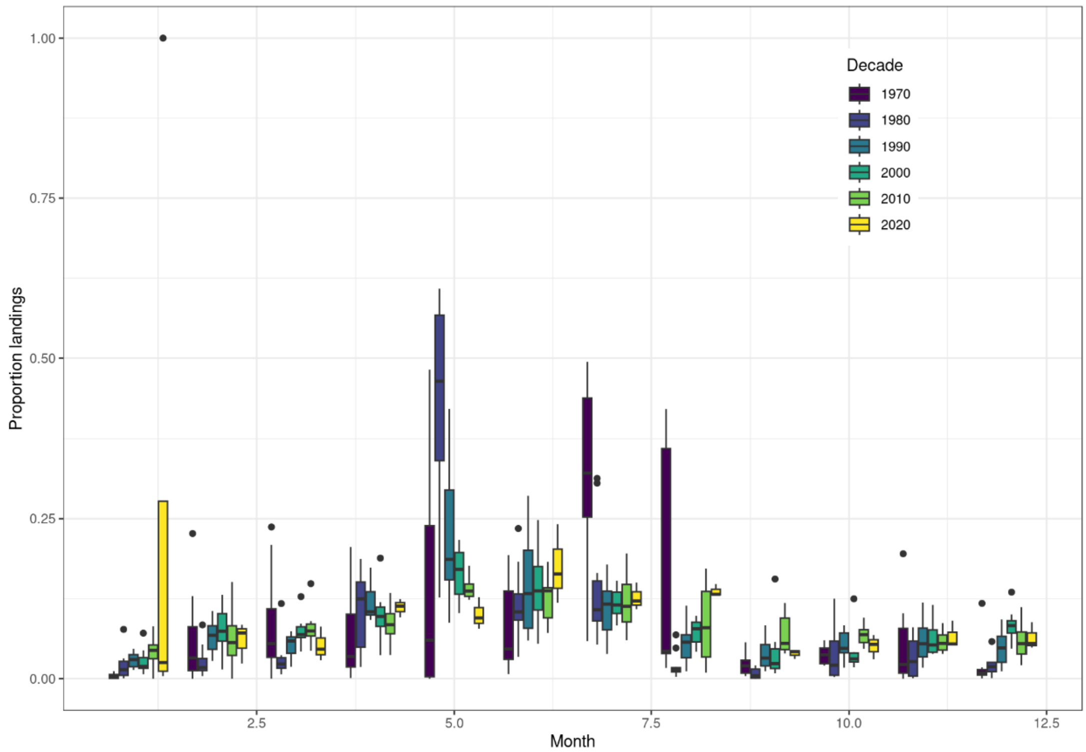
- Update the assessment method, currently a Bayesian surplus production model is used to assess the stock.
- CPUE series used as the basis for the assessment is no longer considered representative of the stock dynamics
- Add age data from Iceland and Greenland. Aging methodology has been revised and prior age analysis is assumed to be incorrect.
- Include data on catch composition from all fishery operations.
- Stock structure is uncertain.

Scorecard on data quality

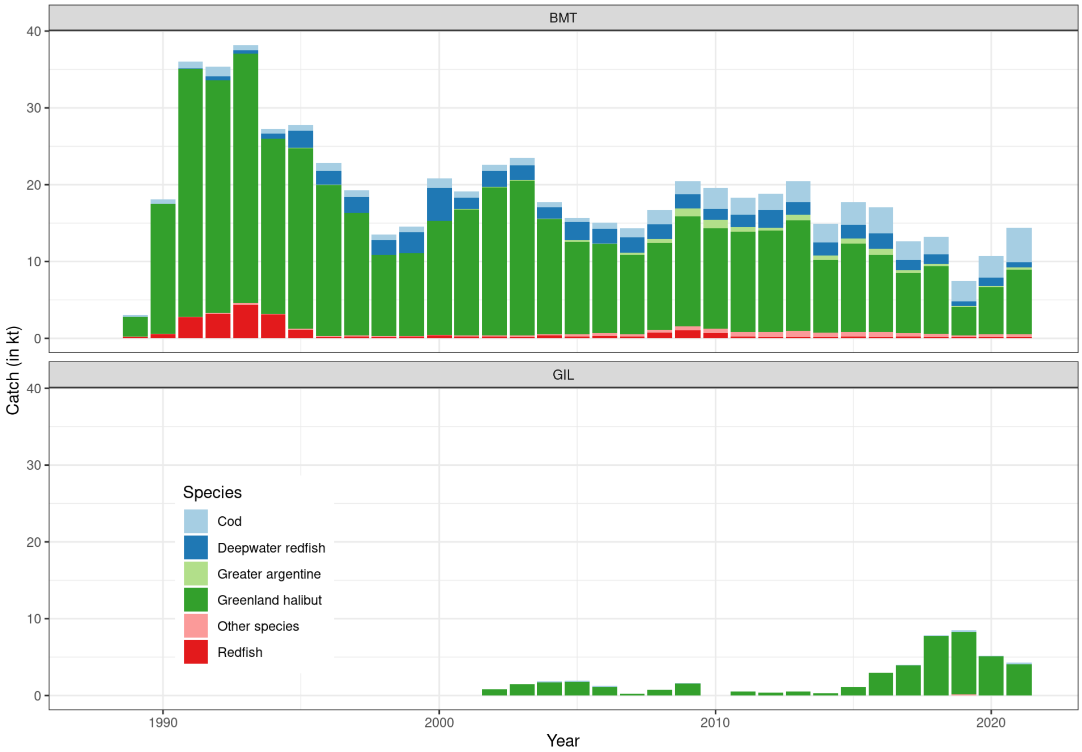
Not used

Multispecies, mixed fisheries issues

The fishery in Icelandic waters started in the 1960s, and it is believed to have been fairly targeted and seasonal in the beginning (see **?@fig-landing_season**). Changes in the fishing practices in recent years in Icelandic waters has lead targeting of species mixtures and effort that is more evenly distributed through the year (fig. **?@fig-landing_season** and **?@fig-catchcomp**). This temporal trend is evident in the halibut fisheries while most of the hauls recorded in the logbooks suggest that the halibut fairly targeted. The main bycatch species are cod and deep water redfish.

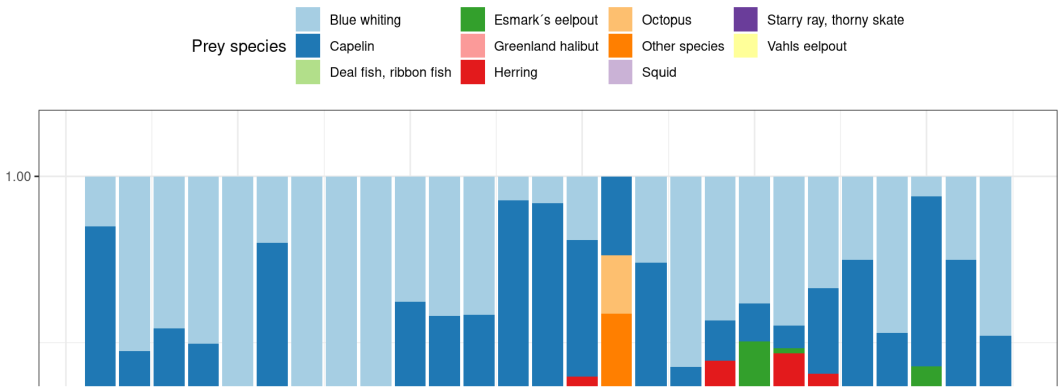


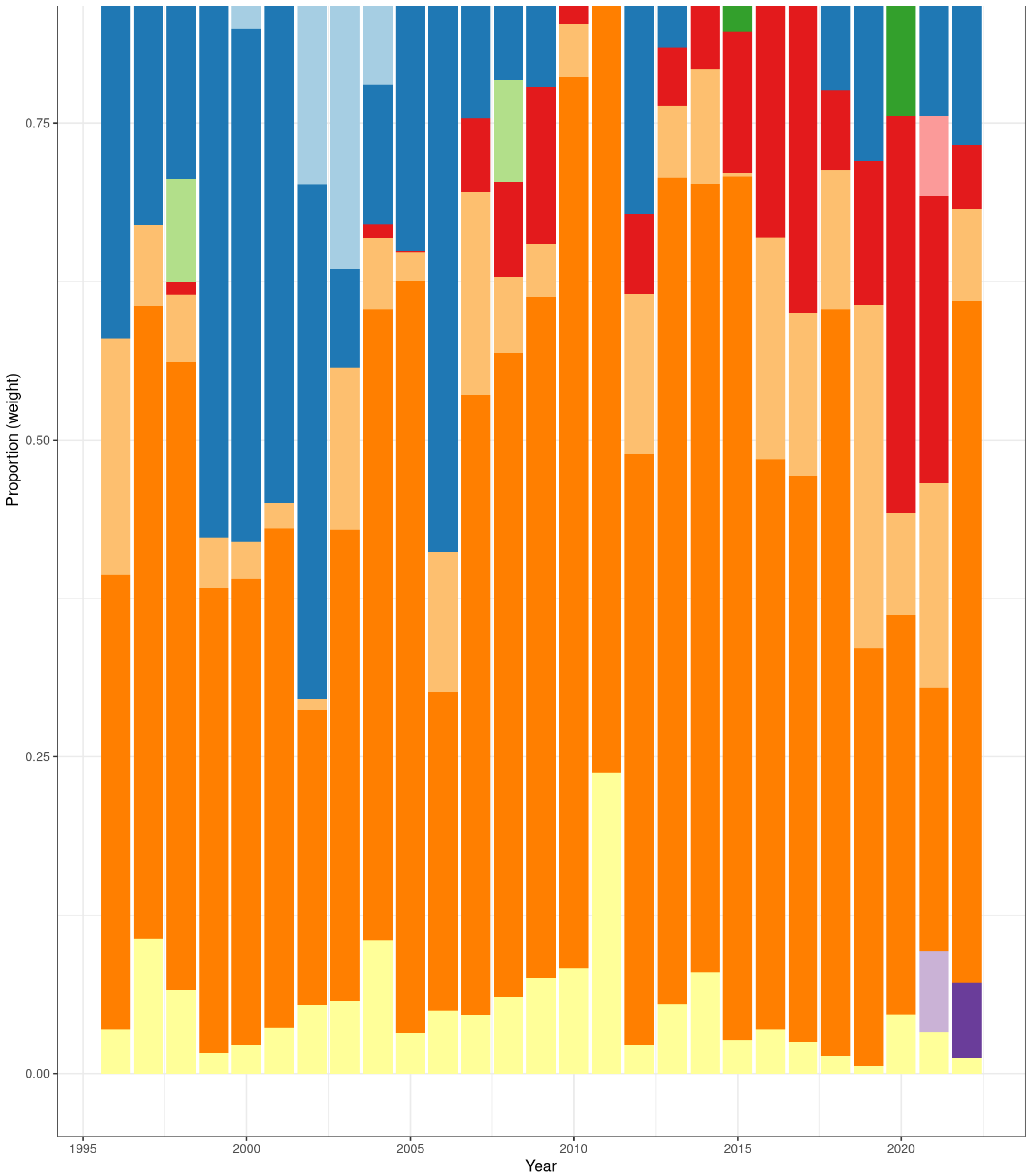
Greenland halibut. Boxplot of the proportion within a year landed by month by Icelandic fishing vessels from ICES area 5a.



Greenland halibut. Species composition in commercial catches in Icelandic waters where more than 5% of the total catch is Greenland halibut.

Observations of diet is shown in figure **?@fig-stomplot**. Pelagic species constitute a substantial proportion of the diet (roughly half), where capelin and blue whiting were more prevalent in the diet in the years prior to 2010. Since 2010 herring started to become more common in the stomachs.



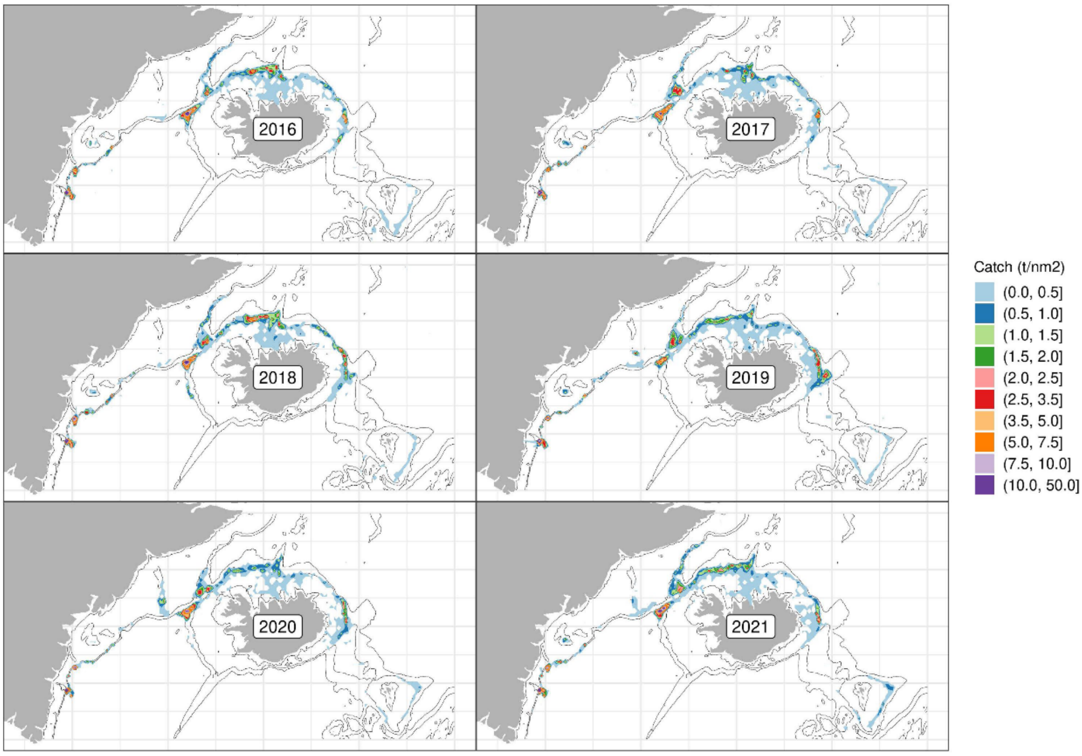


Greenland halibut. Stomach contents from Greenland halibut from Icelandic autumn survey, 10 most common species shown.

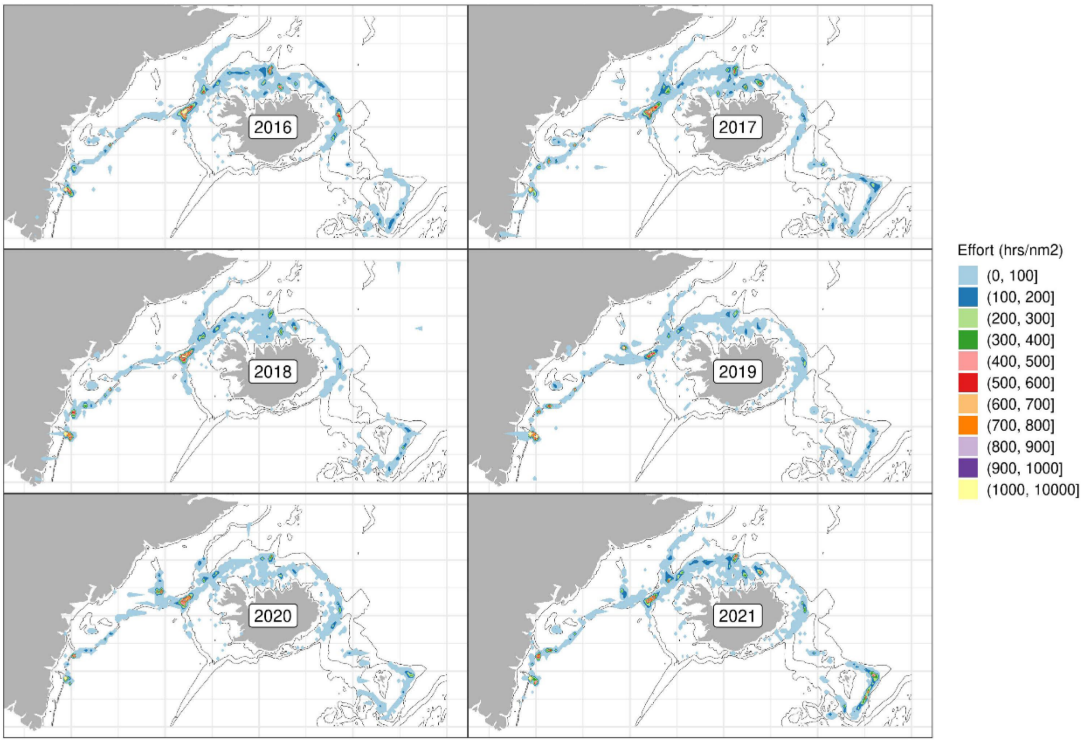
Stock Assessment

Catch – quality, misreporting, discards

Spatial distribution of the 2020 fishery and historic catch and effort in the trawl fishery in Subareas 5, 6, 12 and 14 is provided in Figures **?@fig-catchdist** and **?@fig-effdist**. Fishery in the entire area did in the past occur in a seemingly continuous belt on the continental slope from the slope of the Faroe plateau to southeast of Iceland extending north and west of Iceland and further south to southeast Greenland. Fishing depth ranges from 350-500 m southeast, east and north of Iceland to about 1500 m at East Greenland.



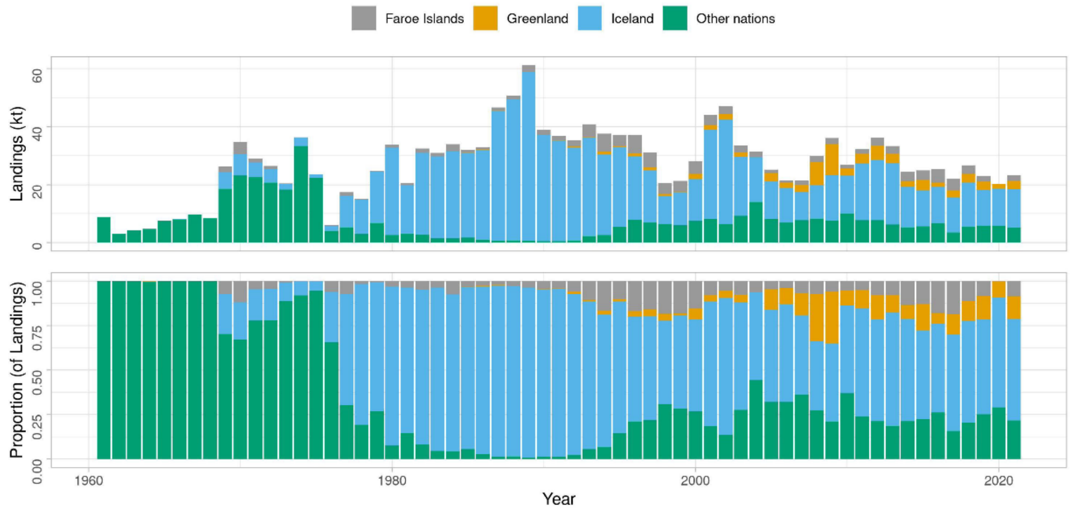
Greenland halibut. Geographical distribution of the fishery in division 5, 6, 12 and 14 from last six years. The 100 m, 500m and 1000 m depth contours are shown. Reported catch from logbooks, note that logbook data from the Faroe Islands is incomplete..



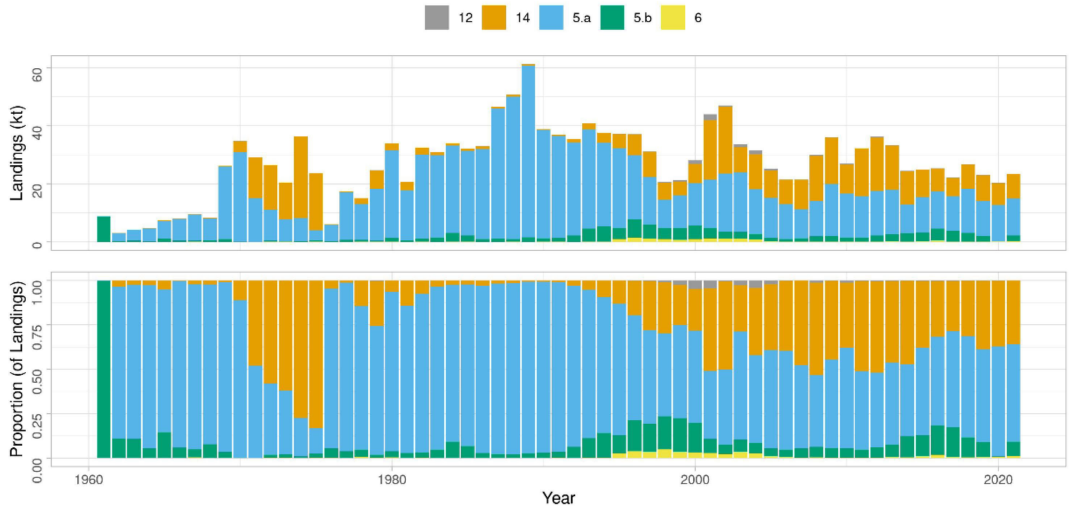
Greenland halibut. Geographical distribution of the fishery in division 5, 6, 12 and 14 from last six years. The 100 m, 500m and 1000 m depth contours are shown. Reported effort from logbooks, note that logbook data from the Faroe Islands is incomplete.

Landing trends

In 1980–1990, about 75–90% of catches were caught by Iceland (Figure **?@fig-landingsplot**). Since 1990, the Icelandic proportion has decreased, and has in recent years been 50–60%. Highest catches were recorded in 1986, about 60 thous. tonnes. Landings in Icelandic waters (usually allocated to Division 5a) have historically been predominated by the total landings in areas 5+14 (Icelandic waters), but since the mid-1990s fisheries in Subarea 14 and Division 5b have developed. Landings have since 1997 been between 20-31 thous. tonnes (Figure **?@fig-landingsplotb**).

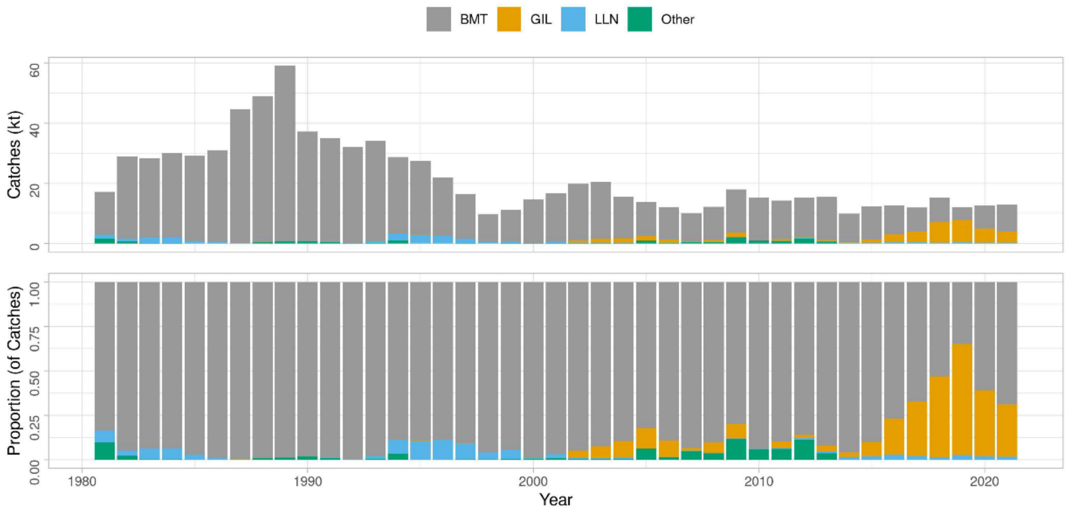


Greenland halibut. Landings from ICES Subareas 5,6,12 and 14 by nations (Greenland, Iceland, and Faroe Islands) in 1961-2020. All gears combined.

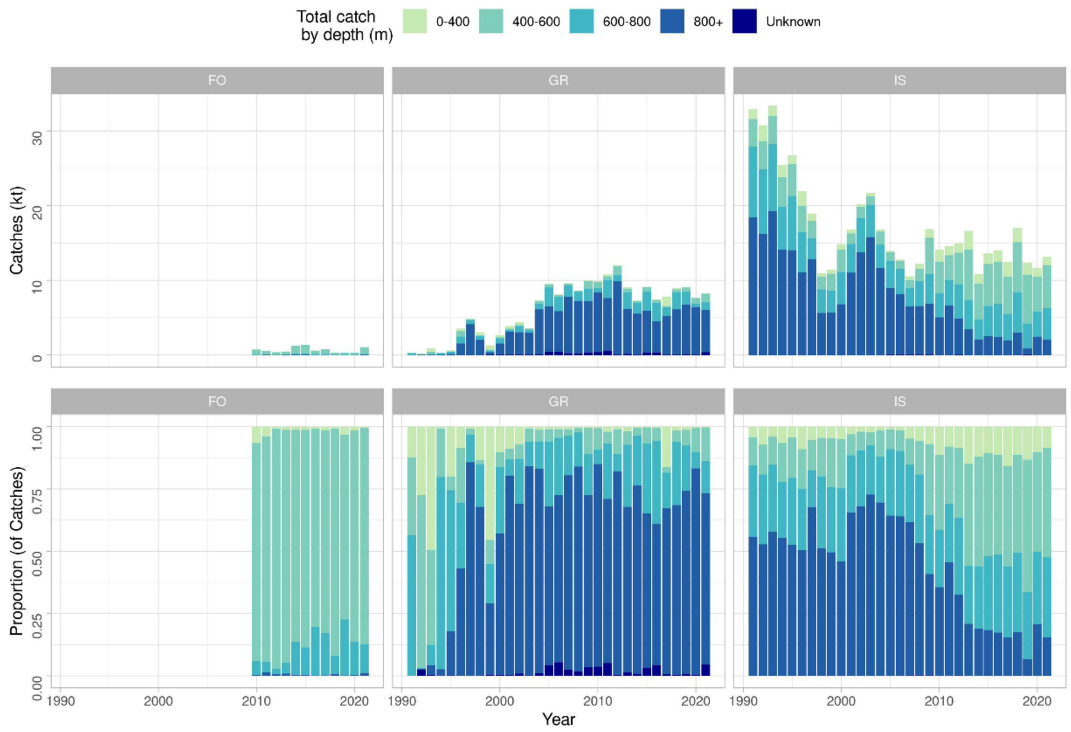


Greenland halibut. Spatial distribution of catch between ICES subareas 5.a, 5.b, 6, 12 and 14 in 1961-2020. All gears combined

Demersal trawl has been the main fishing gear for Greenland halibut in Icelandic waters, followed by gillnets, while a small proportion of the catch is taken on longlines and in shrimp trawls. Since 2015, landings by gillnets have, however, increased, reaching 62% of total catch in 2019 (Figure **?@fig-landingsbygear**). The Greenland halibut trawl fishery is considered clean with respect to by-catches. The mandatory use of sorting grids in the shrimp fishery in Icelandic and Greenland waters since 2002 is observed to have reduced by-catches of Greenland halibut considerably. Greenland halibut is caught in relatively deep waters, with most of the catch (70%) taken between 400-800 meters depth. In 2003, most of Greenland halibut was caught at 800 meters or deeper (73%), but since then, catch has increased steadily in more shallow waters (Figure **?@fig-depthplot**). Changes in depth range where Greenland halibut was caught seem to be reasonably synchronized with changes in fleet and therefore gear structure that target Greenland halibut in most recent years (Figures **?@fig-landingsbygear** and **?@fig-depthplot**).

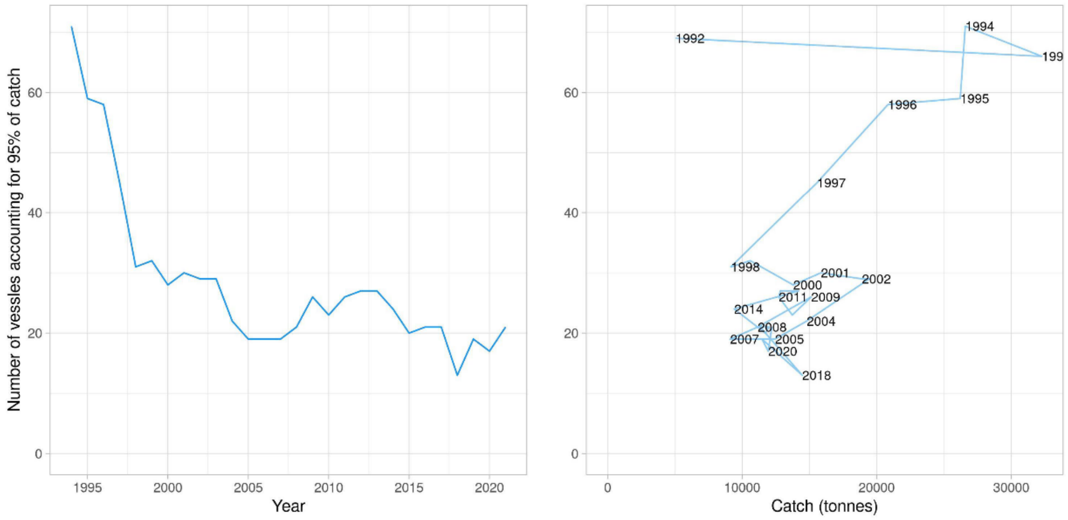


Greenland halibut. Total catch (landings) by fishing gear since 1994 in Icelandic waters, according to statistics from the Directorate of Fisheries.



Greenland halibut. Depth distribution of catches in Faroese (FO), Greenlandic (GR) and Icelandic (IS) waters according to combined logbooks, note that logbook data from the Faroe Islands is incomplete.

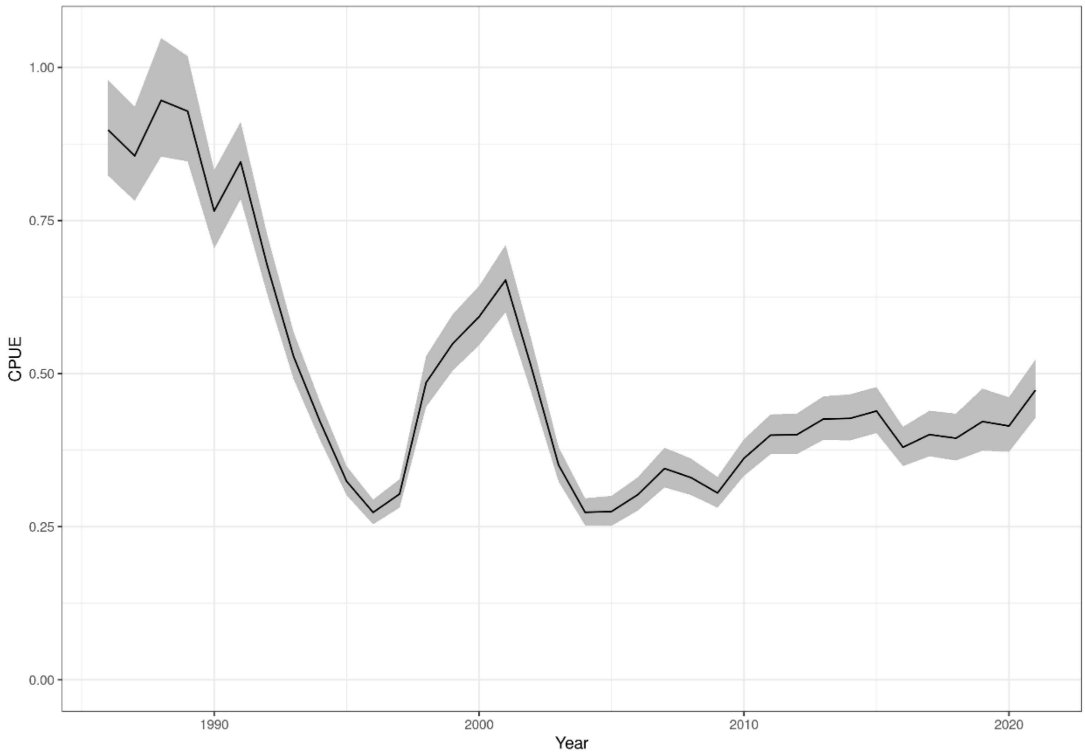
The number of vessels accounting for 95% of the catch of Greenland halibut in Icelandic waters changed from about 75 vessels in 1994-1998 to little less than 20 (Figure **?@fig-numboatsplot**). This change coincided with reduced catches. Since 1998, the number of vessels accounting for 95% of the catch has been relatively constant despite variable annual catches, with the lowest number of vessels observed in 2018



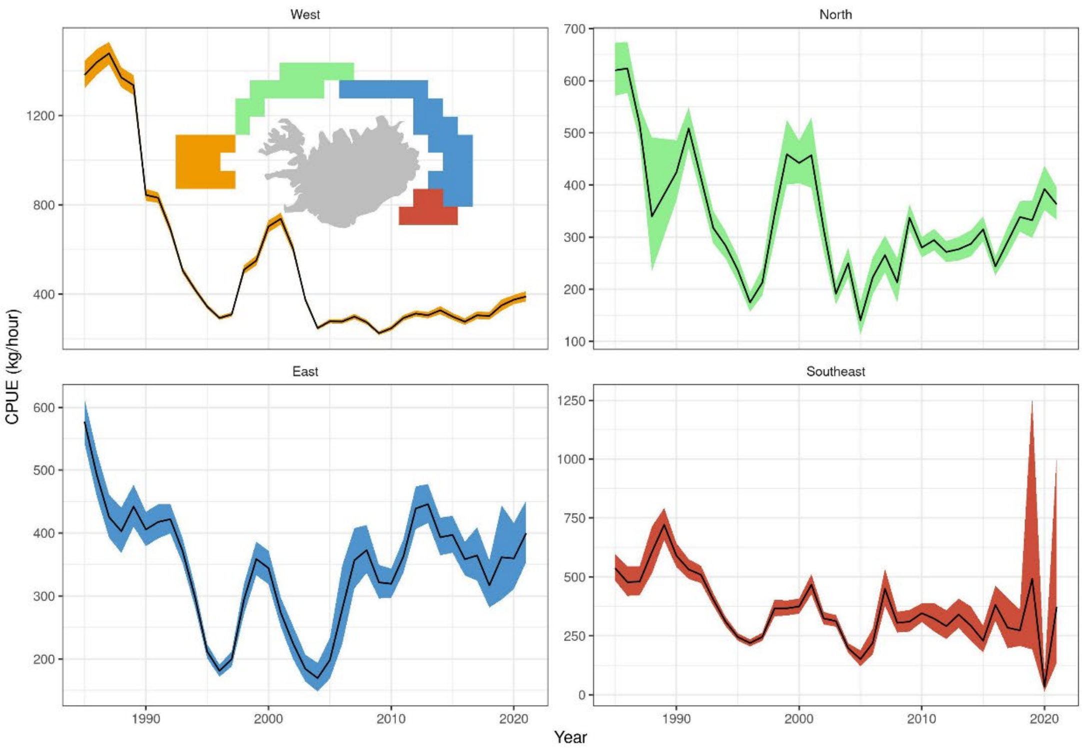
Greenland halibut. Number of vessels (all gear types) accounting for 95% of the total catch annually since 1994. Left: Plotted against year. Right: Plotted against total catch. Data from the Directorate of Fisheries.

Catch per unit effort

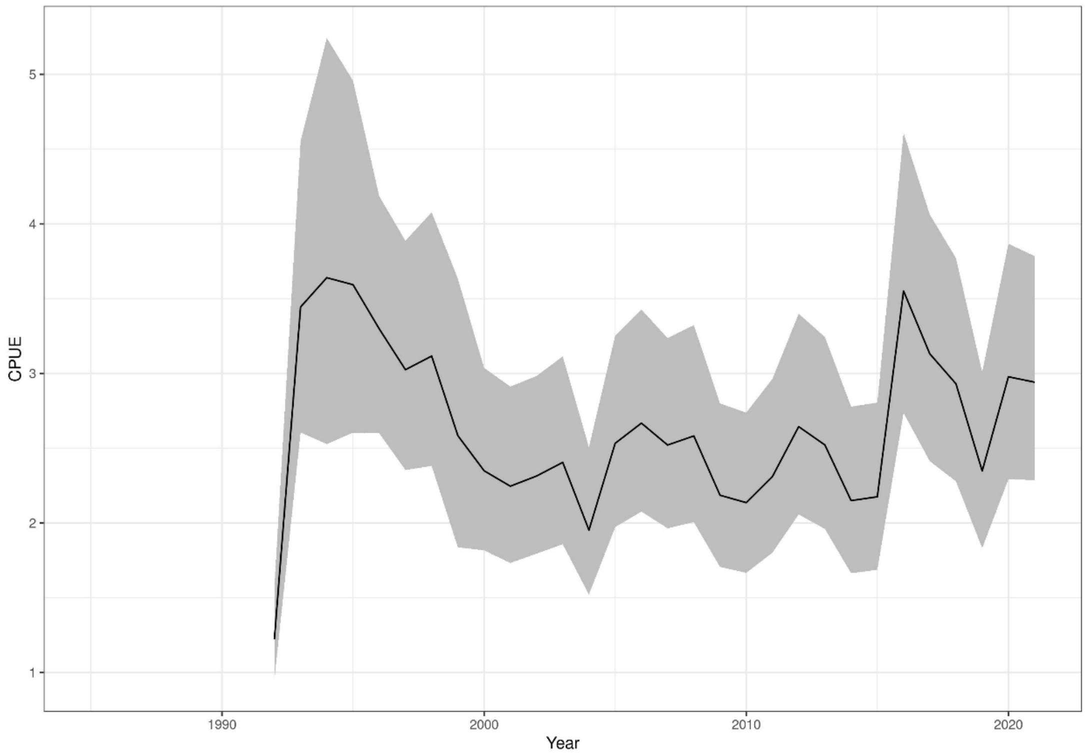
Estimates of catch per unit effort (CPUE) for the Icelandic trawl fleet directed at Greenland halibut for the period 1985–onwards is provided in Figure **?@fig-cpueplot**. The overall CPUE index for the Icelandic fishery is compiled as the average of the standardized indices from the whole area. Catch rates of Icelandic bottom trawlers decreased for all fishing grounds during 1990–1996 but peaked again in 2001. Since 2003, CPUE has been relatively stable. The Icelandic CPUE series has for many years been used as one of the biomass indicators in the assessment of the stock. The CPUE from trawlers in subareas 12, 14 (Greenland), shown in Figure **?@fig-grcpue**, and 5b (Faroese waters) have not been used in the assessment, as the stock production model is not able to accommodate the contrasting indices (Icelandic CPUE and Greenlandic/Icelandic autumn surveys) and these CPUE series are therefore not used.



Greenland halibut. Catch per unit effort (CPUE, log-transformed) from the Icelandic trawler fleet in 5a. 95% CI indicated.



Greenland halibut. Catch per unit effort (CPUE) from the Icelandic trawler fleet in 5a, split by area indicated by the overlayed figure of Iceland. 95% CI indicated.

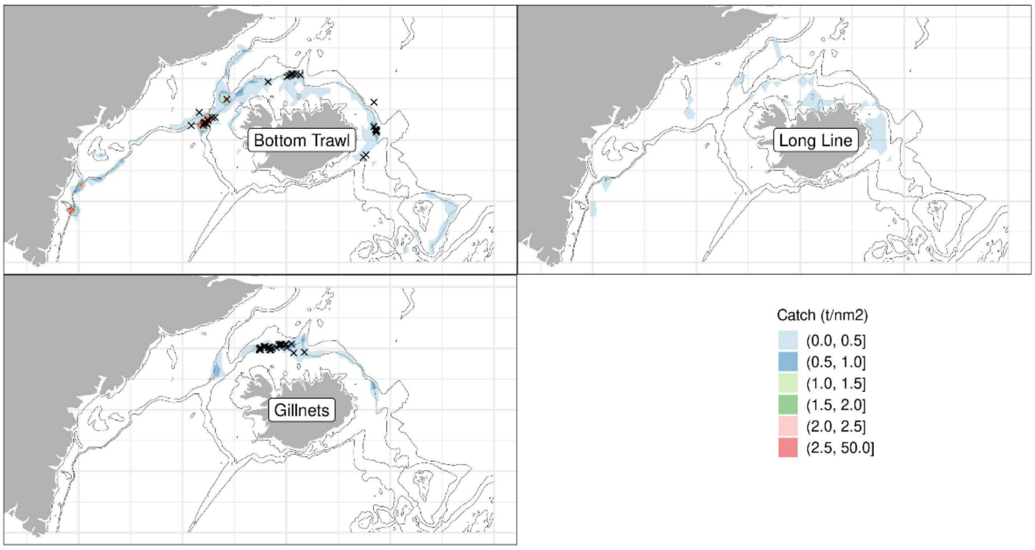


Greenland halibut. Standardised estimates of CPUE from trawl catches east of Greenaland (area 12 and 14). 95% confidence interval is indicated with gray shading.

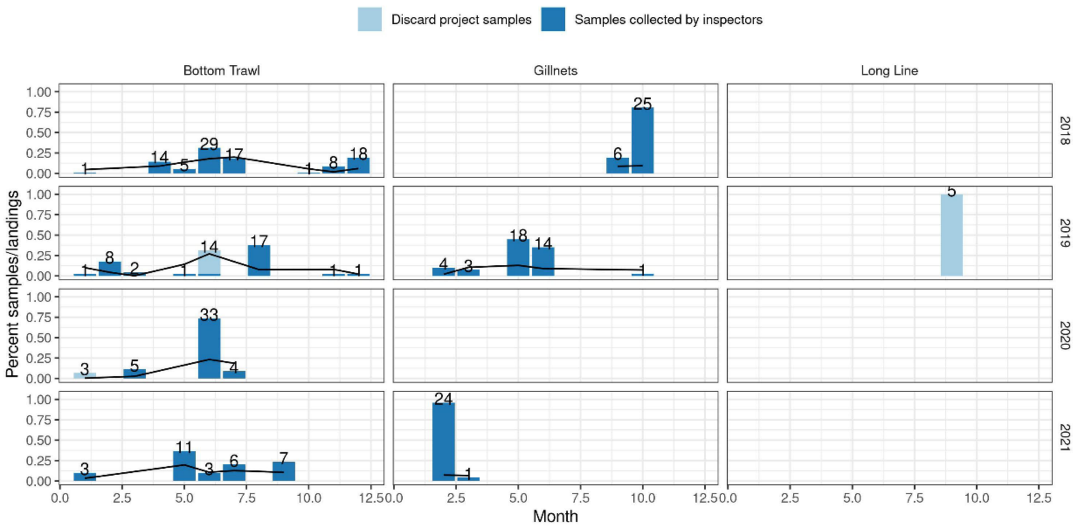
Sampling from Greenland halibut landings

Area 5a

In general sampling is considered good from commercial catches in Icelandic waters from the main gears (gillnets, longlines and trawls). The sampling does seem to cover the spatial and seasonal distribution of catches (see Figures **?@fig-samplingbymonthplot** and **?@fig-samplingposplot**). In 2020 sampling effort was reduced substantially, on-board sampling in particular, due to the COVID-19 pandemic. This reduction in sampling is, however, considered to be sufficiently representative of the fishing operations and thus not considered to substantially affect the assessment of the stock.



Greenland halibut. Fishing grounds in 2021 as reported in logbooks and positions of samples taken from landings (asterisks). Note that sampling locations are only available from Icelandic sources

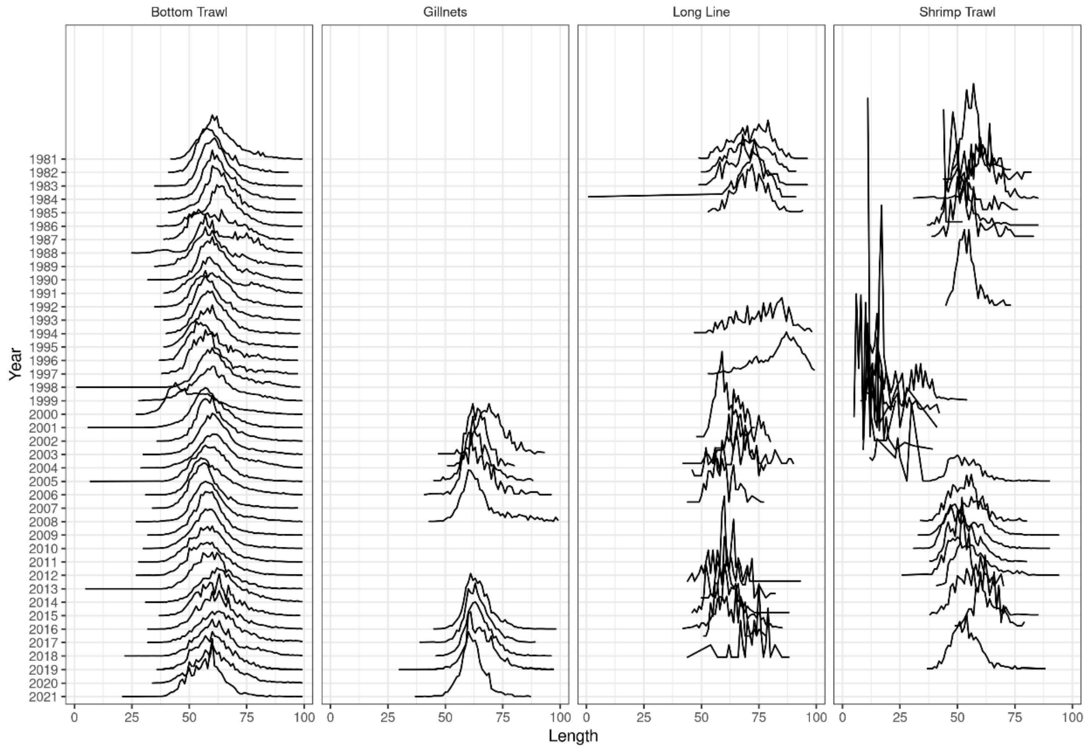


Greenland halibut. Ratio of samples by month (blue bars) compared with landings by month (solid black line) split by year and main gear types. Numbers of above the bars indicate number of samples by year, month and gear. Each sample typically consists of 50 fish.

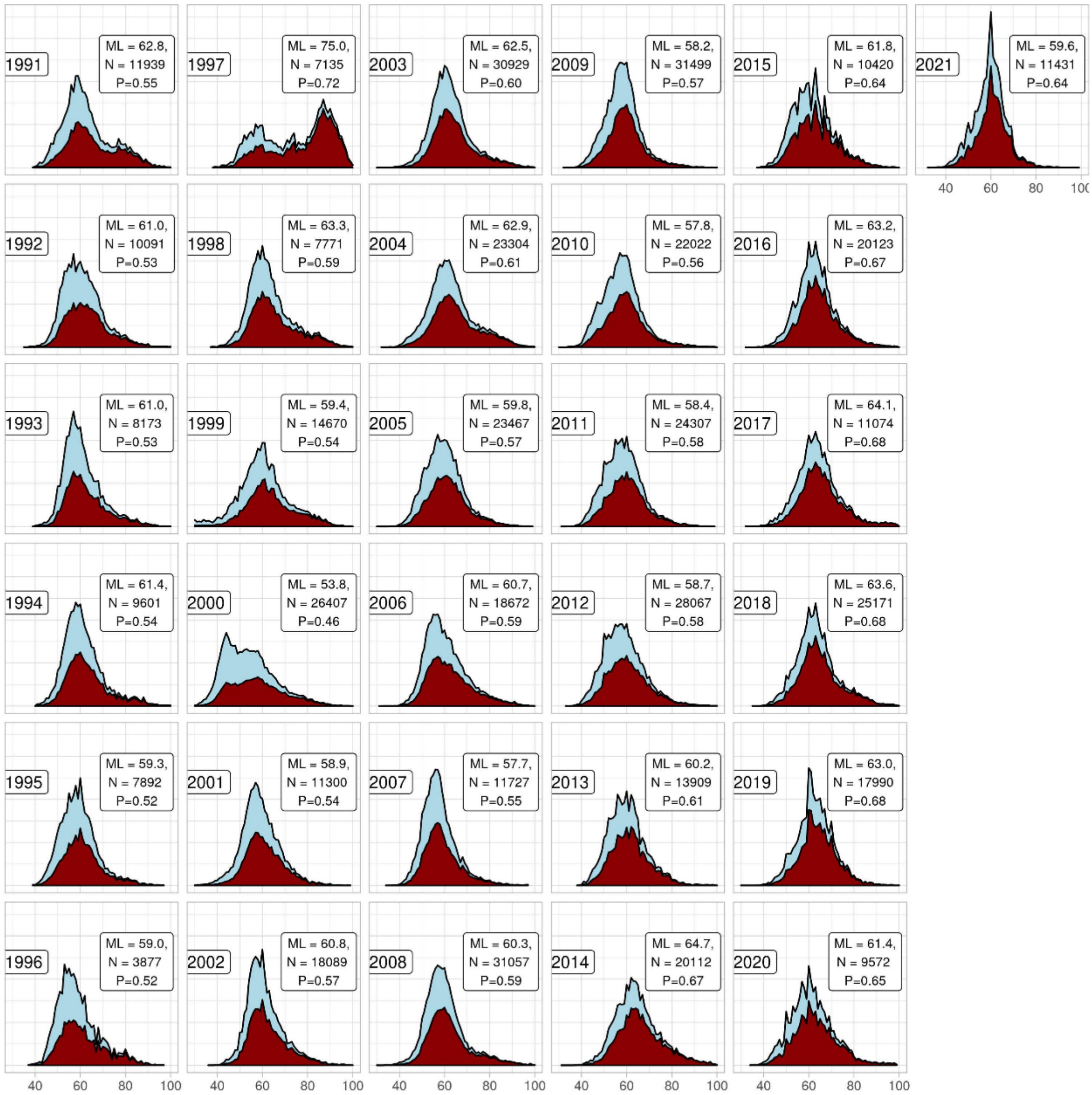
The bulk of the length measurements in Icelandic waters are from the three main fleet segments, i.e. trawls, longlines and gillnets. The number of available length measurements by gear has fluctuated in recent years in relation to the changes in the fleet composition.

Length distributions from the main fleet segments are shown in **?@fig-commldistplot**. The sizes caught by the main gear types (bottom trawl and gillnets) appear to be fairly stable, primarily catching halibut in the size range between 40 and 80 cm. Gillnets tend to catch slightly larger fish, while shrimp trawl appears to catch juvenile halibut when present in Icelandic waters.

There has been a gradual shift towards larger fish in the length distribution of landed catch (Figure **?@fig-commldistsex**). Males measured from landed catch have the tendency to be smaller than females, as observed from the proportion of catches by sex (Figure **?@fig-commldistsex**).

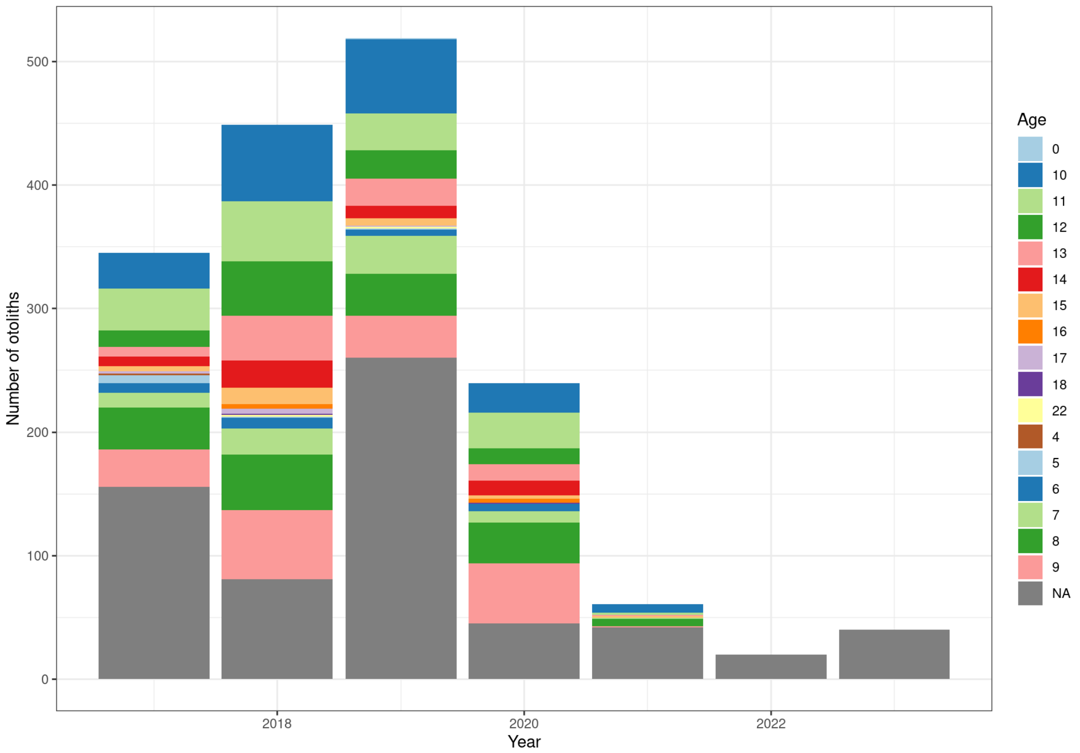


Greenland halibut. Commercial length distributions by gear and year



Greenland halibut. Aggregated commercial length distributions by sex and year.

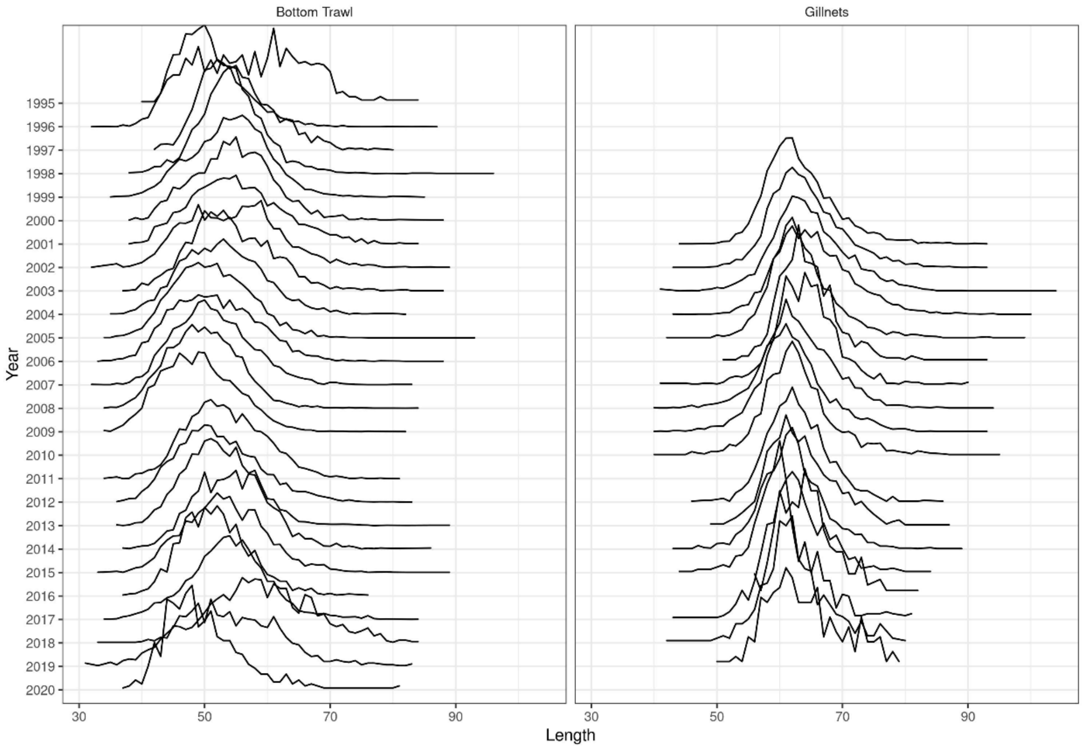
Colection of otoliths from commercial catches resumed in 2017 and those samples have been partially processed (see fig **? @fig-commagereading**). Sampling reduced considerably during the years of the pandemic but sampling is planned to resume to previous levels in 2023.



Greenland halibut. Number of samples from commercial catches, split by age.

Area 5b (Faroese waters)

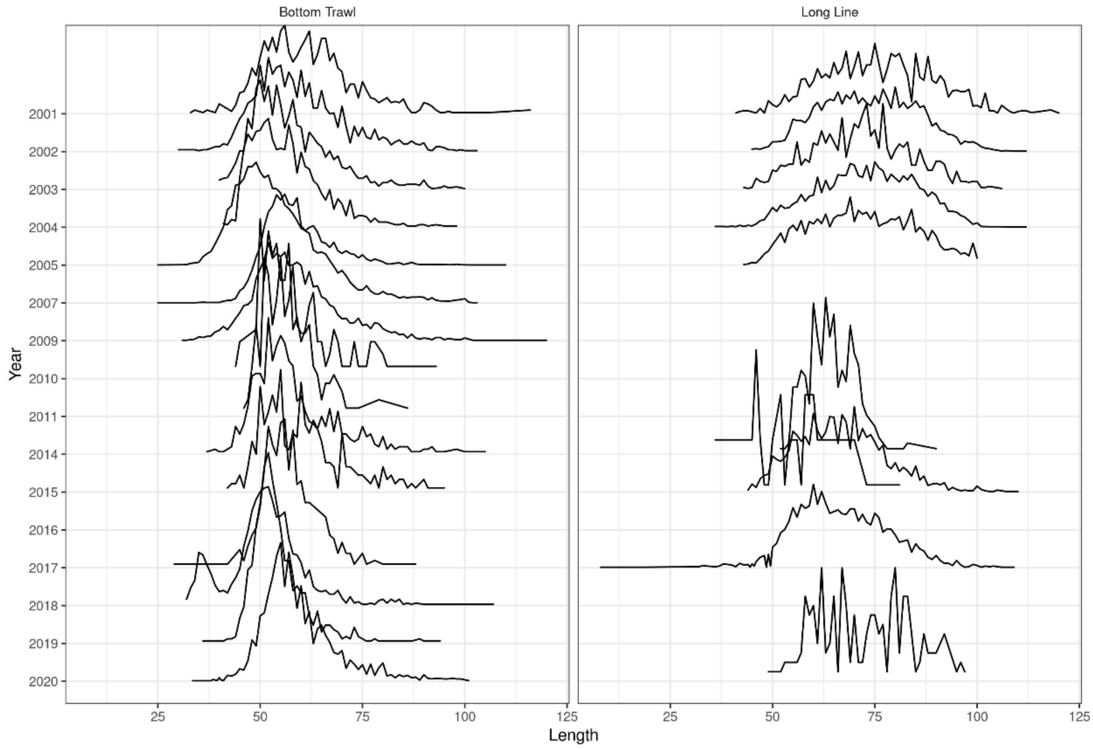
Samples from landed catch are from gillnets and trawl



Greenland halibut. Commercial length distributions by gear and year

Areas 12 and 14 (East Greenland)

Samples from landed catch are from longlines and trawl



Greenland halibut. Commercial length distributions by gear and year

Other areas

No samples are available and reported catches have been negligible in recent years.

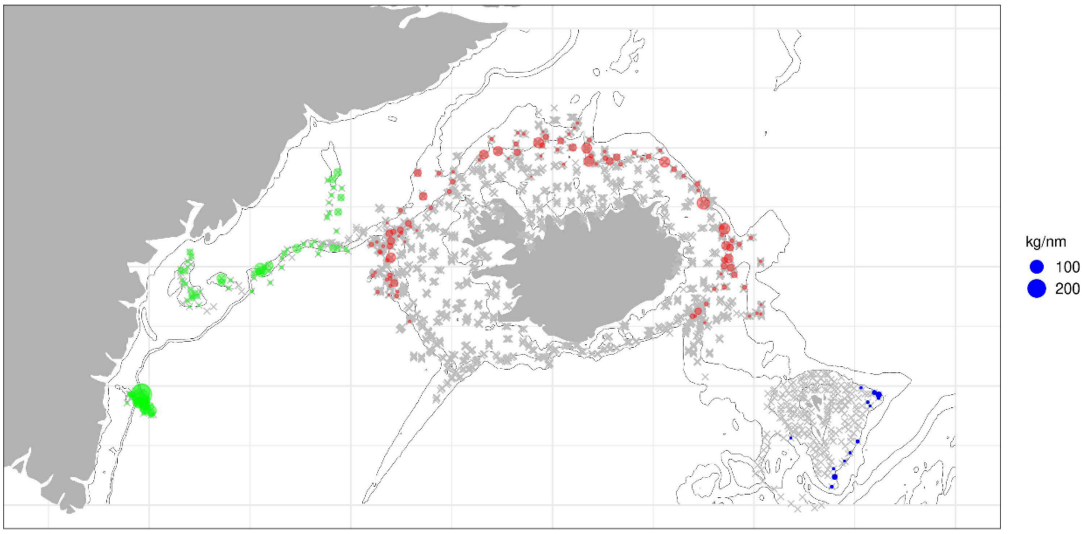
Surveys

Greenland halibut is the primary focus of three surveys, each in the respective EEZ:

- Icelandic groundfish survey in the autumn, started in 1996
- Greenlandic Greenland halibut survey
- Faroese Greenland halibut survey

Icelandic survey

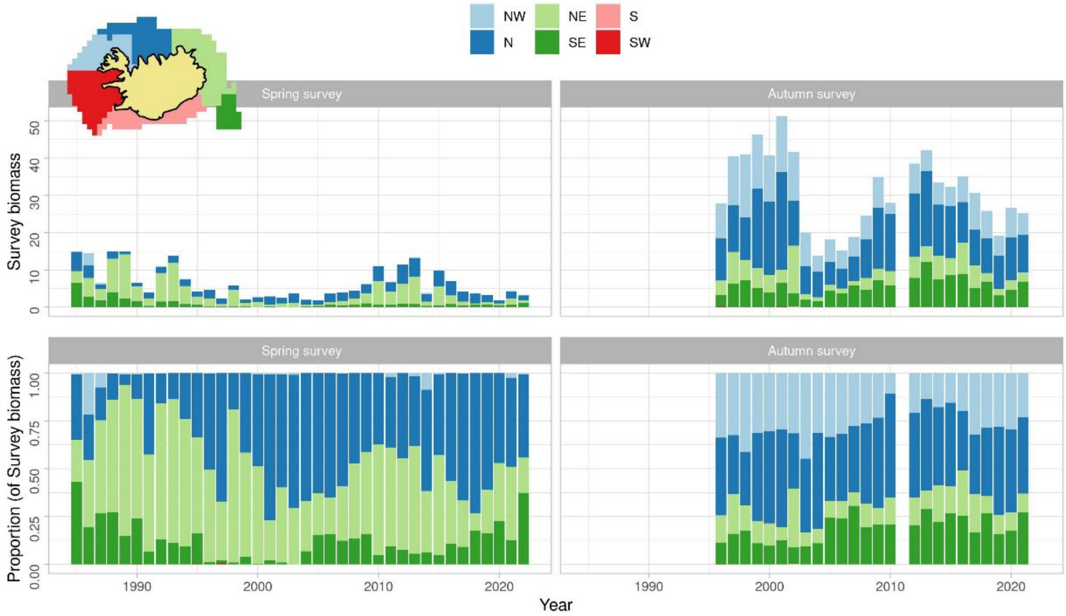
The Icelandic autumn groundfish survey (hereafter autumn survey) was commenced in 1996. The autumn survey was not conducted in 2011. Spatial distribution and abundance in recent years are shown in Figures **?@fig-surveypos** and **?@fig-surveybyarea** while Figure **?@fig-fourplot** shows trends in various biomass indices, and a recruitment index based on abundance of Greenland halibut \(\leq\) 40 cm. Survey length distributions are shown in Figure **?@fig-surveyldist**. In the recent years, Greenland halibut were mainly caught on the continental slope south east, north, and north-west of the country (Figure **?@fig-surveybyarea**).



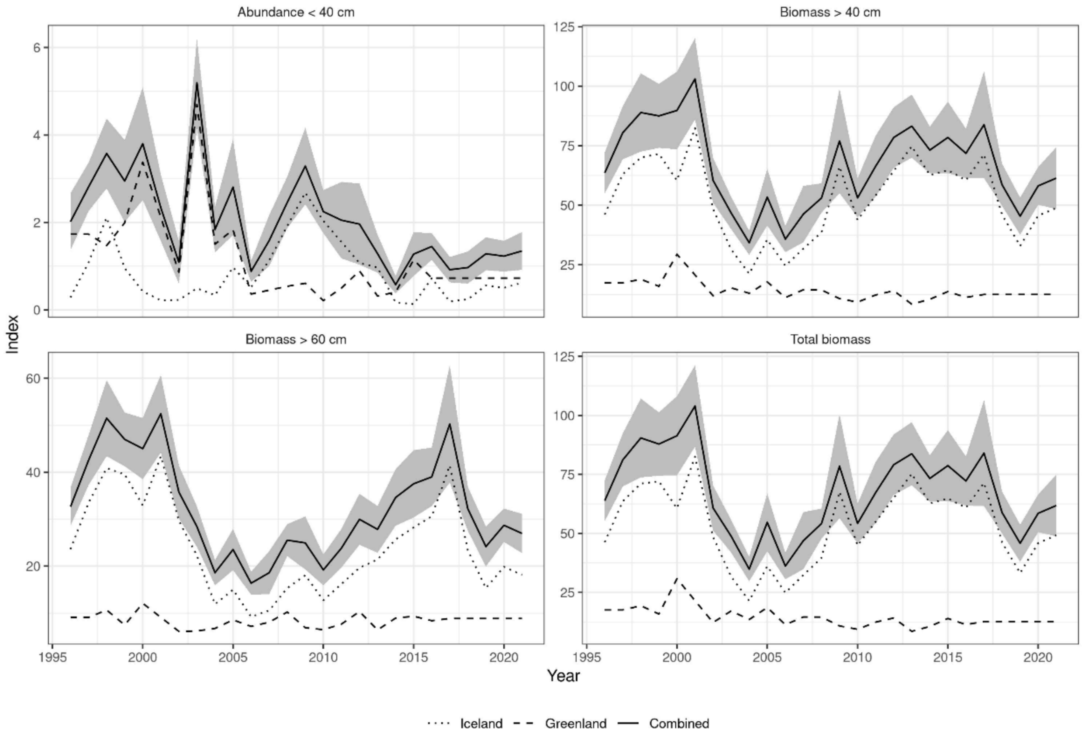
Greenland halibut. Spatial distribution of Greenland halibut in the Icelandic autumn survey (red), Greenlandic Greenland halibut survey (green) and Faroese surveys (blue). Size of the points indicates catch at the location, grey crosses the stations were no halibuts were observed.

Since the survey was commenced in 1996, the distributional pattern has remained quite stable, with the greatest biomass index in the northeast and northwest. Since 1996, biomass index in the west has been steadily decreasing, while increasing in the southeast (Figure **?@fig-surveybyarea**).

Biomass indices for the total stock of Greenland halibut and Greenland halibut larger than 40 cm (harvestable part of the stock), that are based on the combined Icelandic and Greenlandic autumn surveys, showed an increase from 1996-2001. After peaking in 2001, indices dropped but increased steadily from 2004 till 2017 when the stock started to decrease (Figure **?@fig-fourplot**). The same holds for the index of Greenland halibut larger than 60 cm. The index of juvenile abundance (<40 cm) has fluctuated between years, peaking in 2002 but remained low in the past six years (Figure **?@fig-fourplot**). Since 2016 the East Greenland area has not been surveyed, and for the indices the values from 2016 are used for the years after that.

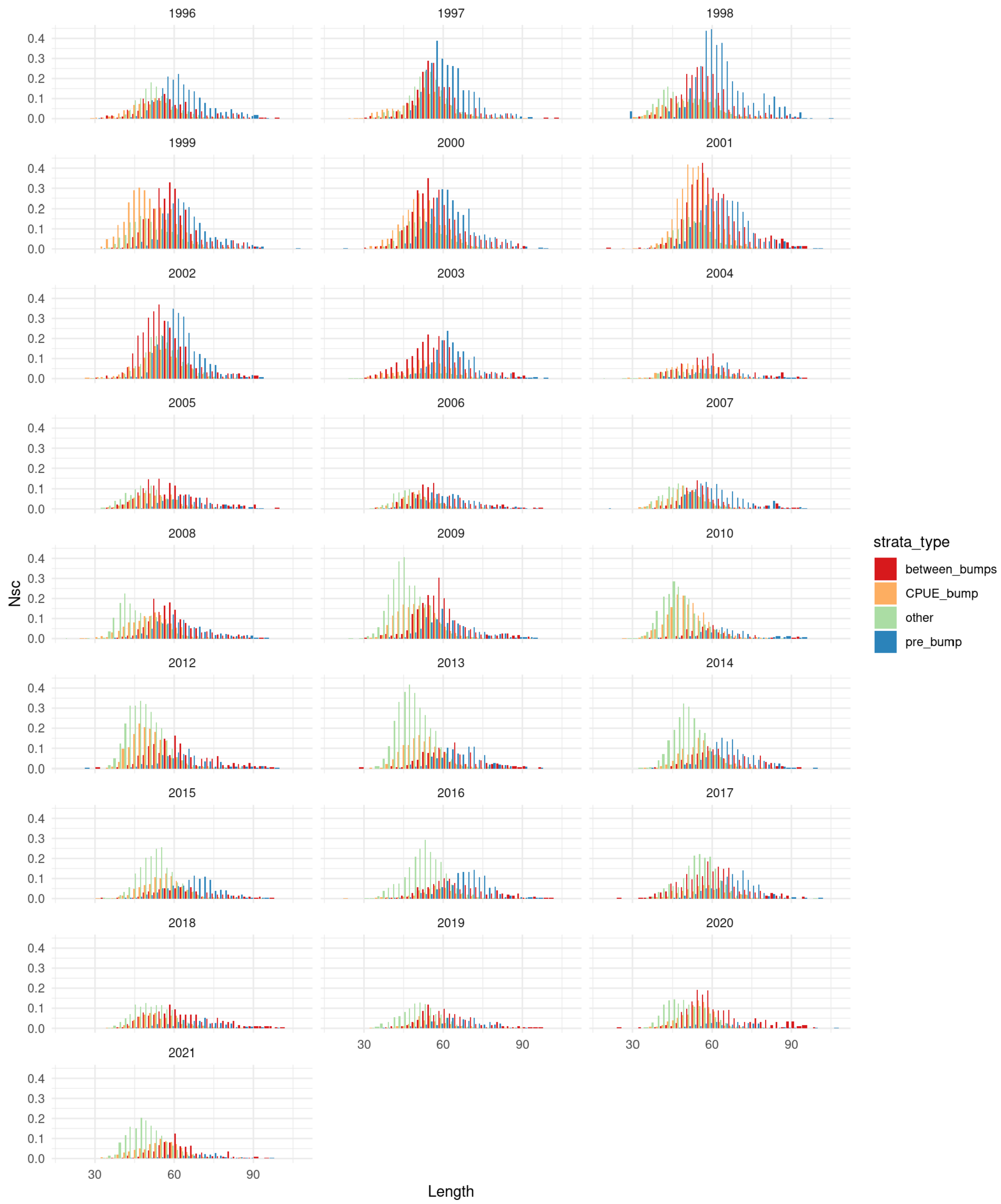


Greenland halibut. Spatial distribution of the biomass index from the spring and autumn surveys. Note that the autumn survey extends into deeper waters.



Greenland halibut. Indices from Iceland (smaller dots) Greenland (larger dots) and combined (straight line) with 95% CI indicated. Harvestable biomass indices (>40 cm) (upper right), juvenile abundance indices (<40 cm) (upper left), biomass indices of larger ind. (>60cm) (lower left) and total biomass indices (lover right)

Survey index trends have a similar trend to CPUE indices, with a spike evident from roughly 1999 – 2001, but differing levels depending on region thereafter. Breaking down survey indices from the autumn survey show that spatial trends are also evident in the survey indices. Specific strata were chosen and joined manually into groupings to emphasize similarities in their length distributions in Autumn survey data. This led to 4 groupings, described as 'pre_bump' with a length distribution that shows domination of indices before 2000, 'CPUE_bump' that indicates domination of indices during the 1999 - 2001 period when CPUE increased, and 'between_bumps' which looks like it contributes to both, depending on the time period. Interestingly, the 'CPUE_bump' length distribution series, beginning in 1999, appears to be a series that increases in length over a few years and could therefore be the result of a large year class. The pre_bump and 'between_bumps' series, however, do appear more stationary in their size distributions, especially, the 'pre_bump' series whose mode is normally 58+ cm. The 'between_bumps' series shifts a bit to the left and right, indicating that it could be a mixture of cohorts visible in the 'CPUE_bump' series and stationary length distributions characteristic of 'pre-bump' areas.



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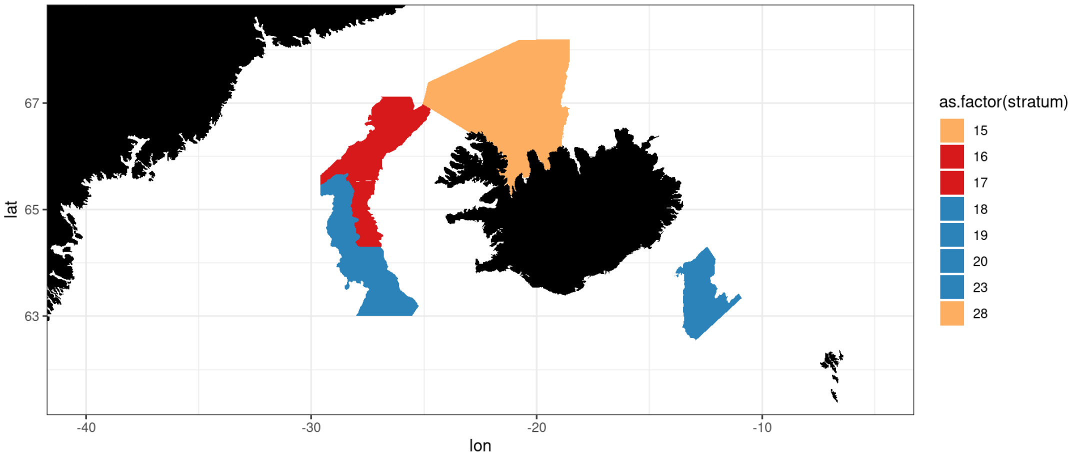
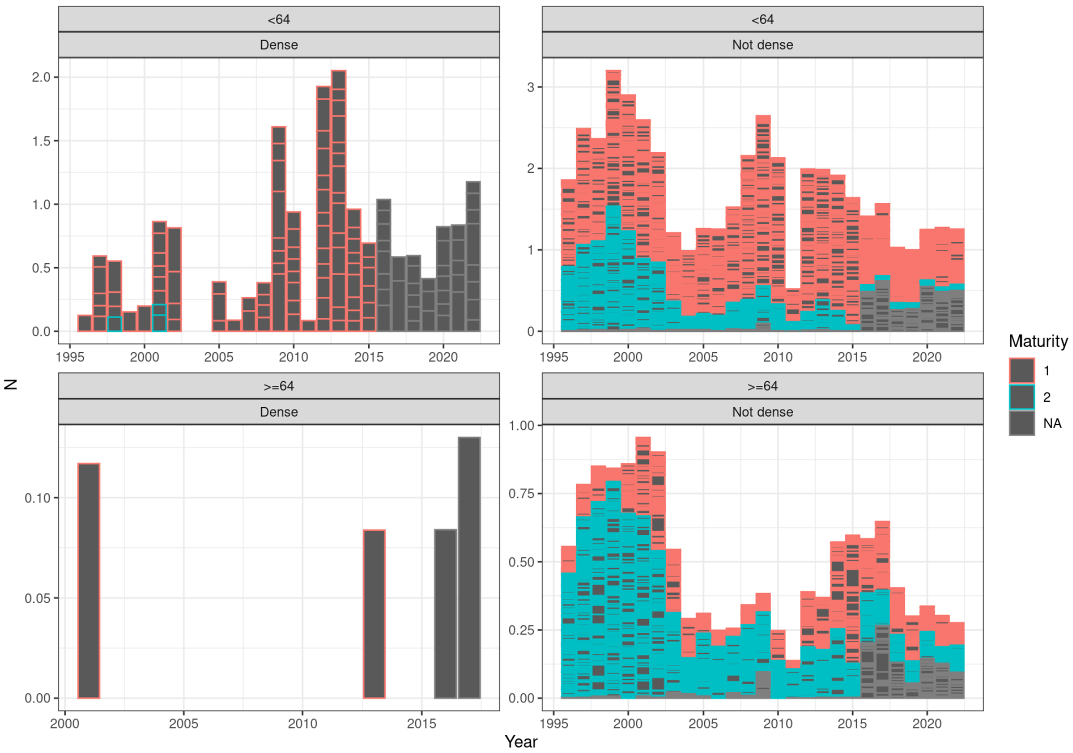
between_bumps
CPUE_bump
other
pre_bump

Greenland halibut. Length distributions from strata grouped together by as having a higher contribution to high autumn survey index values in roughly 1996–1998 (‘pre_bump’), high index values in 1999–2001 (‘CPUE_bump’), both (‘between_bumps’), or later periods in the time series (‘other’). Colors of strata groups correspond with the map in the next figure.



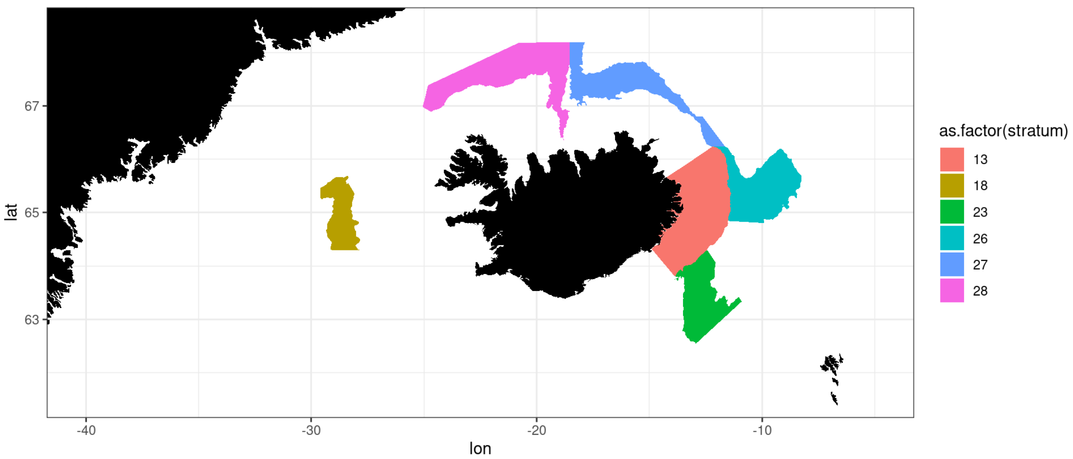
Greenland halibut. strata grouped together by as having a higher contribution to high autumn survey index values in roughly 1996–1998 (‘pre_bump’), high index values in 1999–2001 (‘CPUE_bump’), both (‘between_bumps’), or later periods in the time series (‘other’). Colors of strata groups correspond with the length distributions in the previous figure.

Later high periods during 2008 – 2016 show a larger contribution of smaller Greenland halibut from areas in the east and northeast (‘other’ category above), whereas earlier in time series, strata in the west were dominant (‘CPUE_bump’, ‘pre_bump’, and ‘between_bumps’ series). The contribution of densely aggregated hauls to the survey index, especially in fish < 64 cm, also has increased in this later period, and could disproportionately inflate the index. Densely aggregated hauls were defined as roughly at or above the 99.25th percentile of haul density values across all years.



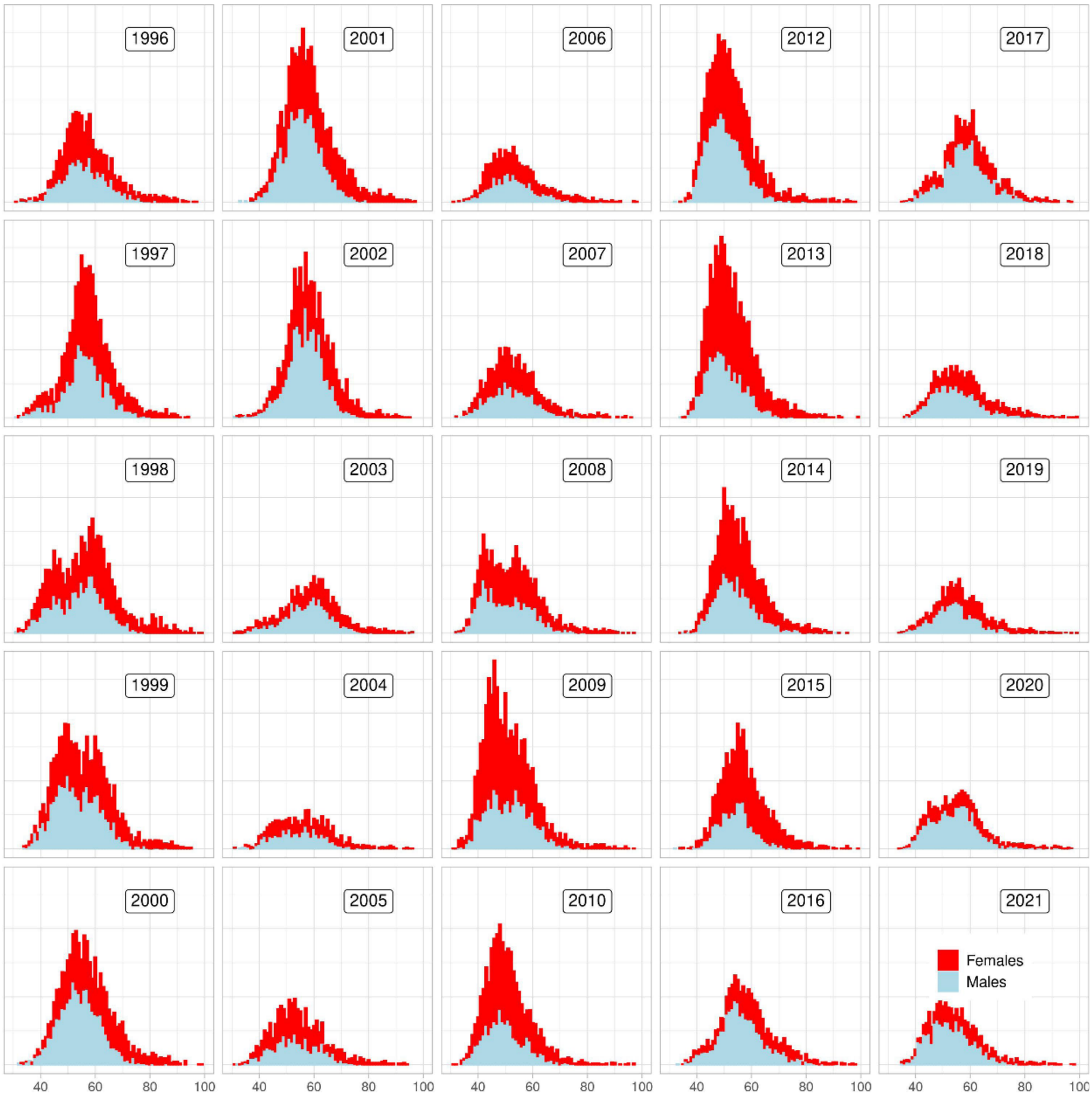
Greenland halibut. Numbers per area are plotted by haul and maturity, with outlined colors representing whether the numbers are of mature (2) versus immature (1) or unknown (NA), to show their contribution to total indices. Hauls are also split by size category (<64, 64+) and whether they are considered 'dense' (greater than roughly 99.25 percentile of density across all years).

Greenland halibut. Trends in numbers within strata are shown for strata that contain dense hauls. Colors correspond with strata in the next figure.



Greenland halibut. Strata containing dense hauls. Colors correspond with the previous figures.

Length distributions from the survey show a similar trend as in landed catch. Females tend to be larger than males and in greater abundance. The average length for females fluctuates from 51-61 cm throughout the years when males fluctuate from 50-59 cm. The length distribution has been gradually increasing since 2010, and in 2019, the mean length of males and females was 54.3 and 59.0 cm, respectively.

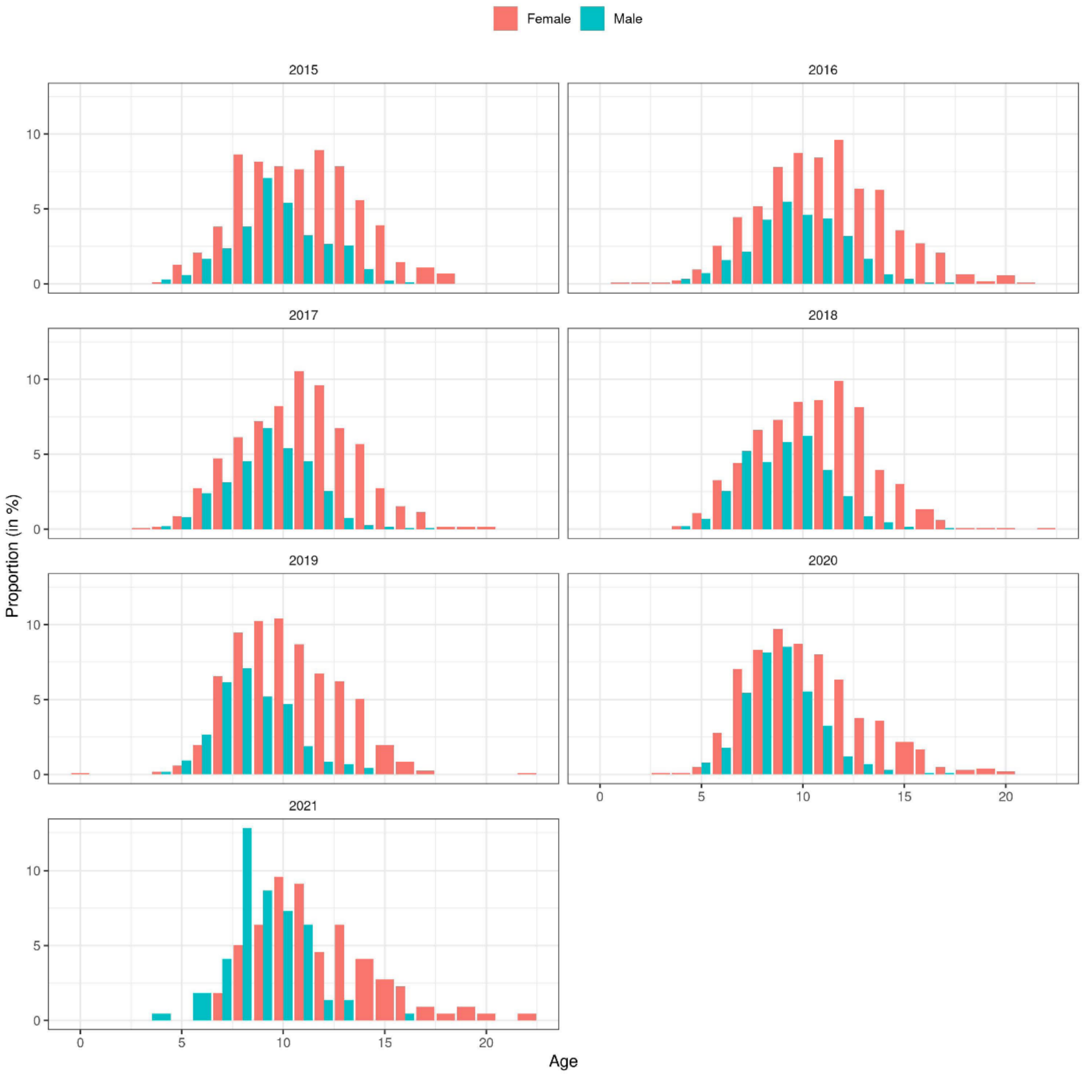


Greenland halibut. Mean length and 95% CI (upper) and length distribution (lower) of females and males from the autumn survey since 1996

Age distribution of the sexes of Greenland halibut from the autumn survey 2015-onwards show that the greatest proportion males are between 9 and 10 years old and range between 4-16 years. The greatest proportion of females are 11-13 years old and range from 3 to 22 years (Figure **?@fig-agedist**).

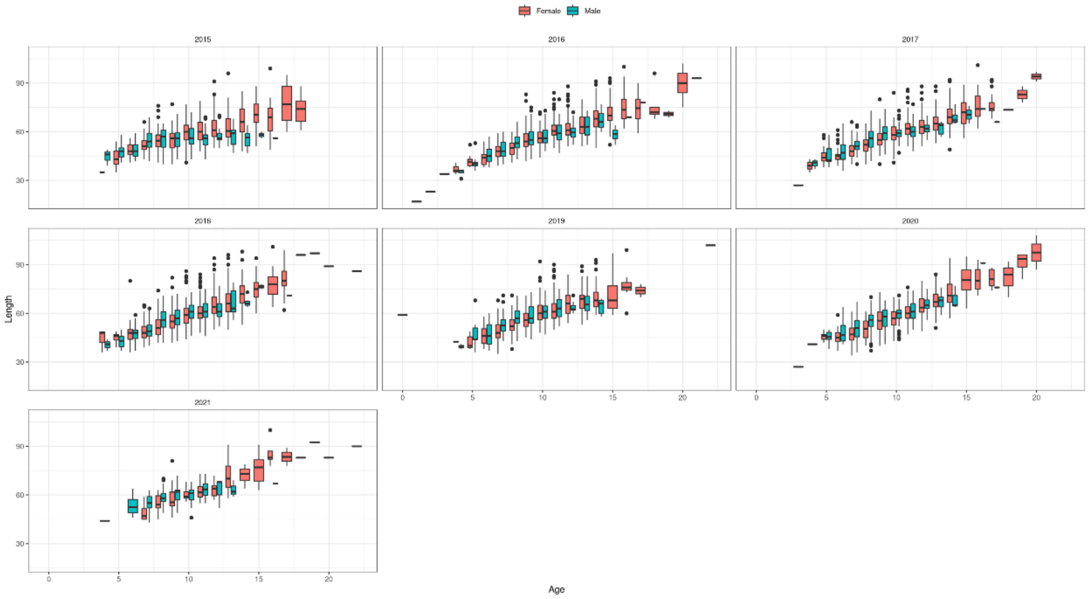
It is worth noting that aging recently resumed after a long period where otoliths were sampled but not age read. Recent advances in age reading techniques suggested that older age reading methods used previously were biased and thus older age-readings are not considered representative of the age structure in the population. Further, otoliths sampled prior to

2015 were not stored in a manner compatible with the newer age-reading method. It is therefore uncertain whether data on the historic age structure will ever be available.



Greenland halibut. Proportion by age from the autumn survey from 2015

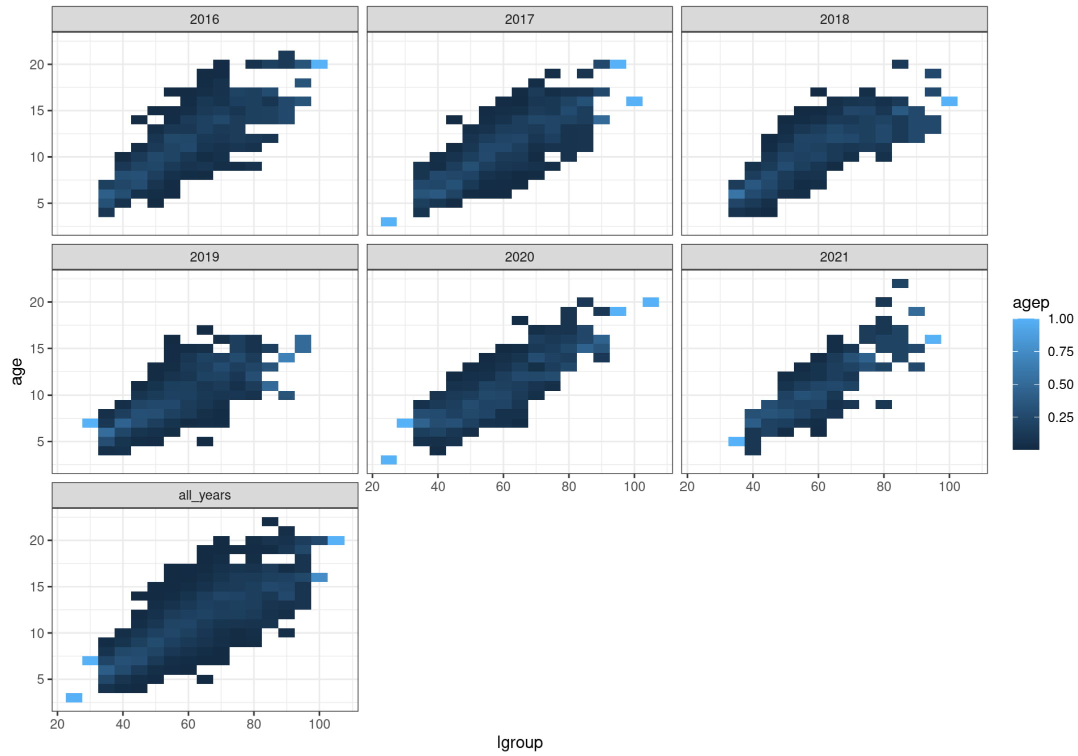
According to the length distribution by age of Greenland halibut, it reaches 60 cm at the roughly the age of 12 on the average (Figure **?@fig-agegr**). The growth of Greenland halibut appears to be similar between the sexes, while female exhibit larger variability in size. It is noteworthy that males tend to be on average smaller in the catches than females, even though both sexes seem to have similar mean length at age. This may suggest differences in behavior of the sexes, such as catchability with respect to gear and/or natural mortality.



Greenland halibut. Distribution of length at age by sex from the autumn survey

Survey age-length keys

As noted above aging of halibut resumed in Icelandic waters in 2014.

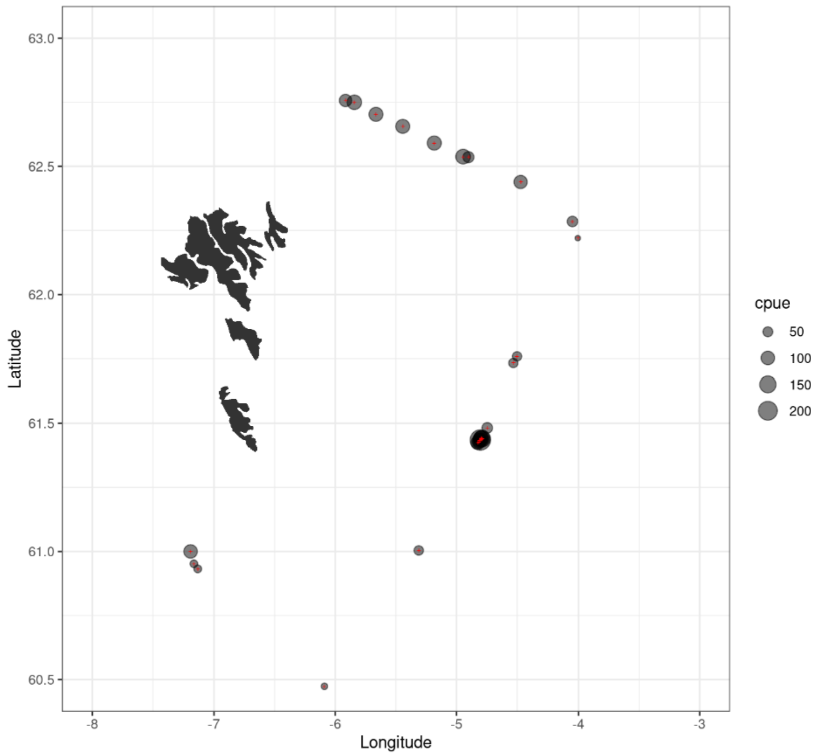


Greenland halibut. Illustration of the Age–Length key obtained from the Icelandic autumn survey.

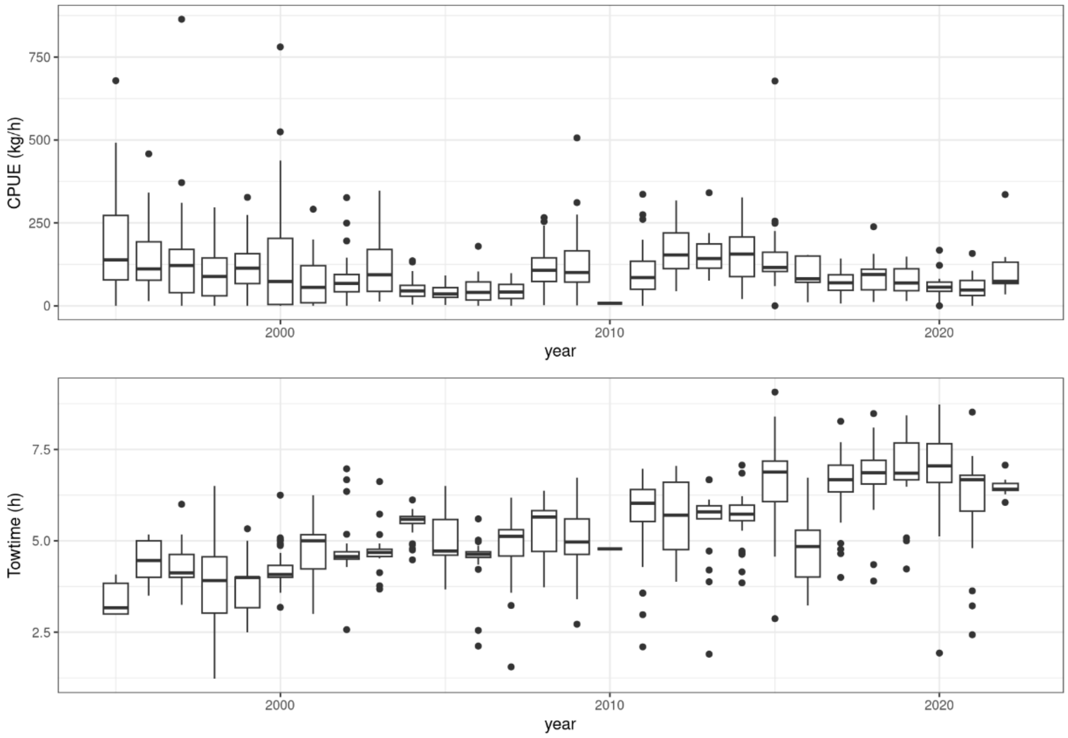
Faroese survey

The annual Greenland halibut survey in Faroese waters was started in 1995. The samples taken using a commercial trawl and the survey design varies between years. The average tow time has increased steadily from an average of 3 hours in 1995 to nearly 7.5 hours in 2020.

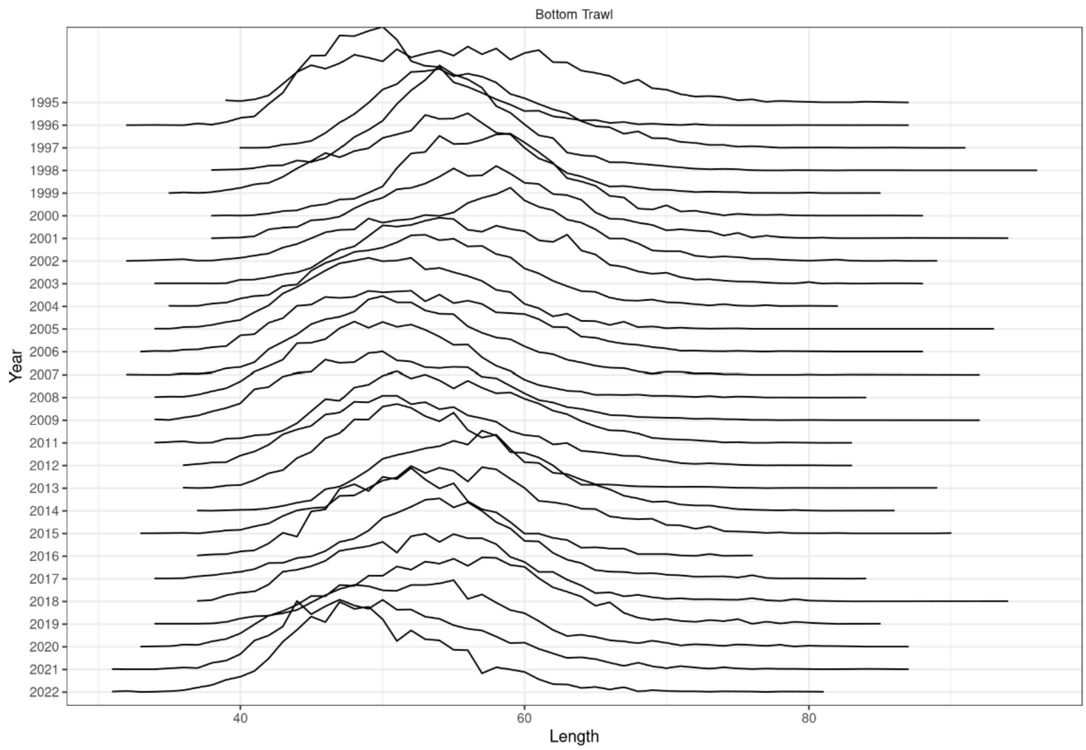
Aging resumed in 2015 and information is available from four years (2015 to 2017 and 2021). Preliminary results from an aging workshop on Greenland halibut ototliths suggest that further calibration between labs is needed to ensure that they are appropriate (Windsland pers. comm).



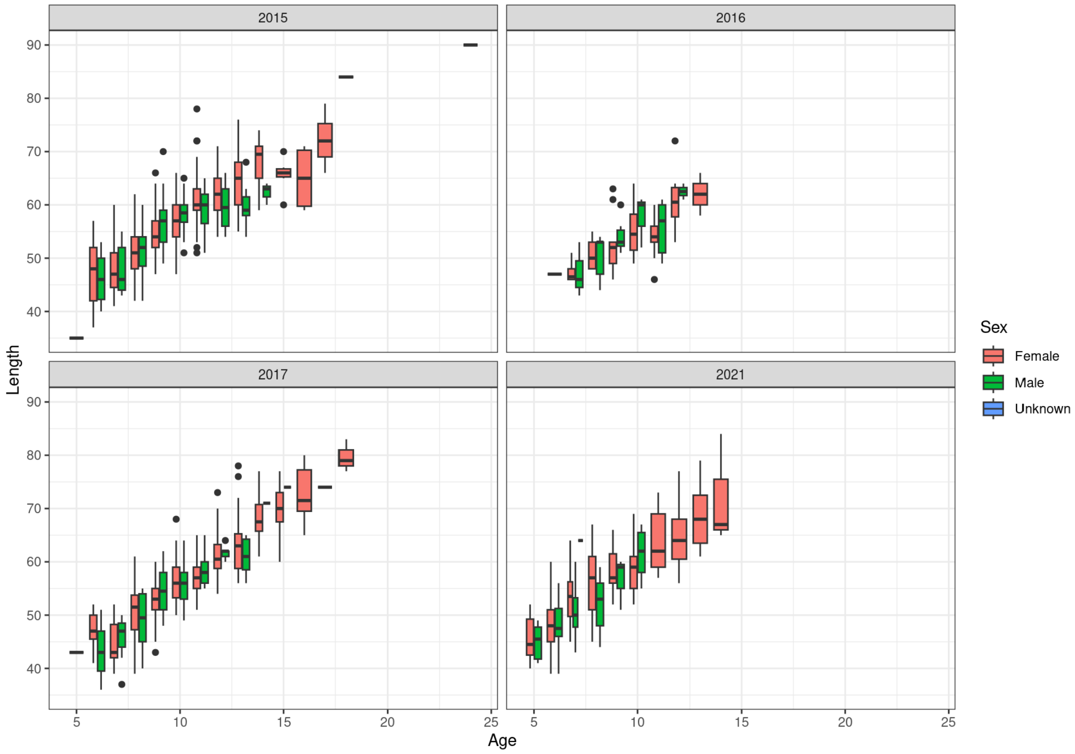
Greenland halibut. Tow stations in the Faroese Greenland halibut survey in 2018.



Greenland halibut. Boxplot of the catch per unit effort (top panel) and towtime (bottom panel) by year in the Faroese survey.



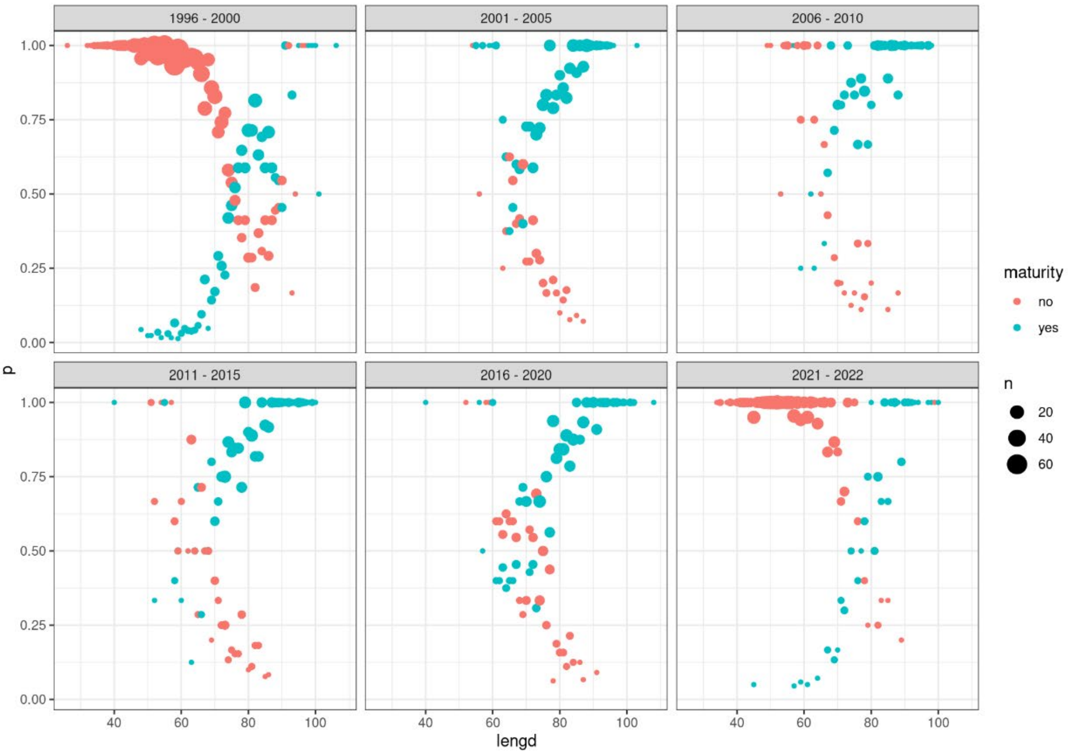
Greenland halibut. Observed length distribution from the Faroese survey.



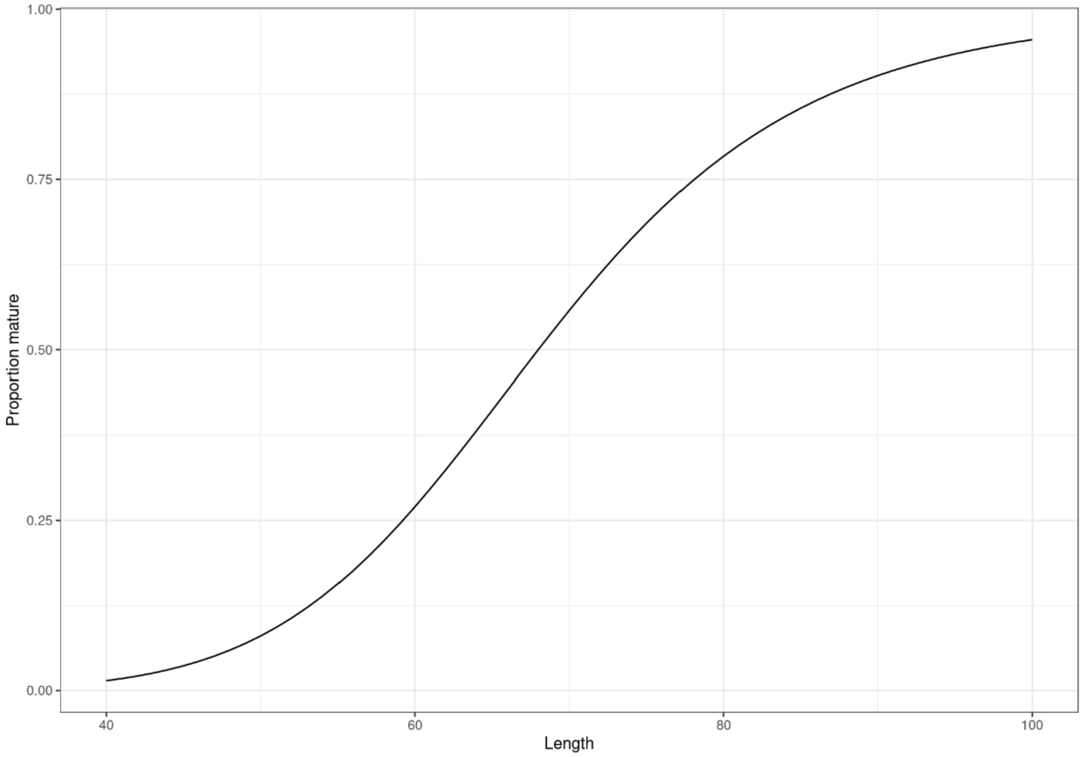
Greenland halibut. Observed age-length relationship from the Faroese survey.

Maturity data

Information on maturity for Greenland halibut is sparse, and the maturity scale used in the surveys is considered to be imprecise. A gonadsomatic index (GSI) value above 1% is considered be a good indicator of maturity (Kennedy pers comm). Information on gonad size is available from the Icelandic autumn survey (fig. **?@fig-gsimat**).



Greenland halibut. Observed propotion female mature by length the Icelandic autumn survey based on GSI > 1%.



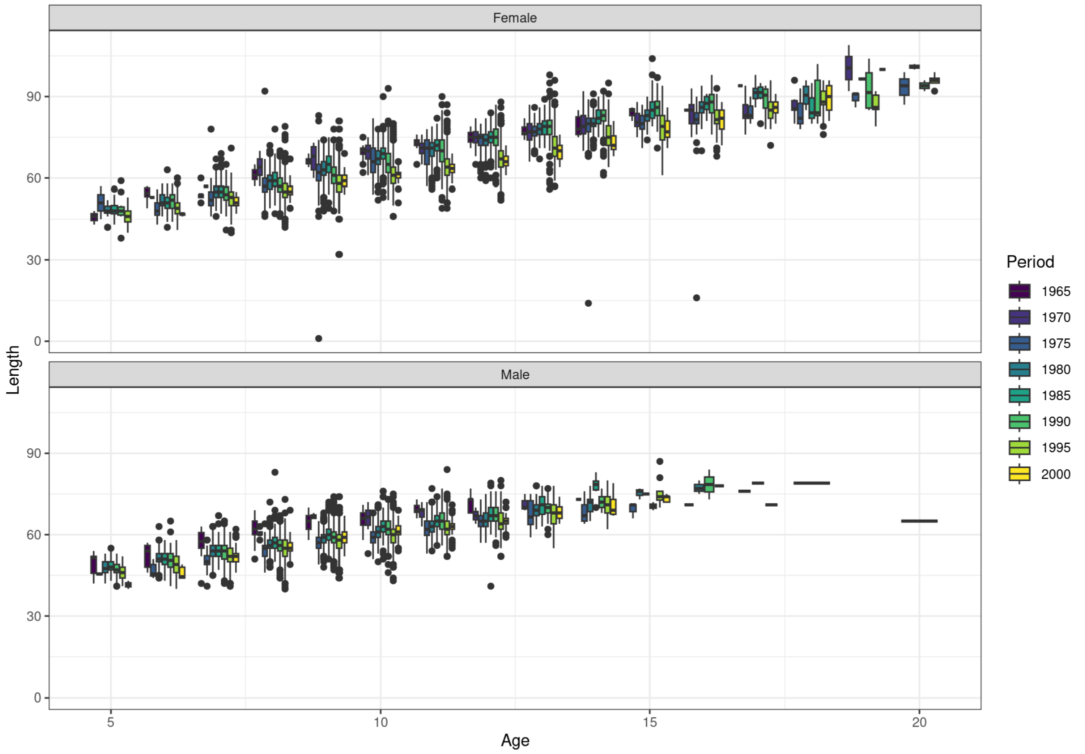
Greenland halibut. Estimated maturity ogive by length.

Greenland halibut in 5, 6, 12 and 14: Assessment using SAM

Overview of the input data

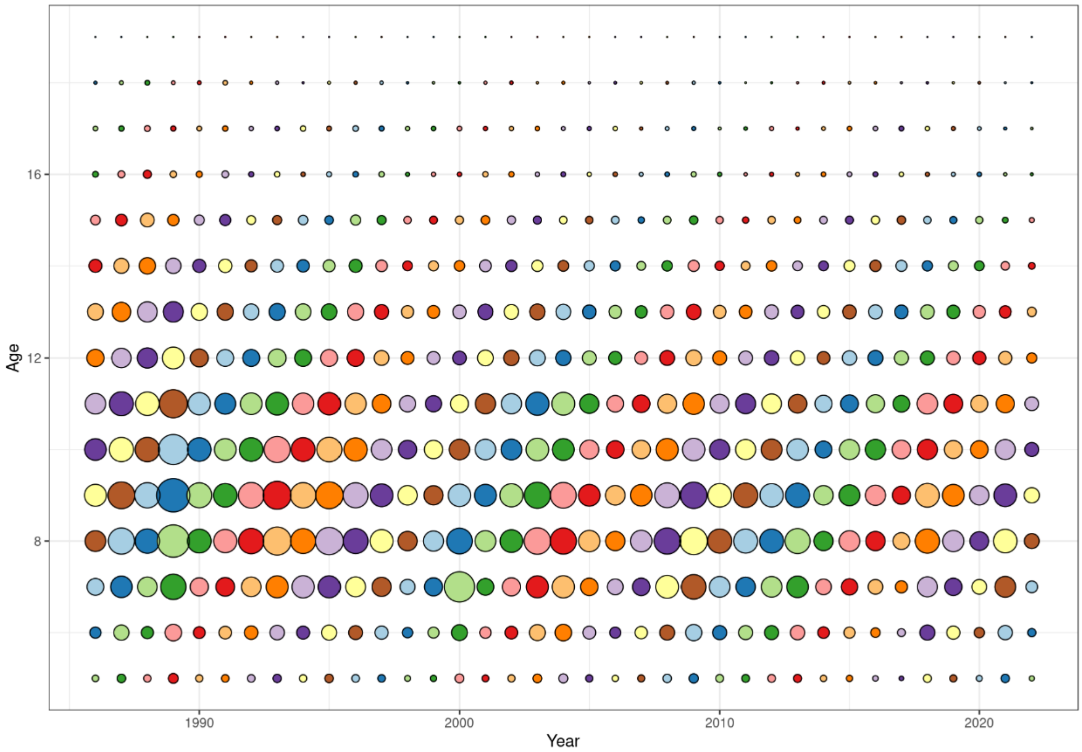
Constructing catch in numbers

Given the sparsity of age data constructing catch at age requires strong assumptions on historical growth, that is generating catch at age requires a fixed age-length-key for all years. Although known to be biased the historical age-readings suggest that this assumption may be valid (**?@fig-ghloldage**). There are however suggestions that this assumption could have been violated around 2000. However this change conincides withan abrupt change in age-readers for Greenland halibut.

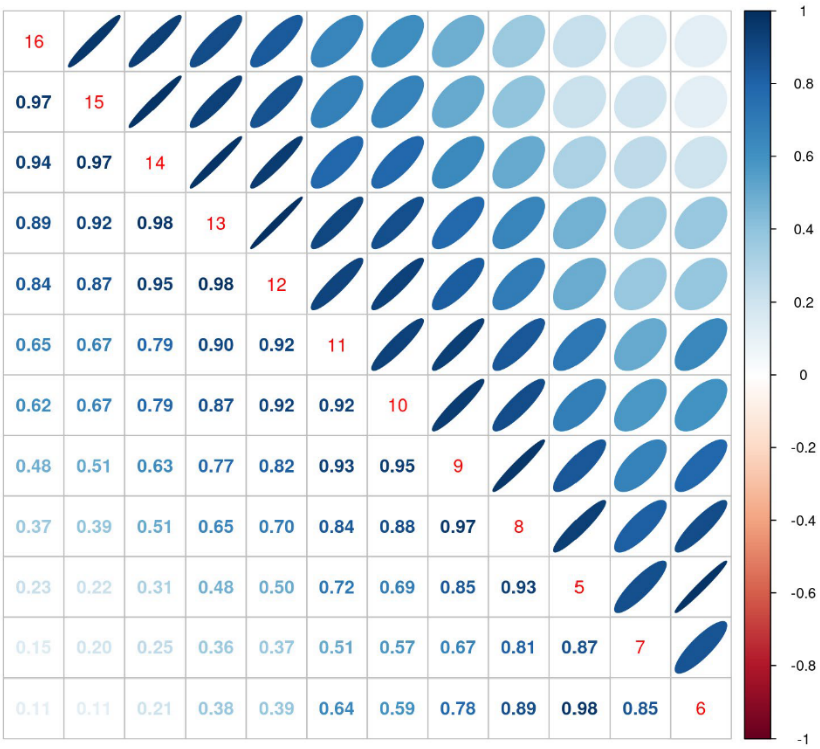


Greenland halibut. Boxplot showing the relationship between age and length by year and sex based on samples from the commercial fleet prior to 2005. Note that these readings are based on older and biased reading methods.

The commercial catch at age is shown in Fig. **?@fig-ghlcatage**.



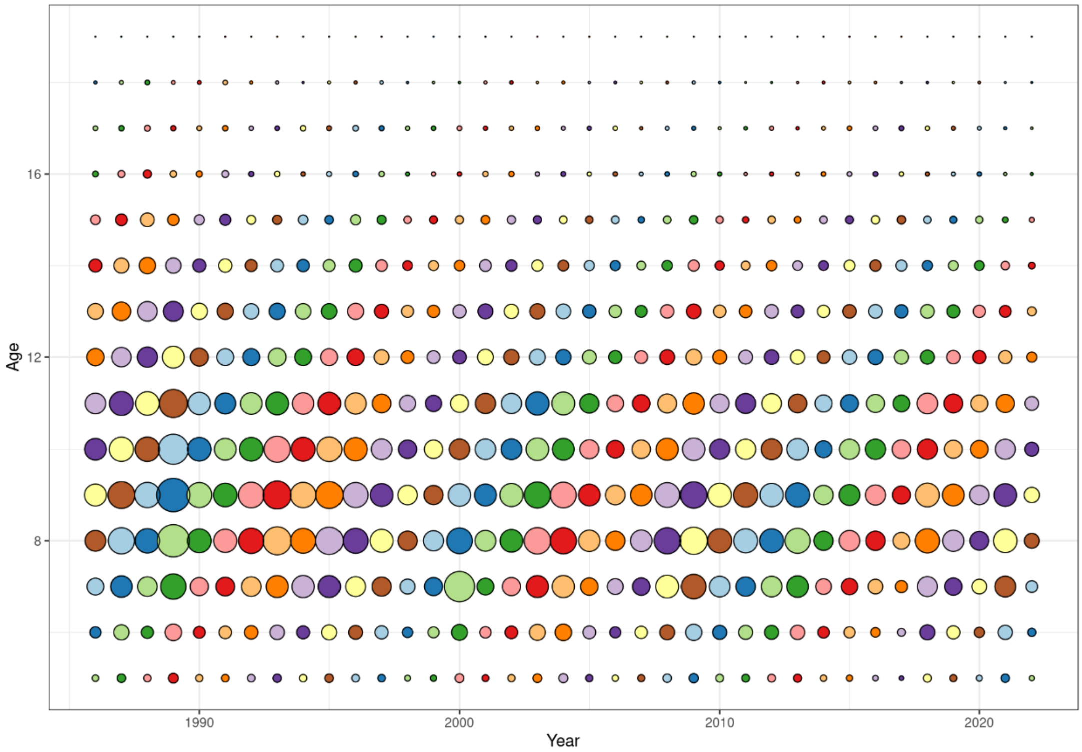
Greenland halibut. Catch at age, point sizes indicate the numbers by age. Points are colored by year class.



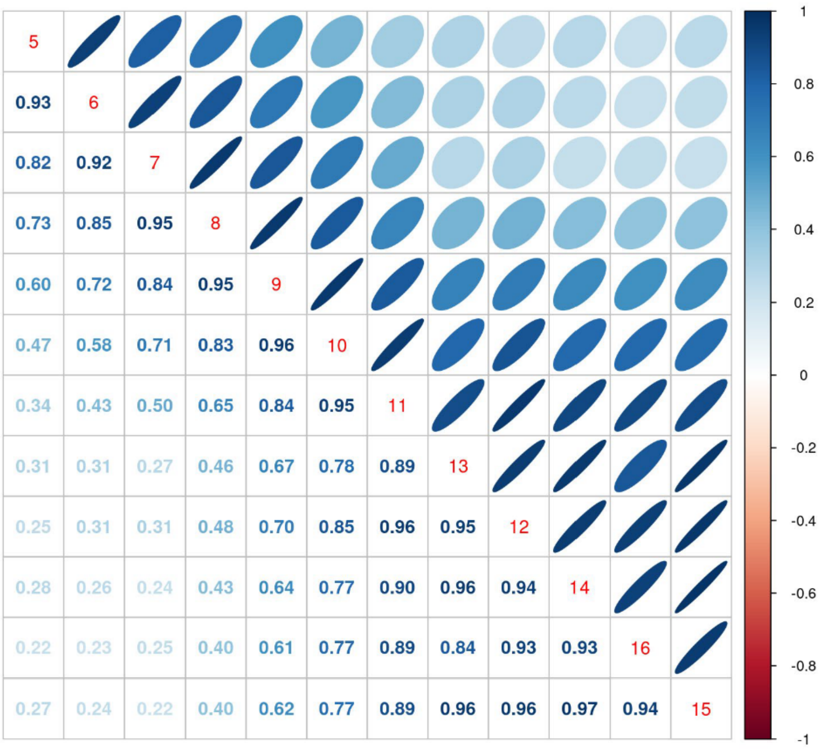
Greenland halibut. Internal consistency of the catch at age matrix. The panels illustrate the correlations between age groups, lower triangle panels show the estimated correlation while the upper show the c between the catch in numbers.

Surveys

Survey abundance at age from the autumn survey is shown in Fig. **?@fig-surveyatagebubble**. Fig. **?@fig-surveycons** shows the consistency in the survey index between ages. Correlation between adjacent year classes is considered satisfactory.



Greenland halibut. Survey numbers at age from the autumns survey, point sizes indicate the estimated swept area abundance by age. Points are colored by year class.



Greenland halibut. Internal consistency of the survey at age matrix. The panels illustrate the correlations between age groups, lower triangle panels show the estimated correlation while the upper show the c between the catch in numbers.

Weights, maturities, growth

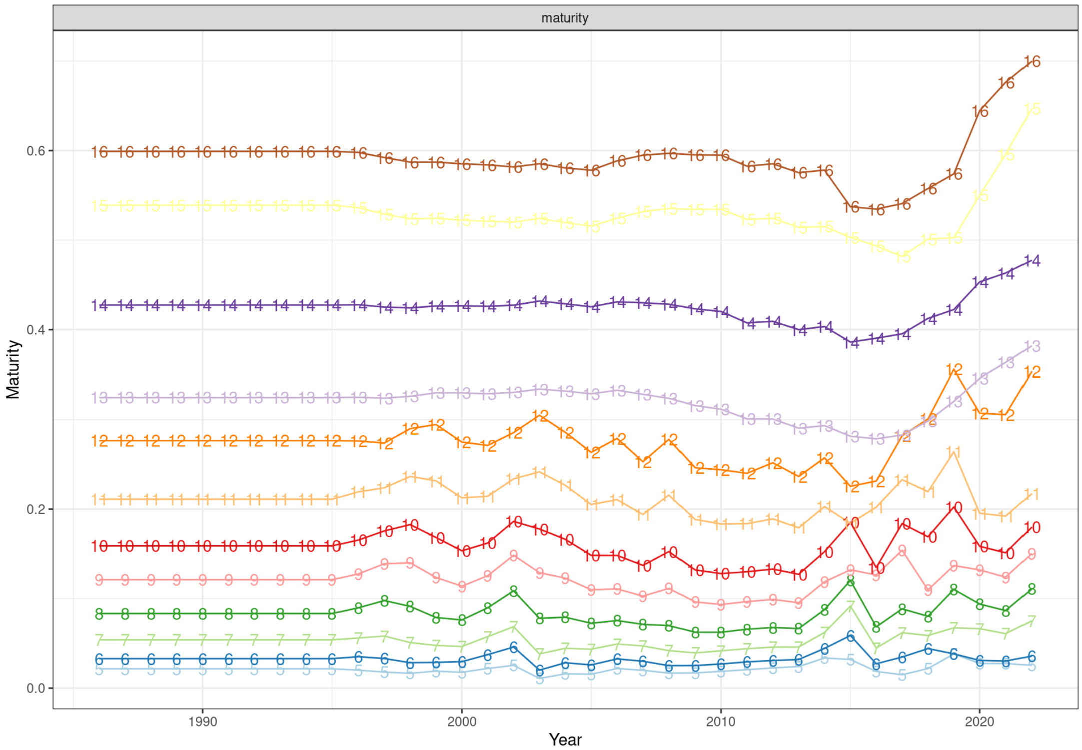
Growth

Mean weight at age in the stock and catch weight is shown in Fig. **?@fig-sweigthatage**. Those data are obtained from the groundfish survey in October and commercial catches respectively. Stock weights are also used as mean weight at age in the spawning stock. The weights are approximated from lengths. For stock weights for age 12 are smoothed using a running 3 year average. Prior to 1996 the stock weights are assumed fixed at 1996 levels.

Greenland halibut. Weight at age observed in the autumn survey and from the commercial catches.

Maturities

Maturity-at-age data are given in Fig. **?@fig-maturityatage**. Those data are obtained from the groundfish survey in October. Based on guidelines from PGCCDBS it was decided to use mature females as the basis for maturity at age. Prior to 1996 the proportion mature is assumed fixed at 1996 levels. Maturity at age was smoothed with a 3 year running average.



Greenland halibut. Proportion mature at age from the spring survey.

Natural mortality

Natural mortality was set as 0.15 in the models presented here. Alternative formulations are been considered in the results section.

Assessment model (SAM)

The assessment model used is the State space Assessment Model (SAM) described in (**SAM?**). The model runs from 1986 onward and ages 5 to 16 are tracked by the model, treating age 16 as a plus group. Observations in SAM are assumed to arise from a multivariate normal process with an expected value derived from the model. SAM allows for the investigation of how to treat patterns in the residuals by defining different parameters by age for observation residual variances and correlations for all data sets. Furthermore, the user can define age groups for survey catchabilities, and related power relationships, and process variances for the \(\log(N)\) and \(\log(F)\) residuals.

For Greenland halibut in 5, 6, 12 and 14 a number of combinations of parameter settings were initially investigated:

- Observation variances for both catch and survey data were split by age.

Adjacent age groups residuals were treated as they were correlated, split into groups of two.

- \(\log(N)\) variance split at age 5 and older ages vs not splitting. All configurations where the variances were split resulted in no-convergence.
- Power relationship for the survey indices.

The results of this exercise can be seen in the following table, where configurations that converged are listed:

conf	log(L)	#par	AIC	Obs. var	Obs. AR	N var.	Surv. Pow.	M
orig	60.09067	17	-86.18134	Fixed	-	All ages		0.15
looseOBS	117.08447	39	-156.16893	1 yr blocks	-	All age		0.15
joinedOBS	66.00363	18	-96.00725	Grouped	-	All ages		0.15
ARsurv	279.50593	23	-513.01185	Grouped	2 yr blocks	All ages		0.15
joinedAR	277.85478	22	-511.70956	Grouped	Grouped	All ages		0.15
Qpowrun	91.16490	30	-122.32980	Grouped	-	All ages	1 yr blocks	0.15
Qpowrun_less	69.60355	23	-93.20709	Grouped	-	All ages	Ages < 10	0.15
Qpowrun_const2	65.21760	20	-90.43520	Shared with comm	-	All ages	Split + grouped	0.15

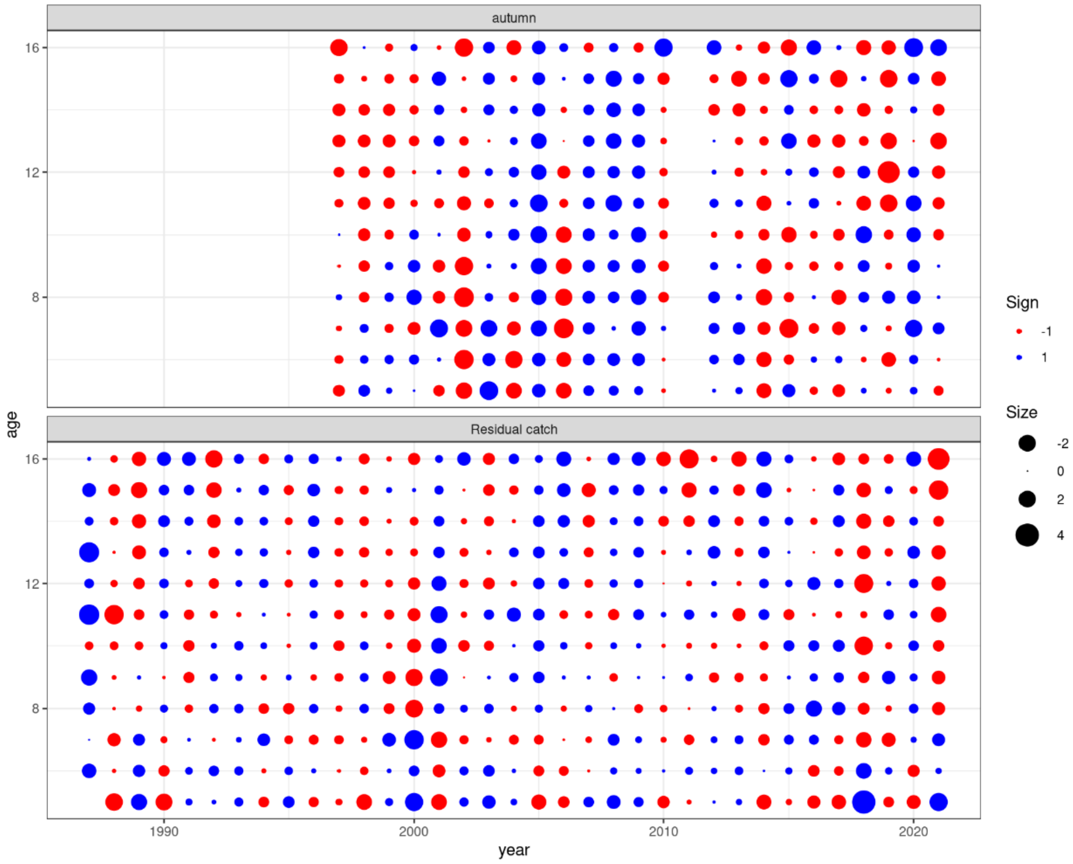
In general treating observation residuals as they were correlated AR(1) processes had the greatest effect on lowering the negative log likelihood. However when the analytical retrospective were compared using the Mohn's \(\rho\):

conf	R(age 5)	SSB	Fbar(9-14)
orig	0.0409435	0.1597640	-0.2023644
looseOBS	0.1117920	0.1724090	-0.1970062
joinedOBS	0.0595587	0.1675293	-0.2030173
ARsurv	0.2649863	0.4471563	-0.3899406
joinedAR	0.2732254	0.4510320	-0.3924108
Qpowrun_less	0.0203933	0.1765176	-0.2291973
Qpowrun_const2	-0.0025711	0.0190363	-0.0334125

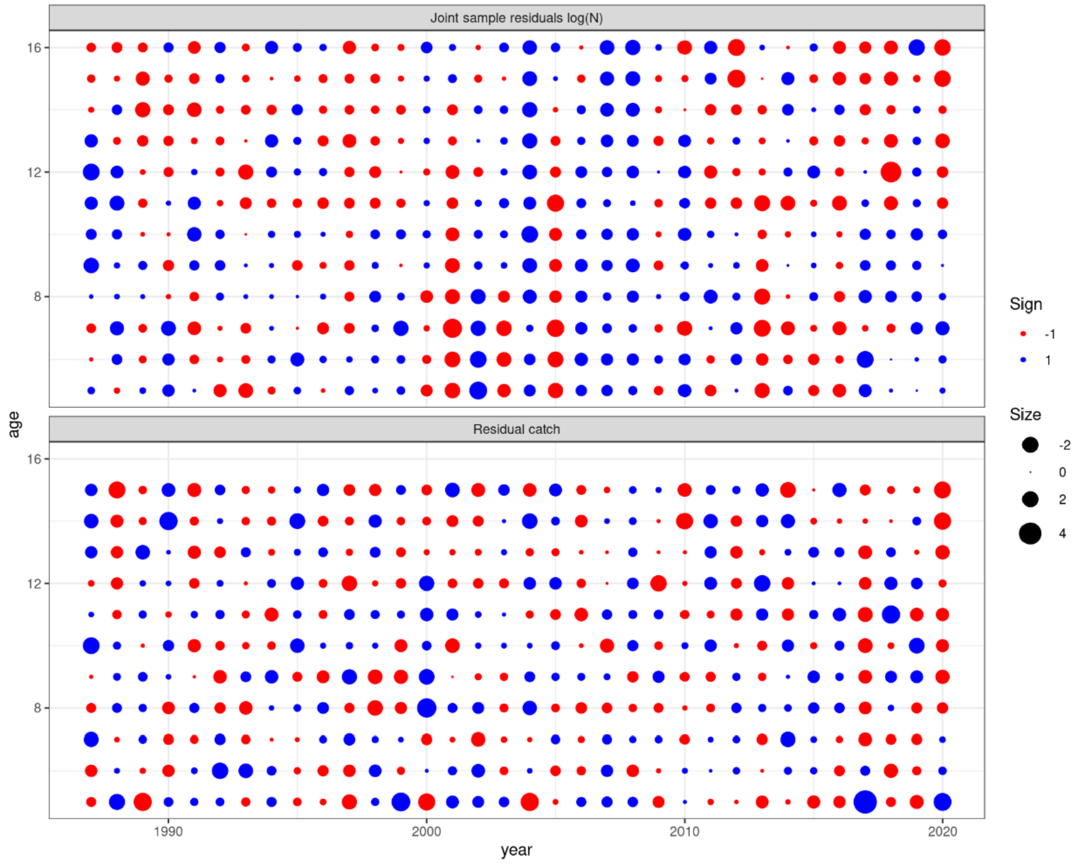
the most stable configuration is the `Qpowrun_const2` model, i.e. the model that assumes a constant observation variances for both commercial and survey observations, a non linear relationship for all indices (same coefficient for ages 8+) and assumes a fixed natural mortality of 0.15, but does not include correlation between ages in the survey.

The fit to data is illustrated in Fig. **?@fig-residplot** where residual patterns in the autumn survey fits were revealed, while the patterns in the commercial catches are weaker. The process residuals for \(\log(N)\) and \(\log(F)\), shown in Fig. **?@fig-presidplot**, also reveal similar patterns. When looking at the survey fits in log-space (fig **?@fig-sifit**) the model appears capture the main trends in both datasets.

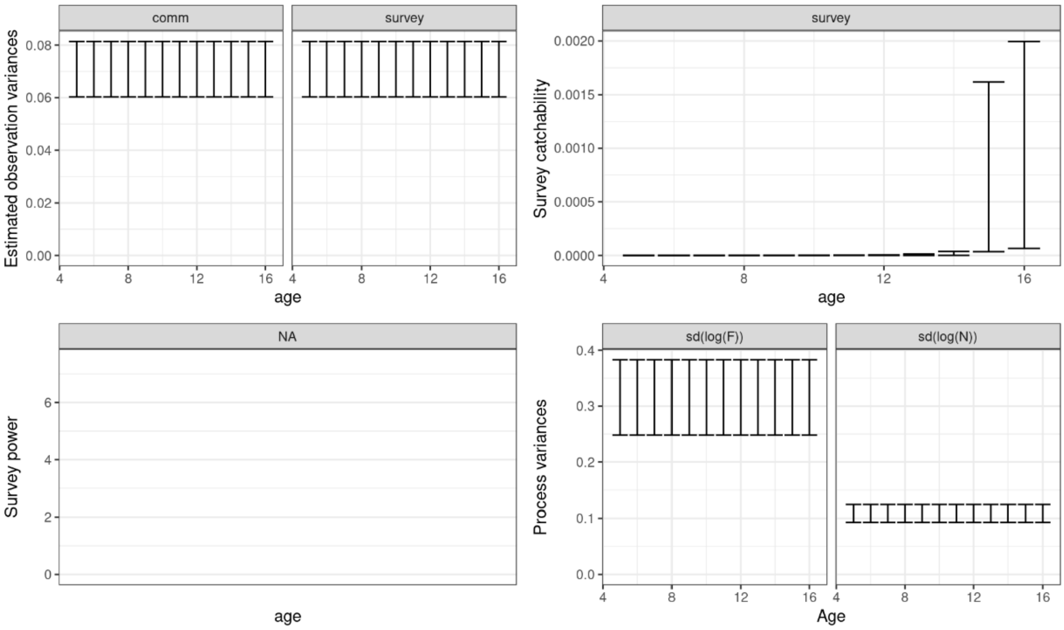
Fig. **?@fig-likplot** shows the estimated model parameters. Observation variances, both survey and commercial, with a common fixed variance. Process variances were fixed across all ages for both \(\log(N)\) and \(\log(F)\), with standard deviation estimated at 0.1 and 0.3 for \(\log(N)\) and \(\log(F)\) respectively. A non-linear relationship was estimated statistically significant for all ages, but decreasing with age. Stability of model parameters and population estimates was investigated using the `simulate` function in SAM and all model fits converged (within confidence limits) to the baseline model.



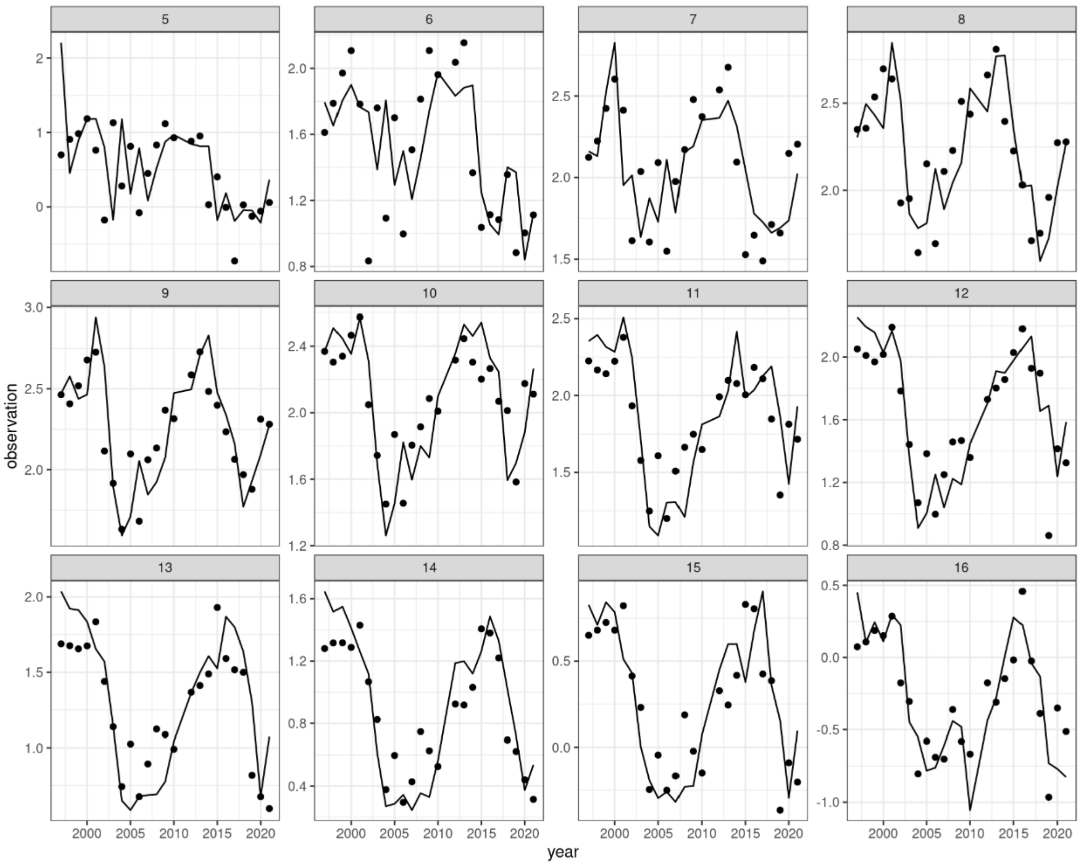
Greenland halibut in 5a. Model residuals from the assessment model. Red circles indicate where the model estimates are higher than the observed while blue indicate models estimates lower than observed.



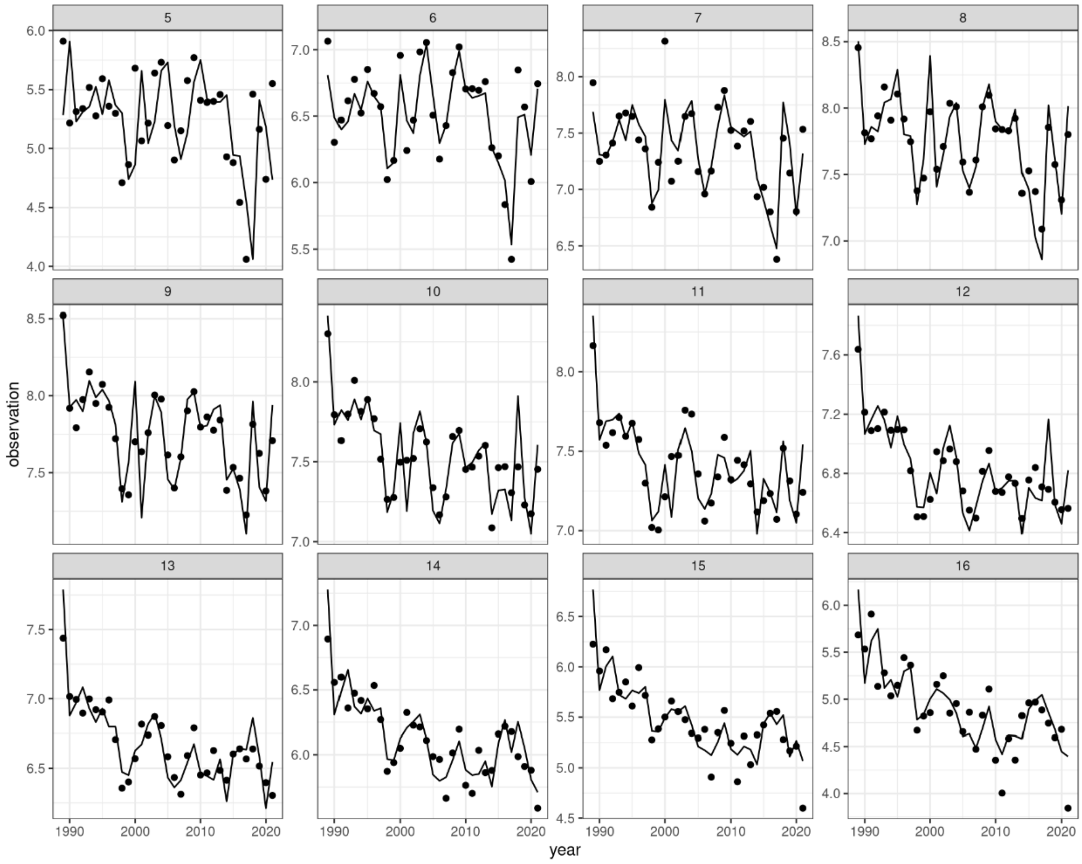
Greenland halibut in 5a. Process residuals from the assessment model.



Greenland halibut in 5a. Illustration of estimated model parameters.



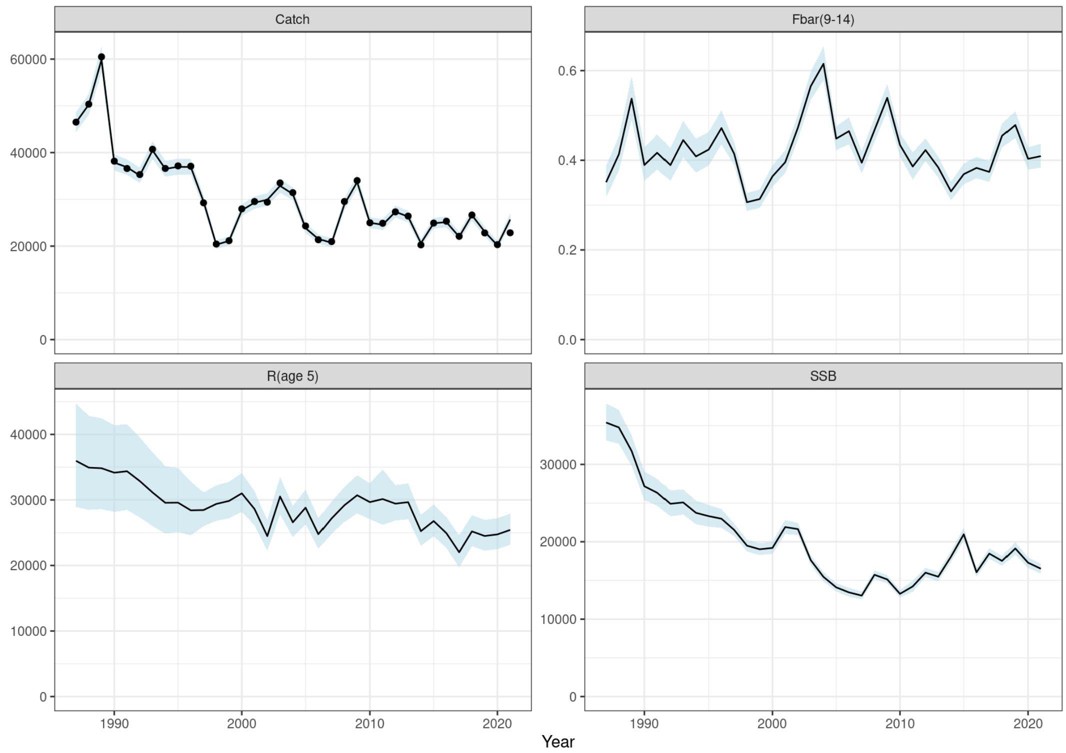
Greenland halibut in 5a. Illustration of the model fit to the survey data by age. Points indicate the log observations while the solid lines the model fit.



Greenland halibut in 5a. Illustration of the model fit to the commercial catch in age. Points indicate the log observations while the solid lines the model fit.

Stock overview

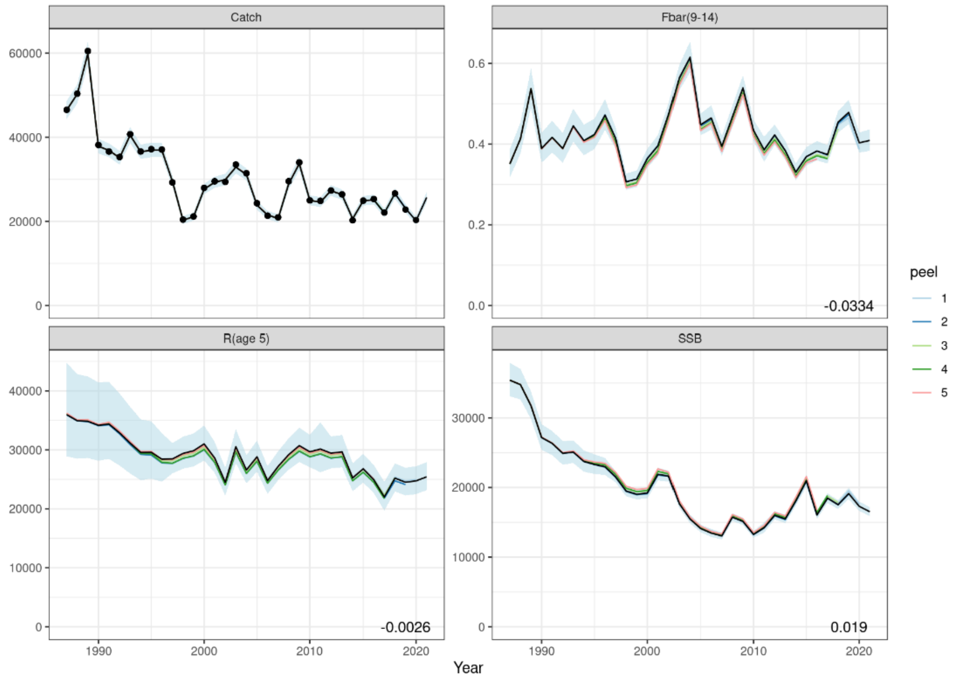
Population dynamics of Greenland halibut estimated by this model (Fig. **?@fig-icesplot**) show a clear increase in the level of recruitment (at age 5) in 2005, and subsequently we see an increase in SSB while total catches remained fairly constant. Spawning stock biomass (SSB) has been slowly increasing from its lowest value at the turn of the century.



Greenland halibut in 5a. Estimates of spawning stock biomass, fishing mortality (weighted average of ages 5 to 10), recruitment and landings from the best model. Black line represents the point estimates and blue ribbon the 90% confidence intervals.

Analytical retrospective

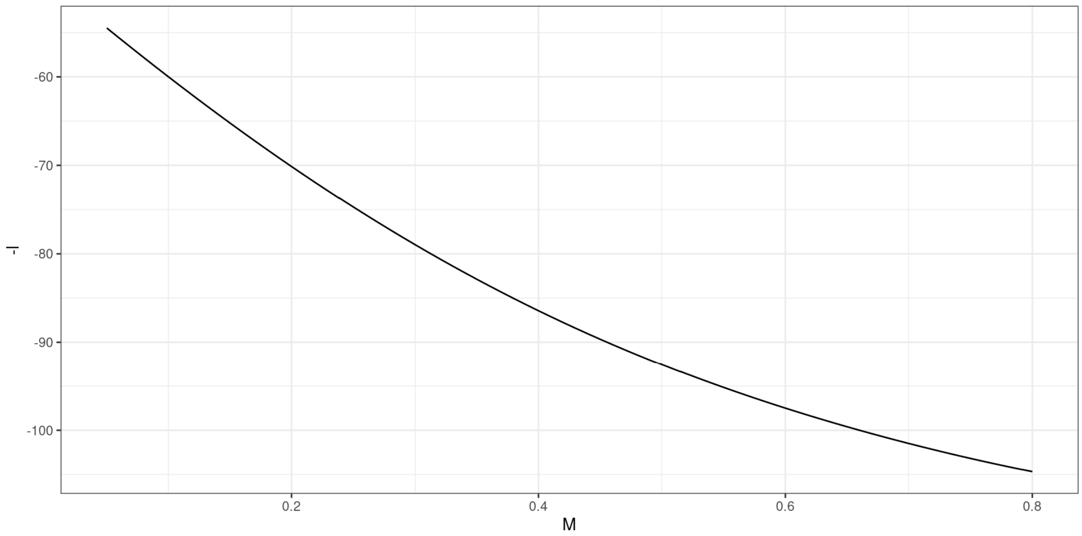
The proposed model had low Mohn's \(\rho\) statistic values for spawning stock biomass, fishing mortality, and recruitment. Analytical retrospective plots do not indicate any substantial deviations in assessment (Fig. **?@fig-retroplot**). These Mohn's \(\rho\) values are well within the range recommended by (carvalho2021cookbook?).



Greenland halibut in 5a. Analytical retrospective estimates of SSB, catch, F and recruitment. Mohns rho is indicated in the bottom right corner.

Sensitivity analysis

A range of M's were investigated (see Fig. **?@fig-profileM**). Investigating the profile likelihood suggests that the data is not informative on the value of natural mortality.



Greenland halibut. Profile likelihood plot (negative log likelihood) for different values of fixed M.

Appropriate Reference Points (MSY)

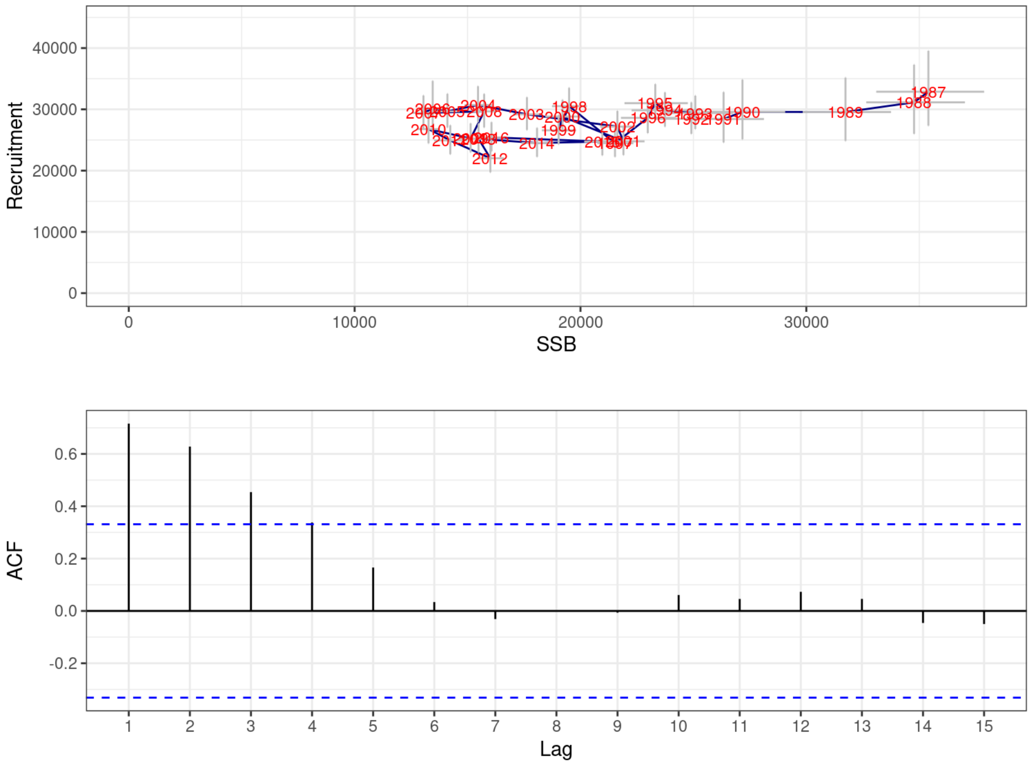
According ICES technical guidelines, two types of reference points are referred to when giving advice for category 1 stocks: *precautionary approach* (PA) reference points and *maximum sustainable yield* (MSY) reference points. The PA reference points are used when assessing the state of stocks and their exploitation rate relative to the precautionary approach objectives. The MSY reference points are used in the advice rule applied by ICES to give advice consistent with the objective of achieving MSY.

Generally ICES derives these reference points based on the level of the spawning stock biomass and fishing mortality. The following sections describe the derivation of the management reference points in terms of fishing mortality (\(F\)) and SSB (\(B\)). It further describes the model for stock–recruitment, weight and maturity at age, and assessment error which in combination with the MCMC results is used to project the stock in order to derive the PA and MSY reference points.

Setting \(B_{lim}\) and \(B_{pa}\)

\(B_{lim}\) was considered from examination of the SSB–Recruitment (at age 5) scatterplot based on the estimates from the stock assessment, as illustrated in fig. **?@fig-ssbrec**. The plot is shows no evidence of impaired recruitment and no clear relation between stock and recruitment (Type 5). In that scenario \(B_{lim}\) is derived from the lowest observed SSB (i.e. \(B_{loss}\) = 13000 t).

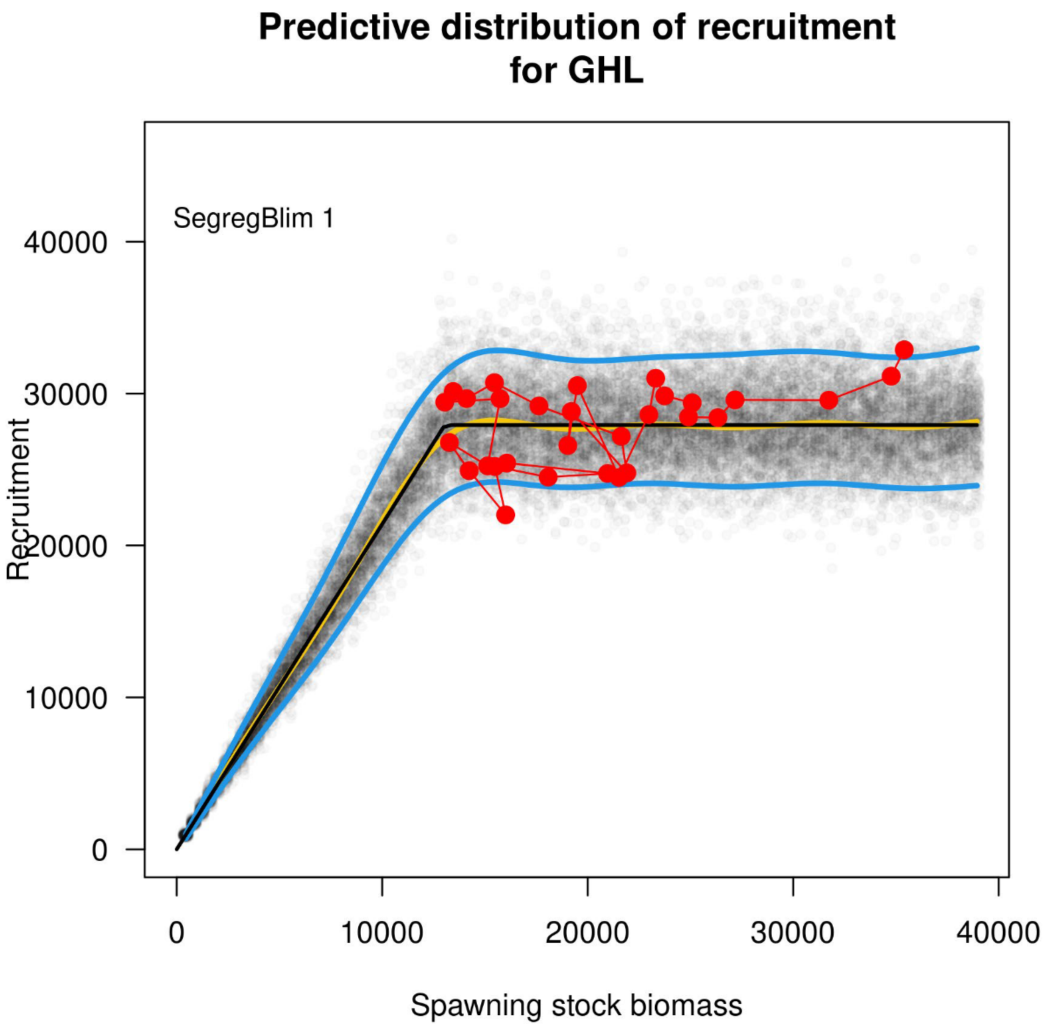
In line with ICES technical guidelines \(B_{pa}\) is then calculated based on multiplying \(B_{lim}\) with \(e^{1.645\sigma_{SSB}}\), where \(\sigma\) is the CV in the assessment year of SSB or 0.08, used for calculating \(B_{pa}\) from \(B_{lim}\). This is considered to reflective of the true assessment error of the SSB as the assessment is seen to be stable and input data are internally consistent. Therefore \(B_{pa}\) should be set at \(B_{lim}e^{1.645*\sigma_{SSB}} = 13500\) t.



Greenland halibut in 5a. Upper panel shows the stimated stock recruitment plot. Grey crossed indicate uncertainty, red text point estimate with the associated year and black lines show the progression of the stock recruitment relationship. The lower panel show the estimated autocorrelation of the recruitment time-series.

Stock recruitment relationship

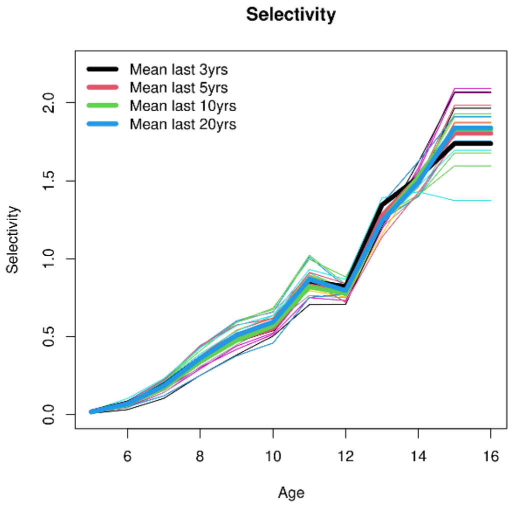
A variety of approaches are common when estimating a stock–recruitment relationship. In the absense of a stock-recruitment signal from the available historical data (Fig. **?@fig-ssbrec**), the ICES guidelines suggest that the ``hockey-stick'' recruitment function is used, i.e. $R_y = \bar{R}_y \min(1,S_y/B_{break})$ where R_y is annual recruitment, S_y the spawning stock biomass, B_{break} the break point in hockey stick function and $\bar{R_y}$ is the recruitment when not impaired due to low levels of SSB. Here $\bar{R}_y$ is considered to be drawn from an auto–correlated log–normal distribution with a mean, CV and ρ estimated based on the estimated recruits after 1990. This is done to account for possible auto-correlation in the recruitment time–series and possible shifts in productivity of the stock. An example of the simulated relationship is shown in fig. **?@fig-segregBlim**.



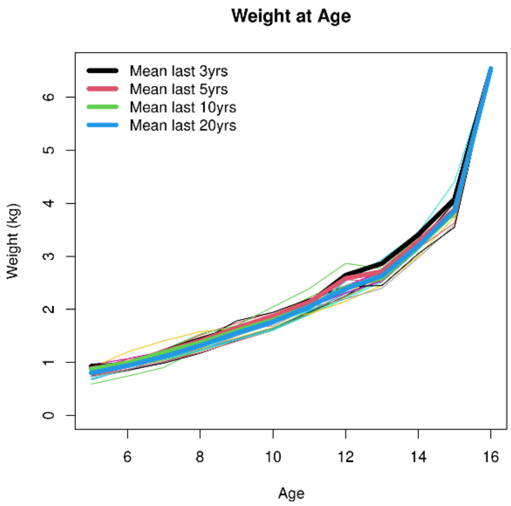
Greenland halibut in 5a. Estimated stock recruitment function used in the projections. Red points and lines show the model estimates, grey points show the simulated recruitment and blue lines the 95th quantiles.

Stock– and catchweights

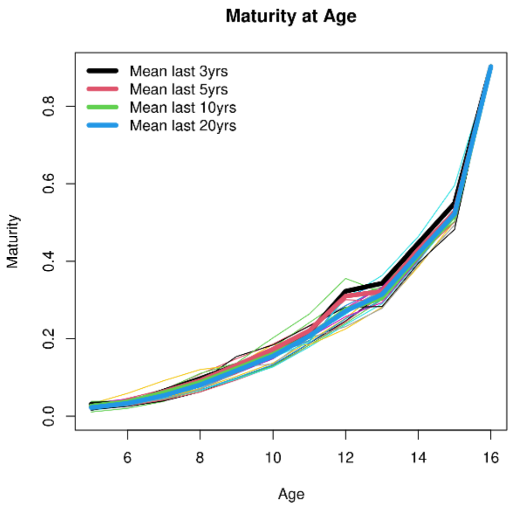
Prediction of weight at age in the stock, selectivity and the maturity at age follow the traditional process from the ICES guidelines, that is the average of the last 10 years of values for weight, selectivity and maturity at age used in the projections. These values are illustrated in figures @ref(fig-progsel) to @ref(fig-progmaa).



Greenland halibut in 5a. Settings for the projections. Estimated selectivity at age by year (narrow coloured lines) illustrated with 3, 5, 10 and 20 year averages (thick lines).



Greenland halibut in 5a. Settings for the projections. Estimated weight at age by year (narrow coloured lines) illustrated with 3, 5, 10 and 20 year averages (thick lines)



Greenland halibut in 5a. Settings for the projections. Estimated maturity at age by year (narrow coloured lines) illustrated with 3, 5, 10 and 20 year averages (thick lines)

Management procedure in forward projections

Illegal landings and discards by the fishing vessels are considered to be negligible (as noted above). Observation error is addressed by the MCMC simulation approach employed in here. The appropriate assessment error is simulated in terms of fishing mortality by assuming F in the projections is a log-normal AR(1) process with the default values for CV as 0.212 and autocorrelation of 0.423.

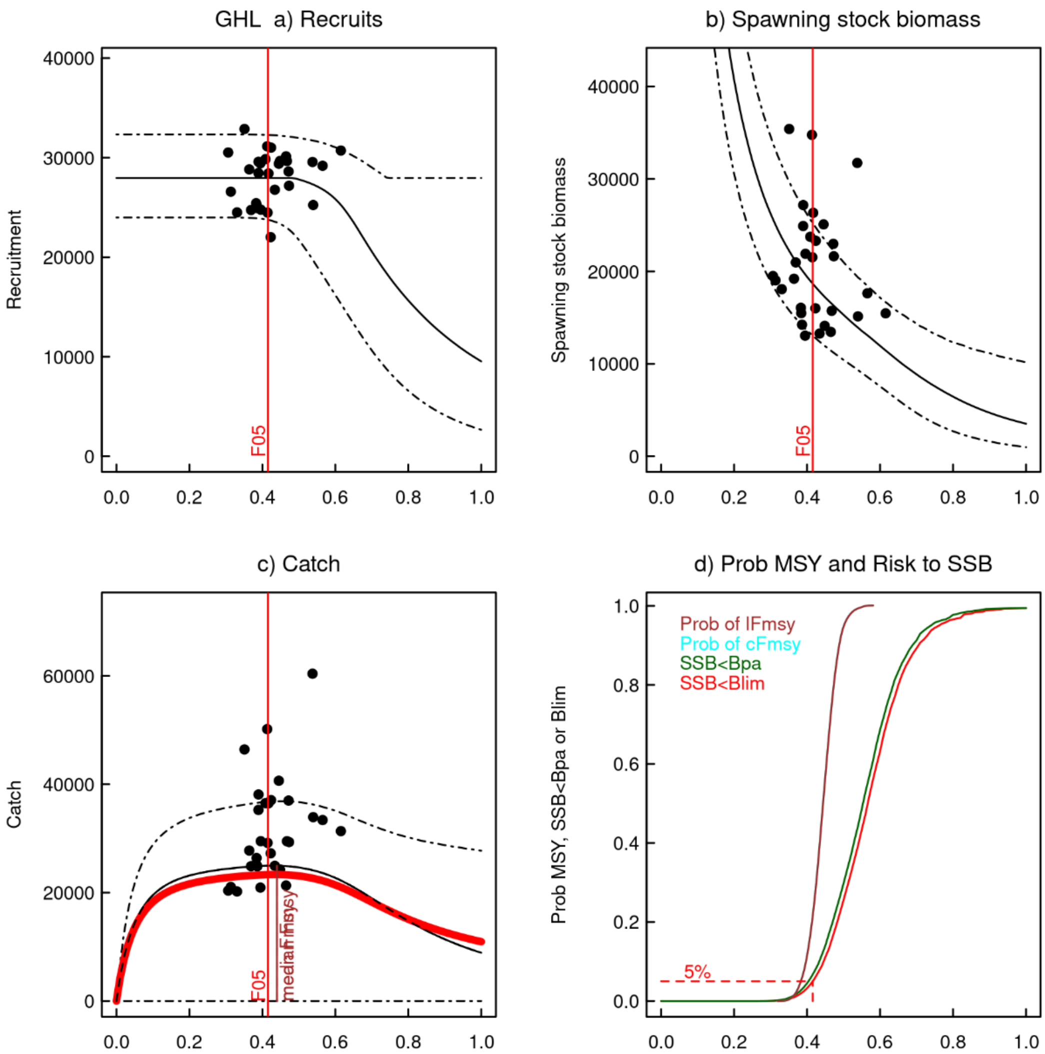
Setting F\(_{lim}\) and F\(_{pa}\)

According to the ICES guidelines, the precautionary reference points are set by simulating the stock using the stock-recruitment, growth and maturity relationship described above, based on a wide range of fishing mortalities, ranging from 0 to 1 and setting F\(_{lim}\) as the F that, in equilibrium, gives a 50% probability of SSB \(> B_{lim}\) without assessment error.

For each MCMC replicate the stock status was projected forward 50 years as simulations, and average of those projected values used to estimate the MSY reference points.The results from the steady state simulations estimate the value of F, F\(_{lim}\), resulting in 50% long–term probability of SSB \(>B_{lim}\) to be at 0.6.

MSY reference points

As an additional simulation experiment where, in addition to recruitment and growth variations, assessment error was added. The harvest rate that would lead to the maximum sustainable yield, F\(_{msy}\), was then estimated. Average annual landings and 90% quantiles were used to determine the yield by F. Fig. **?@fig-progn** shows the evolution of catches, SSB and fishing mortality for select values of F. The equilibrium yield curve is shown in fig. **?@fig-yieldplots**, where the maximum average yield, under the recruitment assumptions, is 6.8 thousand tons.



Greenland halibut in 5a. Equilibrium catch, recruitment, SSB and risk from forward projections. No trigger values used.

In line with ICES technical guidelines, the MSY \(B_{trigger}\) is set as \(B_{pa}\) as this is the first time the reference points are evaluated. Maximum yield is estimated to be obtained at a F of 0.42. F\(_{p05}\), i.e. the maximum F that has less than 5% chance of going below B\(_{lim}\) when the advice rule is applied, is 0.42, thus not limiting the estimate of F\(_{msy}\). The evolution of the spawning stock biomass is shown in figure **?@fig-progn** and equilibrium spawning stock biomass is shown in figure **?@fig-yieldplots**.

When the ICES AR rule is implemented is it appears that the probability of going below B\(_{pa}\) exceeds 0.2, suggesting that on average the effective fishing mortality is lower than the target F\(_{msy}\) of 0.4 suggesting that catch levels could fluctuate more than the fishable biomass level. So a lower fishing mortality could have similar yields while being more stable.

Greenland halibut in 5a. Overview of estimated reference points

Reference point	**Value**	**Basis**
MSYBtrigger	13500	Bpa
5thPerc_SSBmsy	15500	5th quantile of SSB when fishing at Fmsy
Bpa	13500	Blim x exp(1.645 sigma_SSB)
Blim	13000	Lowest SSB (1990) when large recruitment was observed (Type 1)
Flim	0.60	F leading to P(SSB < Blim) = 0.5
Fp05	0.42	F, when ICES AR is applied, leading to P(SSB > Blim) = 0.05
Fmsy_unconstr	0.43	Unconstrained F leading to MSY
Fmsy	0.42	F leading to MSY

WD06: Greenland halibut in 5, 6, 12 and 14: Analytical assessment using the Gadget assessment framework

Bjarki Þór Elvarsson

Overvivew of the input data

The Gadget assessment of Greenland halibut relies on a number of disparate datasets, ranging from survey indices from the autumn survey, landings by gear and area, and catch composition data from the various fleets that target Greenland halibut. An overview is shown in Figure 1. In contrast with the SAM model, where a fixed ALK is used to split catch at length in to catch at age for all years, age data are only available to the model at the time of sampling and past growth is estimated using the Von Bertalanfy growth process in the model.

Length weight relationship

The length weight relationship is estimated based on the available biological information in the Icelandic autumn survey using the following relationship:

$$W_l = \alpha \times l^\beta$$

The observed values are shown in Figure 2.

Model configuration

Overview of settings

- Start year 1985
- Two timesteps, equal in length, within the year
- Age range: 1 to 20^+
- Size range: 4 – 100 cm, 1 cm length groups

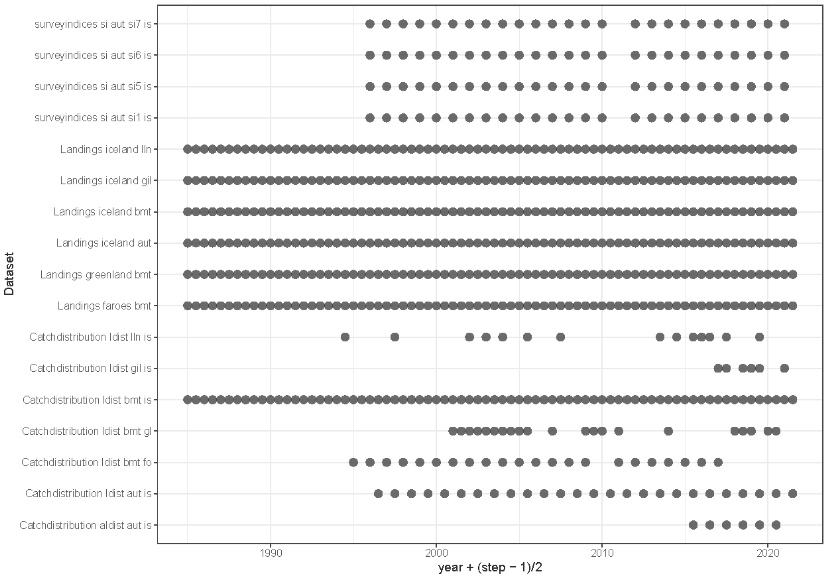


Figure 1: Greenland halibut. Overview of the datasets used and when they are available.

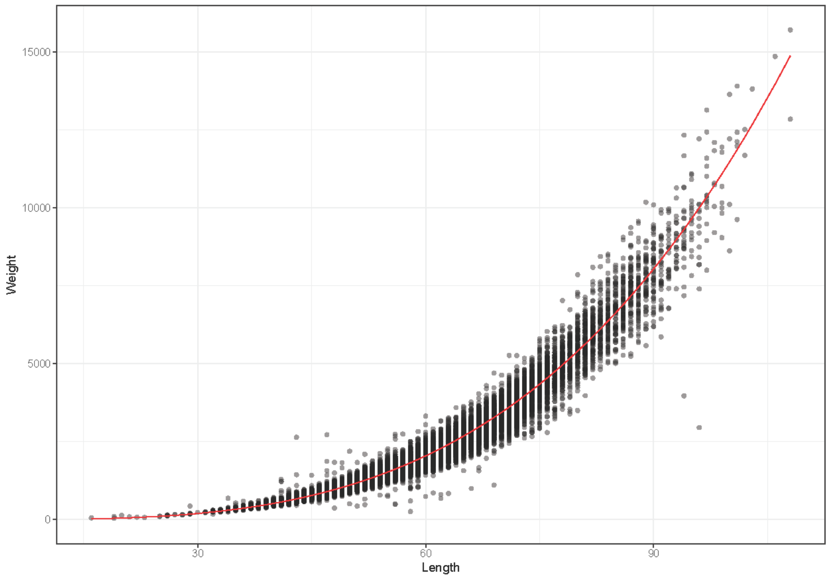


Figure 2: Greenland halibut. Observed length–weight relationship (dots) and the fitted relationship (red line)

- Growth:
  - Length based Von Bertalanffy size update (k, L_∞)
  - Beta-binomial size dispersal with a maximum length group growth set as 15 cm (β)
  - Length – weight relationship estimated externally
- Natural mortality set as 0.15
- Initial population and recruitment
  - Annual recruitment occurs in the first timestep, one parameter per year R_y.
  - Mean length and standard deviation at recruiment is estimated
  - Initial population at age is set as $S \times \mathfrak{n}_a \times e^{-a(M_a+\hat{F})}$
  - Initial mean length at age is defined using the Von B growth curve, and initial numbers at length are dispersed assuming a normal distribution around the mean length with a fixed CV.
- Fishing split by fleet:
  - 6 fleets, 1 survey, 3 bottom trawl (Greenland, Iceland and Faroese), gillnet and longlines in Iceland
  - Logit selectivity for each fleet (α_f, $l_{50,f}$)
- Maturity at length estimated externally based on autumn survey samples
- Likelihood functions:
  - Survey indices are fit assuming that $\log(I) = \alpha + \beta \log(\hat{I})$, where I and $\hat{I}$ are observations and model predictions respectively. α and β are estimated using linear regression.
  - Composition data are assumed randomly sampled and fit using sums of squares of proportions
- Uncertainties are estimated using a spatial bootstrap for the composition data and simulated survey indices based on estimated survey CV.

Maturities

Maturation is defined by a fixed length ogive of the form:

$$m_l = \frac{1}{1 + e^{-\alpha(l-l_{50})}}$$

where the parameters are estimated outside of the model.

Natural mortality

Natural mortality was set as 0.15 in the models presented here, where this value was chosen to represent the female part of the populations.

Assessment model (Gadget)

The assessment model used here was developed using Gadget, an age length modeling framework described in Lentin, Elvarsson, and Butler (2022). The model runs from 1985 onward and ages 1 to 20 are tracked by the model, treating age 20 as a plus group. The observation model is described in the GADGET WD. In addition to the base model described in the WD variation in recruitment and initial number at age were penalized increase the stability in those estimates. Initial numbers were penalized to come from a random normal distribution but with a common scalar to scale them commonly up or down. The penalty function applied to recruitment induces a random walk and is of the form:

$$l_R = \sum_{y=1986}^{Y} \left(-\log(2\pi\sigma_R^2)/2 - \frac{(\log(R_y) - \log(R_{y-1}))^2}{2\sigma_R^2} \right)$$

while the initial conditions parameters are treated as:

$$l_I = \sum_{a=1}^{A} \left(-\log(2\pi\sigma_I^2)/2 - \frac{\log(\mathfrak{n}_a)^2}{2\sigma_I^2} \right)$$

For Greenland halibut in 5, 6, 12 and 14 a number of combinations of parameter settings were initially investigated:

- Four stocks (2 sexes split by maturity, informed by maturity data)
- Including time-varying selectivity for the Icelandic bottom trawl fleet
- Including non-linear relationships in the survey indices of larger fish
- Including time-varying growth
- Fixing asymptotic length (L_∞)
- Including historical biased age data from commercial fisheries and estimating th bias
- Including other survey indices and commercial CPUE

A number of these explorations resulted in model estimates that were unstable or fit poorly with survey data. Parameters that were poorly estimated were given narrower bounds and variation or penalised as described above, and model structure simplified. As noted above the variation in initial conditions and recruitment was penalized, which improved the model stability. Age and maturity data by sex (or lack thereof) suggested that very little was gained by exploring a four stock model, the observed growth curves were not materially different and available data on maturation was poor, compared to increased complexity. Biases in historical age data were not considered to be a viable option until a systematic comparison between age reading methods had been conducted. Avenues that were not explored include mark-recapture experiments but could give better insights into the historical data from the early (pre 1980s) years of exploitation.

Table 1: Greenland halibut. Estimated Mohns ρ by model variant

variant	stock	total.biomass	F	recruitment
Fixed Linf	ghl	0.3720056	-0.3645818	-0.4665174
Base	ghl	0.1754297	-0.1549765	-0.5046561
Total biomass index	ghl	0.0555438	-0.1313167	0.0220613
Slope estimated	ghl	-0.0096143	0.0172979	-0.6146234
No recruitment penalty	ghl	0.2352755	-0.2775325	37.7753849

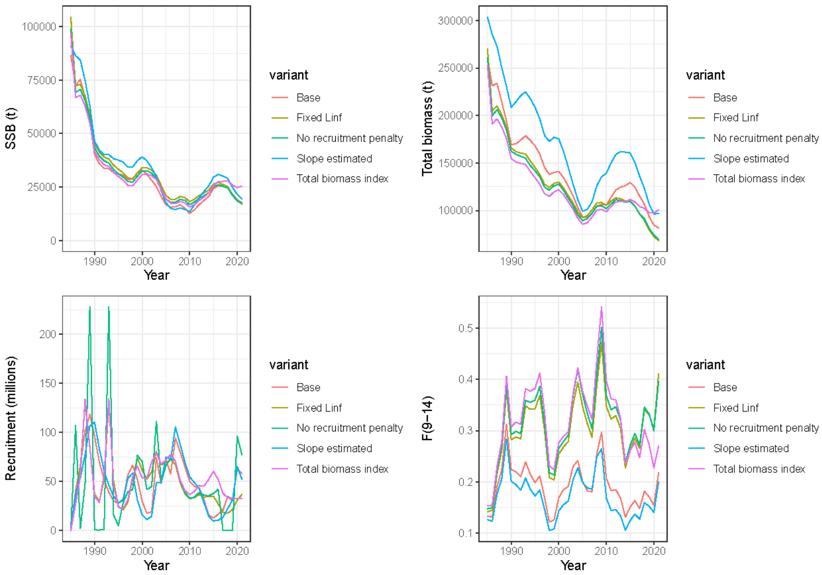


Figure 3: Greenland halibut. Comparison of model results by variant.

The viable model variants exhibited similar population trends and levels, in particular in the estimates of spawning stock biomass. However more variations can be seen in other metrics.

Table 1 shows the estimated Mohn's ρ by model variant. The most stable model configuration is the model where a non-linear relationship is estimated to the larger size ranges, but the variant where

Penalizing recruitment variations has an obvious effect on the estimated recruitment in the years before 2000, but did not appear to have a major effect on the estimated biomass levels. The "Base" and "Slope estimated" model configurations estimate the total population at higher level compared to other configurations. The model fit illustrated in Figure 4 shows that this difference between the model variants can be attributed to the fit to observed growth.

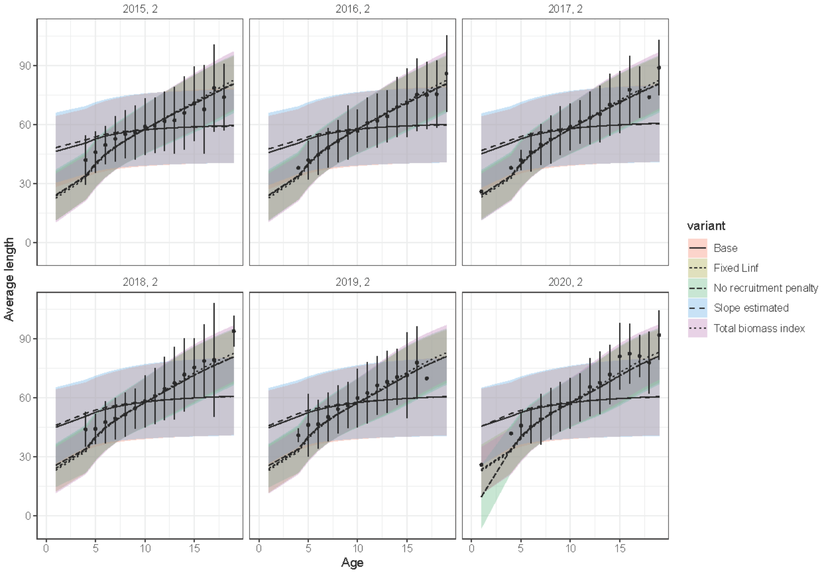


Figure 4: Greenland halibut. Comparison of the estimated growth by model variant to the observed values from the Icelandic autumn survey

The estimated growth in the "Base" and "Slope estimated" model does not fit the observed growth but instead appears to estimate high recruitment length and slower growth compared to other variants. These configurations appear however to fit the observed survey indices better, as illustrated in Figure 5.

This behavior is also evident when the bootstrap replicates are investigated, in particular the fit to survey indices shown in Figure 6 and Figure 7.

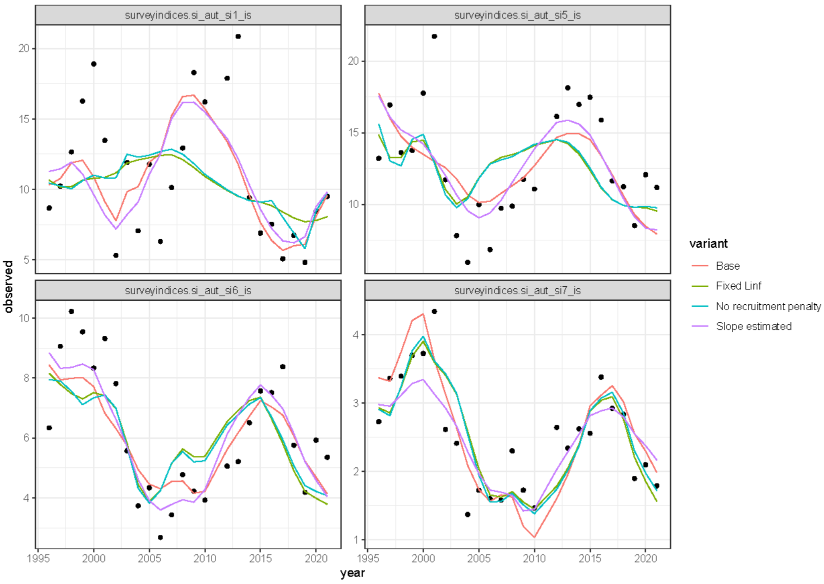


Figure 5: Greenland halibut. Comparison of the fit of the different model variants to the survey indices

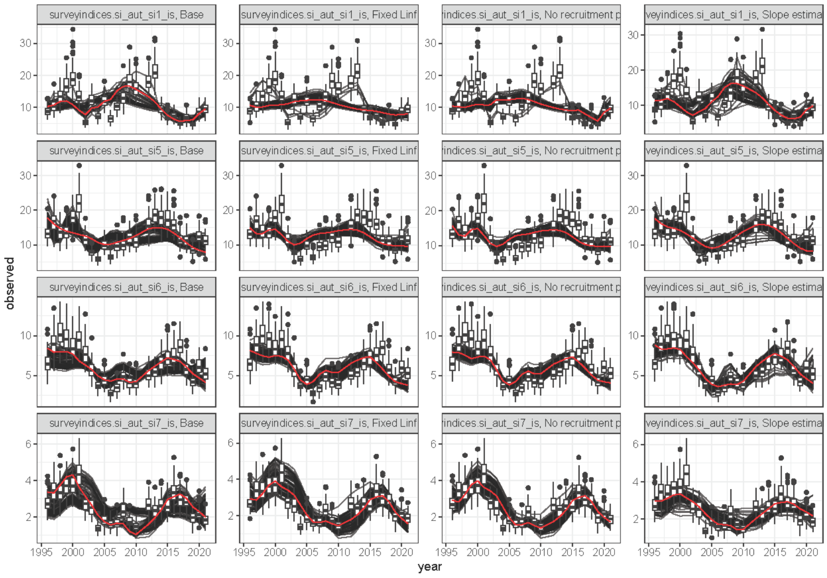


Figure 6: Greenland halibut. Comparison of the fit of the different model variants to the survey indices. Boxplots show the bootstrap replicate data and the black lines individual model estimates.

As the bootstrap replicates appear to jump between states of optimization of the stock, in particular for the models where the growth was poorly fit, and less likely to occur for other configurations. To account for these shifts a model with a single total biomass survey index was also tested. This model variant appeared to be more stable and had acceptable Mohn's ρ's for biomass and fishing mortality. Estimating a non-linear relationship for the total biomass index improved Mohn's ρ considerably.

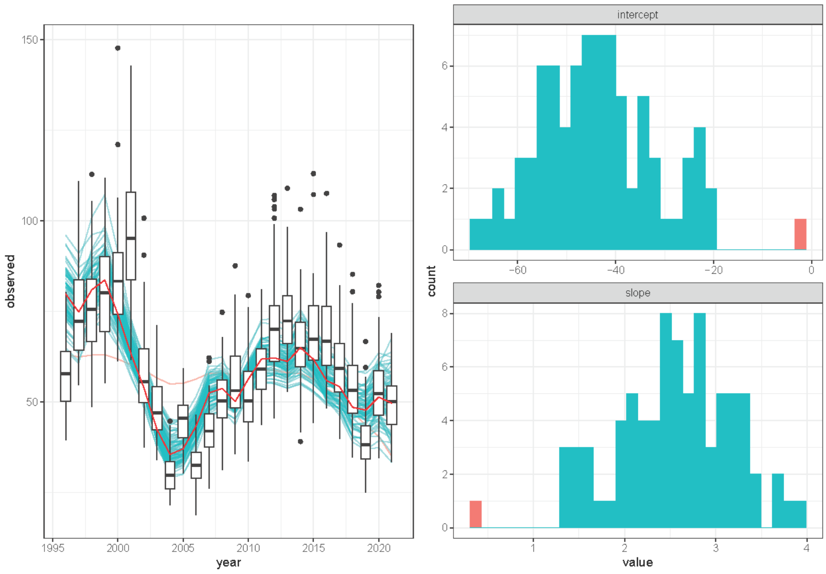


Figure 7: Greenland halibut. Comparison of the fit of the single biomass index variant to the survey indices. Boxplots show the bootstrap replicate data and the lines individual model estimates. Red indicates runs with a catchability slope estimated as < 1.

In comparison shown in Figure 8 where the mean length at age estimated by the model is show from all model variants. From this setup it is apparent that most of the model have a comparable median mean length that follow the age data with a high Linf. The exceptions include the 'Slope estimated' variant, with low median lengths at the oldest ages (blue boxplots), and 'Base' which has a high median length similar to the majority of models, but also a substantial proportion low median lengths at at the oldest ages (represented as point outliers under the red boxplots).

Based on the the above the subsequent analysis will be based the model fit to the single

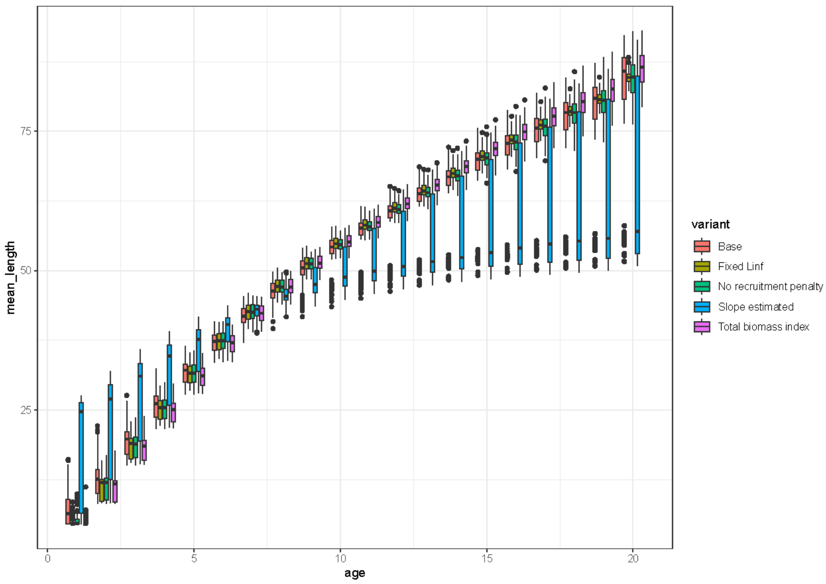


Figure 8: Greenland halibut. Variation in estimated growth by model variant from the bootstrap replicates.

biomass survey index.

Final model

Fit to catch composition data

The model estimated catch composition is illustrated in Figure 9 to Figure 15, with residual plot shown in Figure 16. In general the fit is best to the autumn survey data. Other datasets that have had fairly consistent sampling through the years, such as the bottom trawl samples, show no discernible patterns in the residuals, with the Icelandic bottom trawl and gillnet samples exhibit the lowest deviation in residuals. Observed longline size distributions, however, are fairly inconsistent from year to year and the model seems therefore to have higher propensity to ignore that dataset.

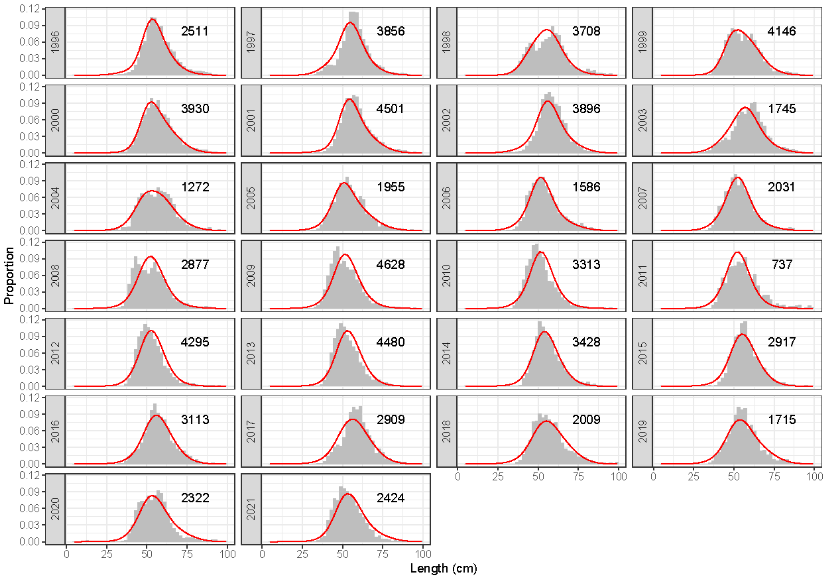


Figure 9: Greenland halibut. Comparison of the observed and estimated size distribution from the autumn survey catches. Observations are shown as grey bars while the estimated proportions by a red line. Number of fish sampled by year is indicated on each panel.

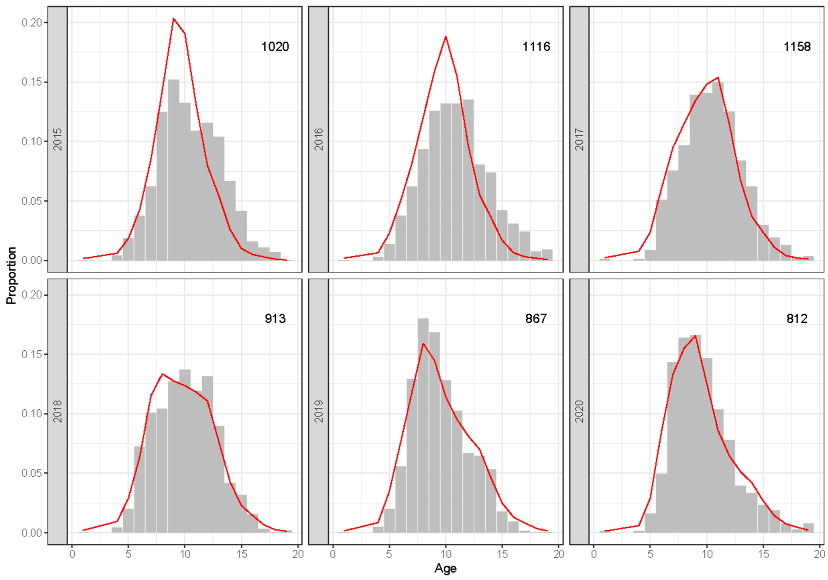


Figure 10: Greenland halibut. Comparison of the observed and estimated age distribution from the autumn survey catches. Observations are shown as grey bars while the estimated proportions by a red line. Number of fish sampled by year is indicated on each panel.

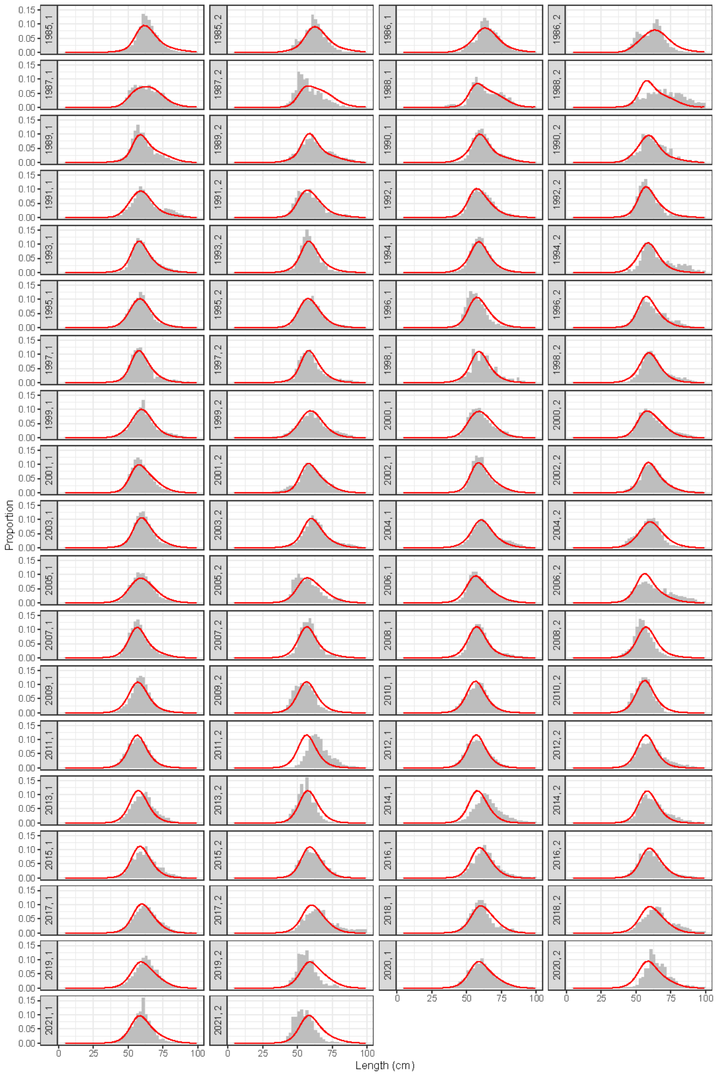


Figure 11: Greenland halibut. Comparison of the observed and estimated size distribution from the commercial bottom trawl catches in Iceland. Observations are shown as grey bars while the estimated proportions by a red line.

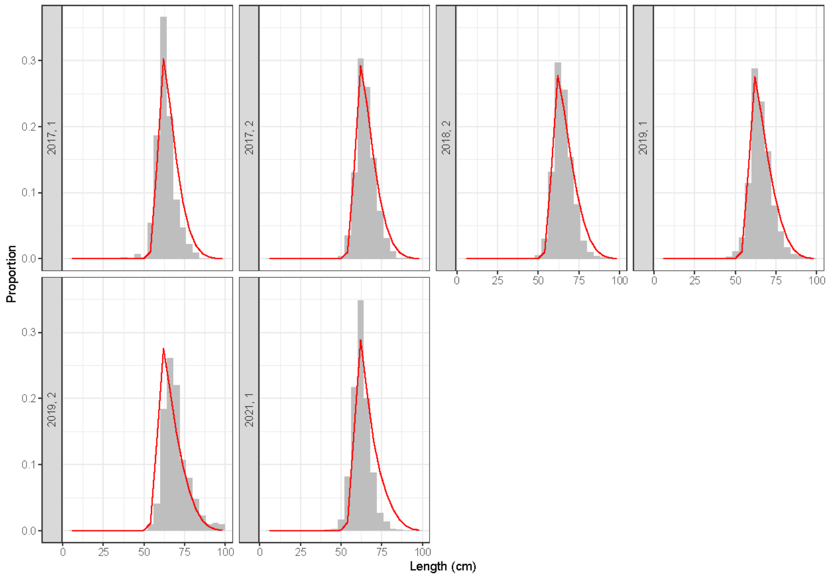


Figure 12: Greenland halibut. Comparison of the observed and estimated size distribution from the commercial gillnet catches in Iceland. Observations are shown as grey bars while the estimated proportions by a red line.

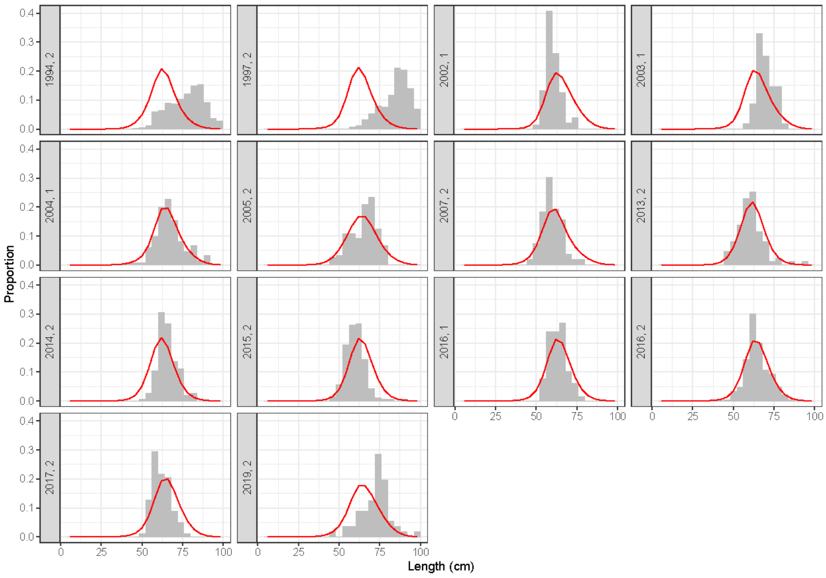


Figure 13: Greenland halibut. Comparison of the observed and estimated size distribution from the commercial longline catches in Iceland. Observations are shown as grey bars while the estimated proportions by a red line.

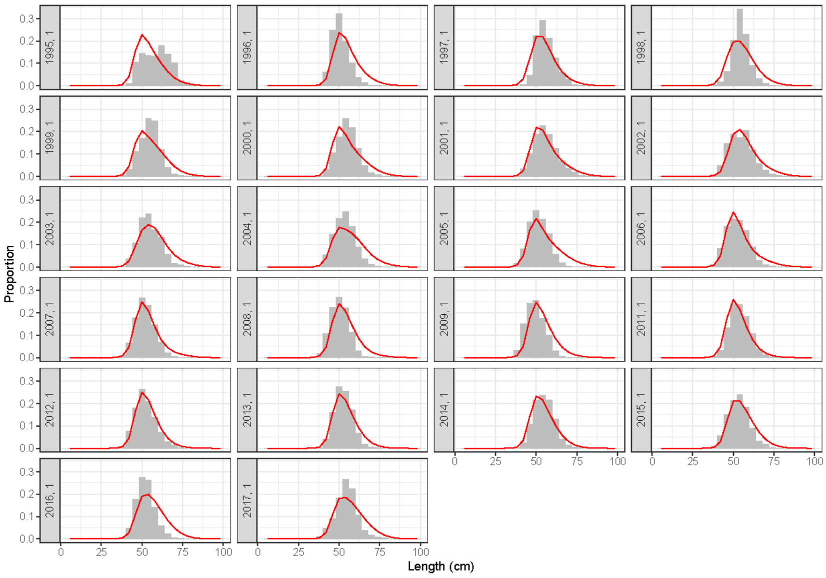


Figure 14: Greenland halibut. Comparison of the observed and estimated size distribution from the commercial bottom trawl catches in Faroe Islands. Observations are shown as grey bars while the estimated proportions by a red line.

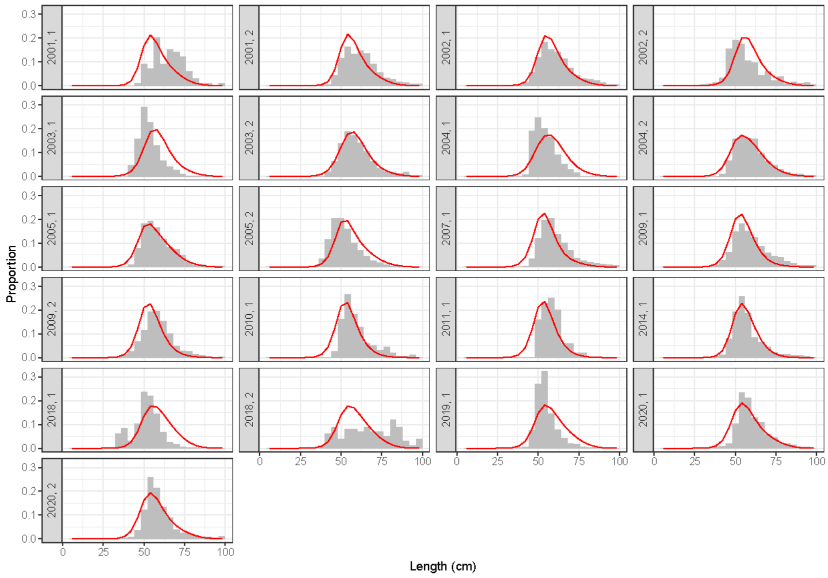


Figure 15: Greenland halibut. Comparison of the observed and estimated size distribution from the commercial bottom trawl catches in Greenland. Observations are shown as grey bars while the estimated proportions by a red line.

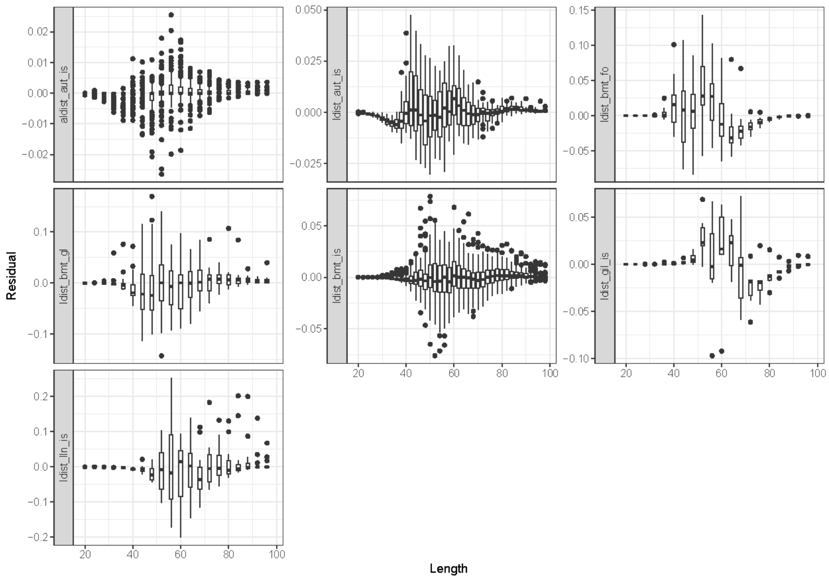


Figure 16: Greenland halibut. Model residuals by catch composition likelihood components

Model results

The results from the selected model configuration are shown in Figure 17. The total and spawning stock biomass are estimated to have decreased since its highest value at the start of the model period and reached its lowest point in SSB around 2005. Fishing mortality appears to fluctuate without trend. Analytical retrospective analysis is shown in Figure 18. The recruitment is estimated to fall outside the uncertainty bounds in the current assessment, suggesting that little information is available on the recruitment at age 1. In the absence of data the recruitment estimates are estimated close to previous year estimates (random walk constraint).

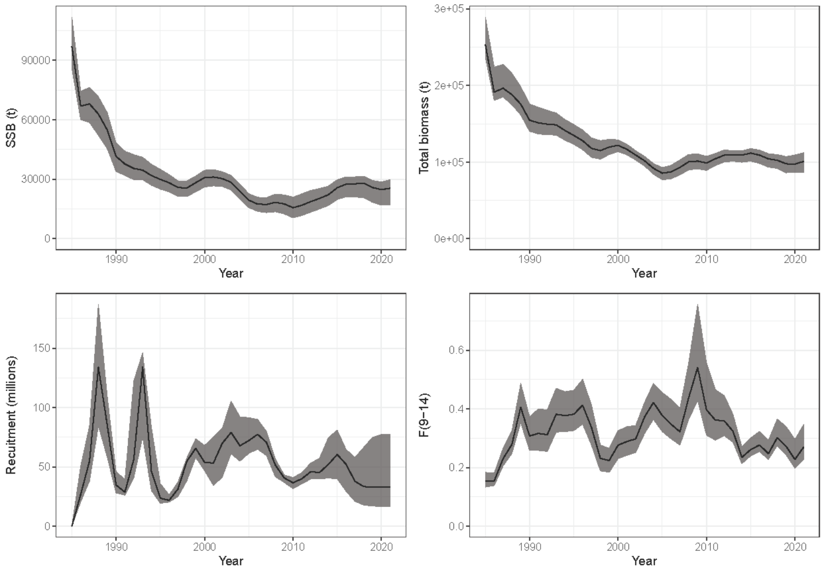


Figure 17: Greenland halibut. Estimates of total stock biomas, spawning stock biomass, fishing mortality and recruitment from the best model. Black line represents the point estimates and yellow ribbon the 90% confidence intervals.

Estimated selection by fleet is shown in Figure 19. The estimated selectivities range considerably, with the Faroese bottom trawl fleet catching the smallest fish while longline and gillnet boats in Iceland the largest. The Greenlandic and the autumn survey catch similar sizes.

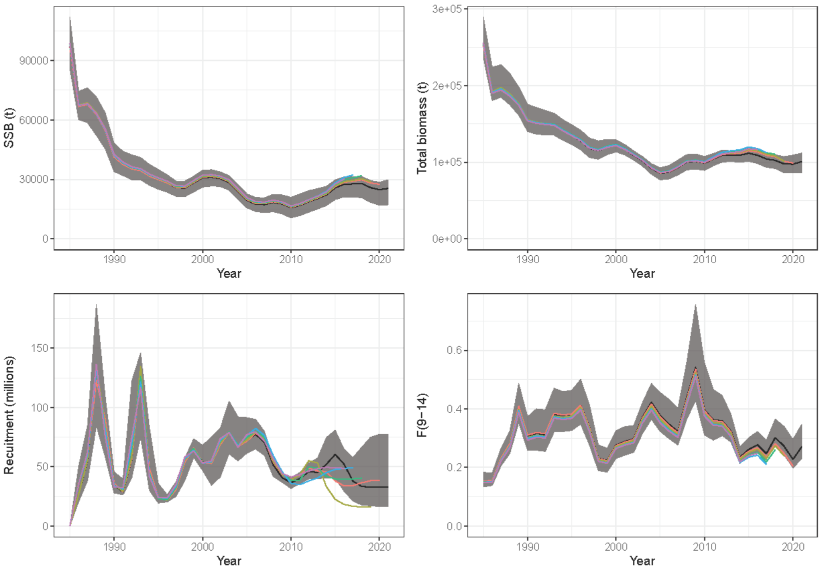


Figure 18: Greenland halibut. Analytical retrospective estimates of total stock biomas, spawning stock biomass, fishing mortality and recruitment from the best model. Colored lines represent the peeled point estimates and yellow ribbon the 90% confidence intervals.

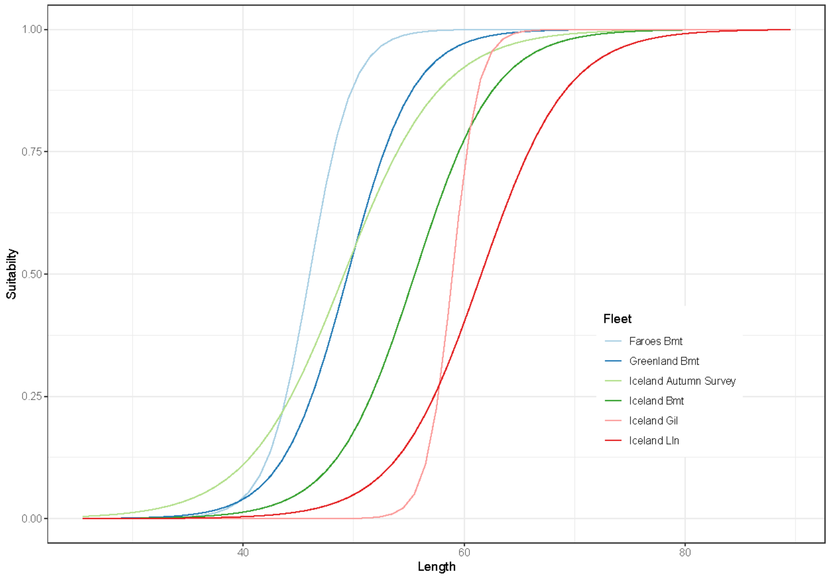


Figure 19: Greenland halibut. Estimated selection functions by fleet.

Conclusions

Overall the gadget model presented here captures the overall trends in the data, and in spite of minor mis-fits the model is usable for assessing the stock and to base advice to managers.

In a complicated such as the gadget model that has many parameters and many data-sets of varying quality it is to be expected that there may be problems with some parameters and fit to some data-sets.

The main problem encountered when building the model were strong year factors in the autumn survey. Although fitting to a single survey seems improve the retrospective estimates it does cause some concern. However as more age data becomes available in the coming years it is expected that this issue would be easier to reconcile within the model.

Most parameters are well defined, although parameters related to recruitment and initial abundance in earlier years, the reason being the limited age data for this period. Penalising deviations, as done here, appears to reduce the variations.

Another parameter that is poorly defined is the recruitment length and its standard deviation. This is also of minor importance as Greenland halibut does not enter the fishery until the age 5 and 6, but by then the beta-binomial length updata has created plausible standard deviation in the length at age.

Reference points

According ICES technical guidelines, two types of reference points are referred to when giving advice for category 1 stocks: *precautionary approach* (PA) reference points and *maximum sustainable yield* (MSY) reference points. The PA reference points are used when assessing the state of stocks and their exploitation rate relative to the precautionary approach objectives. The MSY reference points are used in the advice rule applied by ICES to give advice consistent with the objective of achieving MSY.

Generally ICES derives these reference points based on the level of the spawning stock biomass and fishing mortality. The following sections describe the derivation of the management reference points in terms of fishing mortality (F) and SSB (B). It further describes the model for stock–recruitment, weight and maturity at age, and assessment error which in combination with the MCMC results is used to project the stock in order to derive the PA and MSY reference points.

Setting B_{lim} and B_{pa}

B_{lim} was considered from examination of the SSB–Recruitment scatterplot based on the estimates from the stock assessment, as illustrated in fig. Figure 20. The plot is shows no evidence of impaired recruitment and no clear relation between stock and recruitment (Type 5). In that scenario B_{lim} is derived from the lowest observed SSB (i.e. $B_{loss} = 1.5657 \times 10^4$ t).

In line with ICES technical guidelines B_{pa} is then calculated based on multiplying B_{lim} with $e^{1.645\sigma_{SSB}}$, where σ is the CV in the assessment year of SSB or 0.19, used for calculating B_{pa} from B_{lim}. This is considered to reflective of the true assessment error of the SSB as the assessment is seen to be stable and input data are internally consistent. Therefore B_{pa} should be set at $B_{lim}e^{1.645*\sigma_{SSB}} = 2.1402 \times 10^4$ t.

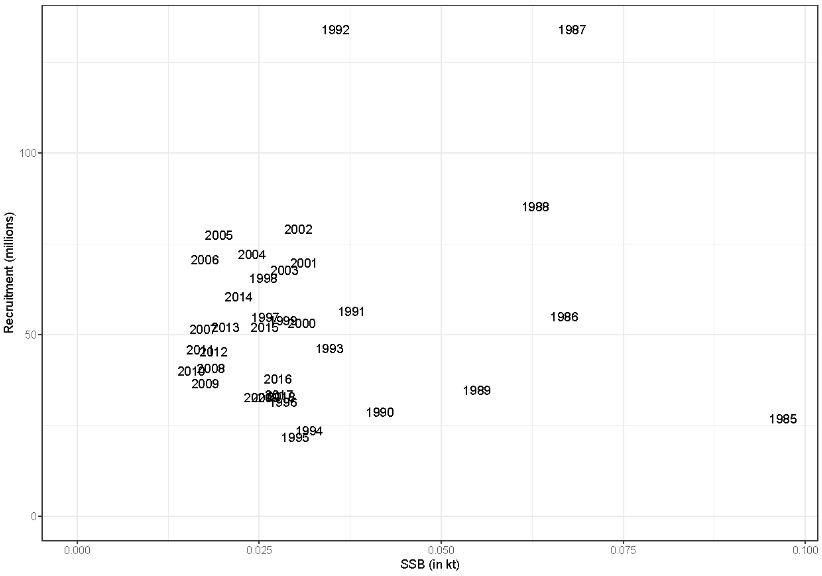


Figure 20: Greenland halibut. Fitted stock recruitment relationship

Stock recruitment relationship

A variety of approaches are common when estimating a stock–recruitment relationship. In the absense of a stock-recruitment signal from the available historical data (Fig. Figure 20), the

ICES guidelines suggest that the "hockey-stick'' recruitment function is used, i.e.

$$R_y = \bar{R}_y \min(1, S_y/B_{break})$$

where R_y is annual recruitment, S_y the spawning stock biomass, B_{break} the break point in hockey stick function and $\bar{R}_y$ is the recruitment when not impaired due to low levels of SSB. Here $\bar{R}_y$ is considered to be drawn from historical estimates after 1995 using a 7 year block-bootstrap from the bootstrap model estimates. This is done to account for possible auto-correlation in the recruitment time–series.

Biological parameters in the forecast

Maturity, growth and length-weight relationship in the forecast are based on the processes estimated within the model and bootstrap replicates. Similarly, fleet selectivities are the same as estimated by the model with catch proportions by fleet fixed to the average of last 5 years.

Management procedure in forward projections

Illegal landings and discards by the fishing vessels are considered to be negligible (as noted above). Observation error is addressed by the MCMC simulation approach employed in here. The appropriate assessment error is simulated in terms of fishing mortality by assuming F in the projections is a log-normal AR(1) process with the default values for CV as 0.212 and autocorrelation of 0.423.

Setting F_{lim} and F_{pa}

According to the ICES guidelines, the precautionary reference points are set by simulating the stock using the stock-recruitment, growth and maturity relationship described above, based on a wide range of fishing mortalities, ranging from 0 to 1 and setting F_{lim} as the F that, in equilibrium, gives a 50% probability of SSB $> B_{lim}$ without assessment error.

For each MCMC replicate the stock status was projected forward 50 years as simulations, and average of those projected values used to estimate the MSY reference points.The results from the steady state simulations estimate the value of F, F_{lim}, resulting in 50% long–term probability of SSB $> B_{lim}$ to be at 0.5.

MSY reference points

As an additional simulation experiment where, in addition to recruitment and growth variations, assessment error was added. The harvest rate that would lead to the maximum sustainable yield, F_{msy}, was then estimated. Average annual landings and 90% quantiles were used to determine the yield by F. The equilibrium yield curve is shown in Figure 21, where the maximum average yield, under the recruitment assumptions, is 2.6554×10^4 tons.

In line with ICES technical guidelines, the MSY $B_{trigger}$ is set as B_{pa} as this is the first time the reference points are evaluated. Maximum yield is estimated to be obtained at a F of 0.24. F_{p05}, i.e. the maximum F that has less than 5% chance of going below B_{lim} when the advice rule is applied, is 0.38, thus not limiting the estimate of F_{msy}. The equilibrium spawning stock biomass is shown in figure Figure 21.

Greenland halibut in 5a. Overview of estimated reference points

Reference point	Value	Basis
Blim	15657	Lowest observed stock biomass
Bpa	21402	Blim x exp(1.645 sigma_SSB)
Btrigger	21402	Bpa
Flim	0.5	F leading to P(SSB < Blim) = 0.5
Fmsy	0.24	F leading to MSY
Fpa	0.38	F, when ICES AR is applied, leading to P(SSB > Blim) = 0.05
HRlim	0.61	HR leading to P(SSB < Blim) = 0.5
HRmsy	0.29	HR leading to MSY
HRpa	0.46	HR, when ICES AR is applied, leading to P(SSB > Blim) = 0.05
MSY	26554	MSY

References

Lentin, Jamie, Bjarki Thor Elvarsson, and William Butler. 2022. *Gadget3: Globally-Applicable Area Disaggregated General Ecosystem Toolbox V3.*

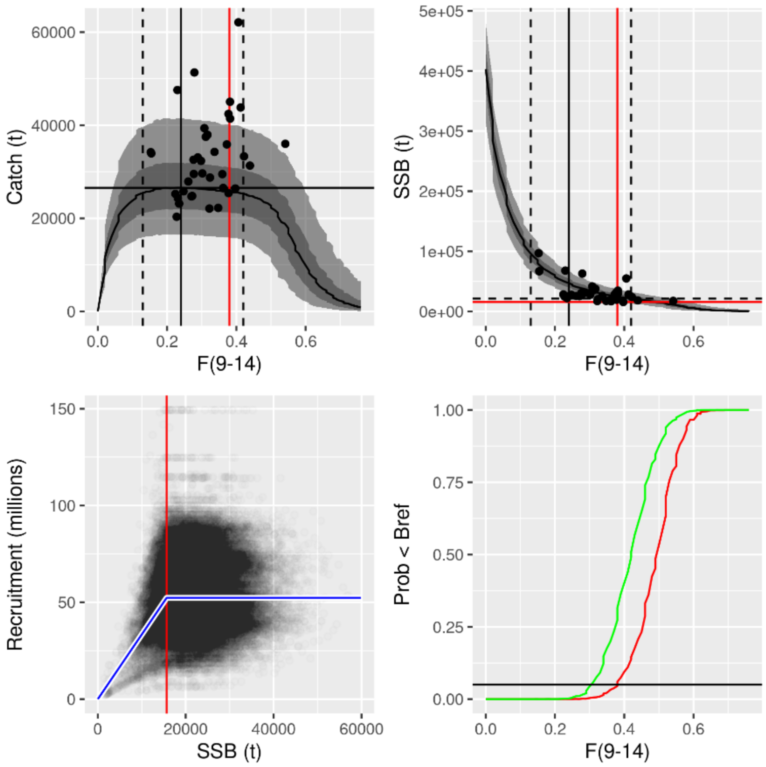


Figure 21: Greenland halibut in 5a. Equilibrium catch, recruitment, SSB and risk from forward projections.

WD08: SAM assessment of Golden redfish (*Sebastes norvegicus*) in ICES subareas 5,6,12, and 14.

Pamela J. Woods

Contents

1 Introduction

Several issues have come up in recent years regarding the assessment of golden redfish *Sebastes norvegicus* using the Gadget assessment framework, prompting a need for this benchmark. First, length-based survey indices of different length ranges are in disagreement with each other. That is, if the assessment is to fit the index of the smallest length range of golden redfish, then it will have to disregard patterns in the largest length range, and vice versa. Second, this disagreement in length indices is also apparent in length distribution data as narrowed distributions with little recruitment visible in recent years, but also little indication of larger sized fish, despite its high longevity. Finally, growth appears to differ slighly by region, but length-at-age data are highly variable and shows a trend toward larger fish at smaller ages in recent years. It is possible this is a result of density-dependent somatic growth.

For this benchmark, a Gadget model and SAM model were developed for the assessment of golden redfish. The Gadget model development was discontinued as it was apparent that there was a long enough time series of age data to run an age-based assessment, and the SAM model explored showed greater stability than the Gadget counterpart. Therefore, in this report, a SAM model is proposed with an updated length-based maturity ogive estimated from maturity data pooled over all years.

2 Scorecard on data quality

Scorecard on data quality was not used

3 Stock Assessment

3.1 Catch data – quality, misreporting, discards

Annual estimates of landings of golden redfish are available since 1905 and in recent decades, recorded by gear (Figure 1). The historical information are largely derived from the Statistical Bulletin, with unknown degree of accuracy, and retrieved from Statlant. For the period between 1980 to 1993, landings of Icelandic vessels were recorded by Fiskifélagið (a precursor to the Directorate of Fisheries). The more recent landings (from 1993 onwards) are from the Directorate of Fisheries as annually reported to ICES. After 2013, all landings in 5,6,12, and 14. are recorded by the Directorate, while foreign vessel landings were obtained from Statlant.

The estimates by the Directorate of Fisheries are based on a full census by weighing fish at the dock when landed or in fish processing factories prior to processing. Information on the landings of each trip are stored in a centralised database of which the Marine and Freshwater Research Institutes (MFRI) employees have full access. Captains are required to keep up-to-date logbooks that contain information about timing (day and time), location (latitude and longitude), fishing gear and amount of each species in each fishing operation. Logbooks are especially useful for providing information on catch location and monitoring its change over time (2). The Directorate of Fisheries and the Coast Guard can, during each fishing trip, check if amount of fish stored aboard the vessel matches what has been recorded in the logbooks, in part to act as a deterrent for potential illegal and unrecorded landings.

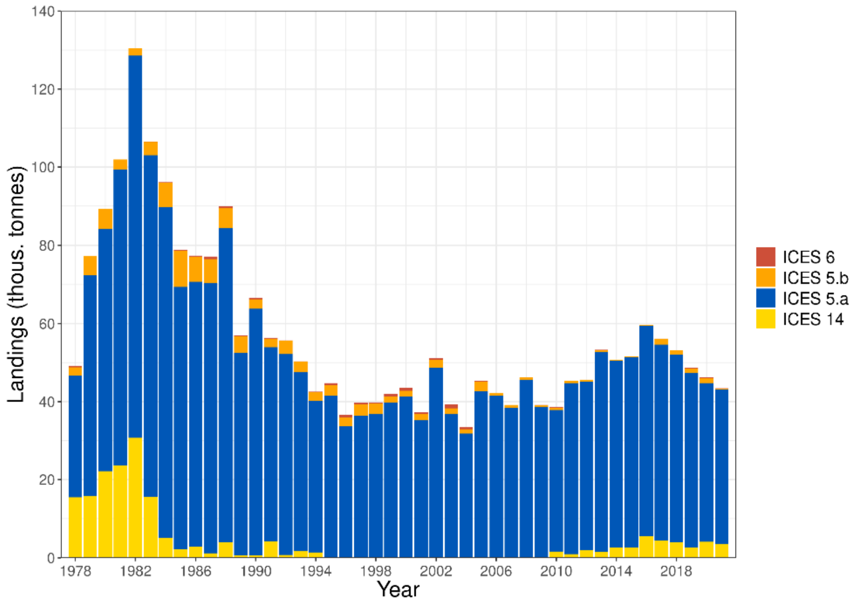


Figure 1: Golden redfish in 5,6,12, and 14. Landings in 5,6,12, and 14.

Nearly all golden redfish is landed gutted and converted to ungutted using a constant conversion factor (see the Directorate of Fisheries website here).

The real gutting factor can vary year to year so the amount of ungutted golden redfish landed may be different than the estimated value. All the bookkeeping of catch is in terms of gutted fish and any reference to ungutted catch is just ungutted divided by the constant conversino so this does not matter in assessment.

Discards are illegal in Icelandic waters but are assumed to take place to some degree. A discard monitoring program of the MFRI, designed to estimate high-grading of cod and haddock, has been in place since 2001, but no estimates of discards exist for golden redfish.

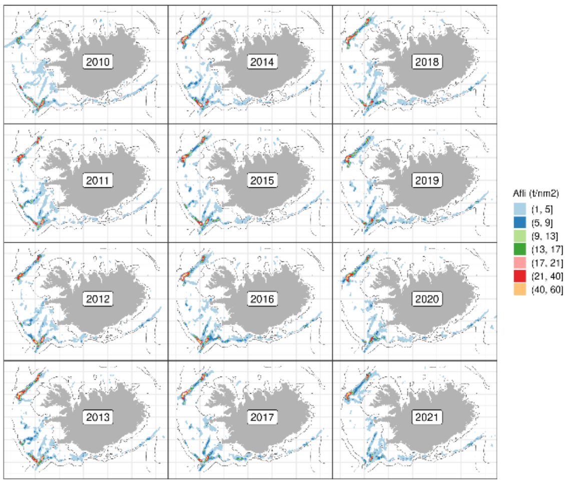


Figure 2: Golden redfish in 5,6,12, and 14. Spatial distribution of the Icelandic fishery as reported in logbooks. All gears combined.

3.2 Survey data

3.2.1 Research cruises

Information on abundance and biological parameters from golden redfish in 5,6,12, and 14 is available from five surveys, the Icelandic groundfish survey in the spring (IGFS, referred to as the 'spring survey') and the Icelandic autumn survey (IAGS, referred to as the 'autumn survey'), the Faroese spring survey, the Faroese summer survey, and the autumn survey in East Greenland. In the SAM model input data, the autumn survey index series is made by combining information from the Icelandic autumn survey, the autumn survey in East Greenland, and the Faroese summer survey, in order to cover the full range of the stock. The spring survey index series is created using the Icelandic spring survey, the Faroese Spring survey, and the Greenland autumn survey, shifted by adding 1 year. Please see WD12 for more details on Faroese and Greenlandic surveys, as well as survey length index calculation.

The Icelandic groundfish survey in the spring, which has been conducted annually since 1985, covers the most important distribution area of the fishable biomass (Fig. 3). The autumn survey commenced in 1996 and expanded in 2000 to include deep water stations (Fig. 4). It provides additional information on the development of the stock and generally includes more large golden redfish than the spring survey. Otoliths are only read from the autumn survey. The autumn survey has been conducted annually with the exception of 2011 when a full autumn survey could not be conducted due to a fisherman strike. Although both surveys were originally designed to monitor the Icelandic cod stock, the surveys are considered to give a fairly good indication of the fishable stock, the spring survey generally catches more golden redfish and showing more contrast between periods of high and low golden redfish density, as it covers a high period in the 1980s. A detailed description of the Icelandic spring and autumn groundfish surveys is given in Sólmundsson et al. [7] and how they are combined with adjacent Faroese and Greenlandic surveys is given in WD12.

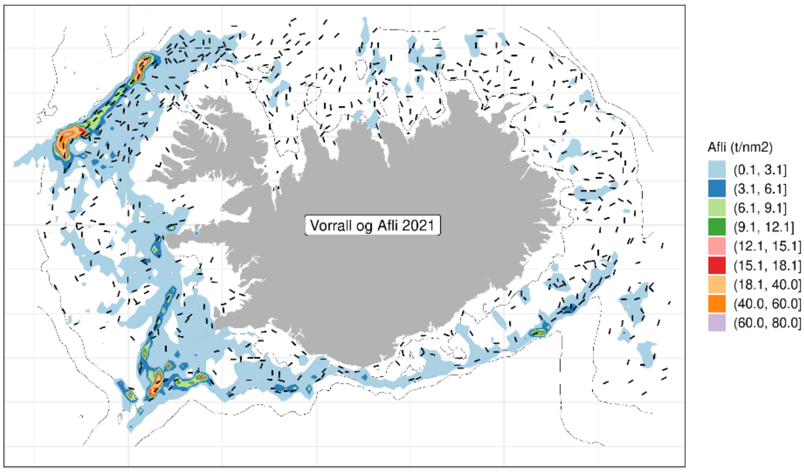


Figure 3: Golden redfish in 5,6,12, and 14. Catch reported in logbooks by depth and gear, and positions of Icelandic spring groundfish survey trawls.

3.3 Weights, maturities, growth

Biological data from the commercial longline and trawl fleet catches are collected from landings by scientists and technicians of the Marine and Freshwater Research Institute (MFRI) in Iceland. The biological data collected are length (to the nearest cm), sex and maturity stage (if possible since most is landed gutted), and otoliths for age reading. Most of the fish that otoliths were collected from were also weighed (to the nearest gram).

3.3.1 Growth

Most golden redfish caught in the spring and autumn surveys have been aged to be 30 years of age or less, although rarely, individuals may attain ages up to 60.

Although golden redfish rarely attain sizes over 60 cm and 2 kg in the surveys and commercial catches, their growth is highly variable from year to year, leading to a wide range of ages possible from roughly 30 cm. Age-length keys are therefore highly variable, and this is thought to be the result of variable growth rather than ageing error, as ageing consistency is anecdotally good. Despite temporal differences in growth, the length-weight relationship is highly stable, so there is likely little variation in condition.

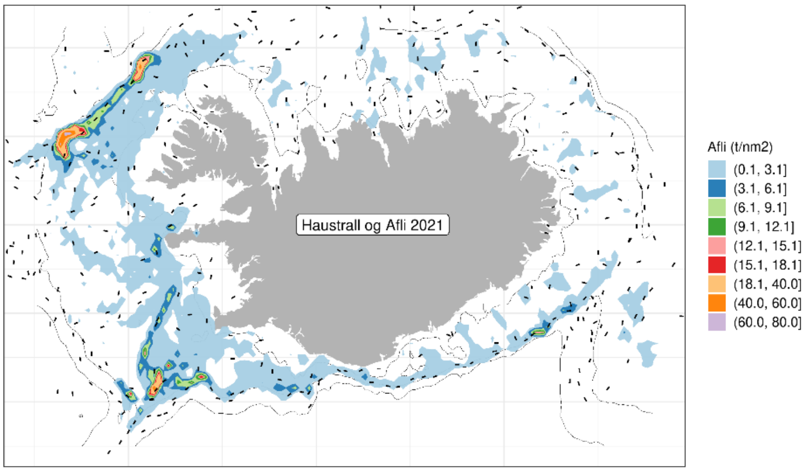


Figure 4: Golden redfish in 5,6,12, and 14. Catch reported in logbooks by depth and gear, and positions of Icelandic autumn survey trawls.

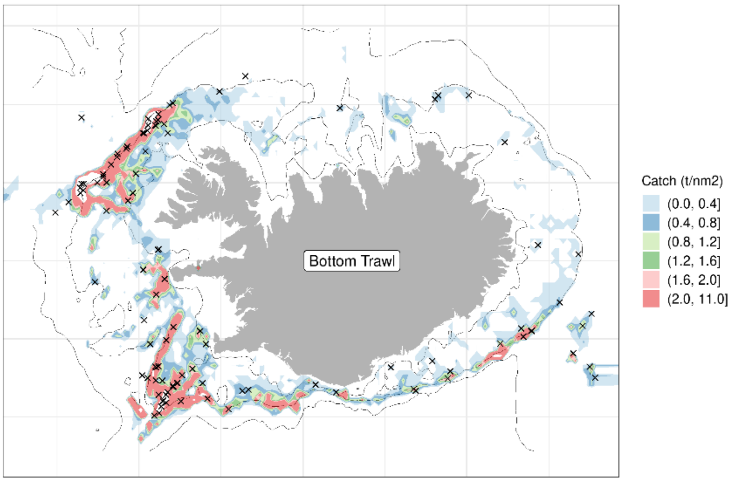


Figure 5: Golden redfish in 5,6,12, and 14. Fishing grounds in 2021 as reported by catch in logbooks (tiles) and positions of samples taken from landings.

Fish weights at length are available from both surveys and commercial data (Figs. 6 and 7). Stock weights were calculated as the mean weight at age taken from the combined spring survey, after converting lengths to weights using an estimated power relationship from fish with both length and weight data collected in both survey and commercial samples. Weights are calculated as the mean weight expected from the length distribution observed for that year. Before 1985, survey data were replaced with catch weight data, which are available from 1980. Where weight at a certain age were missing which occurred only in very rare cases, data from the other data sources were used to fill the gap. To reduce variation among years, stock weights were calculated as a moving average of the current and previous year.

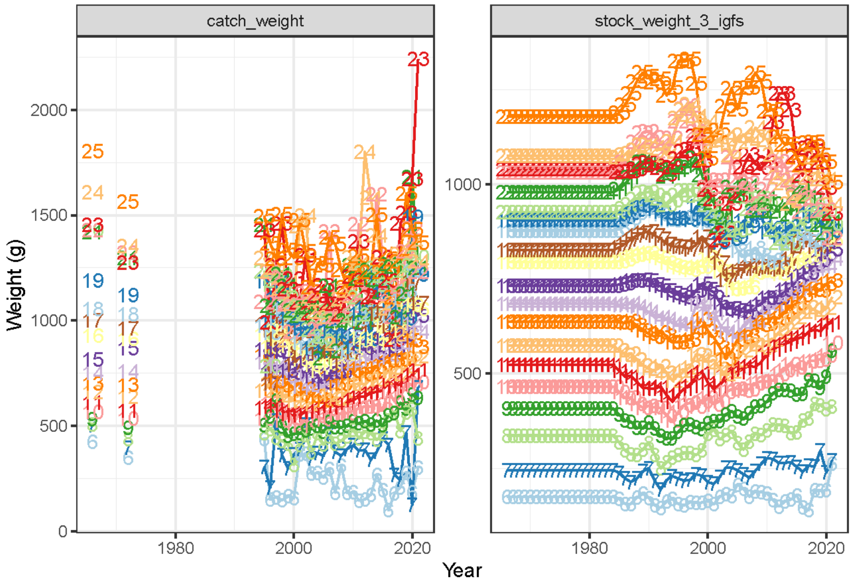


Figure 6: Golden redfish in 5,6,12, and 14. Weight at age observed in the spring survey and from the commercial catches over years.

3.3.2 Maturity

Maturity at length is stable rather stable among years and regions, so a fixed maturity ogive is applied to length distributions and then averaged within ages after the ALK is applied. In the past Gadget model, a fixed ogive has been used: P = 1/(1+exp(-0.3122*(length + 1.5 - 33.54)). To help compare between modeling frameworks, this ogive was maintained during model development, and only a few final candidate models were compared with an updated ogive (labeled 'new mat.' in later comparisons). The updated ogive was based on fitting a maturity-at-length ogive to length data pooled across all years, using maturity data taken from the spring survey. The updated ogive is the one proposed to be used here: although changing the maturity ogive has no impact on model estimation, it does have an impact on calculation of spawning stock biomass and therefore reference point generation. All reference points calculated are based on using the updated maturity ogive (base model labelled with 'new mat.'). To reduce variation among years, maturity at age was taken as the average between this and the previous year for ages less than 15 and the average over this and the three years prior for ages 15 and greater.

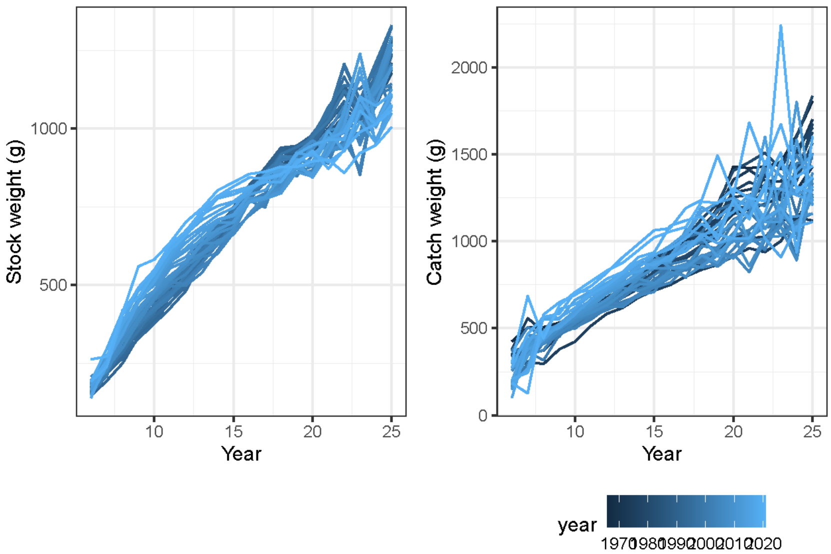


Figure 7: Golden redfish in 5,6,12, and 14. Weight at age observed in the spring survey and from the commercial catches over age.

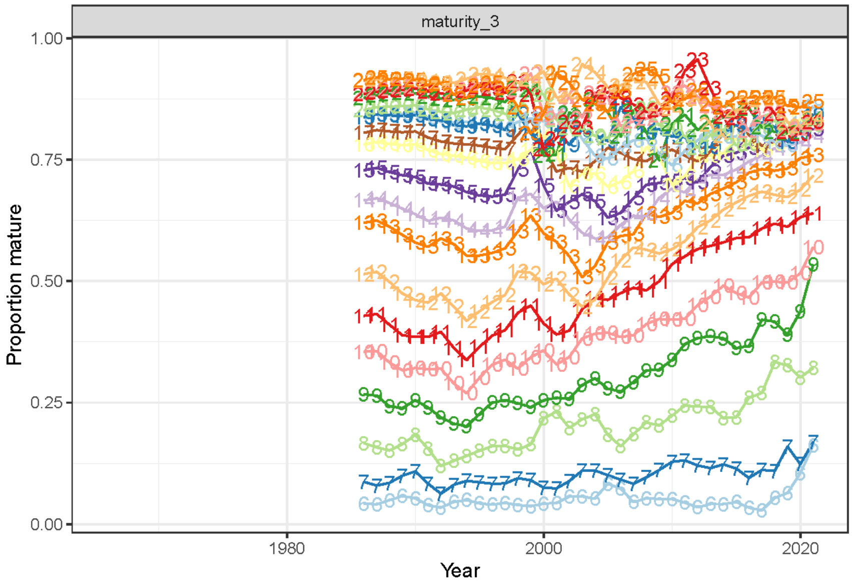


Figure 8: Golden redfish in 5,6,12, and 14. Proportion mature at age from the autumn survey and commercial data over years.

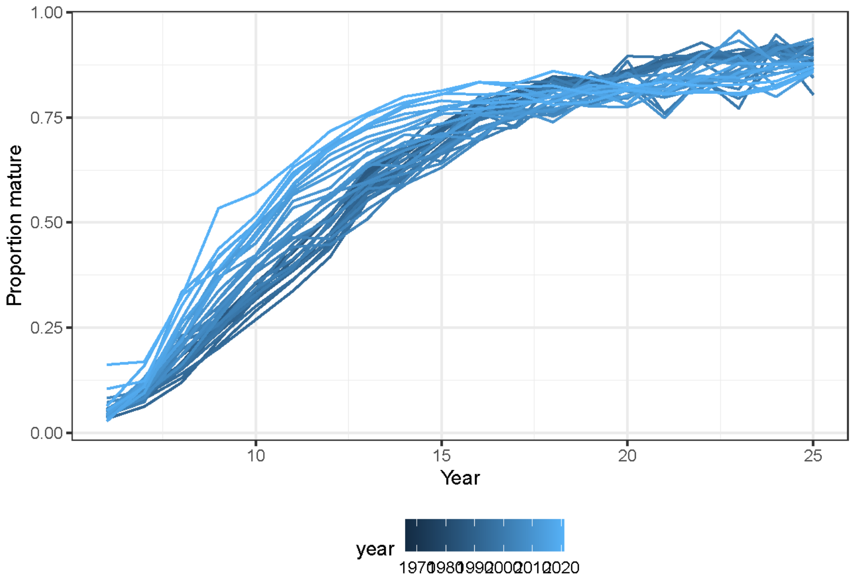


Figure 9: Golden redfish in 5,6,12, and 14. Proportion mature at age from the autumn survey and commercial data over age.

3.4 Variability in biological relationships

Exploratory plots were created to visualize whether variation in biological relationships (maturity at length, length at age, and weight at length), could be detected among sampling types (spring survey, autumn survey, or commercial) or regions around Iceland, between sexes, or over time. Regions were defined according to Bormicon divisions that have been modified slightly to be more easily applicable in Gadget (Stefánsson and Pálsson [8], MRI [4], Fig. 10). Full results are not shown, but the main results included:

- As described above, growth curves appear to vary over time and slightly by region, but not by sex (Figs. 11, 12, 13, 14).
- A fixed maturity ogive is shown in sensitivity analyses to aid in comparability between different modeling frameworks. Maturity at age appears stable across time, space, and sexes. The oldest maturity data appears to show a slightly different trend but this may be due to differences in maturity data gathering.
- Weight at lengths appear stable across time, space and sexes.
- Commercial samples do not appear to differ from survey data.

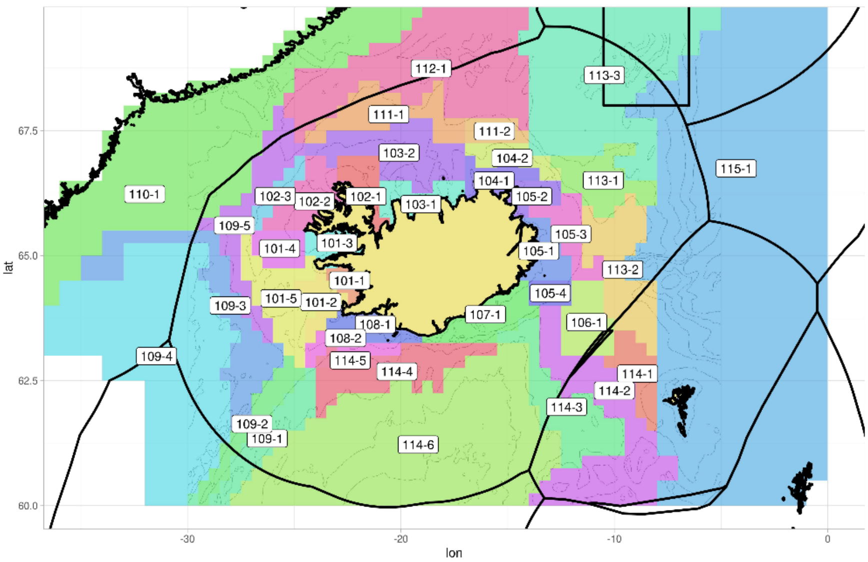


Figure 10: Golden redfish in 5,6,12, and 14. Illustration of Gadget divisions, originally based on Bormicon divisions, used to analyse regional variation. The first three numbers (generally 101-116) indicate division number labels that correspond with plots showing regional variation in life history.

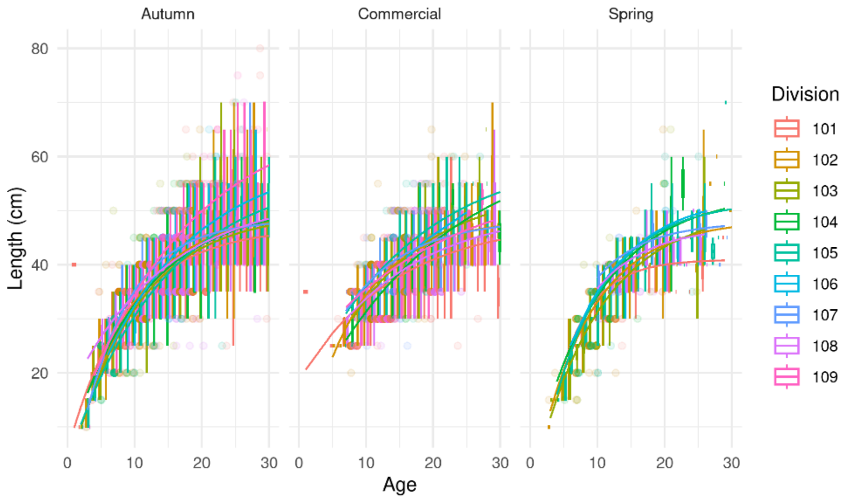


Figure 11: Golden redfish in 5,6,12, and 14. Length at ages of females by region, plotted as boxplots with Von Bertalanffy growth curves overlaid where model fits were possible.

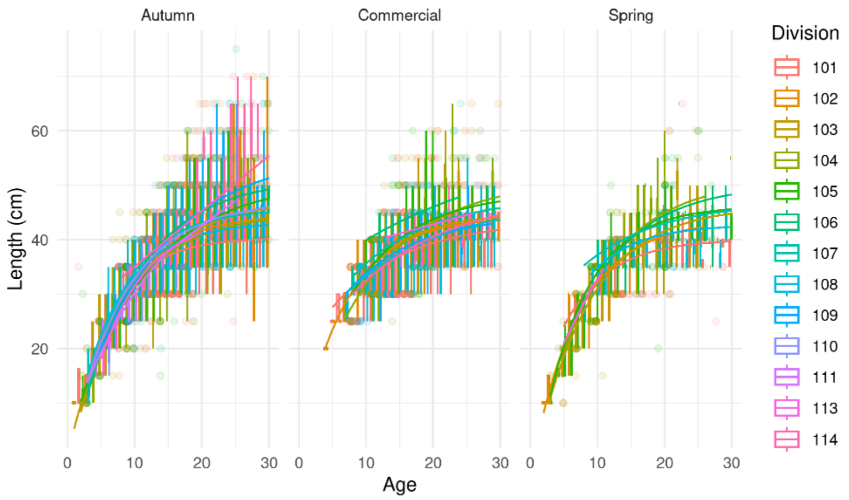


Figure 12: Golden redfish in 5,6,12, and 14. Length at ages of females by region, plotted as boxplots with Von Bertalanffy growth curves overlaid where model fits were possible.

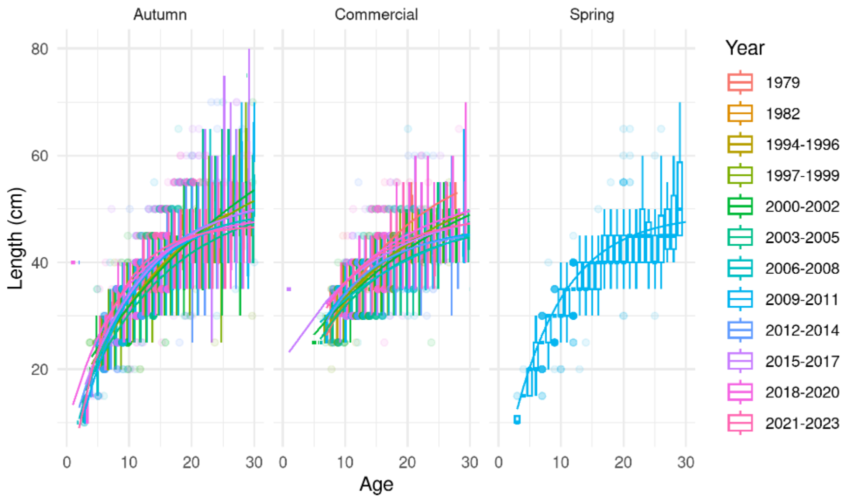


Figure 13: Golden redfish in 5,6,12, and 14. Length at ages of females by year groups, plotted as boxplots with Von Bertalanffy growth curves overlaid where model fits were possible. Only a few years of age data are available for the spring survey.

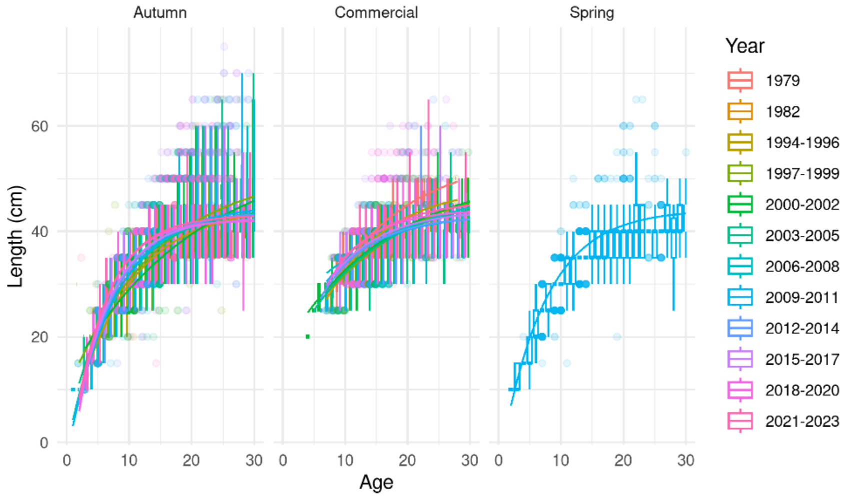


Figure 14: Golden redfish in 5,6,12, and 14. Length at ages of females by year groups, plotted as boxplots with Von Bertalanffy growth curves overlaid where model fits were possible. Only a few years of age data are available for the spring survey.

3.5 Natural mortality

The R package Fisheries Stock Analysis (FSA, Ogle et al. [6]) was used to explore a variety of M estimators using life history information estimated from the spring survey length and age data. Von Bertalanffy growth parameters were estimated as $L_\infty = 46.1$ cm, $K = 0.12$ and $t_0 = 0.16$. Max age of the population was taken to be the oldest golden redfishredfish in the survey data (60), and the temperature experienced was taken to be the mean of 1) the mean of all spring survey bottom temperature records where golden redfish were caught, 2) the mean of all autumn survey bottom temperature records where golden redfish were caught, and 3) the mean of all commercial records of golden redfish. The mean of means was taken to reduce the influence of the number of records as well as seasonality of each data source (5.4°C). Maturation data from the spring survey was used to estimated L_50 as 34 cm (length at 50% mature from a maturation ogive), which was then translated into $t_50 = 10.9$ (age at 50% mature) using the Von Bertalanffy growth parameters. The weight-length power parameter b was estimated to be 3.06 using all golden redfish caught in the spring survey, and this relationship was also used to set W_∞ as 1.33 kg, calculated from the the maximum golden redfish length in all data (85 cm).

The **metaM** function in the FSA package calculates a variety of M estimates based on different life history information, two of which vary with length ("Gislason" and "Charnov" methods). Results of using these methods (with length set to 37 cm, the mean length of commercial samples, for the length-variable methods), indicated that M estimates varied widely, ranging 0.012 - 0.416 with both the mean of 0.14 but a median of 0.10. Methods that relied on K estimates gave the highest estimates. Methods that relied on max age were low, while methods that relied mainly on L_∞ or b were generally mid-range (Fig. 15). "Gislason" and "Charnov" methods are not shown as log-likelihood values were substantially lower when implemented in models than when M was implemented with age-independent values.

In the previous Gadget model, M was set to 0.05 with the plus age group set to 0.1. The same procedure is done in this model, so that all profile likelihoods include a plus group with a natural mortality value set to 0.1. Two profiles of the negative log likelood values (displayed as AIC values but with the same parameter configurations) are shown here. One is based on the base model, and another is based on a sensitivity run with the spring survey index implemented as indices at age (see section on *Other sensitivity analyses* below for more details). Although the model with spring survey indices implemented at age instead of as a single biomass index is not considered an ideal configuration, it heavily emphasizes the age data from the autumn survey, as these are used to create ALKs for both autumn and spring survey index series, and is more stable than the base model. As information regarding natural mortality is likely to come essentially from age data, the profile from this model is shown for comparison.

A profile of the model fit with a spring survey biomass series and freely estimated autumn selectivity shows a minimum AIC value occurring at the lowest tested value, 0.01, with 0.05 just barely beyond a difference in AIC of 2 from this value (< 3) and all greater values increasing in AIC (not shown). For the model including a single spring survey biomass series and autumn survey selectivity fixed to the same value for ages 15+, the profile showed a minimum at 0.07 (Fig. 16). For the same model but with the extra observation parameter estimated at ages 10 – 25+ in years 1996 – 2000, the profile showed a minimum at 0.08, but this was almost the same value as at 0.07, and several models did not converge (Fig. 17). For the model including spring survey indices at age, the profile showed this value to have almost the same negative log likelihood of the model as 0.08, which minimized the negative log likelihood (Fig. 18).

Because the minimum AIC values were within an AIC unit of 2 from M = 0.05 in both models where fixed selectivity was implemented, natural mortality M was left as 0.05 (with 0.1 in the plus group) in models presented here.

3.6 Assessment model

Alternative age-structured and length- and age-structured models were explored (Gadget and SAM), but because of the highly variable growth of golden redfish, it was decided that age-based models may give more stable results if differences in growth are accounted for by applying region- and time-specific age-length keys

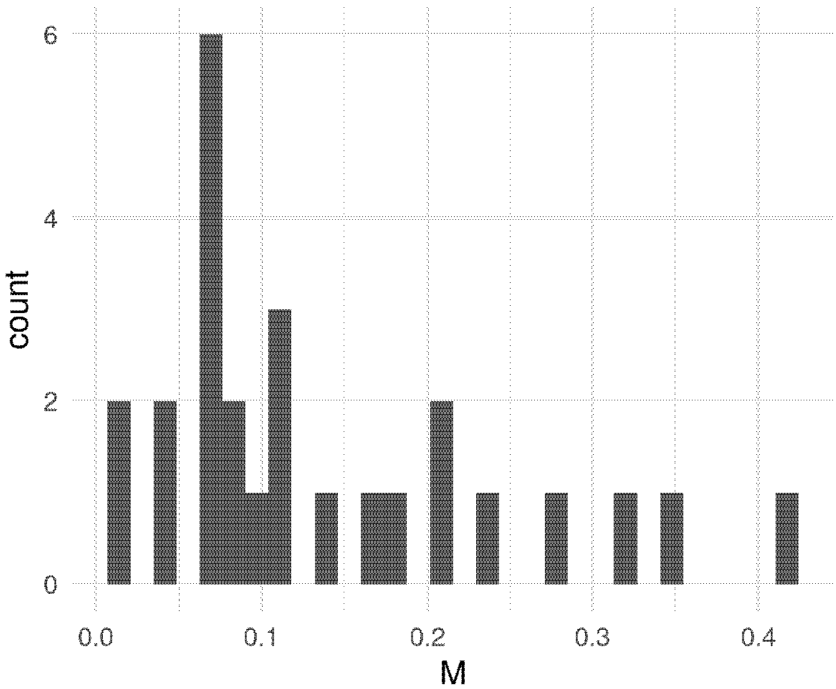


Figure 15: Golden redfish in 5,6,12, and 14. Histogram of life-history based natural mortality (M) estimates.

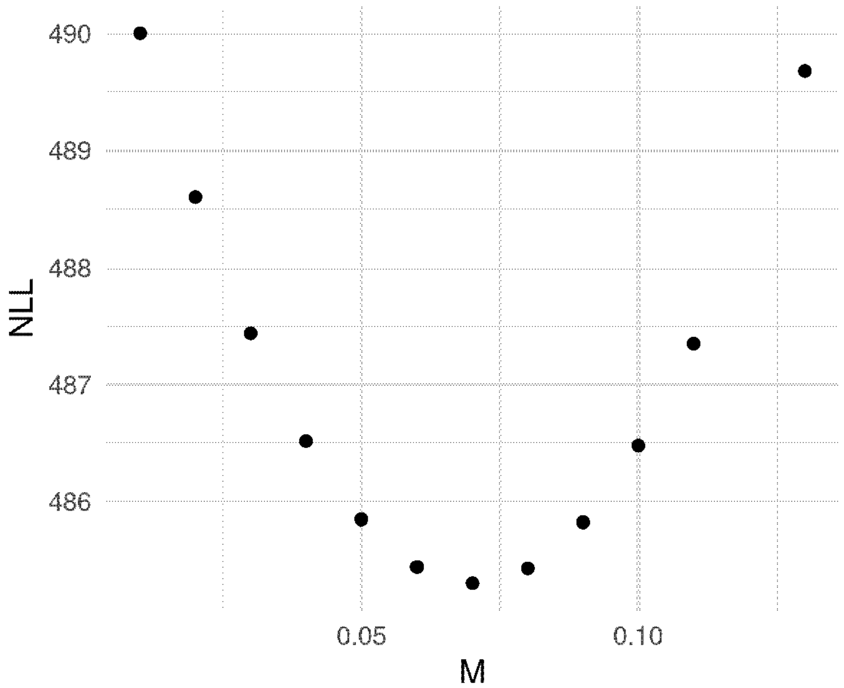


Figure 16: Golden redfish in 5,6,12, and 14. Profile of negative log-likelihood values obtained when the base model is optimized with natural mortality set to the indicated M value.

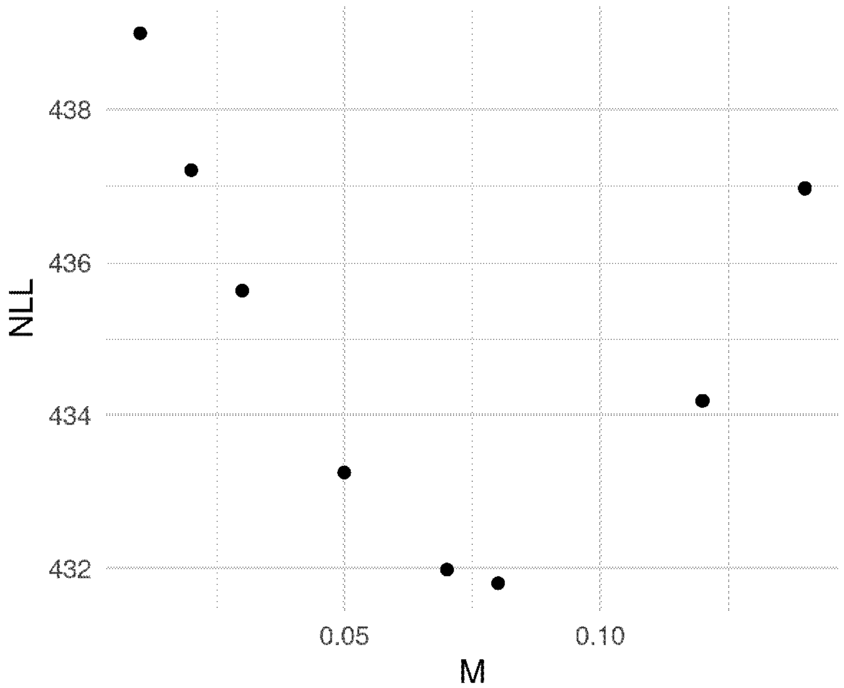


Figure 17: Golden redfish in 5,6,12, and 14. Profile of negative log-likelihood values obtained when the base model is optimized with natural mortality set to the indicated M value.

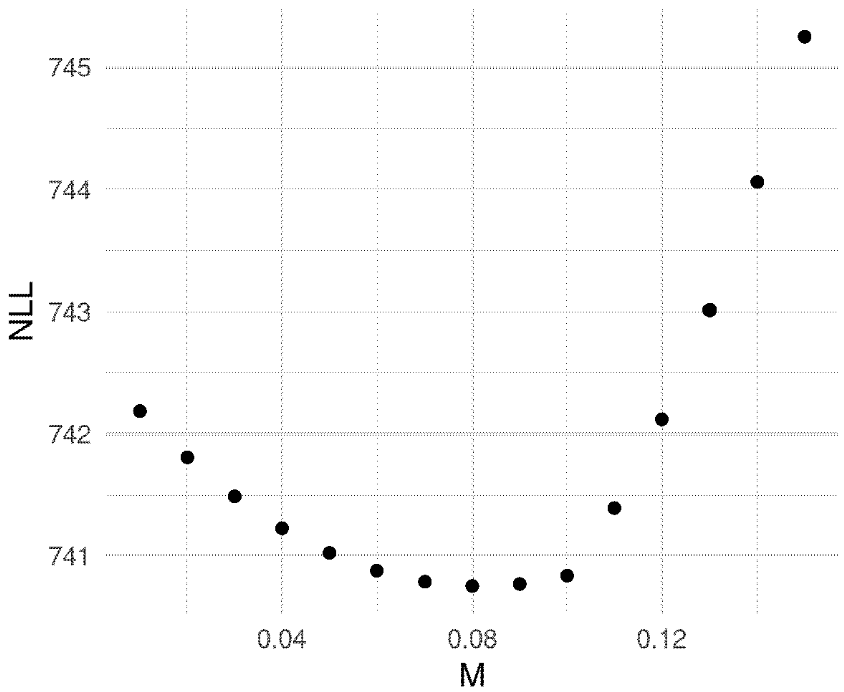


Figure 18: Golden redfish in 5,6,12, and 14. Profile of negative log-likelihood values obtained when the sensitivity-run model including spring survey indices at age is optimized with natural mortality set to the indicated M value.

(ALKs) while generating total catch and survey data. Only survey data were region-specific as most catch occurs in one region, and only catch data was split into biannual groups as surveys only occur at the same time every year. Several structures of Gadget models, but none resolved the issues listed above with the original Gadget model, so these were discontinued.

An age-based assessment was developed using SAM (Nielsen and Berg [5], Berg and Nielsen [1]). The model runs from 1966 onwards and ages 6 to 25+ are tracked by the model, treating age 25 as a plus group. Observations in SAM are assumed to arise from a multivariate normal process with an expected value derived from the model. SAM allows for the investigation of how to treat patterns in the residuals by defining different parameters by age for observation residual variances and correlations for all data sets. Furthermore, the user can define age groups for survey catchabilities, and related power relationships, and process variances for the $\log(N)$ and $\log(F)$ residuals.

SAM model development began with ALK refinement and choice of model age structure that emphasized correlations among consecutive cohort observations within catch-at-age and survey index data. The youngest ages observed in the catches were discarded due to high noise (ages 5 and 6), and the model begins at the earliest age that golden redfish start appearing in the surveys consistently (age 6). Extensions of the maximum age up to 30 were explored but results did not change (see sensitivity analyses), so a maximum age of 25 was maintained as a plus group.

Initial explorations were used to find the most important configuration settings for stability in optimization and model fit. Model choice was based on minimizing AIC, while avoiding configurations for which there was little biological support. These settings included some combination of varying the pattern of linkages among ages of log observation error variances estimated in catch and survey data, joint catchabilities for older fish in the surveys to induce more logistic-shaped survey selectivity, the pattern of power parameter among age indices in non-linear catchability relationships in surveys, the pattern of correlations among ages when AR(1) correlations were included to explain residuals in surveys, and a series of recruitment series breakpoints the distinguish periods of random walks with different recruitment levels. Further parameter refinement was done through examination of residual patterns. Starting values were jittered to test for stability in model outcomes.

3.7 Input data

Spring survey length data ranged from 1985 through 2022, and autumn survey length and age data were available from 1996 - 2021. Age ranges in the model spanned ages 6 – 25+. Although age data range to 60, individual ages detected can be sparse by year in the range 25 – 60. Age-length keys (ALKs) were created and applied within regions (generally east versus west) to account for regional growth differences from autumn survey data. The east ALK was applied to length data from Faroese surveys and the west ALK was applied to length data from Greenlandic surveys. ALKs generated from commercial samples were applied within biannual time periods (January - June and July - December, but not by region) to catch length distributions. All ALKs were created using 2 cm length bins from 6 - 60 cm, with longer bins at lengths 0 – 6, 61 – 70, and 70+.

As little age data are available for the spring survey, it was inputted as a single total biomass series. As the autumn survey began in 1996 and 1996 data was sparse, so an ALK generated from years 1996 – 1997 was applied to 1996 length data. Lagged correlations among adjacent ages in the autumn survey indices indicate that the indices are highly informative for tracking cohorts (Fig. 20). Autumn survey age indices were from 1996 were based on the Cochran index and created using a standard stratification procedure (see WD12, Fig. 19).

Catch at age and total landings are available from the 1950s, but only those from 1995 on are used due to available age data (Fig. 21). An ALK generated by pooling data from years 1995 - 2003 was applied to length distribution data in 1966 and 1972. Catch at age data are not expected to be accurate from these two older years, but they help to stabilize model estimation. Annual ALKs were created from 1995 onwards to account for time-variable growth. These ALKs are time-specific (biannual, January – June versus July – December) and applied to the approximate amount of catch from the corresponding time period. This was done to account for differences in growth patterns between sampling times. Total catch-at-age over sectors is used in tuning. Lagged correlations among adjacent ages in the catch at age data indicate that they are highly informative for tracking cohorts (Fig. 22), but very few fish younger than 7 were found in the catch. Initial explorations indicated that using length distribution data from Faroese and Greenlandic fishing operations in the creation of catch at age created more noise in catch at age data than only Icelandic commercial length distribution data, so these were not used. However, these total catch at ages were scaled according to total landings across all countries and areas fished within the stock.

ALKs were generated by first grouping catch data by season and length bin. Catch at age data from 1995 and 1996 were sparse, so they were created using a weighted sum of their own year's ALK and an ALK created from both years, with weights assigned 0.99 and 0.01 respectively, to reduce the number of 0s. Various similar procedures were explored to try to reduce sparsity in the ALKs over the whole time period; however, because most cohort tracking information comes from age data, these generally either reduced the cohort signal or made no improvement in model fit or stabilisation. Therefore, no further modifications were done, although ALKs were rescaled where necessary to ensure it sums to 1 within a length bin.

Catch-at-age was used as input through 2021 (Fig. 21. Lagged correlations among adjacent ages in the catch at age data indicate that they are highly informative for tracking cohorts (Fig. 22). Age readings from 2022 catch data were not complete at the time of analysis, so this year was excluded.

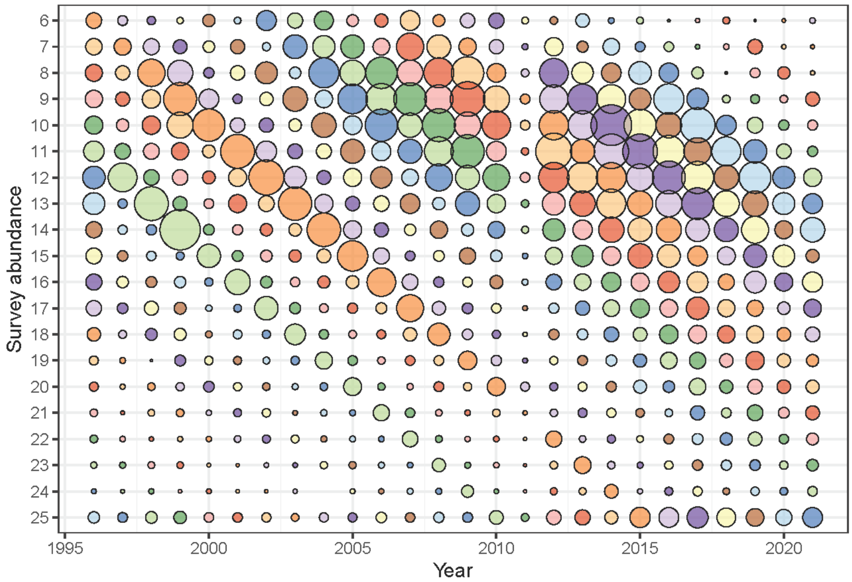


Figure 19: Golden redfish in 5,6,12, and 14. Survey numbers at age from the autumn survey, point sizes indicate the estimated swept area abundance by age. Points are colored by year class.

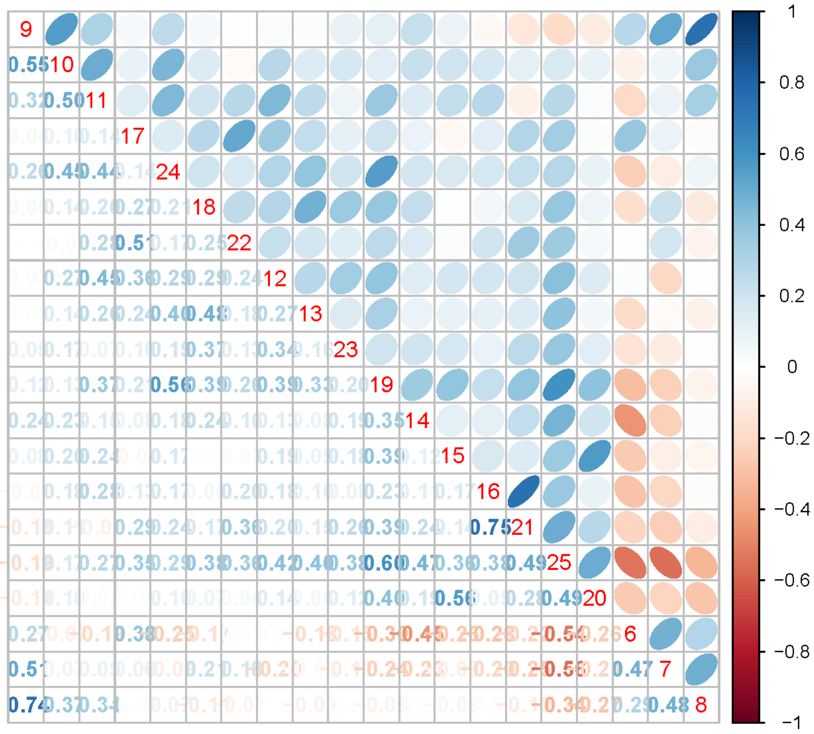


Figure 20: Golden redfish in 5,6,12, and 14. Correlations among observations with a cohort observed at each age in autumn survey indices.

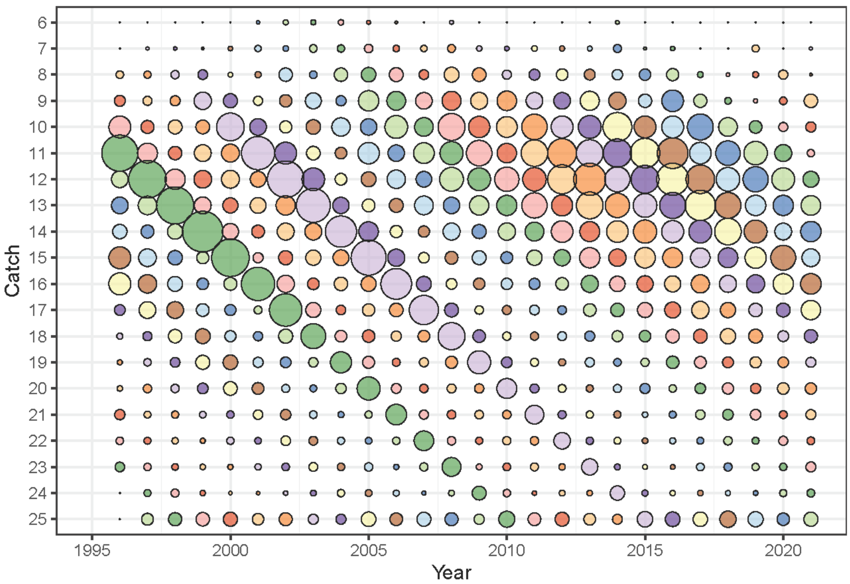


Figure 21: Golden redfish in 5,6,12, and 14. Catch at age, point sizes indicate the numbers by age. Points are colored by year class.

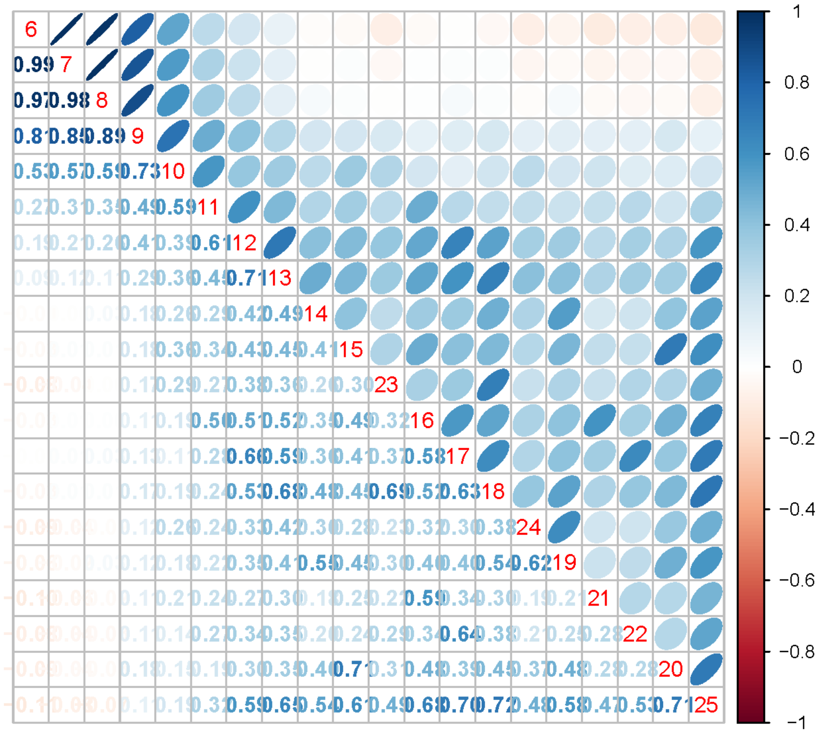


Figure 22: Golden redfish in 5,6,12, and 14. Correlations among observations with a cohort observed at each age in catch at age data.

4 Results

4.1 Proposed model

The model ranged from 1966 to 2022 and included ages 6 - 25+, the last group including all ages over 24. The final model configuration included 3 AR(1) parameters estimating autocorrelation among ages in the autumn survey residuals. One parameter per survey was estimated for the correlations that range 6/7–9/10, where '/' denotes the two ages being correlated, 10/11–13/14, and 14/15–24/25+. For models where survey catchability was fixed at the same estimated parameter across ages 15 - 25+, the 14/15–24/25+ correlation could no be estimated so it was instead joined with the second parameter to reflect 10/11–24/25+. Observation variances were set for catch at age data to be different parameters for ages 6–7, 8–9,10–17, and 18–25+. The spring survey biomass series had its own estimated observation variance. For the autumn survey, observation variances were set to be different parameters for ages 6–9, 10–11, 12–17, 18–25+. In addition to this observation parameter variance, an additional parameter was estimated for ages 10 – 25+ in years 1996 – 2000 of the autumn survey, as changes in the autumn survey occurred during this period and age data appeared generally more variable during this period for older ages. Breaks in constant recruitment series were inserted beginning with years 1994, 2001, and 2014, as this fit the data better than a single random walk series. All other parameters used default settings.

4.2 Diagnostics

Fits to the catch-at-age data and survey numbers-at-age indices can be found in Fig. 23. The fit to total catch and landings data can be found in Figs. 24 and 25. Catch and spring survey data are followed the closest by the model, whereas fits to the autumn survey series are slightly more noisy but follow a similar pattern. Fits to landings data are quite variable, but more recent fits catch at age data are better.

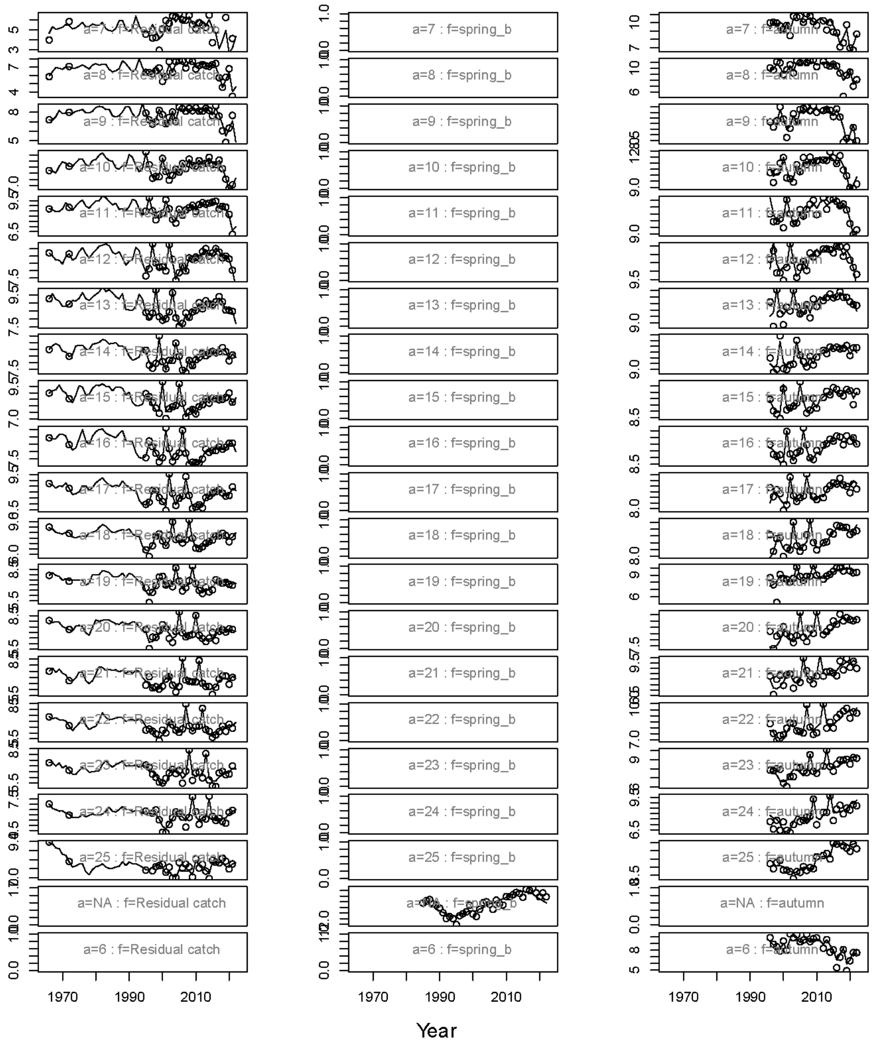


Figure 23: Golden redfish in 5,6,12, and 14. Fit to the numbers at age input data to the proposed SAM model (columns left to right: catch, spring survey, and autumn survey.

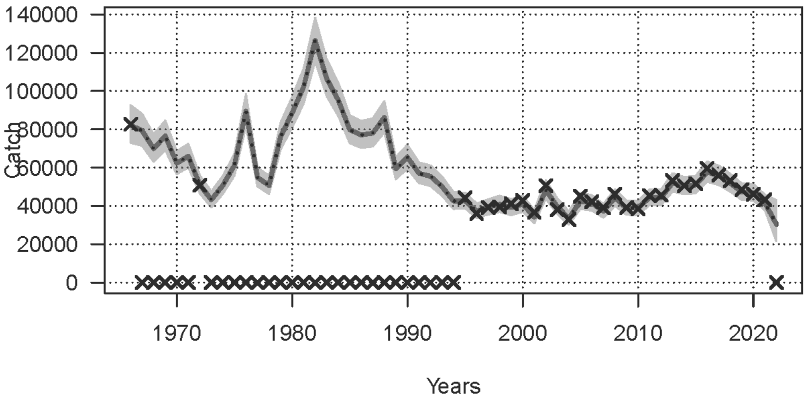


Figure 24: Golden redfish in 5,6,12, and 14. Fit to the total catch in the proposed SAM model.

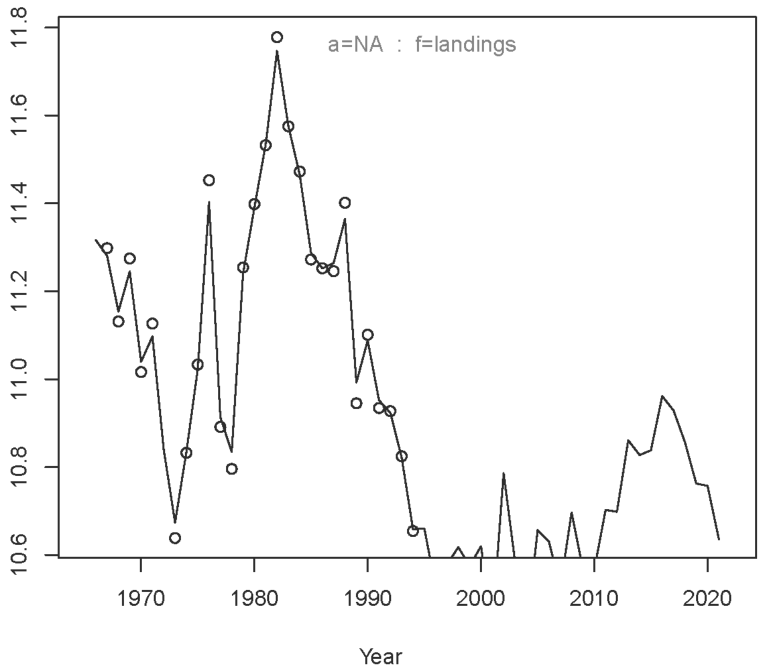


Figure 25: Golden redfish in 5,6,12, and 14. Fit to the landings input data to the proposed SAM model.

Neither observation nor process residuals show obvious trends (Figs. 26 and 27).

An overview of model parameter estimates can be seen in Fig. 28. Parameters with similar values were joined across ages within data sources if estimates overlapped substantially; therefore those left show appreciable differentiation.

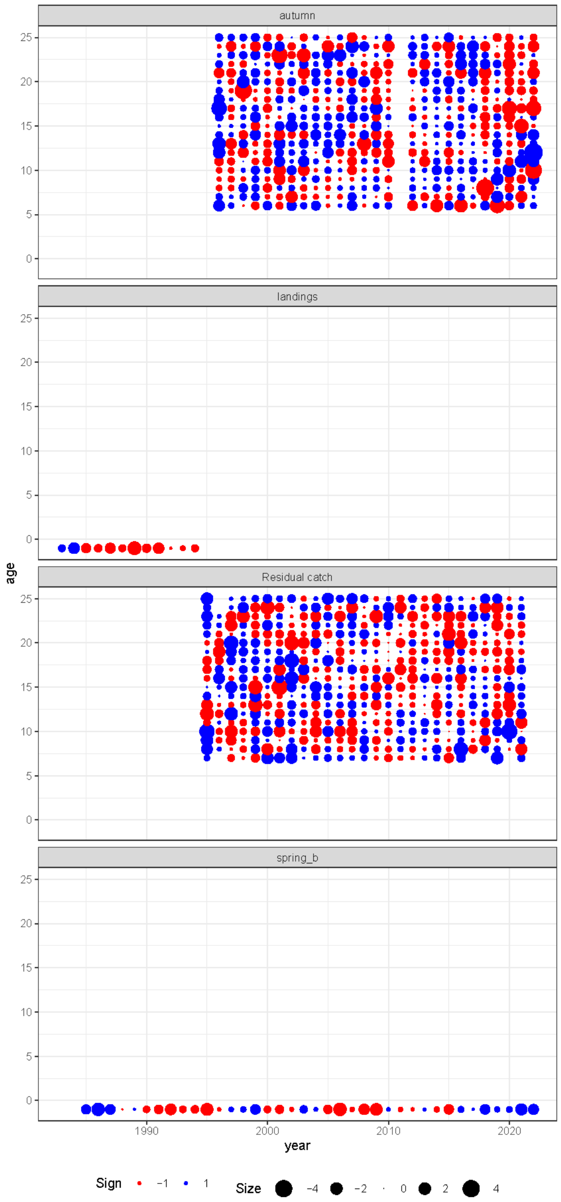


Figure 26: Golden redfish in 5,6,12, and 14. Observation error residuals of the proposed SAM model.

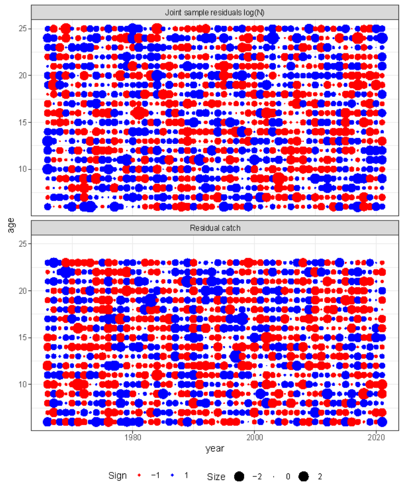


Figure 27: Golden redfish in 5,6,12, and 14. Process error residuals of the proposed SAM model.

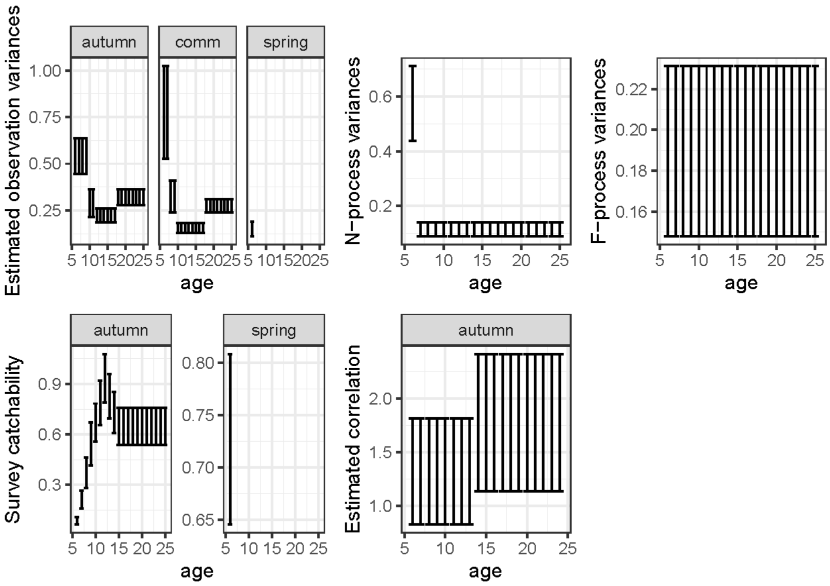


Figure 28: Golden redfish in 5,6,12, and 14. Overview of the proposed SAM model parameter estimates.

4.3 Stock overview

Model results shown here are with the updated maturity ogive implemented (corresponding with models labeled with 'new mat.' in the sensitivity analyses). Population dynamics of the golden redfish estimated in this model show a clear trend of dynamic recruitment period from 1990 - 2013. Relatively high recruitment during 2000 – 2013 corresponds with increased spawning stock biomass (SSB) and catches after 2010 (Fig. 29). However, recruitment has decreased greatly in 2014 and shows a prolonged period of low recruitment. It is difficult to suggest whether this indicates a productivity shift or a long low period in a highly autocorrelated recruitment series. Fishing mortality has declined since 1990, but is rather steady in recent years. The spawning stock biomass observed over the past decade in this model is higher than that observed in the previous Gadget model, largely as a result of variable growth: a high number of relatively old fish in the stock are better accounted for in this model, increasing the numbers of old spawners. Faster growth of smaller fish indicates a greater contribution of smaller fish to the spawning biomass as well. Any trends prior to the onset of age data (1996) should be taken with caution due to a lack of data supporting the model during this period.

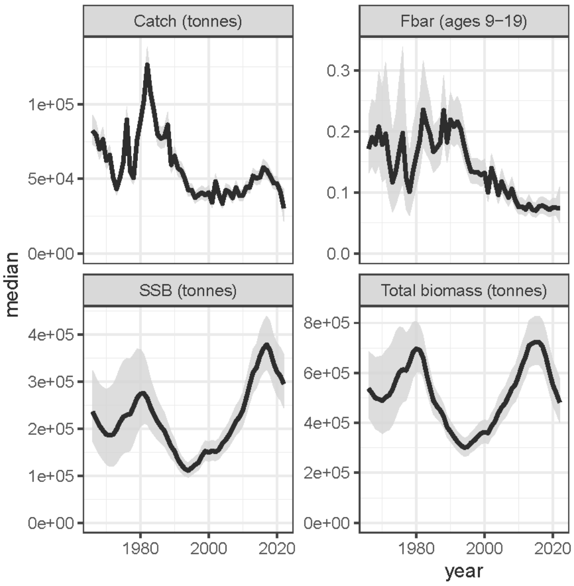


Figure 29: Golden redfish in 5,6,12, and 14. Model results of population dynamics overview: estimated catch, average fishing mortality over ages 9 - 19 (Fbar), recruitment (age 6), and spawning stock biomass (SSB).

4.4 Retrospective analyses

The proposed model had relatively low Mohn's ρ statistic values for spawning stock biomass, fishing mortality, and recruitment (Table 2, Fig. 30). Higher Mohn's ρ values for recruitment are likely a result of high uncertainty due to low selectivity at the smallest age (6) detectable by the surveys. Mohn's ρ values are within the range recommended by Carvalho et al. [2] (< 0.2).

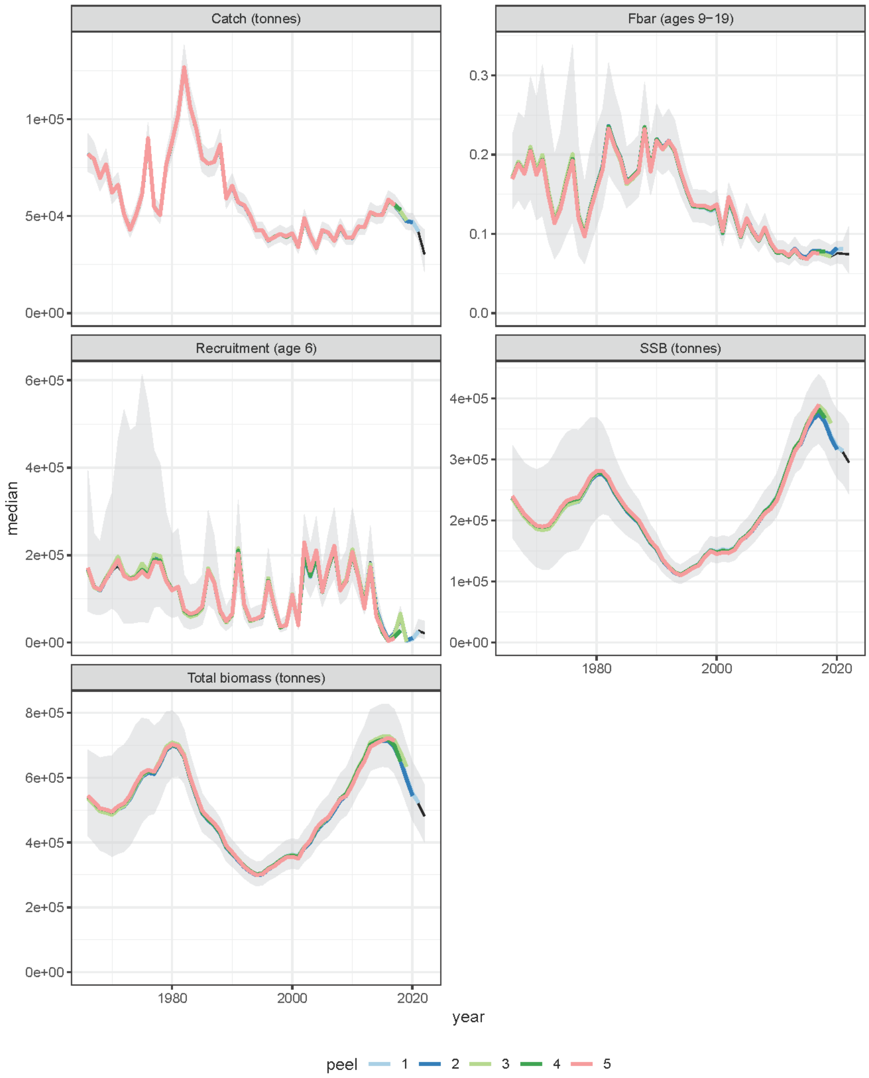


Figure 30: Golden redfish in 5,6,12, and 14. Retrospective analyses: estimated catch, average fishing mortality over ages 9 - 19+ (Fbar), recruitment (age 6), and spawning stock biomass (SSB).

Table 1: Golden redfish in 5,6,12, and 14. Mohn's *ho* calculated from analytical retrospective analyses of the proposed model.

R(age 6)	SSB	Fbar(9-19)
-0.249	0.017	0.03

4.5 Leave-one-out analysis

Fig. 31 shows the results comparing the full model estimates with estimates where the survey time series has been omitted from the observation likelihood. The results show that the model relies heaviest on the spring survey data in addition to the catch at age data.

4.6 Other sensitivity analyses

Several changes to the model structure or data input were explored to determine how responsive the model fits were to such changes. These changes are all in relation to the base model configuration with included 1) removal of the extra observation variance parameter for ages 10 – 25+ in years 1996 – 2000, 2) replacing single total biomass survey index with a spring survey index at age created by applying the autumn ALK to next year's spring survey data with the ages and years advanced by 1, and an ALK made from years 1996 – 2000 for years prior to 1997 ('IGFS ages'), 3) implementing fixed survey index selectivity for older ages ('fixed survey selectivity'), in one case with power catchability parameters estimated for ages 6 – 7 and 8, 4) Winsorising survey indices (described in greater detail below), 5) changing the plus age of the model to either 20 or 30, or 5) some combination of the these. Other model configuration components were kept as close to the base model as possible, but sometimes needed to change to maintain stability, or when a better model fit was gained.

4.6.1 With or without extra observation variance estimated

The model proposed here includes an extra parameter of observation variance that reflects a higher amount of uncertainty during the earliest years of the autumn survey, for ages 10 – 25+ and years 1996 – 2000. This extra observation variance was retained because it's inclusion caused AIC of the model fit to drop substantially; however, it has very little effect on final model results excluding a small shift downward in recent biomass levels (Fig. 32). Therefore, the proposed model includes this parameter, but comparisons made in all other sensitivity analyses shown below are made with models excluding this term, as its inclusion also may cause greater estimation difficulties (see section *Ranges in natural mortality*).

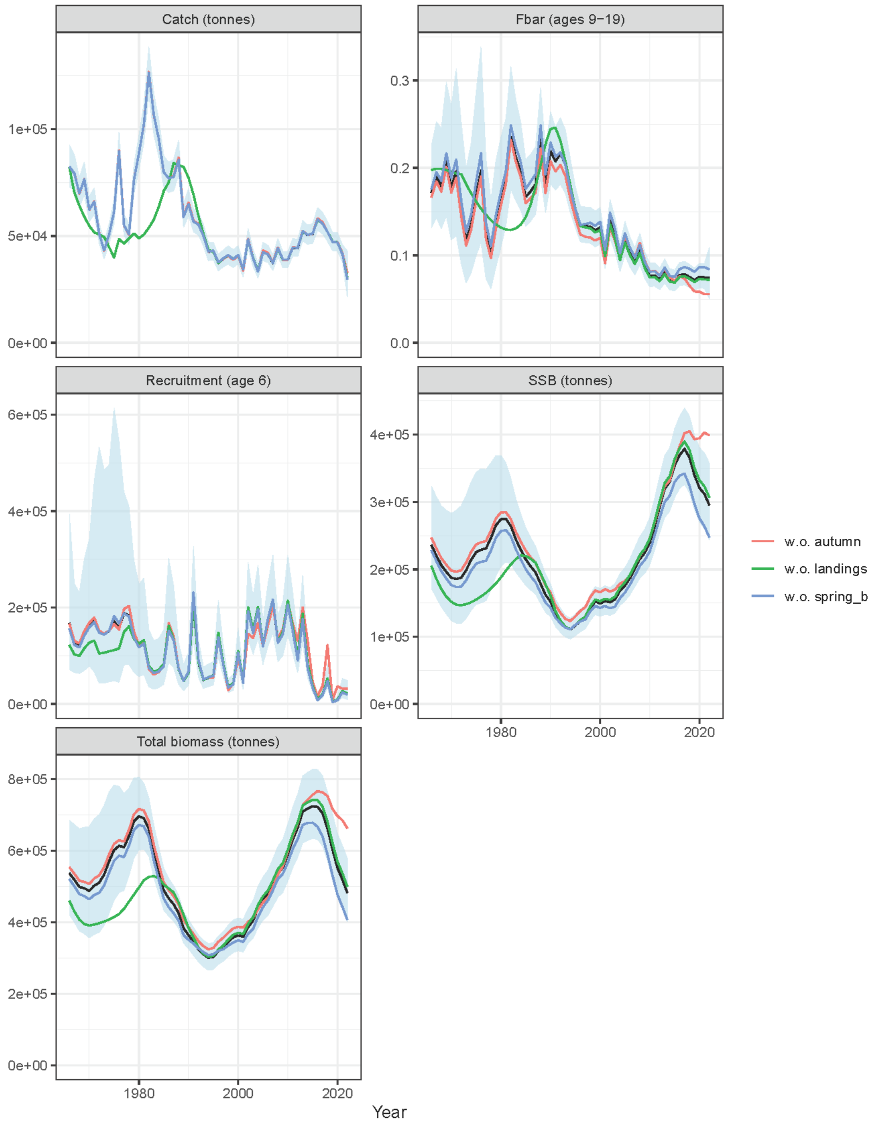


Figure 31: Golden redfish in 5,6,12, and 14. Leave-out estimates of SSB, catch, F and recruitment.

4.6.2 Implementing the spring survey indices as indices at age

In all cases where the spring survey index was included as indices–at–age, except when both winsorisation and fixed survey selectivity were implemented together (more below), the same model configuration was maintained and in addition, observation variances for the spring survey index were implemented as the same parameter within age groups 6—7, 8–11, 12–17, 18–19, 20–21, and 22–25+, autocorrelation was included as the same parameter within groups 6/7 – 13/14 and 14/15 – 24/25+, catchability power parameters were included for the autumn survey as one for age 6 and one for ages 7–8, and catchability power parameters were estimated for the spring survey as one for ages 6–7 and one for ages 8–9. When winsorisation and fixed survey selectivity were implemented together, the model became unstable except under the default configurations for observation variances (1 parameter across all ages per data source), AR residual correlation (none implemented), and catchability power relationships. Implementing catchability power relationships was not implemented because although ages 6 and 7 may have a slight non-linear relationship, this appears to be driven by relatively few data points.

Implementing spring survey indices at age uses the age data collected during the autumn survey twice, perhaps reducing uncertainty in the model artificially. Therefore, this is not considered an ideal configuration, but it does aid in model stability. Because no age data are available before 1997 of the spring survey, length distributions from earlier years needed to be converted to numbers at age using an ALK generated from 1996 - 2000 autumn survey data. This practice is also not preferred because more recruitment information seems to come from the age proportion data than the length proportion data, i.e., length distribution data show little contrast among cohorts. As a result cohort tracking is difficult in length distribution data but is apparent in the ALKs. When an ALK is then applied from another year, data sources informing recruitment in the 1990s become inconsistent: strong cohort signals that are apparent in the autumn survey index data at roughly ages 10 in the late 1990s are dampened by including spring survey index data from the 1980s with a 'wrong' ALK applied. As a result, recruitment series from these models during the 1990s are generally less certain and show decreased fluctuations (Fig. 34).

4.6.3 Fixed/free selectivity

Fixed selectivity was implemented as 19+ for cases where the spring survey index was implemented age indices–at-age, and 12+ when the spring survey index was implemented as a winsorised single biomass index or 15+ as an unmodified single biomass index. Implementing a fixed survey index from a lower ages then those chosen caused the model to become unstable or resulted in a worse fit. In the case of the base model chosen with 15+ fixed selectivity, changing the age range to 14+ or 16+ increased the AIC slightly by 1-2 AIC, and further shifts in the age range either larger or smaller caused AIC to increase or the model to become unstable. These configurations were compared with cases where selectivity was instead estimated freely by age.

In general, fixing selectivity from freely estimated parameters decreased the most recent peak in biomass from the past decade. It had a similar effect on the model results to winsorisation or increasing maximum age to 30, and therefore only had a minimal effect when one of these configurations was implemented. Estimating catchability power parameters (non-linear relationships) for ages 6-7 and 8 had very little effect when fixed selectivity was implemented (Figs. 35, 42). For the case in which the spring survey index was implemented as a single biomass series with no modification, the effect was the same but stronger (Fig. 34).

4.6.4 Winsorisation of survey indices

Sebastes stocks in general are known for schooling behavior that can lead to a high influence of a few dense hauls biasing survey indices toward high variability or inducing greater year to year variability. Some procedures in the index calculation already counteract this effect (i.e., stratification and scaling by actual tow rather than standard tow length, WD12), and winsorised indices were additionally explored in sensitivity analyses. The winsorisation procedure implemented involves, on a year by year basis, finding the hauls that equal or exceed the 95th percentile of total biomass within a haul, then scaling numbers at length and

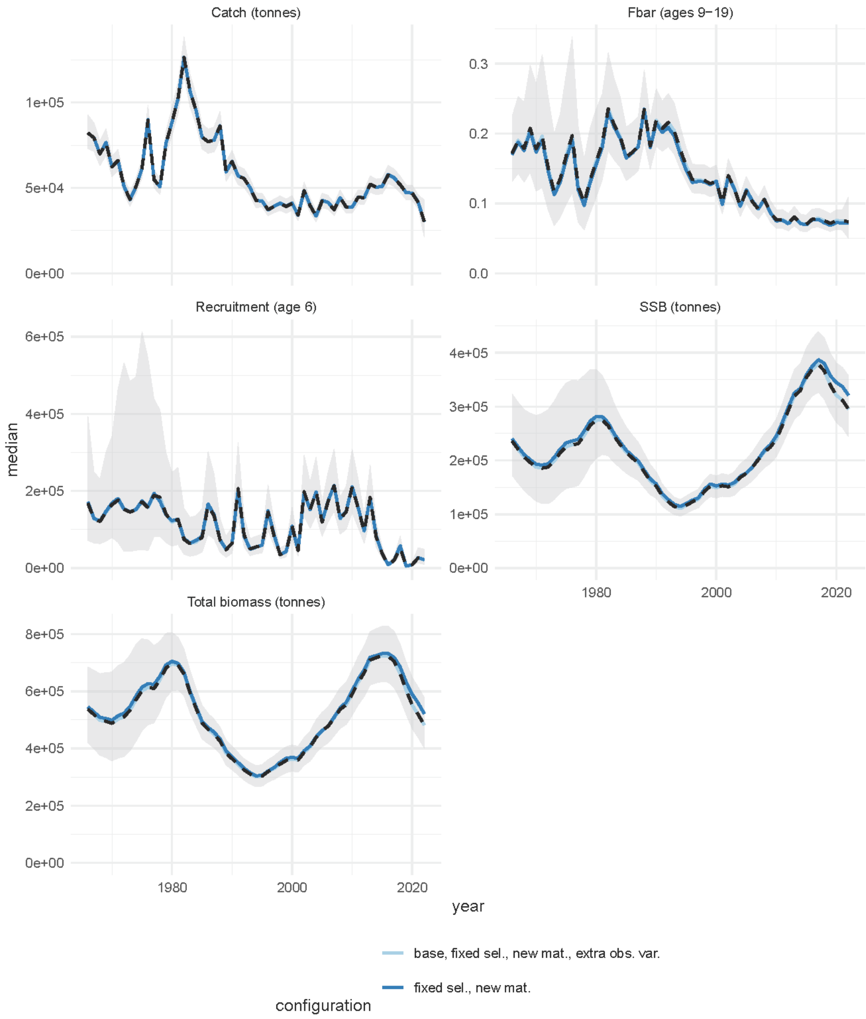


Figure 32: Golden redfish in 5,6,12, and 14. Sensitivity analyses of the proposed base model configuration with autumn survey selectivity fixed to the same parameter at ages 15+, the updated maturity ogive, and the extra observation variance estimated for ages 10-25+ for years 1996-2000 (blacke dashed lines for emphasis), compared with the same but no extra observation variance estimated: estimated catch, average fishing mortality over ages 9 - 19 (Fbar), recruitment (age 6), and spawning stock biomass (SSB).

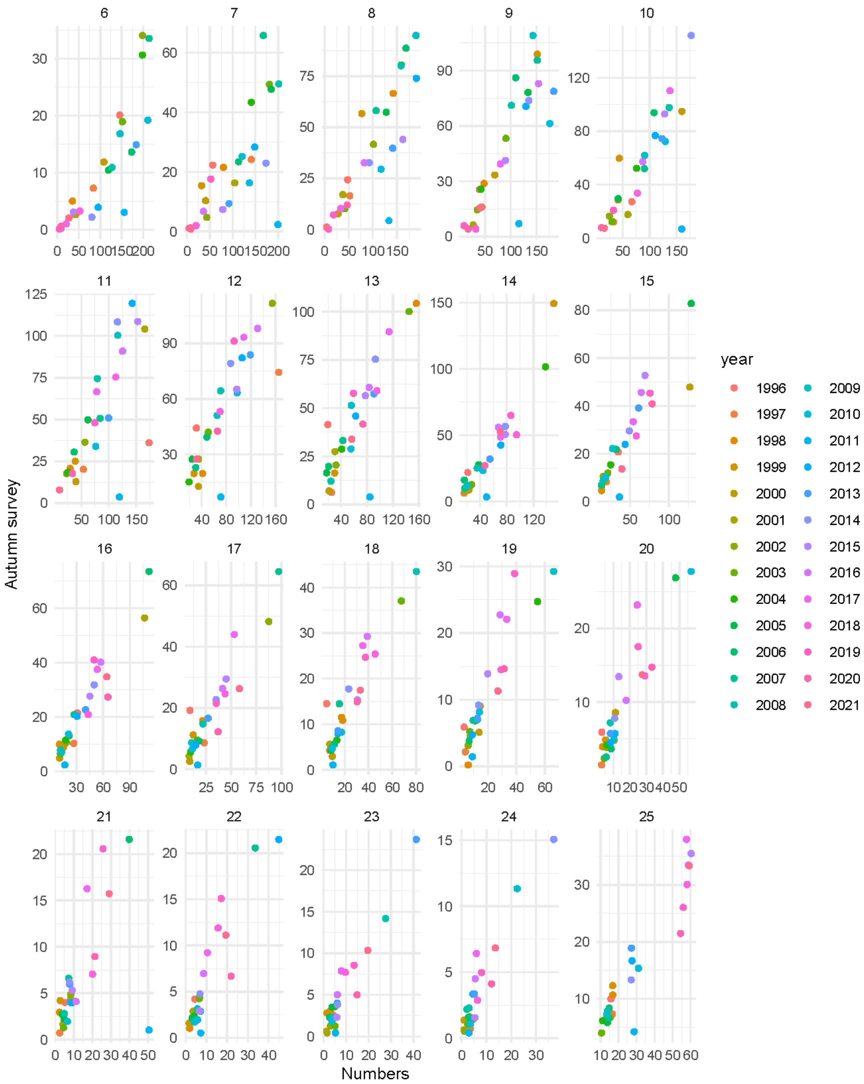


Figure 33: Golden redfish in 5,6,12, and 14. Autumn survey indices versus numbers estimated in the base model with selectivity fixed at the same parameter for ages 15+ (both in thousands).

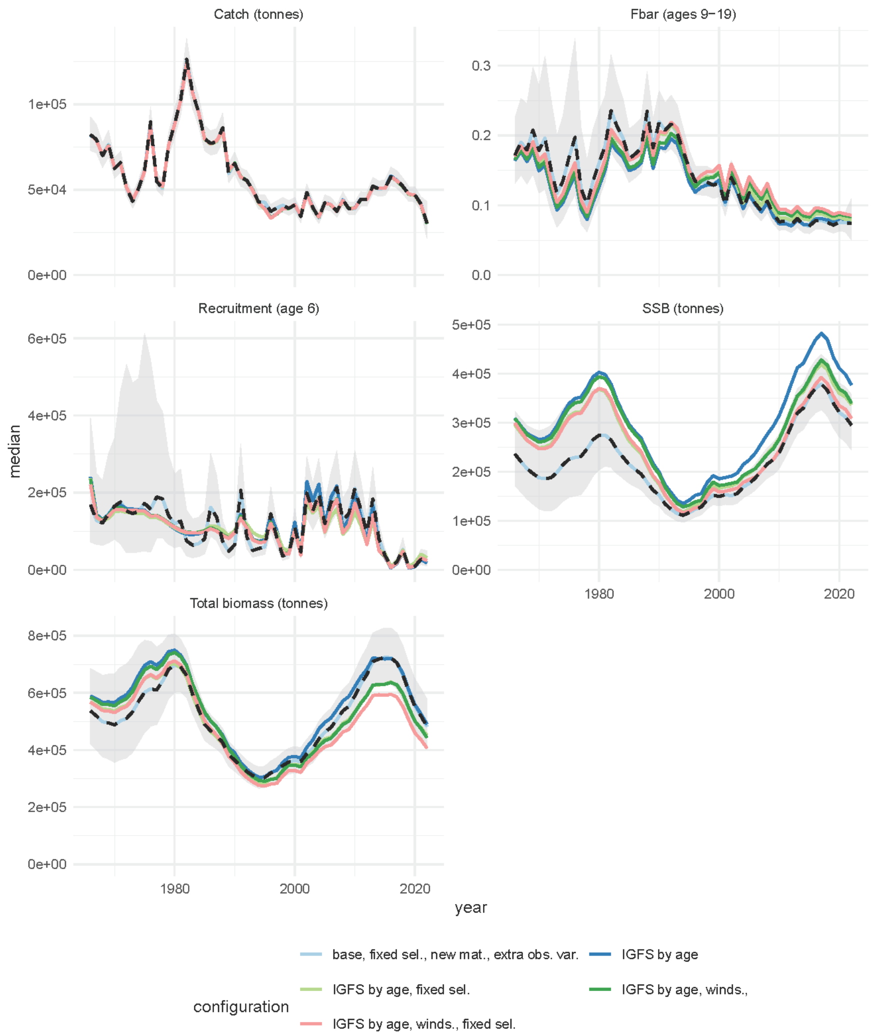


Figure 34: Golden redfish in 5,6,12, and 14. Sensitivity analyses on the inclusion of age-based spring survey indices: estimated catch, average fishing mortality over ages 9 - 19 (Fbar), recruitment (age 6), and spawning stock biomass (SSB). The version of the base configuration with 'new mat.' included is the one proposed here with an updated length-based maturity ogive; all others shown use the old maturity ogive. This configuration is represented by dark blue lines that are redrawn with black dashed lines for emphasis and their 95% confidence intervals or shown with light grey ribbons. Configurations with 'new mat.' labels only differ from the same without 'new mat.' in the SSB panels, as changing maturity ogives has no impact on SAM model estimation.

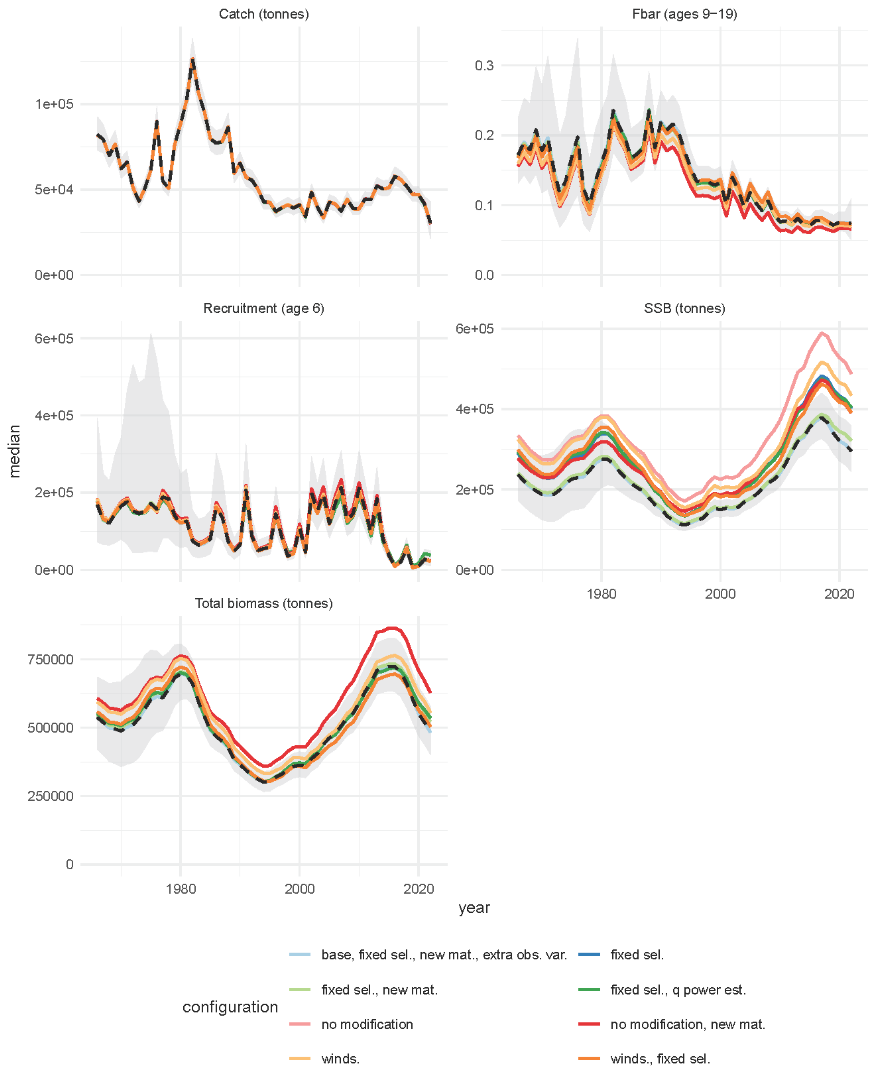


Figure 35: Golden redfish in 5,6,12, and 14. Sensitivity analyses of using winsorised indices, fixing survey selectivities of older fish to the same parameter, and estimating nonlinear relationships for ages 6-8 in the autumn survey: estimated catch, average fishing mortality over ages 9 - 19 (Fbar), recruitment (age 6), and spawning stock biomass (SSB). The version of the base configuration with 'new mat.' included is the one proposed here with an updated length-based maturity ogive. This configuration is represented by dark blue lines that are redrawn with black dashed lines for emphasis and their 95% confidence intervals or shown with light grey ribbons. Configurations with 'new mat.' labels only differ from the same without 'new mat.' in the SSB panels, as changing maturity ogives has no impact on SAM model estimation. 39

biomass at length of these hauls down to a level at which the total numbers equals the numbers of the haul corresponding with the 95th percentile in biomass. For models using winsorised survey indices, winsorisation was applied to both spring and autumn survey indices, but only to the portion of the combined index that is generated from data within Iceland (which in both case, composes the majority of data).

The level of winsorisation is something that can be chosen as appropriate to the distribution of the data at hand. From the histograms of the distributions of log total numbers within a haul in a given year, it appears that a 95\% cutoff is relatively high considering the number of hauls that deviate from the lognormal distribution, and that a value closer to 98\% would sufficiently cut out most of the hauls that create a tail that exceeds would be normally expected (Fig. 36, 37). As 98 – 99\% show the same trends, sensitivity analyses are based here on a 99\% cutoff to emphasize what differences modifying only a few hauls each year could result in.

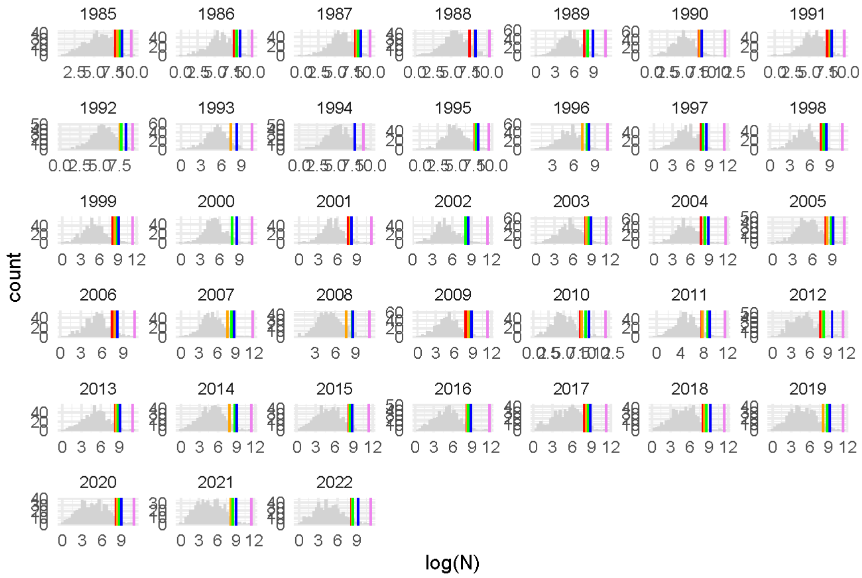


Figure 36: Golden redfish in 5,6,12, and 14. Histograms of the log of the total numbers of golden redfish in hauls of the spring survey by year, along with the 95th, 96th, 97th, 98th, and 99th percentiles shown as vertical lines (respectively red, orange, green, blue, and purple).

Winsorisation created marginally lower LLN values (as seen in lower AIC values), and also changed the trend in the input data toward having lower stock levels in recent years (Figs. 35, 34). This is not a surprise given that winsorised indices show the same trend of lower levels in recent years (Figs. 39, 38).

4.6.5 Model age structure

Changing the maximum age to 20+ had a large impact on results with the model estimating a larger biomass and high uncertainty around these levels. This trend is likely to be partially caused by the increased average natural mortality across the whole population, as the plus group is implemented with a value of 0.1. Using 20+ as a plus group also causing a high number of the total index across years to fall into the plus group,

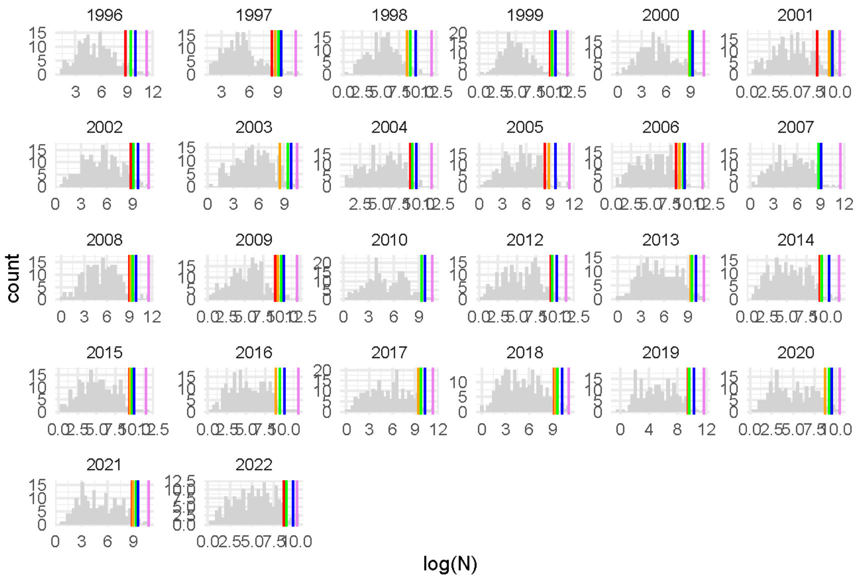


Figure 37: Golden redfish in 5,6,12, and 14.Histograms of the log of the total numbers of golden redfish in hauls of the spring survey by year, along with the 95th, 96th, 97th, 98th, and 99th percentiles shown as vertical lines (respectively red, orange, green, blue, and purple).

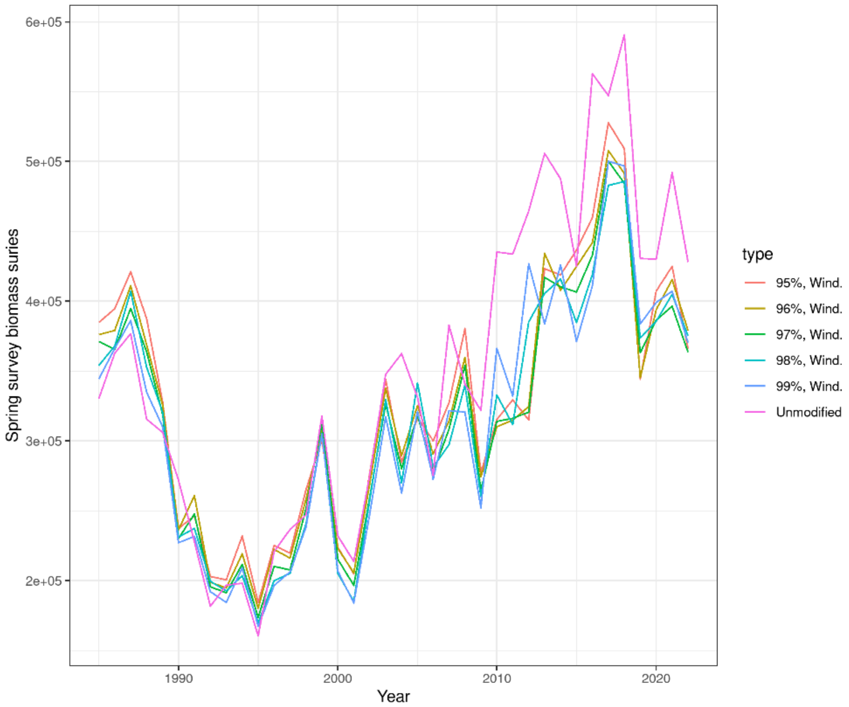


Figure 38: Golden redfish in 5,6,12, and 14. Comparison of winsorized indices with unmodified versions of the autum survey data. The winsorised index has been scaled upwards by a factor of 1.1 - 1.5 to be on a similar scale to the unmodified version.

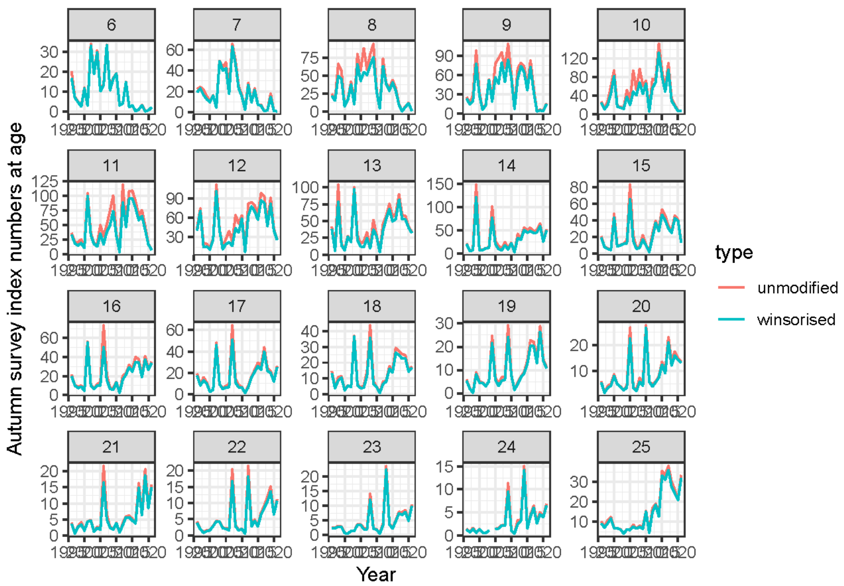


Figure 39: Golden redfish in 5,6,12, and 14. Comparison of winsorized indices with unmodified versions of the autum survey data.

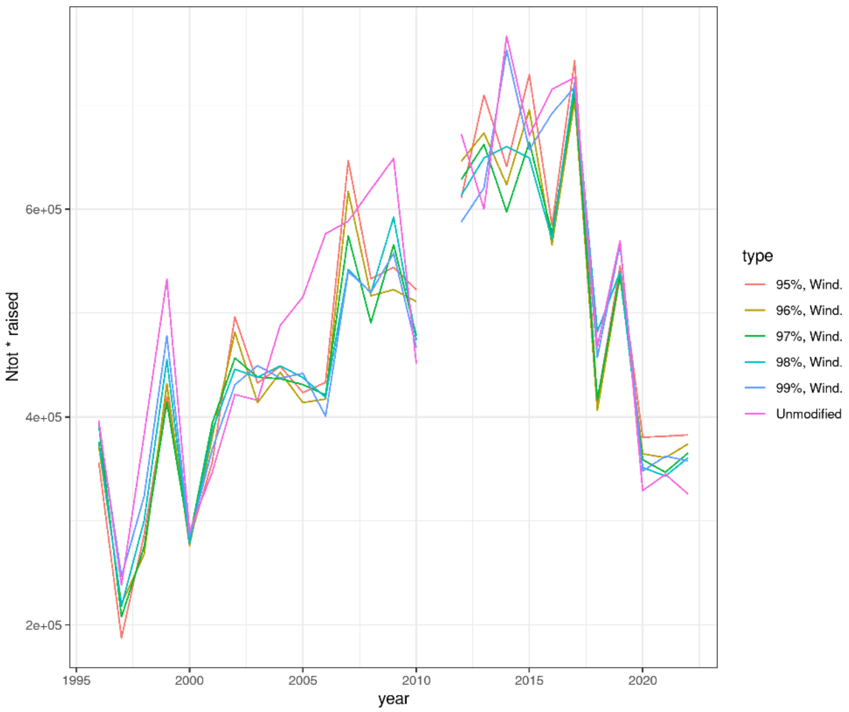


Figure 40: Golden redfish in 5,6,12, and 14. Comparison of winsorized indices with unmodified versions of the autum survey data. The winsorised index has been scaled upwards by a factor of 1.1 - 1.5 to be on a similar scale to the unmodified version.

so this model is not considered further (Fig. 41). Changing the maximum age to 30+, on the other hand, reduced biomass levels, but only marginally, especially when compared to the 25+ base configuration with fixed selectivity applied (Fig. 42). As data in the age range 25 - 30+ tend to become more sparse and can affect model stability, maintaining the 25+ cutoff with fixed selectivity implemented was considered sufficient.

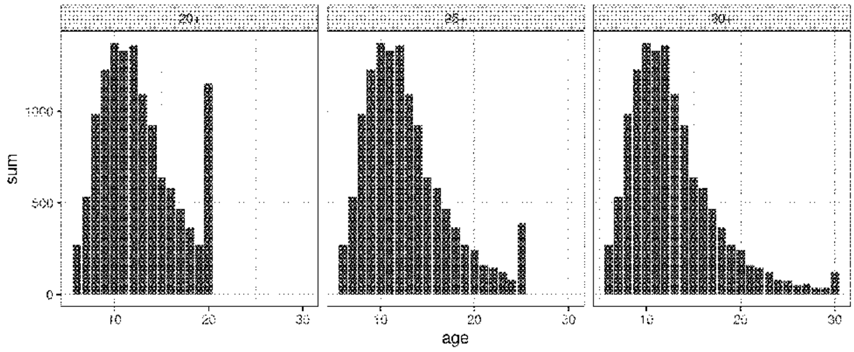


Figure 41: Comparison of age structures, summed over all years, by plus group configuration.

4.6.6 Ranges of natural mortality

A range of Ms was investigated (see Figs. 16 and 18) along with size dependent M using both the Gislason and Chernov method. The profile likelihood when a fixed autumn survey selectivity is implemented for ages 15+ shows a minimum close to 0.07 and no other indicator based on life history attributes showed a clear indication of M. Therefore the assumption of natural mortality as 0.05 for all ages was maintained, as 0.07 could not be distinguished from values roughly 0.03 - 0.10. A value of 0.1 was maintained for the plus group. However, it is clear that this choice does have an effect on the perceived stock status, but not trends, as the biomass series shifts upward / downward with higher / lower M values (Fig. 43)

4.7 Conclusions

Sensitivity analyses indicate that when a single selectivity is estimated across older ages (fixed selectivity configuration), this configuration has similar results to when maximum age is set to 30 or winsorisation is applied, and that estimating catchability at young ages in the autumn survey does not have an appreciable additional effect when applied with the fixed selectivity configuration. This configuration also has a more stable analytical retrospective and leave one out analyses than when selectivity is estimated freely among all ages (results not shown), suggesting that the information derived from the data is more consistent with autumn survey selectivity parameters constrained to be the same at older ages. Assuming this constraint also avoids a potential overestimation of biomass that is possible when both survey and commercial selectivity is estimated as as dome-shaped, as it avoids the assumption that there are many more fish available than can be observed. Therefore, it is proposed that the base model includes the fixed selectivity configuration, but that the winsorisation is not applied, survey selectivity is estimated as linear at all ages, and the maximum age is set to 25+.

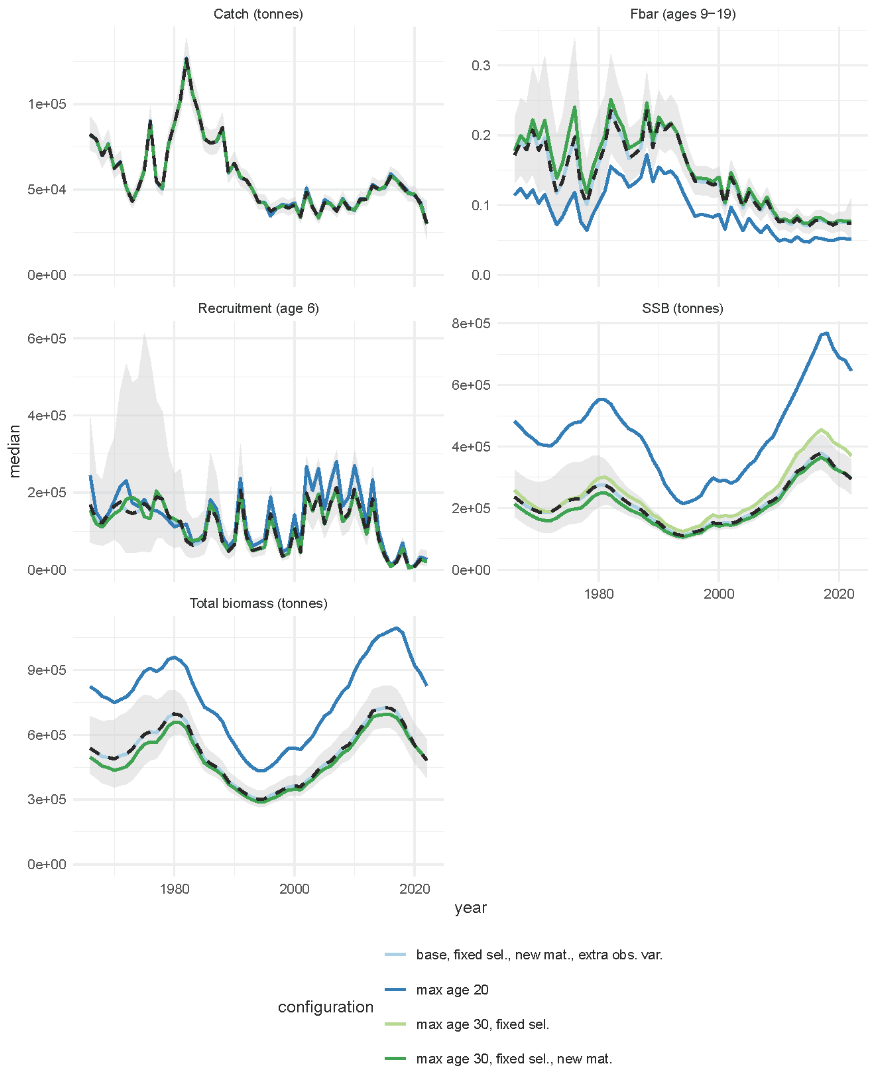


Figure 42: Golden redfish in 5,6,12, and 14. Sensitivity analyses of different model plus group changes and fixing survey selectivities of older fish to the same parameter: estimated catch, average fishing mortality over ages 9 - 19 (Fbar), recruitment (age 6), and spawning stock biomass (SSB). The versions with 'new mat.' included is the one proposed here with an updated length-based maturity ogive. This configuration is represented by dark blue lines that are redrawn with black dashed lines for emphasis and their 95% confidence intervals or shown with light grey ribbons. Configurations with 'new mat.' labels only differ from the same without 'new mat.' in the SSB panels, as changing maturity ogives has no impact on SAM model estimation.

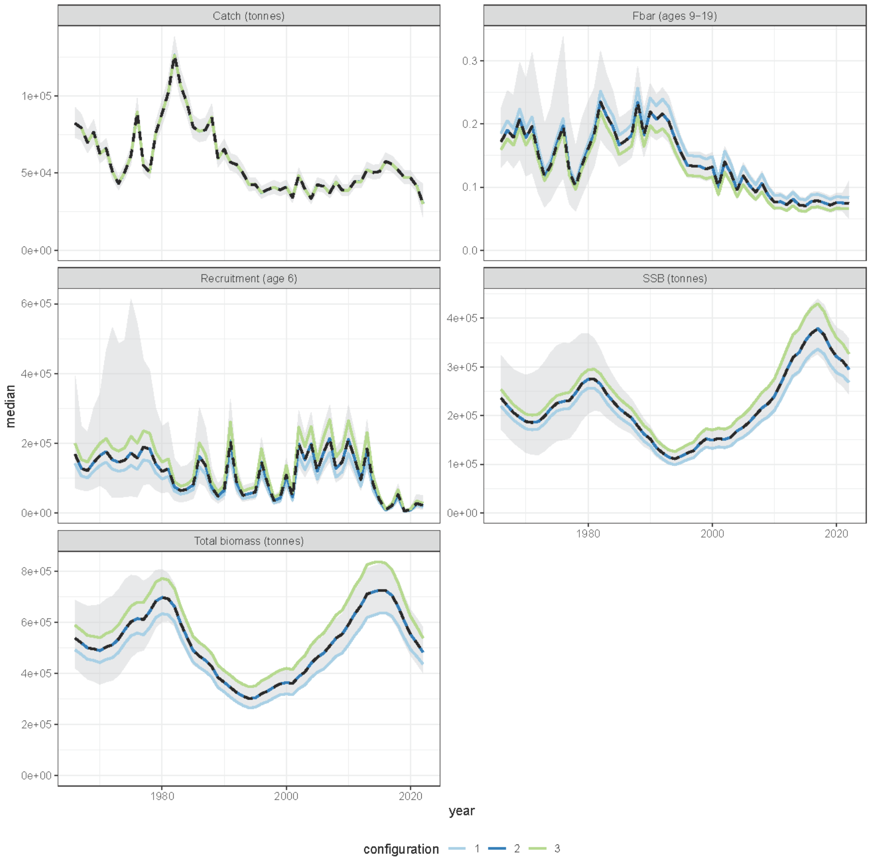


Figure 43: Golden redfish in 5,6,12, and 14. Sensitivity analyses of different natural mortality value assumptions: estimated catch, average fishing mortality over ages 9 - 19 (Fbar), recruitment (age 6), and spawning stock biomass (SSB). Base models and their 95% confidence intervals are indicated by black dashed lines with light grey ribbons.

Table 2: Golden redfish in 5,6,12, and 14. Sensitivity analyses of different model configurations: AIC values. Configuration labels indicate the major changes in relation to the base model. AIC values may only be comparable where data changes are not induced. Using spring survey-at-age (IGFS by age) or changing max ages changes the number of data points in relation to the base models.

configuration	AIC
IGFS by age	1683.0617
IGFS by age, fixed sel.	1665.6187
IGFS by age, winds.,	1579.8201
IGFS by age, winds., fixed sel.	1603.1114
base, fixed sel., new mat., extra obs. var.	928.4945
fixed sel.	1031.7020
fixed sel., new mat.	1031.7020
fixed sel., q power est.	1007.6170
max age 20	702.1293
max age 30	1747.6521
max age 30, fixed sel.	1743.6361
max age 30, fixed sel., new mat.	1743.6361
max age 30, new mat.	1747.6521
no N process error	1124.3480
no modification	1032.5477
no modification, new mat.	1032.5477
winds.	1002.9914
winds., fixed sel.	998.2592

5 Short term projections

Short term projections are performed using the standard procedure in SAM using the `forecast` function. Three year averages are used for stock and catch weights, and maturity. From this projection the advice is derived. The advice is based on the calendar year; however, the majority of the stock is fished according to the Icelandic fishing year starting in September each year. This causes a mismatch between the assessment model, which is based on the calendar year, and status quo catch rates. In order to provide realistic assumptions of status quo fishing rates, the standard projection procedure in SAM was adapted to accommodate these differences. So given the assessment in year $y+1$ the interim year catches are based on the following fishing mortality:

$$F_y = \left(\frac{8}{12}F_{sq} + \frac{4}{12}F_{mgt}\right)$$

and therefore the total catches for year $y+1$ will be:

where

$$C_{y+1} = \frac{F_{mgt}}{F_{mgt}+M}\left(1-e^{-(F_{mgt}+M)}\right)B_y$$

As recruitment over the past 8 years has been consistently lower than historical values, the stock is projected as the recruitment resampled over the previous 5 years, continuing current practice from recent years.

Table 3: Golden redfish in 5,6,12, and 14. Listing of the CV for key model outputs.

variable	cv
SSB (tonnes)	0.105
Total biomass (tonnes)	0.100
Fbar (ages 9-19)	0.104
Recruitment (age 6)	0.640
Catch (tonnes)	0.051

6 Appropriate Reference Points (MSY)

According ICES technical guidelines (ICES [3]), two types of reference points are referred to when giving advice for category 1 stocks:

precautionary approach (PA) reference points and *maximum sustainable yield* (MSY) reference points. The PA reference points are used when assessing the state of stocks and their exploitation rate relative to the precautionary approach objectives. The MSY reference points are used in the advice rule applied by ICES to give advice consistent with the objective of achieving MSY.

Generally ICES derives these reference points based on the level of the spawning stock biomass and fishing mortality. The following sections describe the derivation of the management reference points in terms of fishing mortality (F) and SSB (B). It further describes the model for stock–recruitment, weight and maturity at age, and assessment error which is used to project the stock stochastically in order to derive the PA and MSY reference points.

6.1 Setting B_{lim} and B_{pa}

B_{lim} was considered from examination of the SSB–Recruitment (at age 6) scatterplot based on the estimates from the stock assessment, as illustrated in Fig. 44. The figure shows that the recruitment is fairly independent of the size of SSB. The trend in increasing recruitment with decreasing spawning stock biomass suggests this stock could be considered a Stock Category Type 4 pattern. However, this pattern is largely driven by recent consistent extremely low recruitment that has been observed at high spawning stock biomass levels. As it is unclear whether these extremely low recruitment levels will continue in the future and turn out to indicate a long-term downwards productivity shift, it may not be precautionary to consider this stock Category 4, which is mainly described as having high recruitment at low spawning stock levels, but rather Category 5. According to the Category 5 pattern, B_{lim} is derived from the lowest observed SSB B_{loss} = SSB(1994) = 110893). In line with ICES technical guidelines B_{pa} is then calculated based on multiplying B_{lim} by the standard factor, $e^{\sigma*1.645}$ where σ is the CV in the assessment year of SSB, used for calculating B_{pa} from B_{lim}. However the estimated σ is not considered to reflective of the true assessment error of the SSB due to various uncertainties and thus the CV used here to determine B_{lim} is 0.2, which is the default ICES value for assessment error. Therefore B_{pa} should be set at $B_{lim}e^{1.645*0.2} = 110893t * 1.4 = 154094t$.

6.2 Management procedure in forward projections

Illegal landings and discards by Icelandic fishing vessels are considered to be negligible (as noted above). The currently proposed assessment model is more stable than historical assessments. In the projections described below the effect of assessment model is modeled as auto correlated log-normal variable with the mean as the true state of the stock. When deriving the assessment error CV based on the assessment (Table 3), the CV estimates are rather low, so default fishing mortality CV value of 0.212, and the default of 0.423 was kept for the correlation parameter ϕ to model assessment error. Default values were taken because estimates derived from the the model as listed in Table 2 are likely to be underestimates given various uncertainties regarding assessing this stock for the first time.

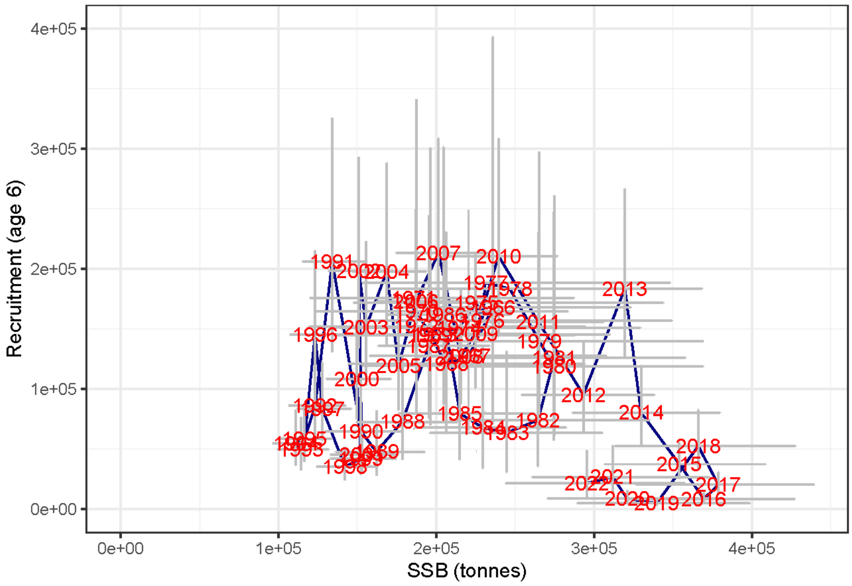


Figure 44: Golden redfish in 5,6,12, and 14. Estimated stock recruitment plot. Grey crossed indicate uncertainty, red text point estimate with the associated recruitment year and black lines show the progression of the stock recruitment relationship.

6.2.1 Stock recruitment relationship

A variety of approaches are common when estimating a stock–recruitment relationship. In the absence of a stock-recruitment signal from the available historical data (Fig. 44, the ICES guidelines suggest that the "hockey-stick'' recruitment function is used, i.e.

$$R_y = \bar{R}_y \min(1, S_y/B_{break})$$

where R_y is annual recruitment, S_y the spawning stock biomass, B_{break} the break point in hockey stick function and $\bar{R}_y$ is the recruitment when not impaired due to low levels of SSB. Here $\bar{R}_y$ is considered to be drawn from an auto–correlated log–normal distribution with a mean, CV and ρ estimated based on the estimated recruits. This is done to account for possible auto-correlation in the recruitment time–series.

Although recruitment appears to have shifted downwards after 2014 and remained stable at the lower level, it is possible that current low recruitment levels are due to a very long lag in autocorrelation as Golden redfish is a rather long-lived species. ICES guidelines suggest that productivity shifts should not be assumed in long-term projections unless there compelling evidence suggesting that a shift has occurred. Instead, the full recruitment series should be used with appropriate autocorrelation. Because golden redfish is a long-lived species, high autocorrelation is not unlikely, so the recruitment series from 1990 onwards, when recruitment estimates become more certain, were used to estimate the segmented regression.

As this series shows both a period of high recruitment and low recruitment, recruitment values observed were not log–normally distributed as is normally expected 45. Instead, fitting a log–normal distribution to observations with relatively high percentages of both high and low recruitment generated a very high estimated variance. Using such a high variance in projections could lead to generating recruitment far above those that have been observed. As a result, the over–dispersed log–normal was additionally truncated so that residuals of generated recruitment values did not exceed the maximum and minimum residuals of those observed in the data on the log scale. Fig. 46 shows the fit to a segmented regression setting B_{loss} to B_{lim}.

6.2.2 Stock and catch weights

Prediction of weight at age in the stock, selectivity and the maturity at age follow ICES guidelines, except that is the average of the last 20 years of values for weight, maturity, and selectivity in the projections as this stock is long-lived ans it is desirable to avoid unnecessary influence of current conditions. These values are illustrated in Figures 51 to 48. A longer period of twenty years was deemed prudent because if changes in growth appears in both smaller and older fish are due to density dependence, then they are expected to shift greatly from current conditions as the total biomass decreases in upcoming years. As the stock is roughly just past an all–time high and expected to decline sharply in the short–term, using values over the past 10 years may be biased toward recent conditions.

As for commercial selectivity, it is apparent that here has been a shift just prior to a decade ago, likely as a result of a shift in fishing toward the southwest of Iceland and away from the southeast. Prior to this time, greater selectivity of older fish was observed. This shift has coincided with a large proportion of old fish composing survey data in the southeast, where little current fishing occurs, but has in the past 49. As it is suspected that the cause for a shift toward fishing more in the southwest is the result of increased CPUE as biomass has increased, it is not unlikely that some of the fishing could shift to the southeast again as the stock decreases over the next decade, resulting in a shift toward heavier fishing pressure on older fish 50.

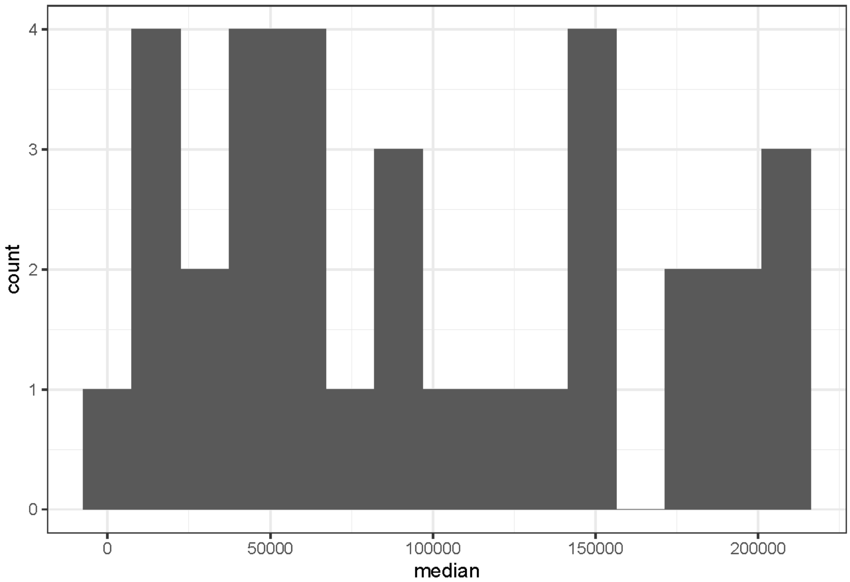


Figure 45: Golden redfish in 5,6,12, and 14. Histogram of estimated recruitment.

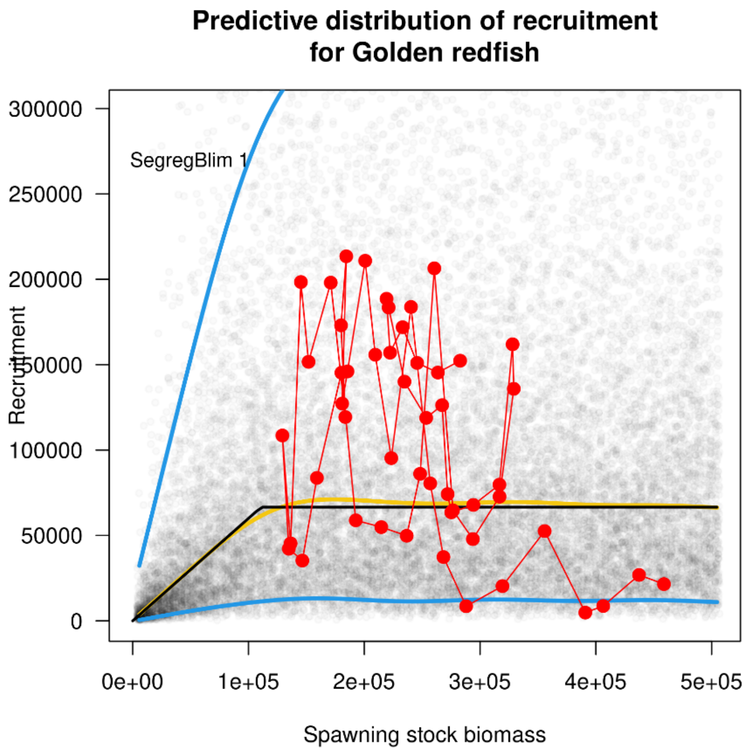


Figure 46: Golden redfish in 5,6,12, and 14. Segmented regression fitted to spawning stock biomass and recruitment (age 6). Blue lines indicate 95% confidence intervals without trimming of the recruitment residuals. Trimming, as implemented in long-term projections, effectively reduced the range of forecasted recruitment to be more similar to values observed in the past, reducing the range between actual 95% confidence intervals.

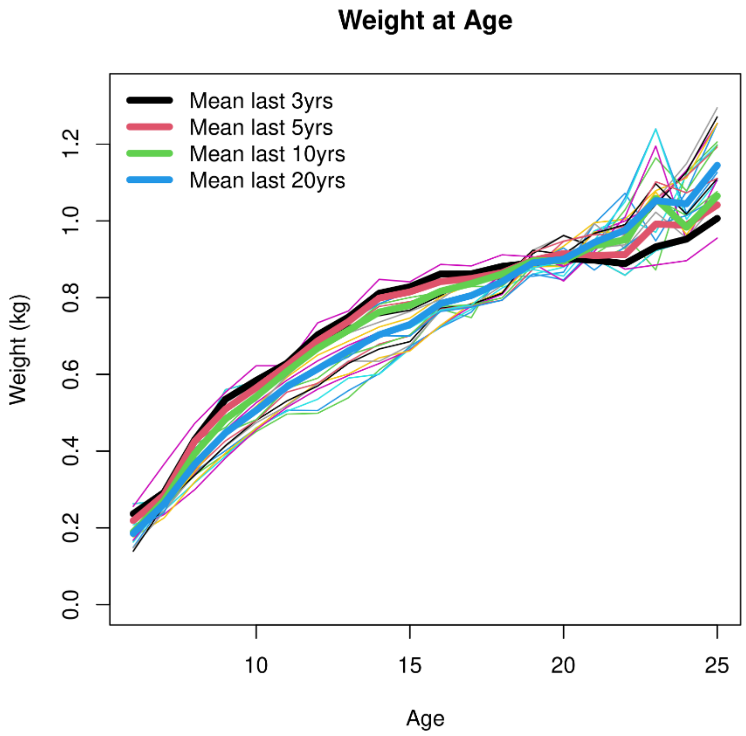


Figure 47: Golden redfish in 5,6,12, and 14. Settings for the projections. Estimated weight at age by year (narrow coloured lines) illustrated with 3, 5, 10 and 20 year averages (thick lines)

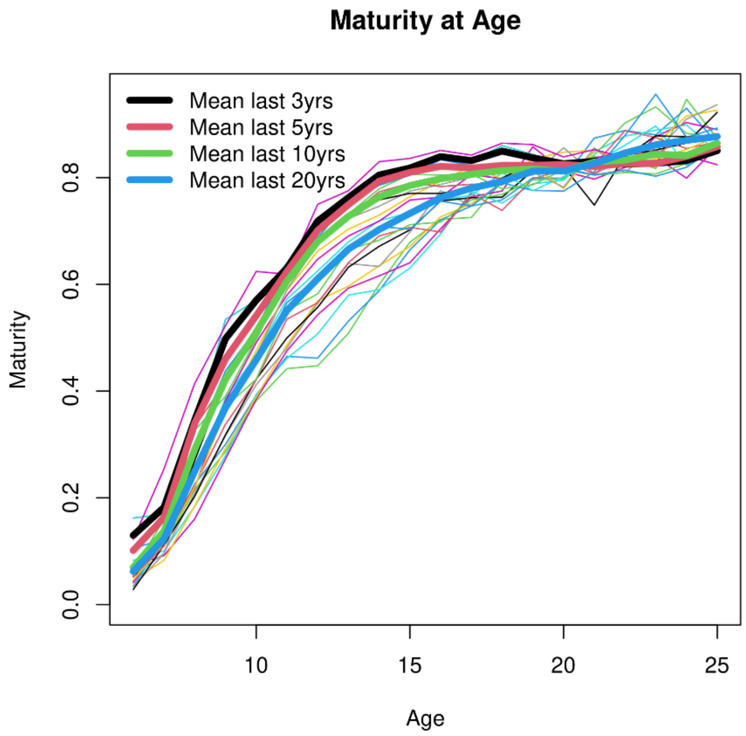


Figure 48: Golden redfish in 5,6,12, and 14. Settings for the projections. Estimated maturity at age by year (narrow coloured lines) illustrated with 3, 5, 10 and 20 year averages (thick lines)

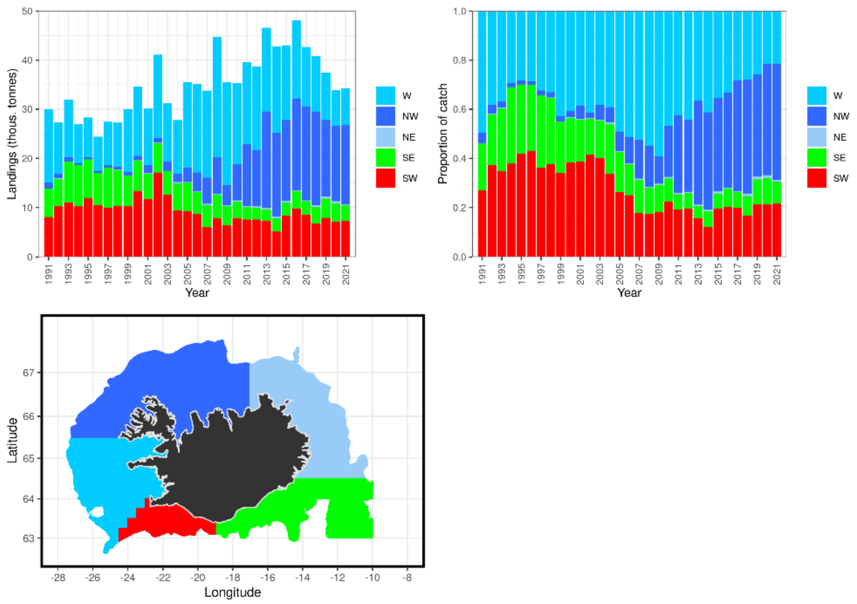


Figure 49: Golden redfish in 5,6,12, and 14. Changes in location of fishing over time.

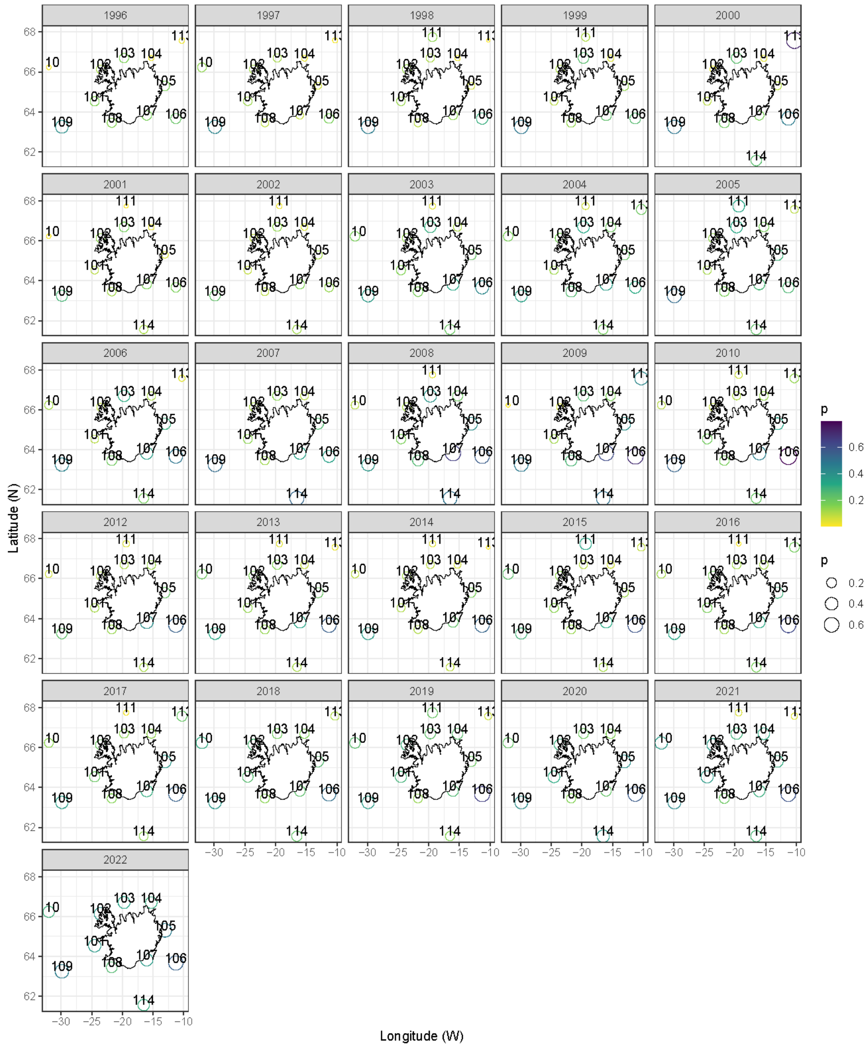


Figure 50: Golden redfish in 5,6,12, and 14. Proportions of golden redfish greater age 18+ summed within regions around Iceland in the autumn survey. Regions are labeled at their mean location by their division number (first three numbers in the Fig. 10 map, generally 101-116)

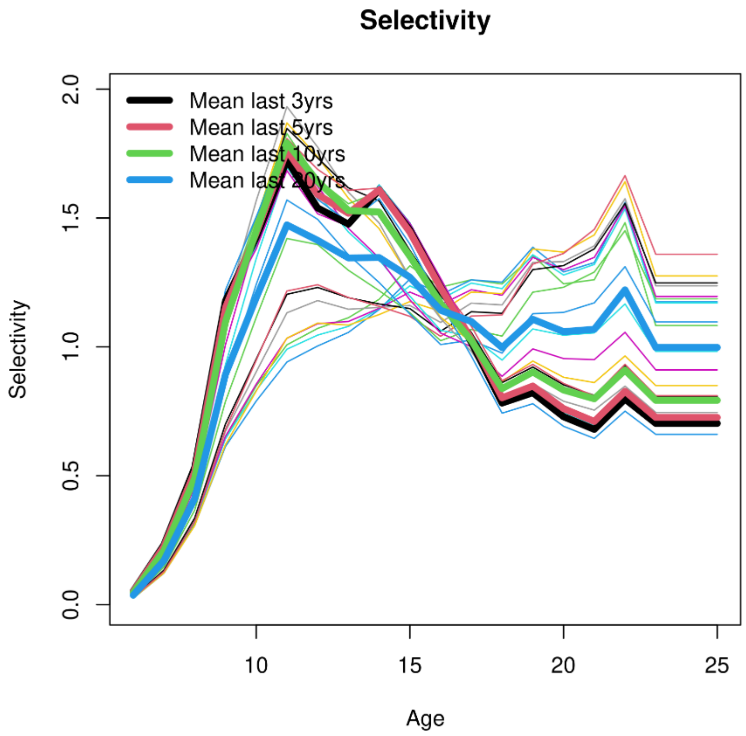


Figure 51: Golden redfish in 5,6,12, and 14. Settings for the projections. Estimated selectivity at age by year (narrow coloured lines) illustrated with 3, 5, 10 and 20 year averages (thick lines).

6.3 Setting F_{lim} and F_{pa}

According to the ICES guidelines, the precautionary reference points are set by simulating the stock using the stock-recruitment, growth and maturity relationship described above, based on a wide range of harvest rates, ranging from 0 to 0.2 and setting F_{lim} as the F that, in equilibrium, gives a 50% probability of SSB $> B_{lim}$ without assessment error.

For each replicate the stock status was projected forward 200 years as simulations, and average of the last 50 years of those projected values was used to estimate the MSY reference points.

The results from the long–term simulations estimate the value of F, F_{lim}, resulting in 50% long–term probability of SSB $> B_{lim}$ to be at 0.17.

6.4 MSY reference points

As an additional simulation experiment where, in addition to recruitment and growth variations, assessment error was added. The harvest rate that would lead to the maximum sustainable yield, F_{msy}, was then estimated. Average annual landings and 90% confidence intervals were used to determine the yield by F. Fig. 54 shows the evolution of catches, SSB and fishing mortality for select values of F. The equilibrium yield curve is shown in Figs. 52, and with the $B_{trigger}$ implemented in an HCR in 53, where the maximum average yield, under the recruitment assumptions, is around 40 thousand tons. However, this long-term yield value is extremely sensitive to expected recruitment, so if the recent low recruitment values proves to be the result of a productivity shift in the future, rather than an auto-correlated low period, then this expectation will likewise need to be shifted greatly downward.

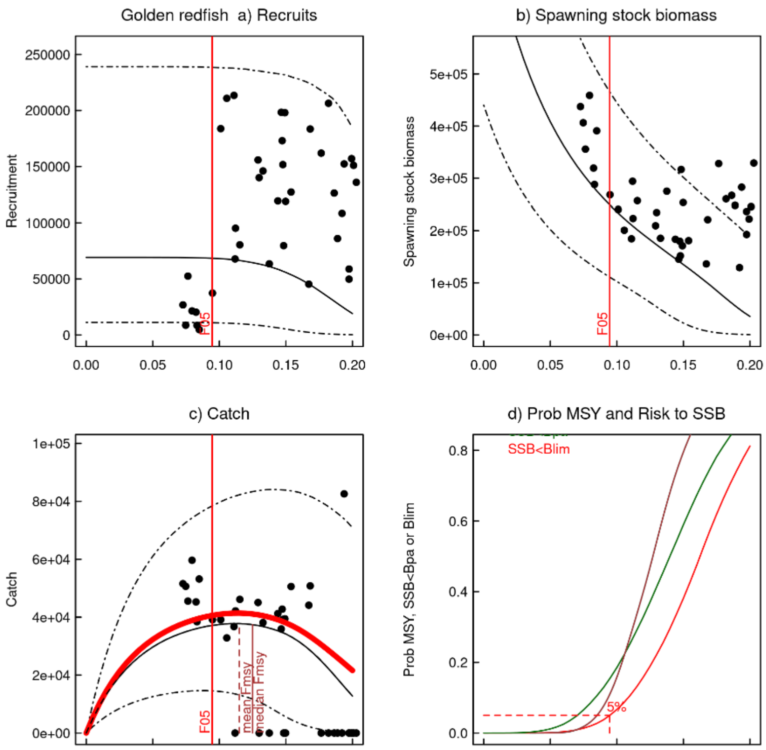


Figure 52: Golden redfish in 5,6,12, and 14. Equilibrium catch, recruitment, SSB and risk from forward projections, generated from Eqsim. No trigger was implemented in these projections, used to derive F_{msy}. Dash-dotted lines indicate 5th and 95th percentiles of simulated results; solid lines represent medians.

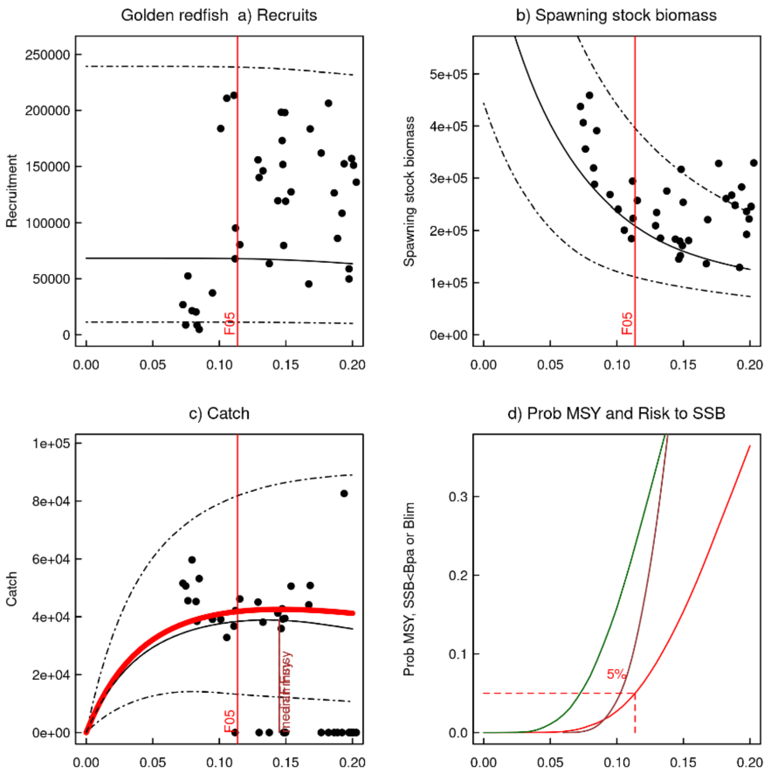


Figure 53: Golden redfish in 5,6,12, and 14. Equilibrium catch, recruitment, SSB and risk from forward projections, generated from Eqsim. The trigger was implemented in these projections, used to derive F_{p05}. Dash-dotted lines indicate 5th and 95th percentiles of simulated results; solid lines represent medians.

In line with ICES technical guidelines, the MSY $B_{trigger}$ is set to be set at B_{pa} in simulations with the ICES advice rule implemented (i.e., constant target fishing rate above $B_{trigger}$, which is scaled down by the ratio $SSB/B_{trigger}$ when $SSB < B_{trigger}$). Maximum yield is estimated to be obtained at a F of 0.112. F_{p05}, i.e. the maximum F that has less than 5% chance of SSB going below B_{lim} when the advice rule is applied, is more than the F maximizing yield 0.112, thus not limiting the estimate of F_{msy}. The evolution of the spawning stock biomass is shown in Figure 54 for select F values in the HCR. Higher Fs are associated with greater fluctuations in recruitment, catch, and realized F.

Golden redfish in 5,6,12, and 14. Overview of estimated reference points

Reference point	Value	Basis
MSYBtrigger	154000	Bpa
5thPerc_SSBmsy	87000	5th quantile of SSB when fishing at Fmsy
Bpa	154000	Blim * exp(1.645*sigma_SSB)
Blim	111000	Lowest SSB (1994) (Type 5)
Flim	0.167	F leading to P(SSB < Blim) = 0.5
Fp05	0.114	F, when ICES AR is applied, leading to P(SSB > Blim) = 0.05
Fmsy_unconstr	0.112	Unconstrained F leading to MSY
Fmsy	0.112	Unconstrained F leading to MSY

7 Future Research and data requirements

It is clear that large changes in growth have occurred in recent years in golden redfish, both for older and younger fish. It is possible that these changes could be due to density dependence, but ecosystem shifts have also been observed in other species around Iceland. As a result, these changes in growth should be monitored and studied in more detail if possible. If it becomes clear that growth shifts as expected during the decline of the stock expected over the next 5 - 10 years, then growth may be predicted by a cohort or annual effect, and this may improve short-term forecasts and how closely actual harvest rates result from those expected under implementation of the ICES advice. As these changes in growth have likewise modified our current view of spawning stock biomass, it would also be prudent to know whether the changing age structure of the spawning stock biomass affect recruitment. Studies of maturation and fecundity may be informative in this endeavor.

Commercial selectivity changes and causes for them should be additionally monitored. It is not 100% clear whether survey selectivity patterns are in reality vary logistically with age or are in fact more dome-shaped, as both configurations gave a similar fit to the data, but different views of total stock biomass. As changes in growth have recently coincided with shifts in commercial selectivity that appear to be due to spatial shifts in fishing effort, it may also be useful to research whether density dependent shift in growth are spatially explicit.

Not a lot of information is available on natural mortality, which can influence the view of the productivity of the stock. More information on natural mortality could help improve stock assessment. Other areas for potential improvement in the stock assessment are greater analysis of what hauls the winsorisation procedure removes and whether indices of young age groups would be better represented by non-linear relationships. Along the same lines, it is would be useful to analyze why the last decade has shown diverging signals from the spring versus autumn survey indices (see *Leave-one-out analysis*).

Finally, as most of the cohort information come from age readings, it is important to continue good sampling of otoliths from the stock. The addition of further otolith readings either from outside Iceland or from the spring survey within Iceland could improve model stability.

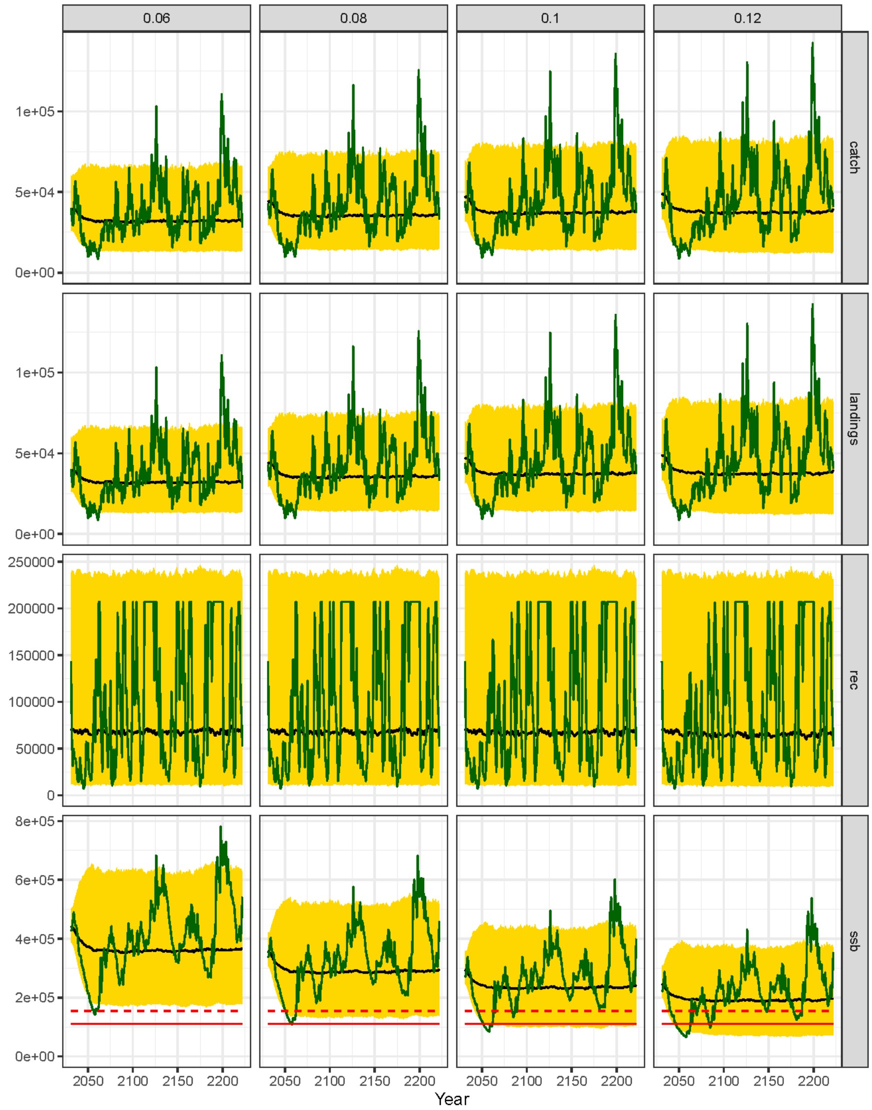


Figure 54: Golden redfish in 5,6,12, and 14. Results from the projections for select fishing mortalities. Black solid line shows the median projection, yellow ribbon the 5 and 95 percentiles and the dashed and solid red lines Bpa and Blim respectively. Green lines show one realisation from the projections.

8 Acknowledgments

Special thanks to Bjarki Þ. Elvarsson, Kristján Kristinsson, and Anders Nielsen for helping to develop this model.

9 Model configuration

```
## # Configuration saved: Fri May  5 13:59:45 2023
## #
## # Where a matrix is specified rows corresponds to fleets and columns to ages.
## # Same number indicates same parameter used
## # Numbers (integers) starts from zero and must be consecutive
## # Negative numbers indicate that the parameter is not included in the model
## #
## $minAge
## # The minimium age class in the assessment
##  6
##
## $maxAge
## # The maximum age class in the assessment
##  25
##
## $maxAgePlusGroup
## # Is last age group considered a plus group for each fleet (1 yes, or 0 no).
##  1 1 0 0
##
## $keyLogFsta
## # Coupling of the fishing mortality states processes for each age (normally only
## # the first row (= fleet) is used).
## # Sequential numbers indicate that the fishing mortality is estimated individually
## # for those ages; if the same number is used for two or more ages, F is bound for
## # those ages (assumed to be the same). Binding fully selected ages will result in a
## # flat selection pattern for those ages.
##   -1   0   1   2   3   4   5   6   7   8   9  10  11  12  13  14  15  16  17
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##
##   17
##   -1
##   -1
##   -1
##
## $corFlag
## # Correlation of fishing mortality across ages (0 independent, 1 compound symmetry,
## # 2 AR(1), 3 separable AR(1).
## # 0: independent means there is no correlation between F across age
## # 1: compound symmetry means that all ages are equally correlated;
## # 2: AR(1) first order autoregressive - similar ages are more highly correlated than
## # ages that are further apart, so similar ages have similar F patterns over time.
## # if the estimated correlation is high, then the F pattern over time for each age
## # varies in a similar way. E.g if almost one, then they are parallel (like a
## # separable model) and if almost zero then they are independent.
## # 3: Separable AR - Included for historic reasons . . .  more later
##  2
##
## $keyLogFpar
## # Coupling of the survey catchability parameters (nomally first row is
## # not used, as that is covered by fishing mortality).
```

```
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##    0   1   2   3   4   5   6   7   8   9   9   9   9   9   9   9   9   9   9
##   10  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##
##   -1
##    9
##   -1
##   -1
##
## $keyQpow
## # Density dependent catchability power parameters (if any).
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##
##   -1
##   -1
##   -1
##   -1
##
## $keyVarF
## # Coupling of process variance parameters for log(F)-process (Fishing mortality
## # normally applies to the first (fishing) fleet; therefore only first row is used)
##    0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##
##    0
##   -1
##   -1
##   -1
##
## $keyVarLogN
## # Coupling of the recruitment and survival process variance parameters for the
## # log(N)-process at the different ages. It is advisable to have at least the first age
## # class (recruitment) separate, because recruitment is a different process than
## # survival.
##  0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
##
## $keyVarLogP
## #
##
##
## $keyVarObs
## # Coupling of the variance parameters for the observations.
## # First row refers to the coupling of the variance parameters for the catch data
## # observations by age
## # Second and further rows refers to coupling of the variance parameters for the
## # index data observations by age
##    0   0   1   1   2   2   2   2   2   2   2   2   3   3   3   3   3   3   3
##    4   4   4   4   5   5   6   6   6   6   6   6   7   7   7   7   7   7   7
```

```
##    8  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##
##    3
##    7
##   -1
##   -1
##
## $obsCorStruct
## # Covariance structure for each fleet ("ID" independent, "AR" AR(1), or "US" for unstructured). | Po:
##  "ID" "AR" "ID" "ID"
##
## $keyCorObs
## # Coupling of correlation parameters can only be specified if the AR(1) structure is chosen above.
## # NA's indicate where correlation parameters can be specified (-1 where they cannot).
## #6-7 7-8 8-9 9-10 10-11 11-12 12-13 13-14 14-15 15-16 16-17 17-18 18-19 19-20 20-21 21-22 22-23 23-2
##   NA  NA  NA  NA  NA  NA  NA  NA  NA  NA  NA  NA  NA  NA  NA  NA  NA  NA  NA
##    0   0   0   0   0   0   0   0   1   1   1   1   1   1   1   1   1   1   1
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##
## $stockRecruitmentModelCode
## # Stock recruitment code (0 for plain random walk, 1 for Ricker, 2 for Beverton-Holt, 3 piece-wise c
##  3
##
## $noScaledYears
## # Number of years where catch scaling is applied.
##  0
##
## $keyScaledYears
## # A vector of the years where catch scaling is applied.
##
##
## $keyParScaledYA
## # A matrix specifying the couplings of scale parameters (nrow = no scaled years, ncols = no ages).
##
## $fbarRange
## # lowest and higest age included in Fbar
##  9 19
##
## $keyBiomassTreat
## # To be defined only if a biomass survey is used (0 SSB index, 1 catch index, 2 FSB index, 3 total c
##  -1 -1 5 4
##
## $obsLikelihoodFlag
## # Option for observational likelihood | Possible values are: "LN" "ALN"
##  "LN" "LN" "LN" "LN"
##
## $fixVarToWeight
## # If weight attribute is supplied for observations this option sets the treatment (0 relative weight
##  0
##
## $fracMixF
## # The fraction of t(3) distribution used in logF increment distribution
```

```
## 0
##
## $fracMixN
## # The fraction of t(3) distribution used in logN increment distribution (for each age group)
## 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
##
## $fracMixObs
## # A vector with same length as number of fleets, where each element is the fraction of t(3) distribu
## 0 0 0 0
##
## $constRecBreaks
## # For stock-recruitment code 3: Vector of break years between which recruitment is at constant level
## 1994 2001 2014
##
## $predVarObsLink
## # Coupling of parameters used in a prediction-variance link for observations.
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##   NA  NA  NA  NA  NA  NA  NA  NA  NA  NA  NA  NA  NA  NA  NA  NA  NA  NA  NA
##   NA  NA  NA  NA  NA  NA  NA  NA  NA  NA  NA  NA  NA  NA  NA  NA  NA  NA  NA
##
##   -1
##   -1
##   NA
##   NA
##
## $stockWeightModel
## # Integer code describing the treatment of stock weights in the model (0 use as known, 1 use as obse
## 0
##
## $keyStockWeightMean
## # Coupling of stock-weight process mean parameters (not used if stockWeightModel==0)
## NA NA NA NA NA NA NA NA NA NA NA NA NA NA NA NA NA NA NA NA
##
## $keyStockWeightObsVar
## # Coupling of stock-weight observation variance parameters (not used if stockWeightModel==0)
## NA NA NA NA NA NA NA NA NA NA NA NA NA NA NA NA NA NA NA NA
##
## $catchWeightModel
## # Integer code describing the treatment of catch weights in the model (0 use as known, 1 use as obse
## 0
##
## $keyCatchWeightMean
## # Coupling of catch-weight process mean parameters (not used if catchWeightModel==0)
##   NA  NA  NA  NA  NA  NA  NA  NA  NA  NA  NA  NA  NA  NA  NA  NA  NA  NA  NA
##
##   NA
##
## $keyCatchWeightObsVar
## # Coupling of catch-weight observation variance parameters (not used if catchWeightModel==0)
##   NA  NA  NA  NA  NA  NA  NA  NA  NA  NA  NA  NA  NA  NA  NA  NA  NA  NA  NA
##
##   NA
##
```

```
## $matureModel
## # Integer code describing the treatment of proportion mature in the model (0 use as known, 1 use as 
##  0
##
## $keyMatureMean
## # Coupling of mature process mean parameters (not used if matureModel==0)
##  NA NA NA NA NA NA NA NA NA NA NA NA NA NA NA NA NA NA NA NA
##
## $mortalityModel
## # Integer code describing the treatment of natural mortality in the model (0 use as known, 1 use as 
##  0
##
## $keyMortalityMean
## #
##  NA NA NA NA NA NA NA NA NA NA NA NA NA NA NA NA NA NA NA NA
##
## $keyMortalityObsVar
## # Coupling of natural mortality observation variance parameters (not used if mortalityModel==0)
##  NA NA NA NA NA NA NA NA NA NA NA NA NA NA NA NA NA NA NA NA
##
## $keyXtraSd
## # An integer matrix with 4 columns (fleet year age coupling), which allows additional uncertainty to
##    2 1996  10   0
##    2 1997  10   0
##    2 1998  10   0
##    2 1999  10   0
##    2 2000  10   0
##    2 1996  11   0
##    2 1997  11   0
##    2 1998  11   0
##    2 1999  11   0
##    2 2000  11   0
##    2 1996  12   0
##    2 1997  12   0
##    2 1998  12   0
##    2 1999  12   0
##    2 2000  12   0
##    2 1996  13   0
##    2 1997  13   0
##    2 1998  13   0
##    2 1999  13   0
##    2 2000  13   0
##    2 1996  14   0
##    2 1997  14   0
##    2 1998  14   0
##    2 1999  14   0
##    2 2000  14   0
##    2 1996  15   0
##    2 1997  15   0
##    2 1998  15   0
##    2 1999  15   0
##    2 2000  15   0
##    2 1996  16   0
##    2 1997  16   0
```

```
##     2 1998  16   0
##     2 1999  16   0
##     2 2000  16   0
##     2 1996  17   0
##     2 1997  17   0
##     2 1998  17   0
##     2 1999  17   0
##     2 2000  17   0
##     2 1996  18   0
##     2 1997  18   0
##     2 1998  18   0
##     2 1999  18   0
##     2 2000  18   0
##     2 1996  19   0
##     2 1997  19   0
##     2 1998  19   0
##     2 1999  19   0
##     2 2000  19   0
##     2 1996  20   0
##     2 1997  20   0
##     2 1998  20   0
##     2 1999  20   0
##     2 2000  20   0
##     2 1996  21   0
##     2 1997  21   0
##     2 1998  21   0
##     2 1999  21   0
##     2 2000  21   0
##     2 1996  22   0
##     2 1997  22   0
##     2 1998  22   0
##     2 1999  22   0
##     2 2000  22   0
##     2 1996  23   0
##     2 1997  23   0
##     2 1998  23   0
##     2 1999  23   0
##     2 2000  23   0
##     2 1996  24   0
##     2 1997  24   0
##     2 1998  24   0
##     2 1999  24   0
##     2 2000  24   0
##     2 1996  25   0
##     2 1997  25   0
##     2 1998  25   0
##     2 1999  25   0
##     2 2000  25   0
##
## $logNMeanAssumption
## #
##  0 0
##
## $initState
```

```
## #
## 0
```

References

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Beaked redfish (*Sebastes mentella*) in Subarea 14 and Division 5.a, Icelandic slope stock (East of Greenland, Iceland grounds) (reb.27.5a14)

BWKNORTH 2023 13-17 February 2023 MFRI, Hafnarfjörður, Iceland

Kristján Kristinsson and William Butler

Contents

1 Stock description

The "Workshop on Redfish Stock Structure" (ICES 2009) reviewed the stock structure of beaked redfish (*Sebastes mentella*) in the Irminger Sea and adjacent waters. ACOM concluded, based on the outcome of the WKREDS meeting, that there are three biological stocks of beaked redfish in the Irminger Sea and adjacent waters (Figure 1):

- a 'Deep Pelagic' stock (NAFO 1–2, ICES V, XII, XIV >500 m) – primarily pelagic habitats, and including demersal habitats west of the Faeroe Islands;
- a 'Shallow Pelagic' stock (NAFO 1–2, ICES V, XII, XIV <500 m) – extends to ICES I and II, but primarily pelagic habitats, and includes demersal habitats east of the Faeroe Islands;
- an 'Icelandic Slope' stock (ICES Va, XIVb) – primarily demersal habitats.

This conclusion is primarily based on genetic information, i.e. microsatellite information, and supported by analysis of allozymes, fatty acids and other biological information on stock structure, such as some parasite patterns (Cadrin et al. 2010).

The adult redfish on the Greenland shelf has traditionally been attributed to several stocks, and there remains the need to investigate the affinity of adult beaked redfish in this region. The East Greenland shelf is most likely a common nursery area for the three biological stocks. Recent studies confirm the connectivity between beaked redfish in East Greenland and other areas (Saha et al. 2017). Further studies are needed to understand e.g. the connection between the slope stocks in both East Greenland, Iceland and the Faroe Islands.

Based on the new stock identification information, ICES recommended three potential management units that are geographic proxies for biological stocks. The management units were partly defined by depth and whose boundaries are based on the spatial distribution pattern of the fishery to minimize mixed stock catches (Figure 2):

- Management Unit in the northeast Irminger Sea: ICES subareas 5.a, 12, and 14.
- Management Unit in the southwest Irminger Sea: NAFO Areas 1 and 2, ICES subareas 5.b, 12 and 14.
- Management Unit on the Icelandic slope: ICES subareas 5.a and 14, and to the north and east of the boundary proposed in the MU in the northeast Irminger Sea.

Icelandic slope beaked redfish on the continental shelf and slope of Iceland (the Icelandic Waters ecoregion, which is defined to be within the Icelandic 200 NM EEZ and includes ICES Division 5.a and part of ICES Subarea 14 – Figure 3) is mainly found in the warmer waters in the western, southern, and south-eastern parts of continental slope at 450–800 m depth (Figure 4). Only the fishable stock of Icelandic slope beaked redfish is found in Icelandic waters, i.e. mainly fish larger than 30 cm.

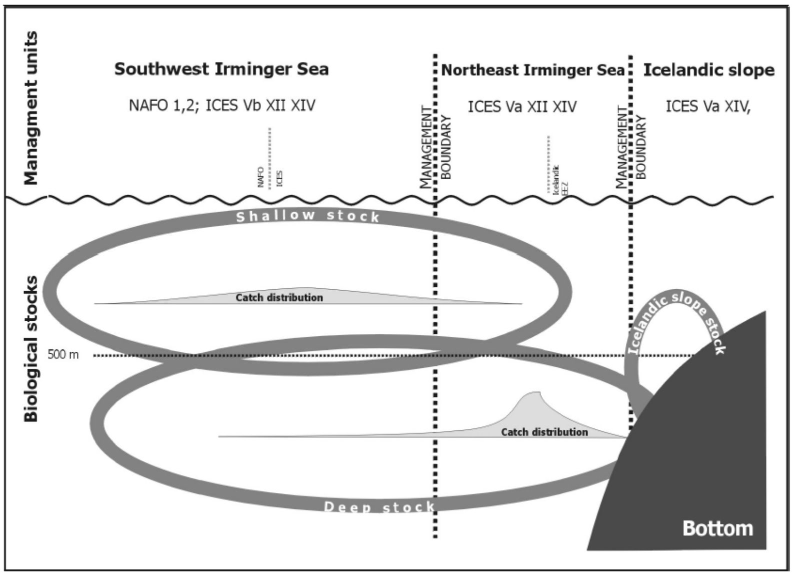


Figure 1: Schematic representation of biological stocks and potential management units of beaked redfish in the Irminger Sea and adjacent waters. The management units are shown in Figure 2. Included is a schematic representation of the geographical catch distribution prior to 2014.

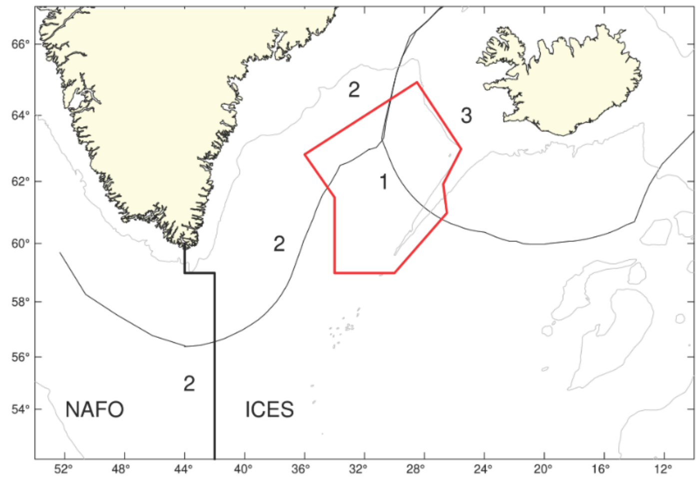


Figure 2: Management unit boundaries of beaked redfish in the Irminger Sea adjacent waters. The polygon bounded by red lines, i.e., 1 indicates the region for the 'deep pelagic' management unit in the northwest Irminger Sea, 2 is the "shallow pelagic" management unit in the southwest Irminger Sea, and 3 is the Icelandic slope management unit.

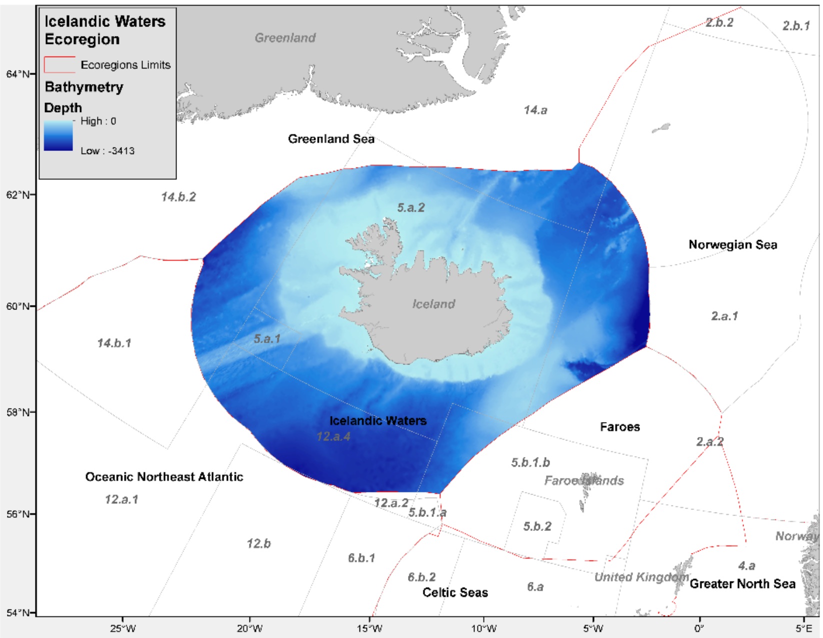


Figure 3: Icelandic Waters ecoregion.

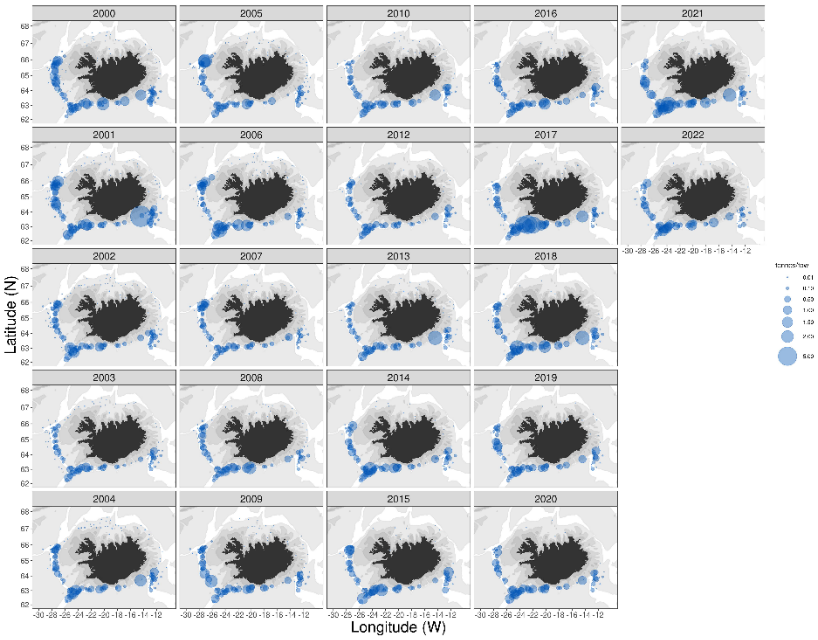


Figure 4: Icelandic slope beaked redfish. Geographical distribution from the autumn survey (IS-SMH) 2000-2022. The survey was not conducted in 2011.

2 Current advisory process

The current assessment approach (ICES DLS method, based on survey trends) is not considered to capture true state of the stock.

3 Issue list

- An analytical assessment is not conducted on this stock. The current assessment approach (ICES DLS method, based on survey trends) is not considered to capture true state of the stock.
- Survey time series is relatively short (2000-2022) for such a long lived species.
- Age and length data is available from the Icelandic autumn survey, but age data is only avlailable for few years.
- Length catch composition is available from the Icelandic commercial bottom trawl fleet since 1975, but very little age data are available.
- Stock structure is uncertain (see above). The connection between the Icelandic slope beaked redfish with the deep pelagic stock in the Irminger Sea and with the stock found on the East Greenland shelf is not very well known.

4 Scorecard on data quality

Scorecard on data quality was not used.

5 Multispecies and mixed–fisheries issues

The fishery for the Icelandic slope beaked redfish stock in Icelandic waters started in 1950, and is a targeted fishery. Traditionally, the fishing grounds were southeast of Iceland (along the slope of the Iceland-Faroe Islands Ridge), along the south coast, and south-west, west, and north-west of Iceland at depths from 450 to 800 m (Figure 5). In recent years, however, the main fishing grounds have been at the slope south-west and north-west of Iceland and very little fishery is now conducted southeast and west of Iceland. Although no direct measurements are available on discards, it is believed that there are no significant discards of Icelandic slope beaked redfish.

Figure 6 shows that Icelandic slope beaked redfish is mainly a directed fishery (where more than 50% of the total catch in a haul is beaked redfish). During the 2008–2021 period, 65–85% of the total beaked redfish catch were from hauls directed at the species (Figure 6). During the same period, 10–30% of the hauls are "clean" beaked redfish hauls, that is, no other species were reported in the catch.

The proportion of beaked redfish in tows where more than 50% of the total catch was beaked redfish decreased from 96% in 1997 to around 77% in 2012. Since then this proportion has increased slightly.

Beaked redfish is mainly caught in a mixture with greater silver smelt (Figure 7). The proportion of greater silver smelt in beaked redfish catches has increased from about 1% in 1997 to 11–14% in 2009–2018 but has since then decreased. The second highest by-caught species is golden redfish where the proportion in recent decade has been between 5% and 7%. It is likely that the proportion of golden redfish was higher prior to 2010 as the species were not separated in the catches.

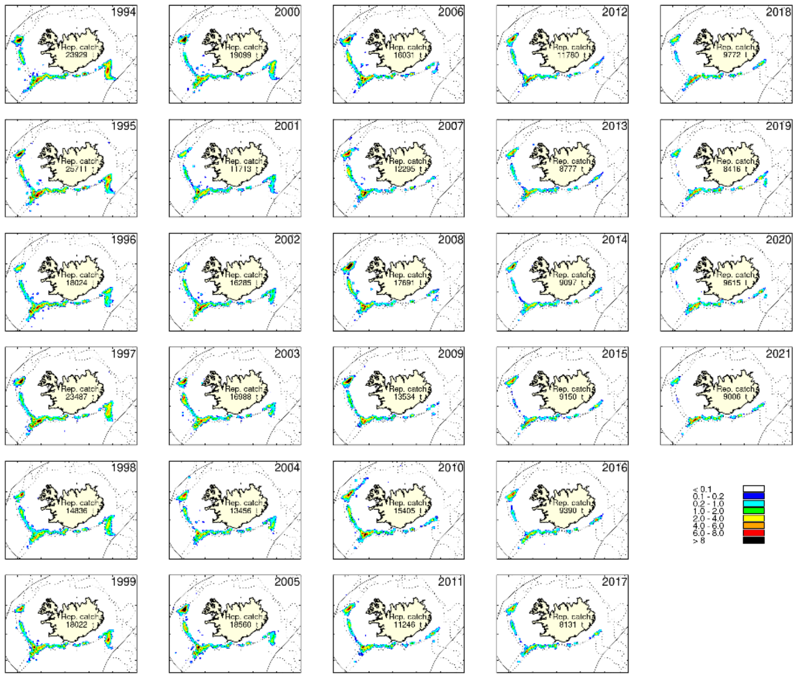


Figure 5: Icelandic slope beaked redfish. Fishing grounds 1994–2021.

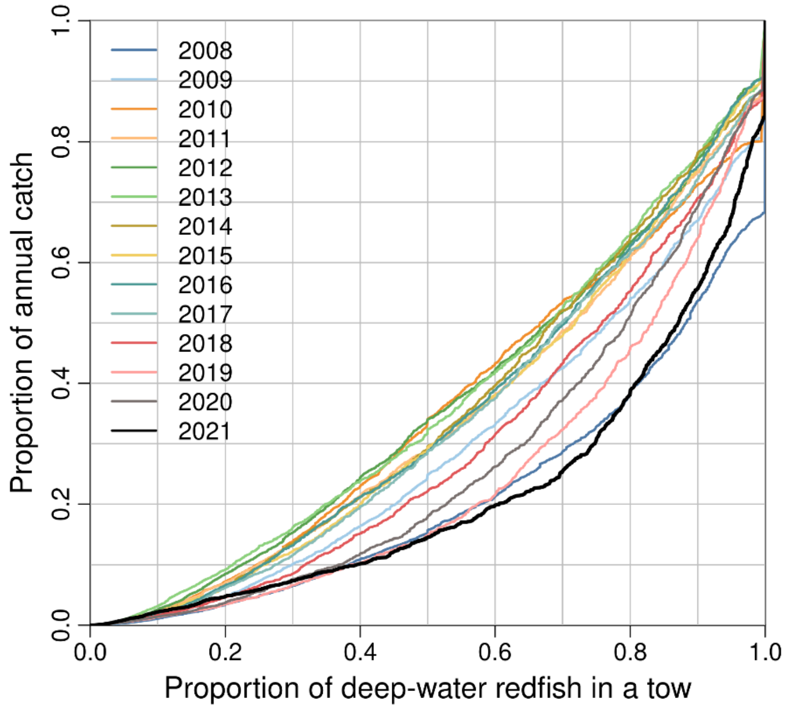


Figure 6: Cumulative plot for Icelandic slope beaked redfish caught with bottom trawl in 2008-2021. During this period 15 35% of the total deep-water redfish catch are from hauls where deep-water redfish was less 50% of the total catch. This means that most of deep-water redfish is a directed fishery which is defined as were deep-water redfish is more than 50% of the total catch in a haul. During this period, 10–30% of the hauls are clean deep-water redfish hauls, that is, no other species were caught or reported in the log-books.

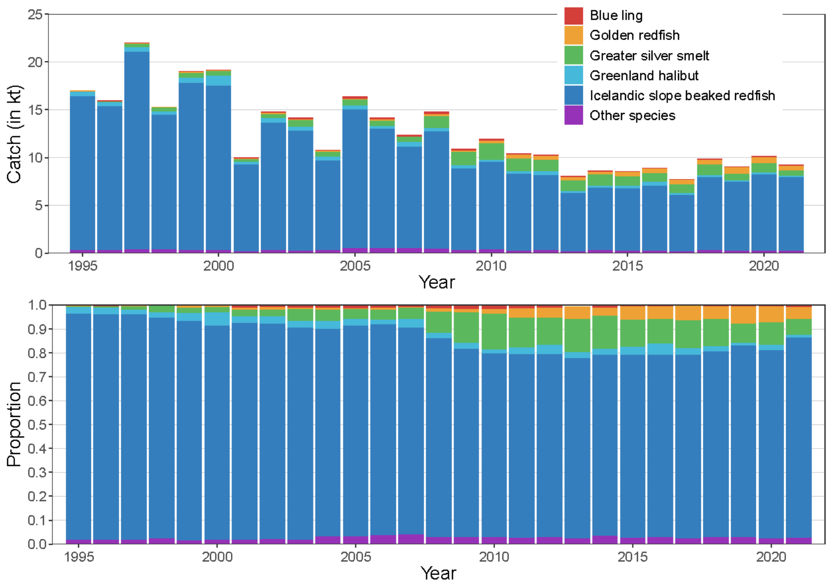


Figure 7: Icelandic slope beaked redfish. Species composition in the bottom trawl commercial catches in Icelandic waters and where more than 50% of the total catch in a haul was beaked redfish (approx. 65–85% of the total hauls). Upper: Catch in thousand tonnes as reported in log-books. Lower: Proportional species composition.

6 Ecosystem Drivers

Beaked redfish is, like other redfish (*Sebastes*) species, viviparous, i.e. eggs are fertilized, develop and hatch internally and larvae extruded soon after they hatch from eggs. The females carry sperm and non-fecundated eggs for several months before fertilization takes place in winter. Beaked redfish produce many, small larvae (40–400 thousand larvae) that are extruded soon after they hatch from eggs and disperse widely as zooplankton (Jónsson and Pálsson 2006). Knowledge on the biology, behavior and dynamics of beaked redfish reproduction is very scarce.

Little is known about the geographic location and timing of fertilization (mating grounds where copulation occurs) and extrusion of larvae (larval extrusion grounds) of Icelandic slope beaked redfish, but it is similar to those for the pelagic beaked redfish stocks (Magnusson, Magnusson, and Sigurdsson 1995). It is known that mating and copulation takes place in the autumn (September-November), but the exact location of copulation is not known. The fertilization of eggs occurs in the winter (February-March). The extrusion of larvae occurs in the spring (April-June), but its exact location of the extrusion area is unknown. The extrusion areas of the pelagic beaked redfish stock and the Icelandic stock may merge to some extend, and they are in the open seas in the Irminger Sea, southwest of Iceland (Magnusson, Magnusson, and Sigurdsson 1995). The extrusion takes place mainly at 500–700 m depth in waters with temperature around 6°C.

The released larvae is thought to drift to their nursery grounds on the continental shelf of East Greenland and to some extent to West Greenland, where they settle to the bottom (Planque et al. 2013). They are difficult to distinguish from their sibling species, golden redfish (*S. norvegicus*), which has the same nursery areas.

As mentioned earlier, only the fishable stock of Icelandic slope beaked redfish is found in Icelandic waters, i.e. mainly fish larger than 30 cm (Magnússonl and Magnússon 1988; Saborido-Rey et al. 2004). The nursery areas of both deep pelagic stock and the stock found on the continental shelf of Iceland are believed to be on the continental shelf of East Greenland at depths of 200–400 m. The proportion of juveniles recruiting to each stock is not known.

6.1 Recruitment

The recruitment of redfish is highly unpredictable with really strong year classes in some years and with long periods of low recruitment. Very little is known about the processes driving the year-to year reproductive success of redfish and is probably related to optimal ocean conditions during the larval and juvenile stages (Love, Yoklavich, and Thorsteinson 2002).

Indices for 0–group redfish (both golden redfish and beaked redfish) in the Irminger Sea and at East Greenland areas were available from the Icelandic 0-group surveys from 1970–1995. Thereafter, the survey was discontinued. Figure 8 and Figure 9 show the annual distribution and density of redfish in these surveys. Above average year class strengths were observed in 1972, 1973–1974, 1985–1991, and in 1995.

Abundance and biomass indices of redfish smaller than 17 cm from the German annual groundfish survey, conducted on the continental shelf and slope of West and East Greenland down to 400 m, show that juveniles were abundant in 1993 and 1995–1998 (ref). The 1999–2006 survey results indicate low abundance and were similar to those observed in the late 1980s. Since 2008, the survey index has been very low and was in 2013–2016 the lowest value recorded since 1982. Juvenile redfish were only classified to the genus *Sebastes* spp. as identification of small specimens to species level is difficult due to very similar morphological features of golden redfish and beaked redfish.

Annual variability in recruitment of redfish species seems to be synchronous over a wide geographical scale. For instance, similar pattern in annual recruitment of beaked redfish and golden redfish in the EGIF area and in the Irminger Sea. The 1985 and 1990 year classes are strong whereas most recent ones are small.

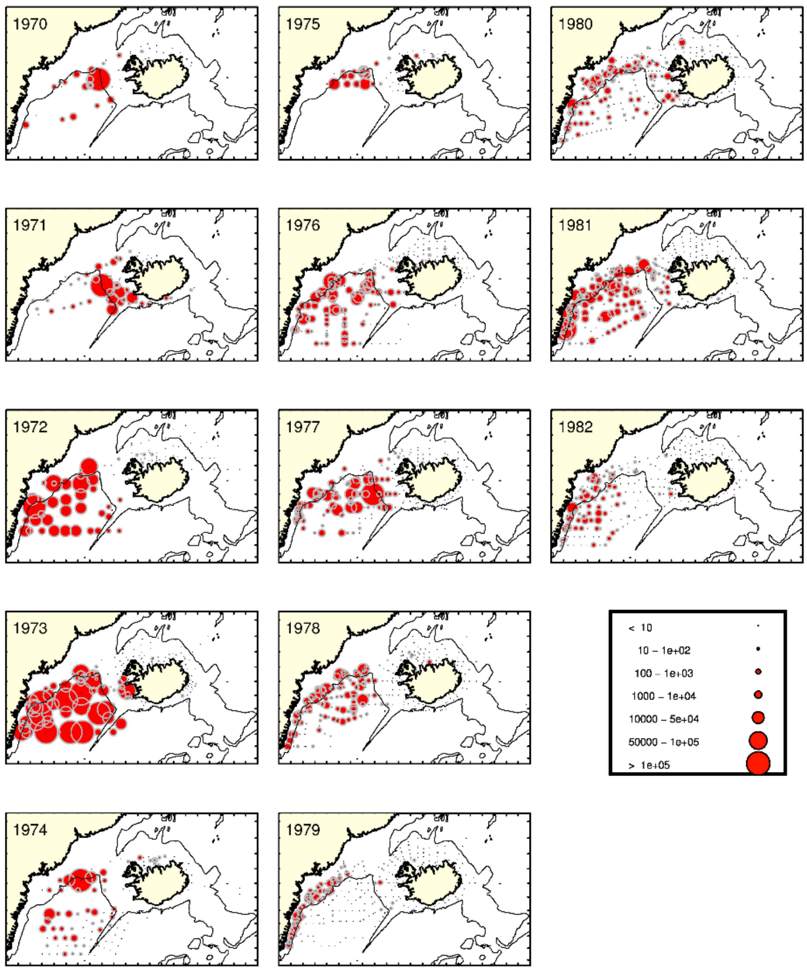


Figure 8: Annual distribution and density (number/tow) of 0-group redfish 1970-1982.

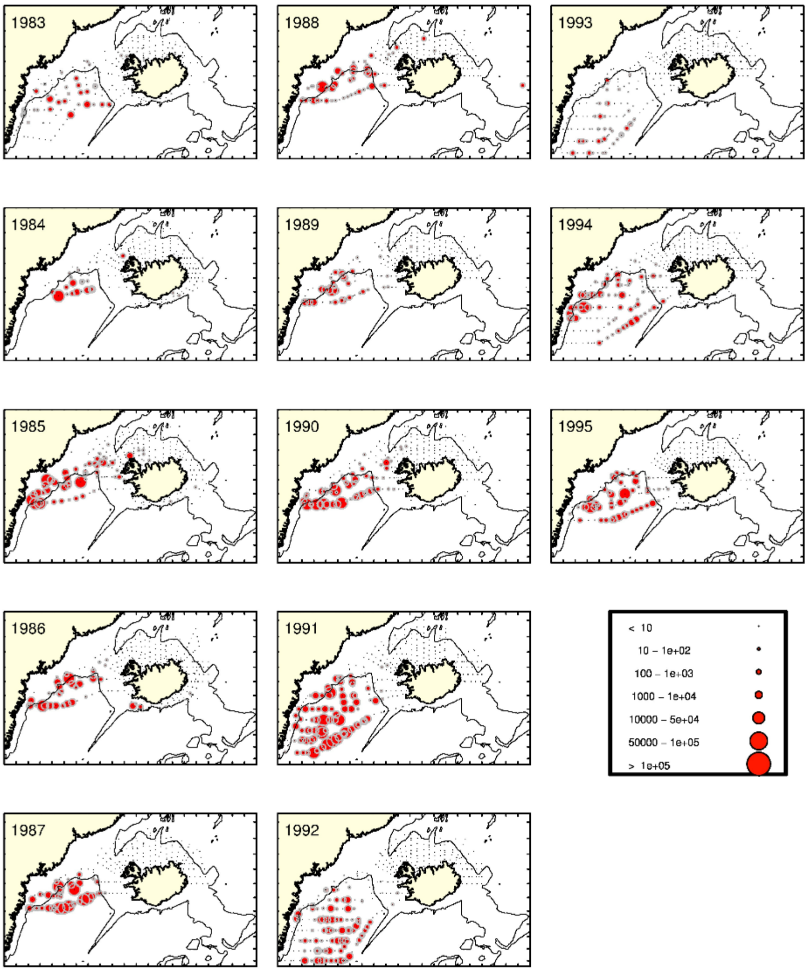


Figure 9: Annual distribution and density (number/tow) of 0-group redfish 1983-1995.

6.2 Migration

Spatial and seasonal migration are still largely unidentified although it is known that adult beaked redfish undertake large migrations between copulation grounds, larval extrusion grounds and feeding grounds (Magnusson, Magnusson, and Sigurdsson 1995). In 2003–2008, 2,777 beaked redfish were tagged at 500-800 m depth *in situ* with remotely operated Underwater Tagging Equipment (UTE) (Sigurdsson, Thorsteinsson, and Gústafsson 2006; Planque et al. 2013). The main objective of the research has been studying both vertical and horizontal migration pattern of beaked redfish. Most of the fish were tagged with dummy tags identical in size and shape of a data-storage tag (DST). The experiment included tagging 105 redfish with DST recording pressure and temperature, but no fish with these tags have been recaptured.

The tagging was done in six tagging cruises conducted in the Irminger Sea and on the shelves southwest and west of Iceland (Figure 10). Of the tagged fish 62 have been recaptured to date or 2.3% (Figure 11) with fish having been in the sea for up to 6 years from tagging.

Most of the fish were recaptured close to the tagging site, but a few fish showed long distance migration. Five were recaptured more than 250 nautical miles from the tagging site (Figure 12). Two fish showed migration between defined management units of beaked redfish (Figure 11 and Figure 13). The recaptures are heavily dependent on the fishing fleet which operates only in part of the year (fishing season 3–6 months) in a very concentrated are in the Irminger Sea. This explains why most of the fish are caught close to where they were tagged.

Six of the beaked redfish tagged on the south-western slope of Icelandic waters (the Icelandic slope stock) were recaptured on the south-east slope (four fish) and the west slope (Figure 12). The fish recaptured on the south-east slope where were tagged in October and recaptured in June-August with a travelling distance of approximately 300 NM. The recapture site on the west slope was about 200 NM from the tagging site.

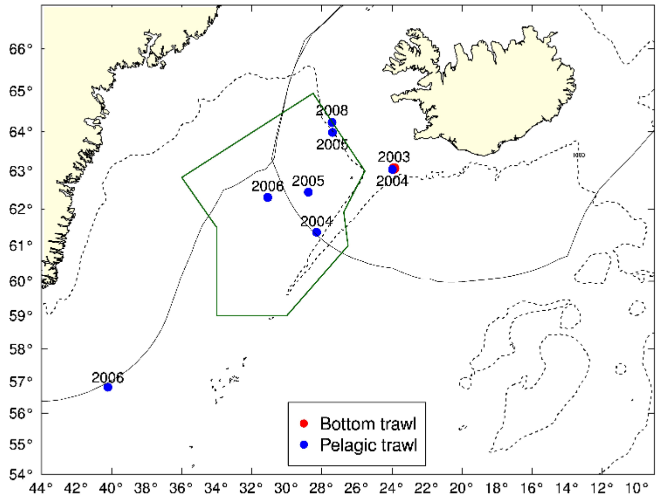


Figure 10: Tagging sites of beaked redfish 2002 2008 in the Irminger Sea and adjacent waters.

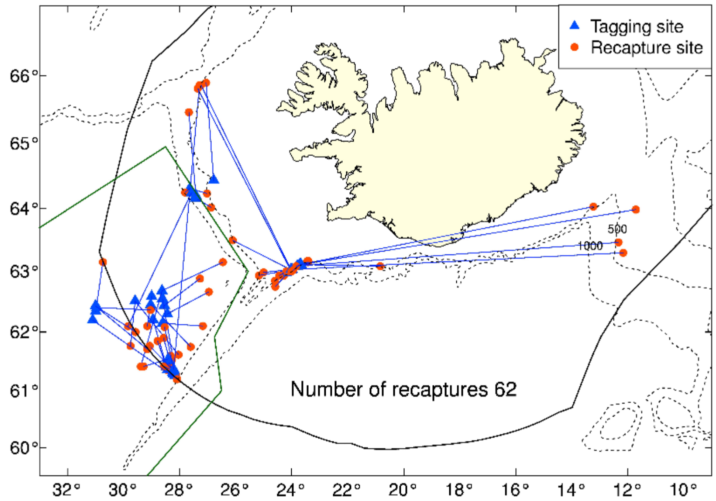


Figure 11: Tagging sites (blue triangles) and recapture sites (red circles) of 62 recaptured beaked redfish. The blue lines are drawn between tagging and recapture sites.

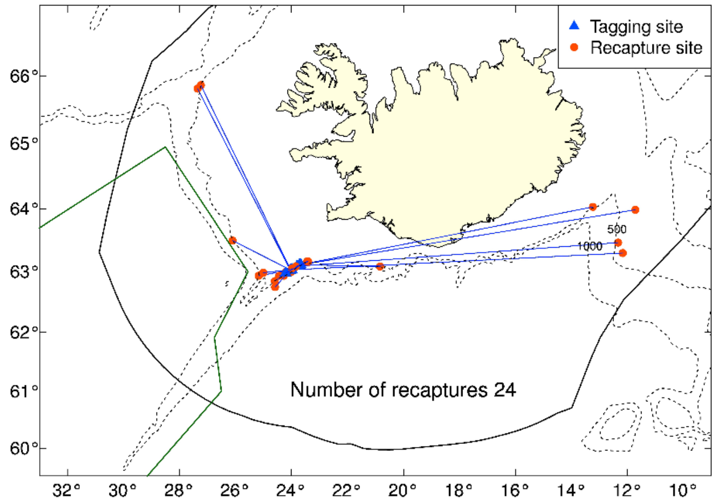


Figure 12: Tagging sites (blue triangles) and recapture sites (red circles) of 24 recaptured beaked redfish tagged with bottom trawl on the south-west slope of Iceland. The blue lines are drawn between tagging and recapture sites.

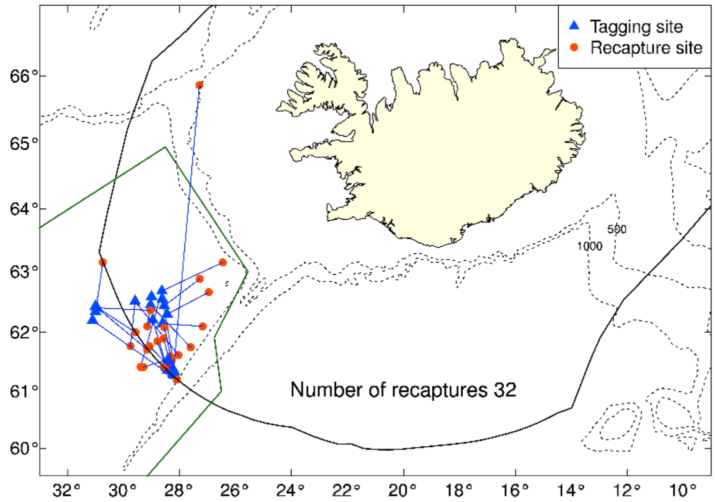


Figure 13: Tagging sites (blue triangles) and recapture sites (red circles) of 32 recaptured beaked redfish in the northern part of the Irminger Sea. The blue lines are drawn between tagging and recapture sites.

7 Stock Assessment

7.1 Catch – quality, misreporting, discard

Landings data for Icelandic slope beaked redfish are available from 1950 (Figure 14). Until 2010 Icelandic authorities gave a joint quota for golden redfish and Icelandic slope beaked redfish in Icelandic waters. Icelandic fishermen were not required to divide the redfish catch into species and the landings statistic was not split between the two species. Historical information within Statlant (derived from the Statistical Bulletin) or Statistic Iceland, therefore, only contain the total catch of the two species. Various methods have been used to divide the annual catches between species: from 1950-1977 catch statistic is based on various working group reports (WD no. 15 presented at the 2015 NWWG meeting); from 1978-2010 so-called *split-catch* method which uses log-book data of the Icelandic fleet and biological sampling to split the catches; since 2011 the landings are from the Directorate of Fisheries and are reported on species level.

Discards are illegal in Icelandic waters but are assumed to be negligible in the beaked redfish fishery as only the fishable stock is found in Icelandic waters.

During the 1950–1977 period, before the extension of the Icelandic EEZ to 200 NM, Icelandic slope beaked redfish was mainly fished by West-Germany. The catches peaked in 1953 to about 87,000 t but gradually decreased to about 23,000 t in 1977 (Figure 14). Since 1978 the fishery has almost exclusively been conducted by Icelandic vessels. Annual landings gradually decreased from 57,000 t in 1994 to 17,000 t in 2001. Annual landings in 2001–2010 fluctuated between 17,000 and 28,500 t, but were between 8,300 and 12,000 t in 2011–2021 (Figure 14).

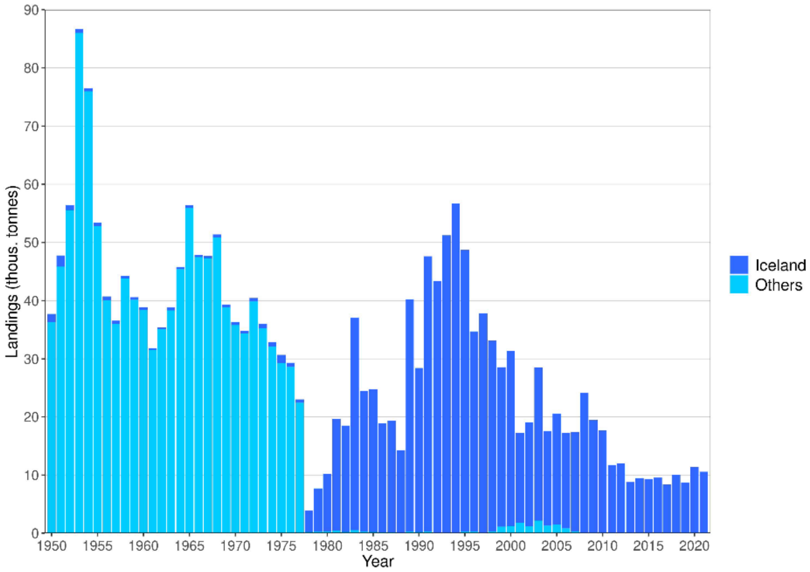


Figure 14: Icelandic slope beaked redfish. Nominal landings (in tonnes) from Icelandic waters (ICES Division 5.a and Subarea 14) 1950–2021.

7.1.1 Biological data from the fishery

The table below shows available biological data for the Icelandic slope beaked redfish from the Icelandic bottom trawl fleet. Data is available since 1977 and concurrent with length measurements the fish is also sex and maturity determined and weighed. Very little age data is available.

Year	Icelandic commercial fishery					
	Samples	Length	Age	Sex	Maturity	Weight
1977	5	965		259	259	
1978	9	999		63	63	
1979	19	2,897		596	596	733
1980	4	561		301	301	
1981	11	2,588		1,094	1,094	
1982	22	4,429		1,205	1,205	271
1983	56	13,092		4,394	4,394	
1984	62	13,858		6,733	3,259	
1985	43	10,922		6,875	4,290	
1986	34	8,939		2,364	135	
1987	16	3,734		3,022	2,152	
1988	23	4,347		1,897	1,241	
1989	37	11,608		5,225	4,066	
1990	20	3,225		1,125	1,029	
1991	27	5,372		2,198	1,435	
1992	29	6,096		2,091	1,450	
1993	47	9,845		3,137	806	
1994	121	27,522		13,750	2,266	25
1995	190	40,755		17,699	2,133	732
1996	53	10,808		4,074	1,436	364
1997	105	22,790		7,148	6,455	2,304
1998	102	19,477	97	6,654	5,164	2,219
1999	169	33,924	10	6,356	5,295	1,640

Year	Icelandic commercial fishery					
	Samples	Length	Age	Sex	Maturity	Weight
2000	211	43,438	28	7,233	4,555	1,819
2001	102	19,696	238	4,657	4,581	1,924
2002	183	33,218	167	4,962	4,909	1,955
2003	187	31,975		5,845	5,795	2,117
2004	148	23,472		4,090	4,085	1,150
2005	573	91,000		3,609	3,608	979
2006	331	51,161		4,463	4,463	1,175
2007	213	31,985		3,831	3,831	1,464
2008	200	33,880		4,691	4,691	1,297
2009	185	30,604	50	3,144	3,144	617
2010	169	28,557	30	2,803	2,803	622
2011	138	21,239		5,502	5,499	1,900
2012	68	11,118		2,160	2,160	491
2013	64	9,468		1,840	1,840	620
2014	93	15,380	25	1,895	1,895	400
2015	58	9,089		1,548	1,548	371
2016	91	13,545	45	1,847	1,847	468
2017	57	10,453		865	865	47
2018	25	4,533	25	566	425	48
2019	41	7,676		318	317	90
2020	29	5,508		345	345	100
2021	25	4,075		220	220	70

Length distributions of Icelandic slope beaked redfish from the bottom trawl fishery show an increase in the number of small fish in the catch in 1994 compared to previous years (Figure 15). The peak of about 32 cm in 1994 can be followed by approximately 1 cm annual increase in 1996-2002. The length distribution in 2004—2021 peaked around 39-42 cm and as in the autumn survey, the mode of the length distribution has shifted to the right.

7.1.2 Effort series

Trends in non-standardized CPUE (kg/hour) is shown in Figure 16. CPUE gradually decreased from 1978 to a record low in 1994. Since then, CPUE has been steadily increasing and was in 2020 and 2021 at the highest level observed in the time series.

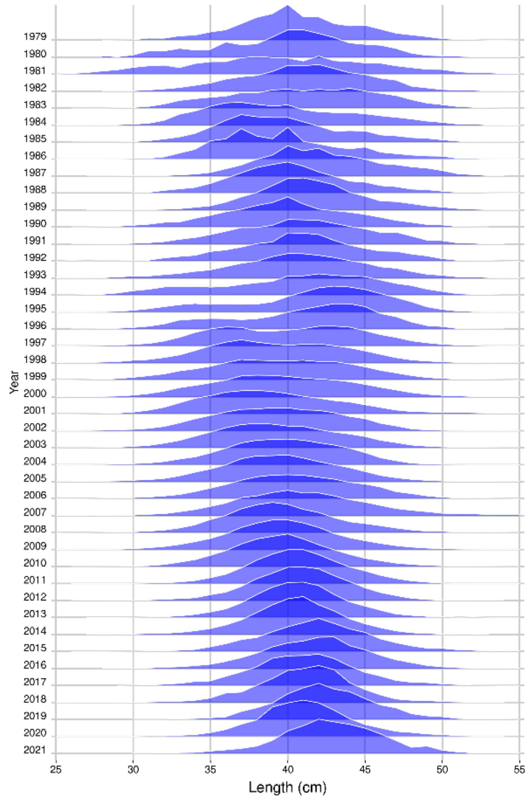
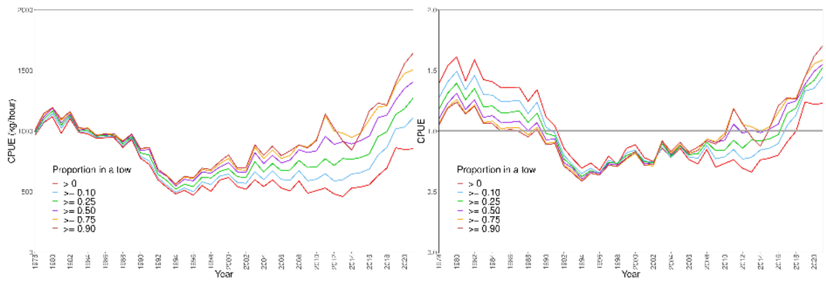


Figure 15: Icelandic slope beaked redfish. Length distribtuion from the commercial catch 1979-2021.



(a) Raw CPUE (b) Raw CPUE, proportion

Figure 16: Icelandic slope beaked redfish. CPUE from the Icelandic bottom trawlers 1978–2021 where beaked redfish catch composed at least 10%, 25%, 50%, 75% and 90% of the total catch in each haul and in all tows where beaked redfish was caught.

7.2 Surveys

Information on abundance and biological parameters of Icelandic slope beaked redfish is available from the Icelandic autumn survey (IS-SMH) 2000 2022. The autumn survey covers the most important distribution area of the Icelandic slope beaked redfish fishery. The survey was partly conducted in 2011 and the coverage 1996-1999 is incomplete (not covering the whole distribution area of the stock). The survey data for those years are for this reason omitted. The table below shows available data from the Icelandic autumn groundfish survey (IS-SMH) 1996 2021.

Icelandic slope beaked redfish - Sampling from the groundfish surveys in Icelandic Waters

Number of individuals that were length measured, aged, sex and maturity deteremined, weighed, counted, and total number of golden redfish (length measured + counted) from the autumn groundfish survey (IS-SMH). Dark blue cells indicate incomplete survey coverage; empty cells (grey) indicate not data.

Year	IS-SMH						
	Length	Age	Sex	Maturity	Weight	Counted	Total
1996	3,112		2,947	2,947	319	12,573	15,685
1997	3,144		3,097	3,097	439	11,831	14,975
1998	3,730		1,962	1,953	623	11,686	15,416
1999	3,866		3,816	3,816	725	14,918	18,784
2000	7,762	1,405	7,714	7,713	1,471	28,381	36,143
2001	6,974		6,197	6,192	1,641	39,056	46,030
2002	6,807		6,316	6,316	1,451	20,641	27,448
2003	5,774		5,755	5,752	1,161	11,433	17,207
2004	5,805		5,729	5,727	1,242	19,969	25,774
2005	5,979		5,976	5,973	1,258	19,516	25,495
2006	6,055	1,304	5,961	5,940	1,481	25,259	31,314
2007	5,242		5,223	5,223	1,192	13,811	19,053
2008	4,665		4,662	4,659	1,106	16,268	20,933
2009	5,605	1,205	5,543	5,462	1,267	16,527	22,132
2010	5,336	1,101	5,202	5,202	1,107	18,012	23,348
2011	1,650		1,648	1,648	329	6,322	7,972
2012	4,990		4,980	4,979	1,430	15,916	20,906
2013	5,098		5,092	5,092	1,199	18,648	23,746
2014	4,571		4,553	4,553	1,281	18,468	23,039
2015	4,069		4,069	4,069	1,168	17,988	22,057
2016	4,527		1,238	1,238	1,238	14,239	18,766
2017	4,639	1,299	1,301	1,301	1,301	28,394	33,033
2018	4,814	1,569	1,569	1,569	1,569	21,060	25,874
2019	4,143	1,176	1,177	1,177	1,177	14,706	18,849
2020	4,154		1,198	1,198	1,199	15,735	19,889
2021	3,267	357	1,117	1,116	1,117	26,981	30,248
2022	3,527		1,161	1,161	1,161	16,164	19,691

The survey indices are designed based indices and the calculation is done by using the Cochran method. *Sebastes* species in the North Atlantic display various kind of pelagic and demersal behavior during their life span and this is taken into account when calculating the indices.

The total biomass and abundance indices were highest in 2000 and 2001, declined in 2002 and have since then been at that level (Figure 17). The biomass index of fish 45 cm and larger shows different trend where the index increased from the lowest value in 2007 to the highest level in 2021 (Figure 17). The abundance index of fish 30 cm and smaller (recruits) has been at very low level since 2007 and no fish below 30 cm was observed in the 2021 survey (Figure 17).

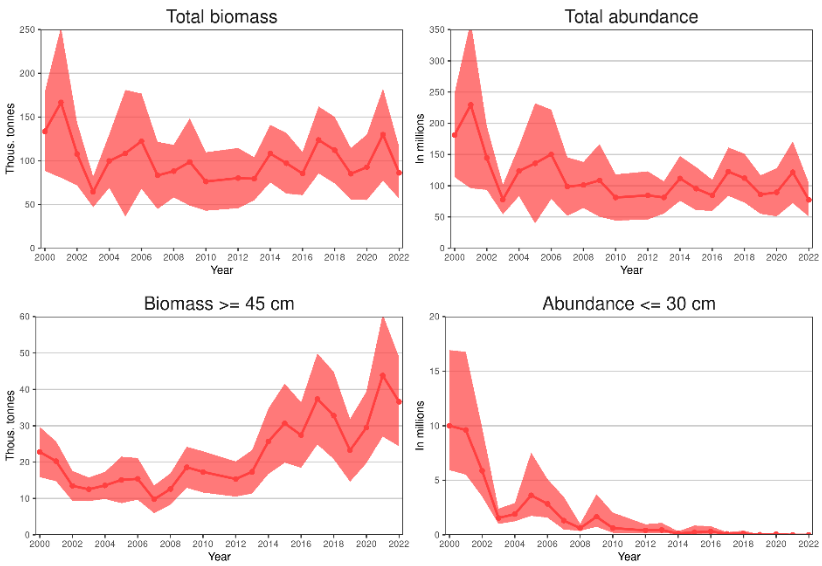


Figure 17: Icelandic slope beaked redfish. Survey indices from the autumn survey 2000–2022. The survey was not conducted in 2011. The figure shows the total biomass index, total abundance index, biomass index of fish 45 cm and larger and abundance index of fish 30 cm and smaller.

The length of the Icelandic slope beaked redfish caught in the autumn survey is between 25 and 55 cm. Since 2000, the mode of the length distribution has shifted to the right, that is, from 34-38 cm in 2000 to about 42-43 cm in 2021 (Figure 18). Much less of fish smaller than 35 cm was observed in the surveys after 2010 compared to previous years.

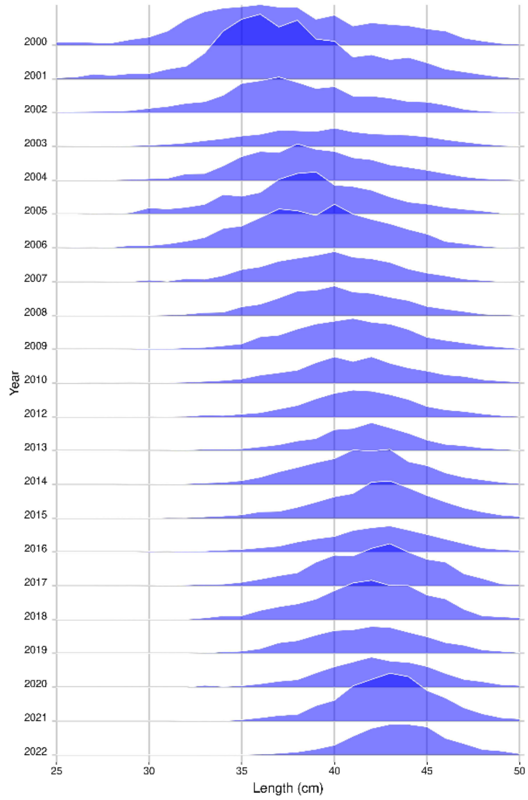


Figure 18: Icelandic slope beaked redfish. Length distribtuion from the autumn survey (IS-SMH) 2000-2021. The survey was not conducted in 2011.

Age reading from the autumn survey (2000, 2006, 2009, 2010, 2017-2019 and 2021) shows that the stock consists of many year–classes and the age ranges from 5 to over 50 years (Figure 19). The 1985 and 1990 cohorts were large and were still relatively strong in the 2021 survey. In the 2017–2019 and 2021 surveys the 2003-2004 cohorts were most abundant.

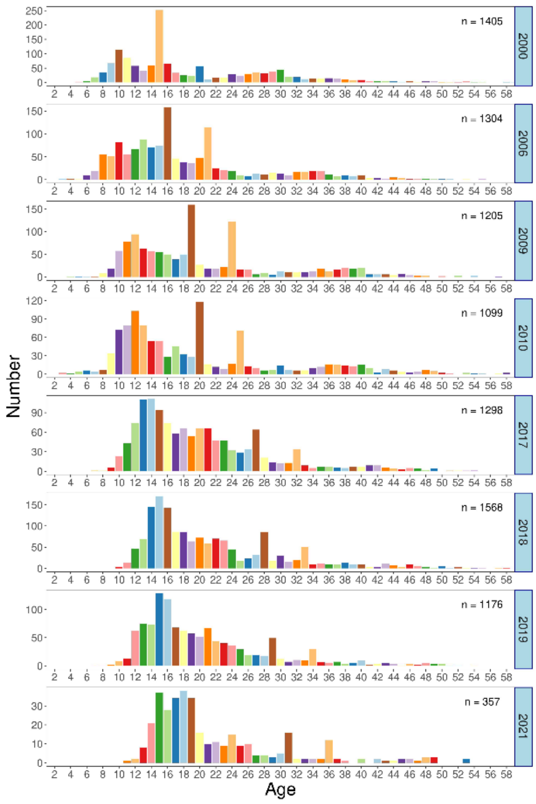


Figure 19: Icelandic slope beaked redfish. Age distribtuion from the autumn survey (IS-SMH). Note that age reading for 2021 is ongoing.

7.3 Weights, maturity and growth

7.3.1 Growth

Growth has not changed over the 2000-2021 period (Figure 20). Growth of both males and females is very little after they reach maturity around ages 15–20 (Figure 21).

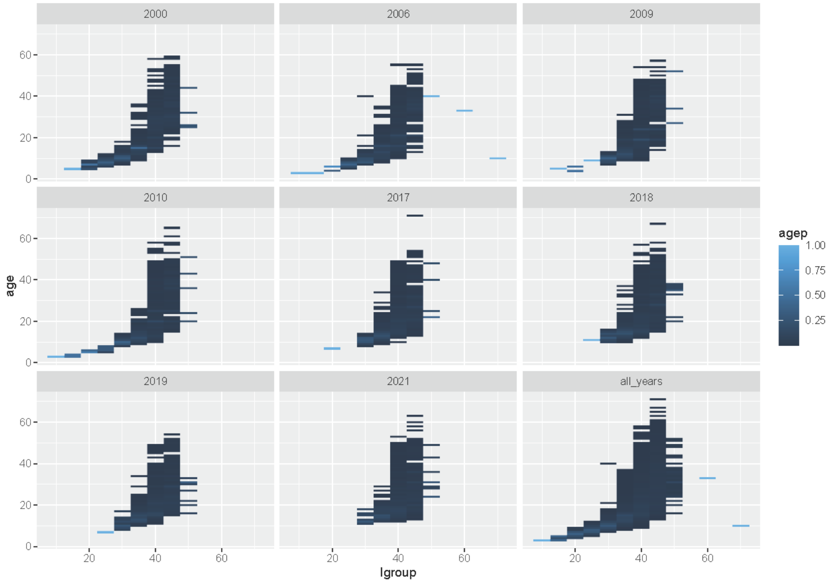


Figure 20: Icelandic slope beaked redfish. Illustration of the Age–Length key obtained from the Icelandic autumn survey.

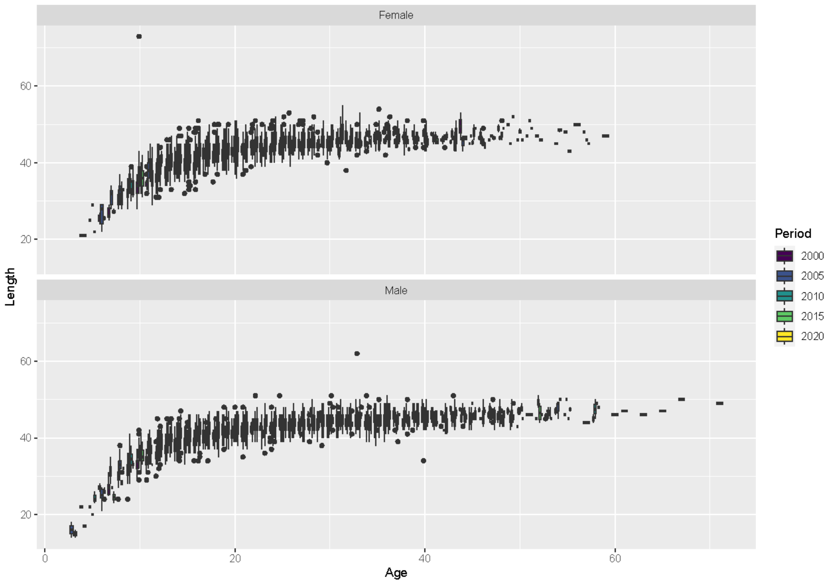


Figure 21: Icelandic slope beaked redfish. Boxplot showing the relationship between age and length by year and sex based on samples from the autumn survey 2000-2022.

7.3.2 Maturity

Figure 22 indicates that males mature earlier and at smaller size than females. Furthermore, it seems that around of age 30 the growth seems to stop or annual growth is very little.

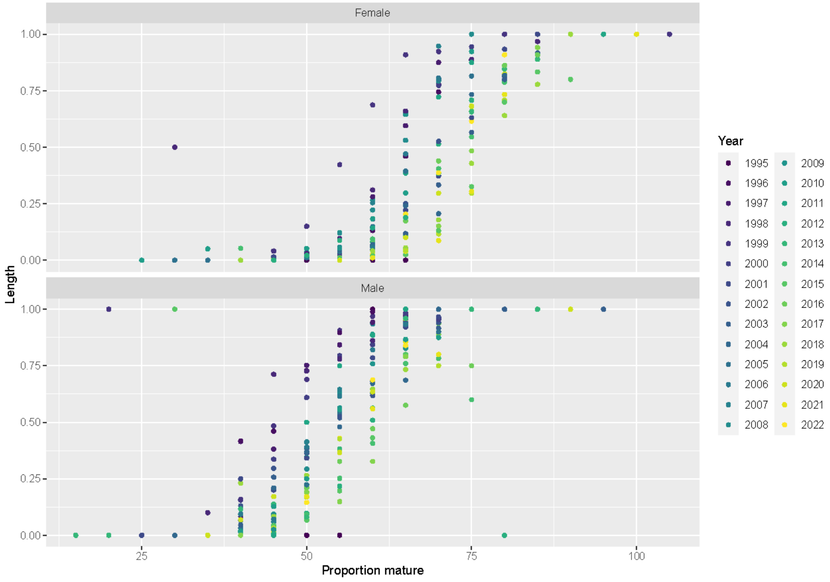


Figure 22: Icelandic slope beaked redfish. Observed propotion mature by length and sex in the Icelandic autumn survey.

7.3.3 Natural mortality

Natural mortality M for long-lived species is considered low. In the assessment model presented here, M was set as 0.05.

8 Current assessment method

An analytical assessment is not conducted on this stock. The current assessment approach (ICES DLS method, based on survey trends) is not considered to capture true state of the stock.

9 Proposed Assessment model

The proposed assessment model uses the Gadget modelling framework. The model runs from 1975 onwards with two six-month timesteps each year. The stock is represented by two sub-stocks: an immature sub-stock and a mature sub-stock. The former has an age range of 3 to 20 years, the latter has an age range of 5 to 50 years. The general gadget observation model is described in the Gadget working document [GADGET WD]. Departures from the setup described in [GADGET WD] will be outlined below.

9.1 Input data and model settings

9.1.1 Data

The model uses multiple disparate datasets. The input data includes:

- Length disaggregated survey indices from the Autumn Survey IS-SMH (2000-2021, excluding 2011).
- Length distributions from the Icelandic commercial bottom trawl fleet (1975-2021).
- Landings per 6-month period from Iceland (1975-2021).
- Age-length distributions from the Autumn Survey.
- Maturation data from the Autumn survey.

An overview of the input data and their annual availability is shown below in figure Figure 23.

9.1.2 Overview of model settings

- The model runs from 1975 to 2021. Each year is divided into two 6-month time-steps.
- Two sub-stocks are modeled:
  - An immature stock that has an age range of 3-20 years.
  - A mature stock that has an age range of 5-50 years. The oldest age is treated as a plus group (50 years and older).

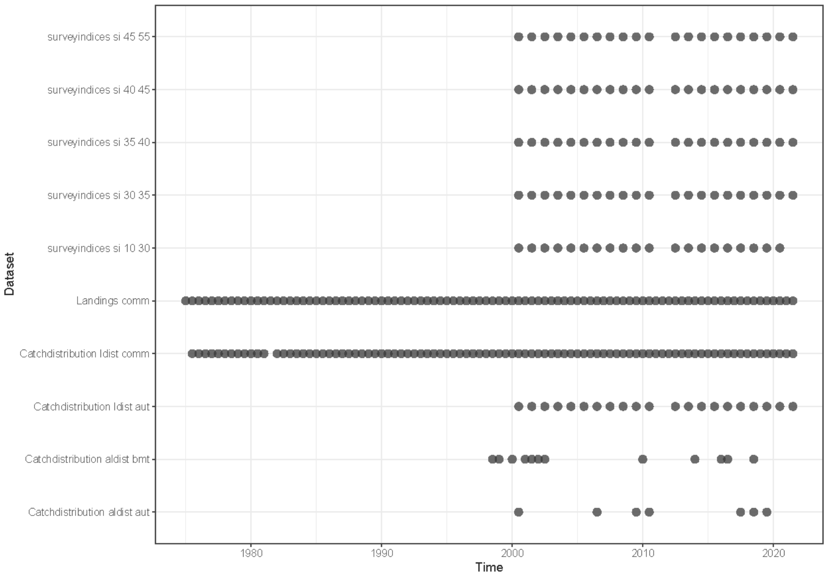


Figure 23: Icelandic slope beaked redfish. Overview of the datasets used in the Gadget model and when they are available.

- Movement from the immature stock to mature stock occurs via:
  - Maturation (using a length-based ogive)
  - Ageing (20 year old fish automatically move to the mature stock at the end of the year).
- Modeled length ranged from 5-60 cm (with no mature individual <18 cm and no immature individuals > 50 cm). Each length group was 1 cm.
- Recruitment to the immature stock occurs at age 3.
- The length increments in the survey were 10-30 cm, 30-35 cm, 34-40 cm, 41-45 cm and 46-55 cm (in total five length bins).
- One commercial fleet (bottom trawl).

9.1.3 Overview of model processes

- Natural mortality:
- M_a, was fixed at 0.05 for all ages of both immature and mature stocks. The value chosen was based on settings in other redfish stocks (fixed - 2 parameters).
- Growth:
- Length-based Von Bertalanffy growth function, k, L_∞, informed by age–length frequencies (estimated - 2 parameters).
- Parameter β of the beta-binomial distribution controlling the spread of the length distribution (estimated - 1 parameter).
- Maximum length group growth was set to 5 cm per timestep.
- Length-weight relationship, α_s, β_s, were fixed based on the means of log-linear regression of Autumn survey data (fixed - 2 parameters).
- Maturity:
- The logistic length-based maturity ogive α_m, l_{50} was estimated from Autumn survey data (estimated - 2 parameters).
- Recruitment:
- Annual recruitment occurs in the first timestep, one parameter per year R_y (estimated - 47 parameters).
- Recruitment scalar, R_c, is multiplied against all R_y to help optimization (estimated - 1 parameter).
- Mean length at recruitment, l_0, is estimated (estimated - 1 parameter).

- Length at recruitment has a CV of 0.1, based on Autumn survey (fixed - 1 parameter).
- Initial population:
- Total initial abundance of both stocks N_0 (estimated)
- Initial numbers-at-age calculated via $N_{0,a} = N_0 \times e^{-a(M_a+F_0)}$
- The additional mortality parameter F_0 determines the steepness of the initial numbers-at-age reflecting previous effects of fishing (estimated).
- Initial numbers-at-age is subsequently split between stocks using an age-based ogive. The age at which 50% of the stock was mature, a_{50}, was estimated from the Autumn survey data and was fixed in the model, the alpha parameter of the ogive α_a was estimated.
- Initial mean length at age were based on the Von Bertalanffy growth function (see above).
- Variance in initial length at age was fixed and based on length distributions obtained in the autumn survey for each stock. (fixed - 48 parameters)
- Fleet operations:
- Two fleets: commercial bottom trawl and Autumn survey fleet
- Logistic fleet selection, α_f, $l_{50,f}$; one set for each of the fleets (Autumn survey or Commercial) (estimated - 4 parameters).

9.1.4 Length weight relationship

The conversion from length to weight uses the following formula:

$$W_l = \alpha \times l^\beta$$

In the model, the alpha and beta parameters are fixed and estimated from biological information collected during the Ielandic autumn survey. The observed values and estimated relationship are shown in Figure 24.

9.1.5 Likelihood data

The table below shows the datasets that are used as likelihood components in the model.

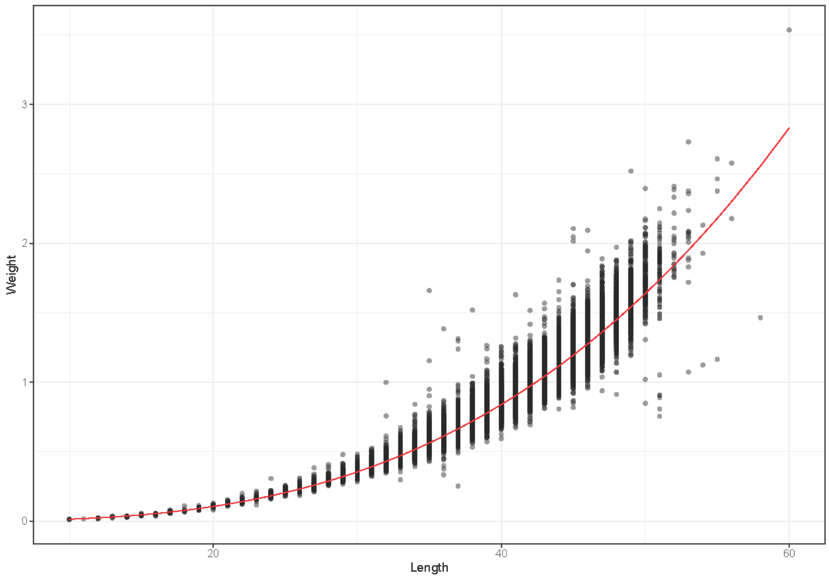


Figure 24: Icelandic slope beaked redfish. Observed length–weight relationship (dots) and the fitted relationship (red line)

Table 1: Overview of the likelihood data used in the model. Survey indices are calculated from the length distributions and are dis-aggregated (sliced) into five groups. All data are obtained from the Marine and Freshwater Research Institute, Iceland.

Component name	Time period	Year range	Delta 1	Type
aldist.aut	2	2000-2021	1 cm	Age-length distribution
aldist.comm	Both periods	1998-2018	1 cm	Age-length distribution
ldist.aut	2	2000-2021	1 cm	Length distribution
ldist.comm	Both periods	1975-2021	1 cm	Length distribution
matp.aut	2	2000-2021		Ration of immature:mature by length group
si.10-30.aut	2	2000-2021	10-30 cm	Survey index
si.30-35.aut	2	2000-2021	30-35 cm	Survey index
si.35-40.aut	2	2000-2021	35-40 cm	Survey index
si.40-45.aut	2	2000-2021	40-45 cm	Survey index
si.45-55.aut	2	2000-2021	45-55 cm	Survey index

9.2 Results

9.2.1 Diagnostics and model fit

Survey indices can be variable for the Icelandic slope beaked redfish due to its tendency to be influenced by a few very large hauls. The index data used as input here are the total raw numbers of fish caught (within length slices) in the entire autumn survey. Although they are expected to represent the entire stock, they are also expected to be highly variable because no treatment or data pre-processing has been performed to reduce this variability. This variability is reflected in the model's fit to the survey index data (Figure 25). In general, the model appears to follow the stock trends historically, although adundance is underestimated from 2000 to 2003 for the 10-30 cm, 30-35 cm and 35-40 cm length groups. Furthermore, the terminal estimates do not deviate from the observed value for the first three length groups; however, for the larger length groups (40-45 cm and 45-55 cm) abundance is underestimated in the terminal year (Figure 25).

9.2.2 Fit to catch composition data

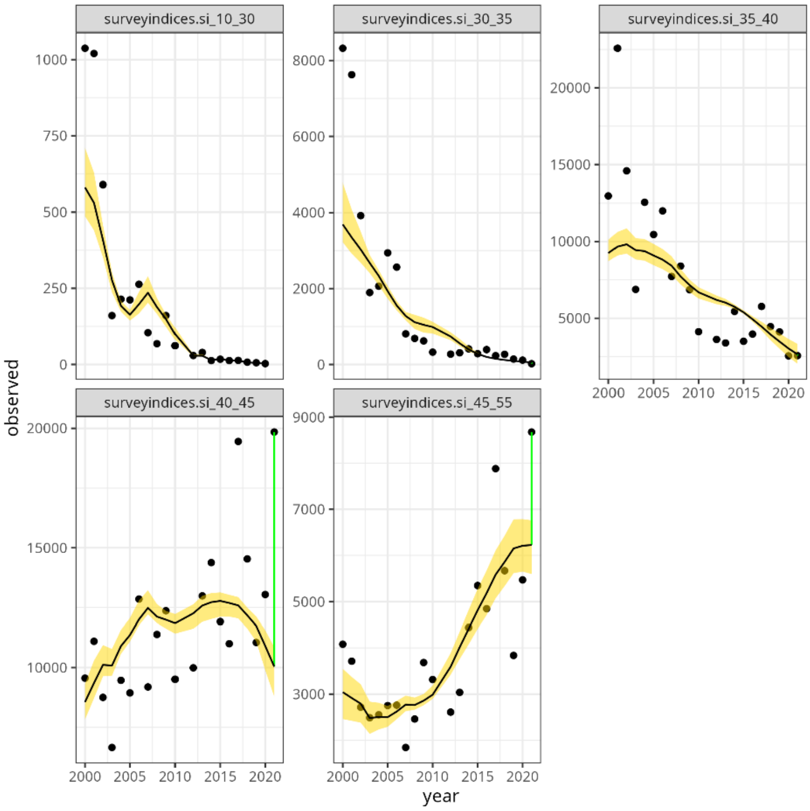


Figure 25: Autumn survey index number fits (lines) to data (points). The yellow ribbon shows the 90% confidence intervals. The vertical green lines highlight the difference between the observed and predicted values in the terminal year.

9.2.2.1 Length- and age-length distributions

The model estimated catch composition is illustrated in Figure 26 to Figure 29, with corresponding residual plots for each catch composition component shown in Figure 30. The model fits to both of the length distributions good (Figure 26 and Figure 28), although in some years, it is noticeable that the model is not capturing the peaks (ca. 40-45 cm fish) in the Autumn survey data (see 2012 to 2015 in Figure 26). The fits to the age distribution data from the autumn survey show that the fit is not particularly good for the oldest ages (30+) where the model underestimates these ages (Figure 27). Furthermore, the model overestimates certain age classes which can be followed through years, first in 2009 as 12-19 years old fish and then again in 2017 and 2018 as 20-28 year old fish. The fit to the commercial age-length distributions are worse; however, this is likely because there are few age readings in each time step (Figure 29). There are no discerable patterns in the residuals for any of the catch composition components (Figure 30)

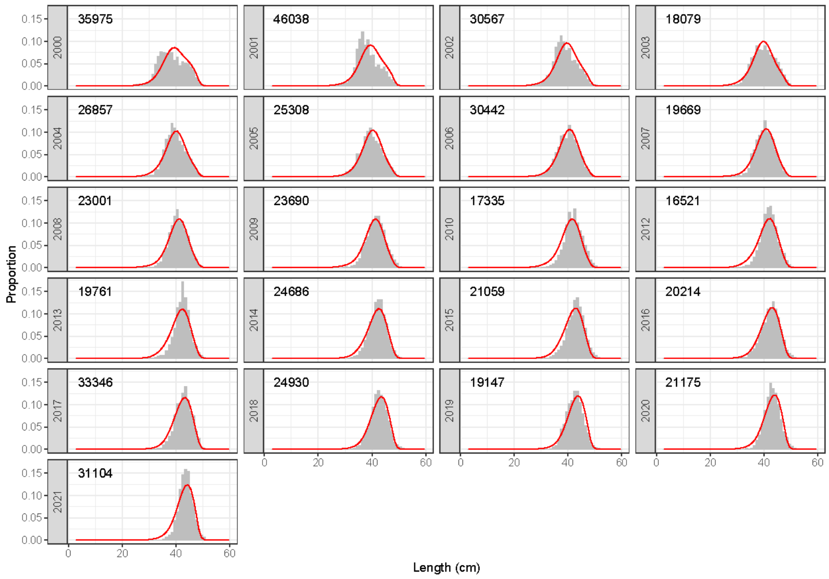


Figure 26: Icelandic slope beaked redfish. Comparison of the observed and estimated size distribution from the autumn survey catches. Observations are shown as grey bars while the estimated proportions by a red line. Number of fish sampled by year is indicated on each panel.

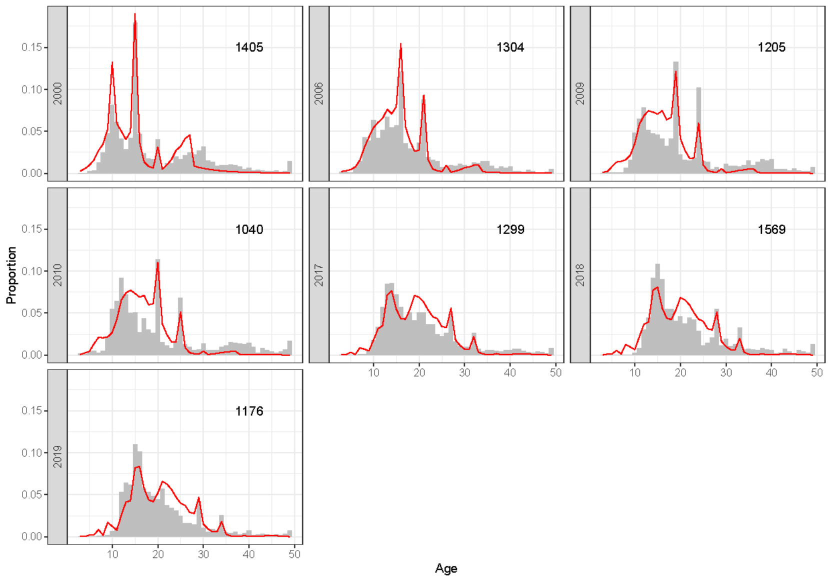


Figure 27: Icelandic slope beaked redfish. Comparison of the observed and estimated age distribution from the autumn survey catches. Observations are shown as grey bars while the estimated proportions by a red line. Number of fish sampled by year is indicated on each panel.

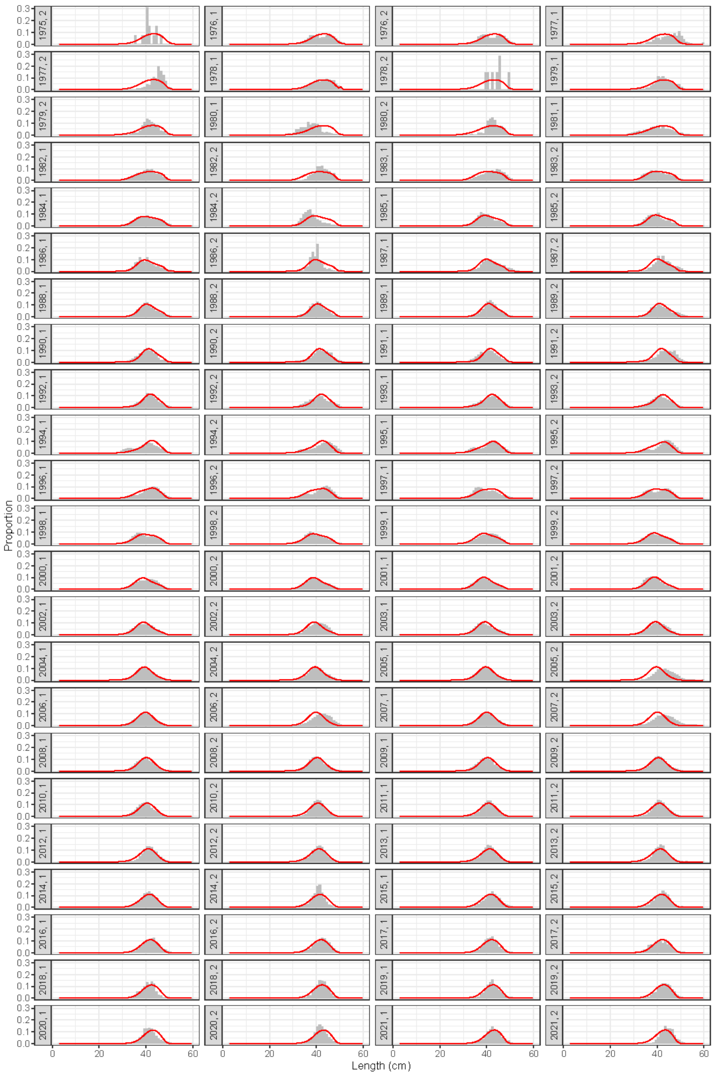


Figure 28: Icelandic slope beaked redfish. Comparison of the observed and estimated size distribution from the commercial catches. Observations are shown as grey bars while the estimated proportions by a red line. Number of fish sampled by year is indicated on each panel.

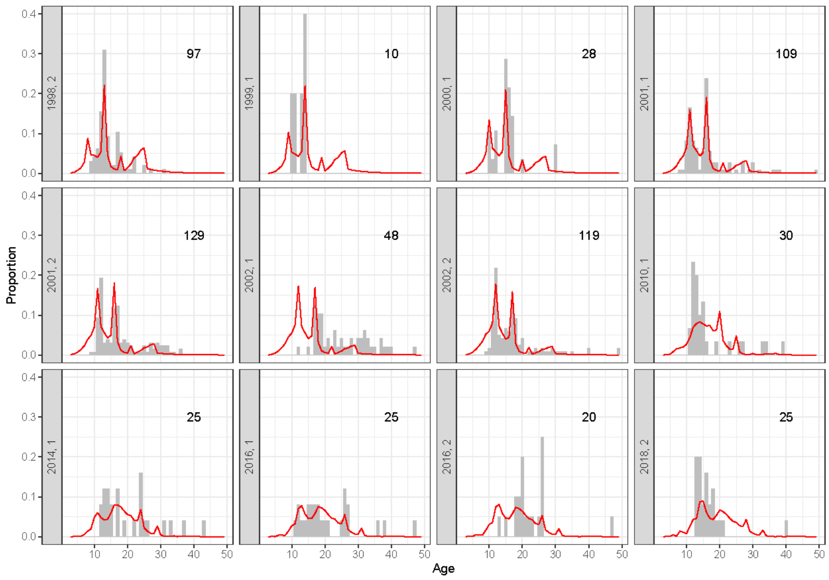


Figure 29: Icelandic slope beaked redfish. Comparison of the observed and estimated age distribution from the commercial bottom trawl catches. Observations are shown as grey bars while the estimated proportions by a red line. Number of fish sampled by year is indicated on each panel.

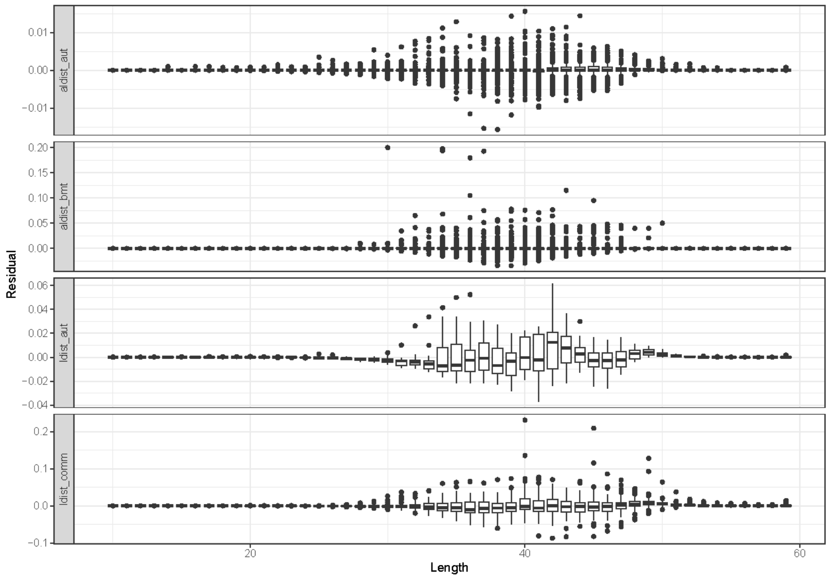


Figure 30: Icelandic slope beaked redfish. Model residuals for each catch composition likelihood component.

9.2.2.2 Growth

For the Autumn survey, the growth patterns predicted by the model closely follow the observed growth from approximately age 10 onwards; however, prior to age 10, growth is underestimated (Figure 31). This noticeable shift is consistent between years suggesting that allowing for age-specific variation in growth will improve the model. The model also fits the growth data from the bottom trawl fairly consistently, although a similar trend of underestimating the growth rate in the younger ages is also apparent in 2001 and 2002 (Figure 32). This suggests that the model is overestimating the recruitment length, although it should be noted that (1) the age-length data is sparser for the younger ages, and (2) that because the stock does not enter the fishery until later ages, the beta-binomial length update will have created plausible standard deviations in the length at age by that time.

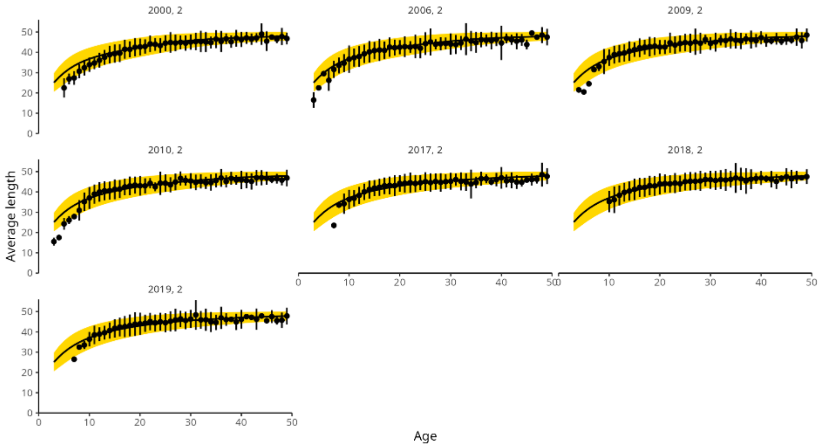


Figure 31: Icelandic slope beaked redfish. Model growth estimations for the Autumn survey. Yellow bands and the black line show where the mean and 90% confidence intervals of the of model predictions, whereas the points and error bars show the mean and 90% confidence intervals of the data.

9.2.2.3 Maturation

The model's fit to the maturation data is shown in Figure 33.

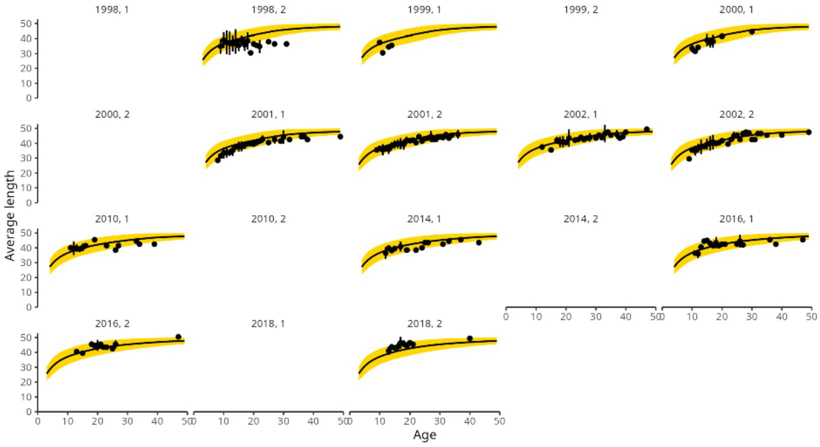


Figure 32: Icelandic slope beaked redfish. Model growth estimations for the commercial fleet. Yellow bands and the black line show where the mean and 90% confidence intervals of the of model predictions, whereas the points and error bars show the mean and 90% confidence intervals of the data.

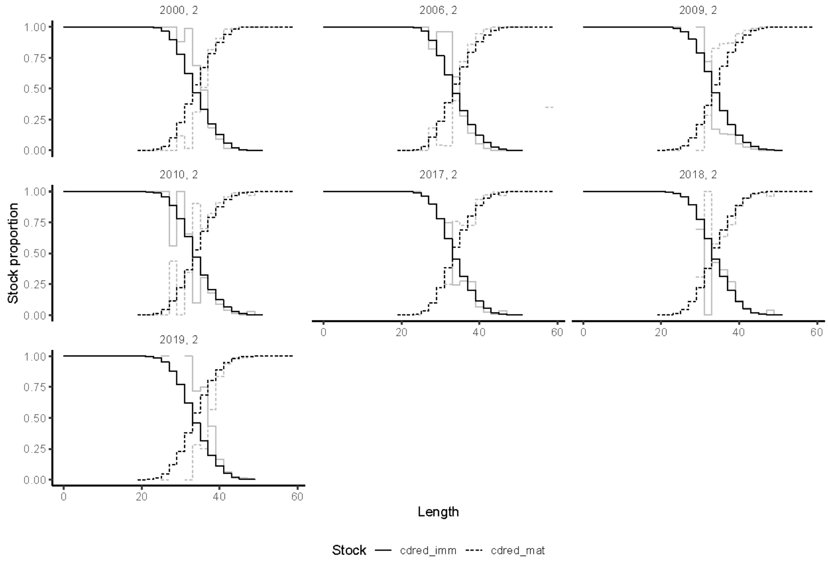


Figure 33: Icelandic slope beaked redfish. Observed (grey lines; Autumn survey) and estimated (black lines) proportions for the mature (dashed lines) and immature (solid lines) sub-stocks per length interval.

9.2.3 Natural mortality

A likelihood profile was run to test a variety of natural mortalities. In each case, the base model was optimised using an updated value of natural mortality (applied to all ages of both stocks). Likelihood weights were taken from the base model. The results show that, given the imposed constraints (i.e. M does not vary between stocks, age-classes, or with time), 0.05 is a suitable value for natural mortality (Figure 34).

9.2.4 Selection by fleet

Estimated length-based selection by fleet is shown in Figure 35.

9.2.5 Stock overview

Annual output from the final model is shown in Figure 36. A steep decline in the spawning stock is seen from the late 1980s to the early 2000s. This is followed by a period of stability in the 2000s and a gradual decline in the 2010s. The SSB is currently at its lowest point in the time-series. Since a recruitment spike in 2003, annual recruitment has also steadily declined, and furthermore, since 2010 recruitment has remained at exceptionally low values resulting in a declining total stock size and a stock composition that is increasingly dominated by older, mature fish. Fishing mortality has declined since the 90s, and was fairly stable around 0.9 from 2013-2019 and 1.1 from 2020-2021.

9.2.6 Retrospective analysis

The analytical retrospective analysis is shown in Figure 37. An upward revision in biomass (and thus downward revision in F) occurs from the 2nd peel onwards. The revision is larger in the third, fourth and fifth peels. As this trend it consistent, it suggests uncertainty in the model output; however, it should be noted that the larger revisions also coincide with the removal of age data. Notably, the last three years of age data from the Autumn survey are removed in the 3rd, 4th and 5th peels (see Figure 27).

9.2.7 Conclusion

Overall the gadget model presented here captures the overall trends in the data, and offers a significant improvement over the current category 3 'survey trend' empirical rule used in assessments. The main issues identified with the model, for instance, the consistent trend in the analytical retrospective analysis, and the fits to the age-length distributions (particularly to younger ages) will likely improve as more age data becomes available in the coming years. We therefore consider the model usable for assessming the stock and to base advice to managers.

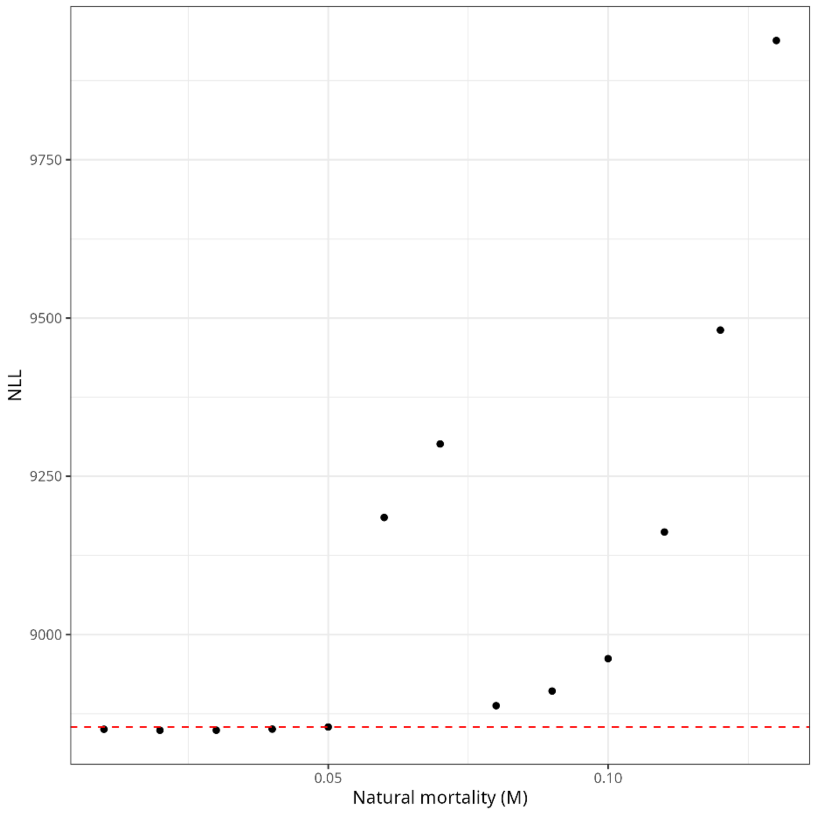


Figure 34: Icelandic slope beaked redfish. Negative log-likelihood profile for natural mortality. The dashed red line shows the nll from the base model.

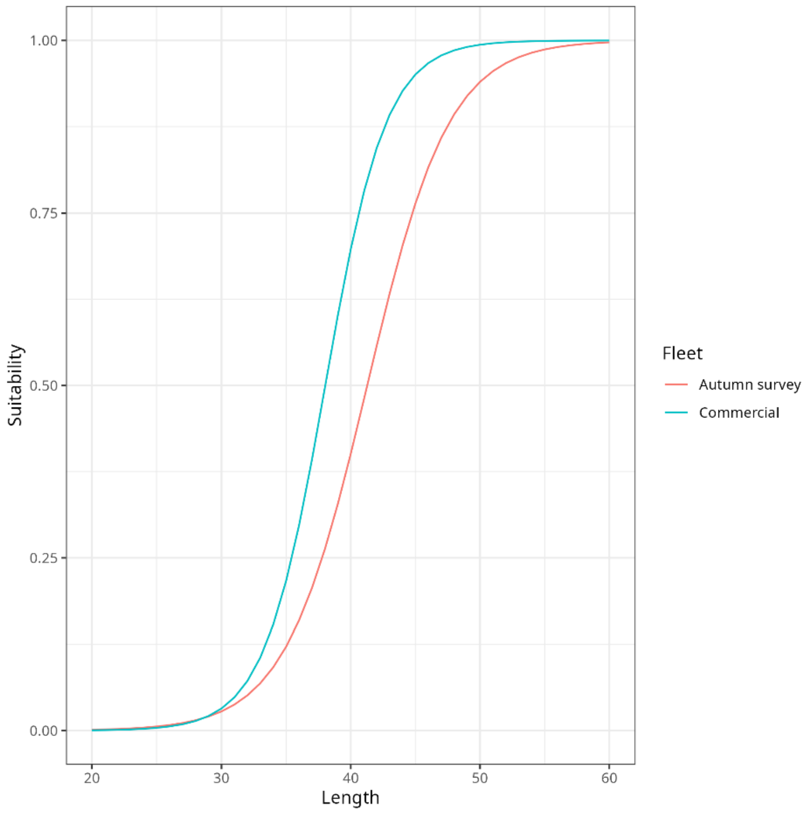


Figure 35: Icelandic slope beaked redfish. Selection by length for the autumn survey and commercial bottom trawl fleet.

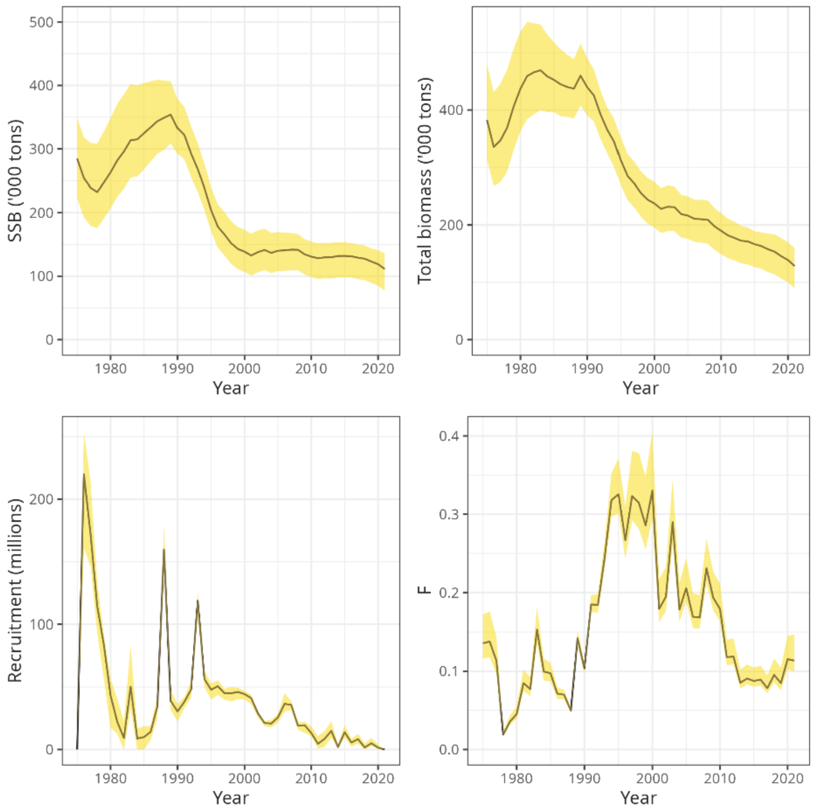


Figure 36: Iceland slope beaked redfish. Estimates of total stock biomass, spawning stock biomass, fishing mortality and recruitment from the best model. The black line represents the best model, the yellow ribbon shows the 90% confidence intervals.

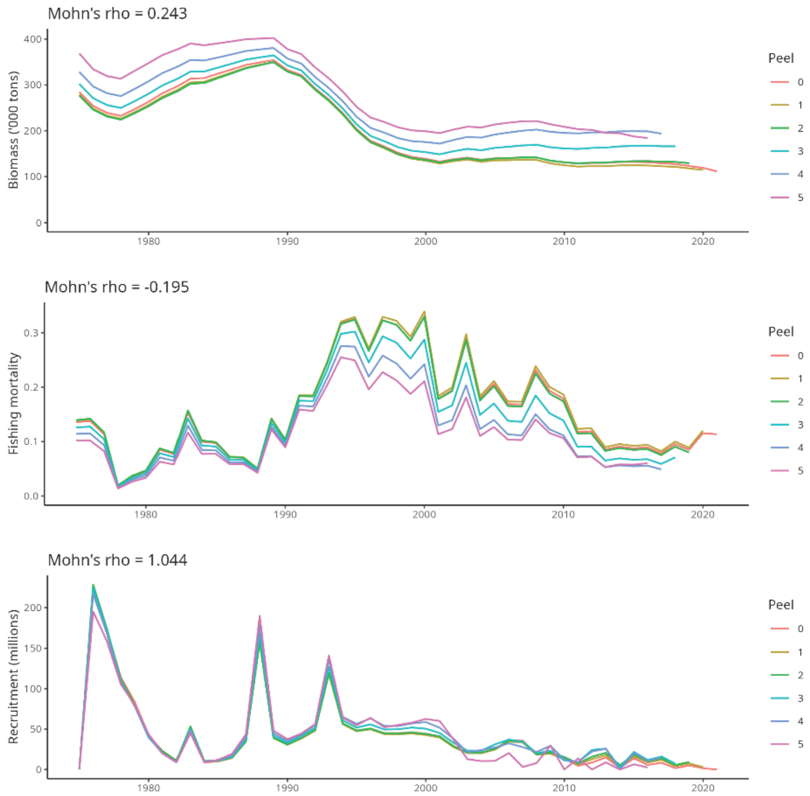


Figure 37: Iceland slope beaked redfish. Analytical retrospective analysis.

10 Reference points

According to ICES technical guidelines, two types of reference points are referred to when giving advice for category 1 stocks: *precautionary approach* (PA) reference points and *maximum sustainable yield* (MSY) reference points. The PA reference points are used when assessing the state of stocks and their exploitation rate relative to the precautionary approach objectives. The MSY reference points are used in the advice rule applied by ICES to give advice consistent with the objective of achieving MSY.

Generally ICES derives these reference points based on the level of the spawning stock biomass and fishing mortality. The following sections describe the derivation of the management reference points in terms of fishing mortality (F) and SSB (B). It further describes the model for stock–recruitment, weight and maturity at age, and assessment error which in combination with the MCMC results is used to project the stock in order to derive the PA and MSY reference points.

10.0.1 Setting B_{lim} and B_{pa}

Initially, B_{lim} was considered from examination of the SSB–Recruitment scatterplot based on the estimates from the stock assessment (Figure 38). The plot shows a wide dynamic range of SSB and evidence that recruitment has been imparied, corresponding to ICES stock Type 2. In this scenario, B_{lim} is derived from the segmented regression change point. However, attempts to fit a segmented regression using the FLCore R package did not produce an adequate fit to the data, primarily because the slope does not go through the origin. Therefore, B_{lim} was calculated by taking the median SSB from 2000-2005 (Figure 38), $B_{lim} = 1.38257 \times 10^5$ t. This period was chosen because the SSB was stable but at a low size and prior to the recruitment prolonged period of low recruitment.

In line with ICES technical guidelines B_{pa} is then calculated based on multiplying B_{lim} with $e^{1.645\sigma_{SSB}}$, where σ is the CV in the assessment year of SSB. However, the estimated σ is not considered to reflective of the true assessment error of the SSB due to various uncertainties and thus the CV used here to determine B_{lim} is 0.2, which is the default ICES value for assessment error. Therefore B_{pa} should be set at $B_{lim}e^{1.645*0.2} = 1.9211887 \times 10^5$ t.

10.0.2 Stock recruitment relationship

A variety of approaches are common when estimating a stock–recruitment relationship. In the absense of a stock-recruitment signal from the available historical data (Fig. **?@fig-ssbrec**), the ICES guidelines suggest that the "hockey-stick'' recruitment function is used, i.e.

$$R_y = \bar{R}_y \min(1, S_y/B_{break})$$

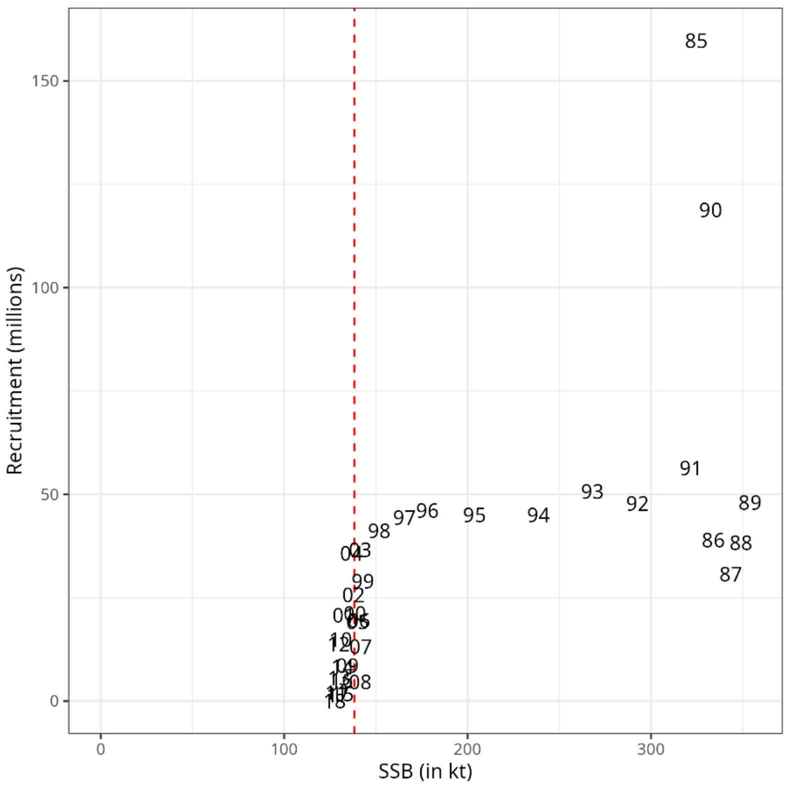


Figure 38: Icelandic slope beaked redfish. Fitted stock recruitment (age 3) relationship. The dashed red line shows B_{lim}.

where R_y is annual recruitment, S_y the spawning stock biomass, B_{break} the break point in hockey stick function and $\bar{R}_y$ is the recruitment when not impaired due to low levels of SSB. Here $\bar{R}_y$ is considered to be drawn from historical estimates after 1984 using a 7 year block-bootstrap from the bootstrap model estimates. This is done to account for possible auto-correlation in the recruitment time–series.

10.0.3 Biological parameters in the forecast

Maturity, growth and the length-weight relationship in the forecast are based on the processes estimated within the model and bootstrap replicates. Similarly, the commercial fleet selectivity is the same as estimated by the model with catch proportions by fleet fixed to the average of last 5 years.

10.0.4 Management procedure in forward projections

Illegal landings and discards by the fishing vessels are considered to be negligible (as noted above). Observation error is addressed by the MCMC simulation approach employed in here. The appropriate assessment error is simulated in terms of fishing mortality by assuming F in the projections is a log-normal AR(1) process with the default values for CV as 0.212 and autocorrelation of 0.423.

10.0.5 Setting F_{lim} and F_{pa}

According to the ICES guidelines, the precautionary reference points are set by simulating the stock using the stock-recruitment, growth and maturity relationship described above, based on a wide range of fishing mortalities, ranging from 0 to 0.5 and setting F_{lim} as the F that, in equilibrium, gives a 50% probability of SSB $> B_{lim}$ without assessment error.

For each MCMC replicate the stock status was projected forward 200 years as simulations, and the average of the last 50 years of projected values were used to estimate the MSY reference points. The results from the steady state simulations estimate the value of F, F_{lim}, resulting in 50% long–term probability of SSB $> B_{lim}$ to be at 0.11.

10.0.6 MSY reference points

As an additional simulation experiment where, in addition to recruitment and growth variations, assessment error was added. The harvest rate that would lead to the maximum sustainable yield, F_{msy}, was then estimated. Average annual landings and 90% quantiles were used to determine the yield by F. The equilibrium yield curve is shown in Figure 40, where the maximum average yield, under the recruitment assumptions, is 1.1639×10^4 tons.

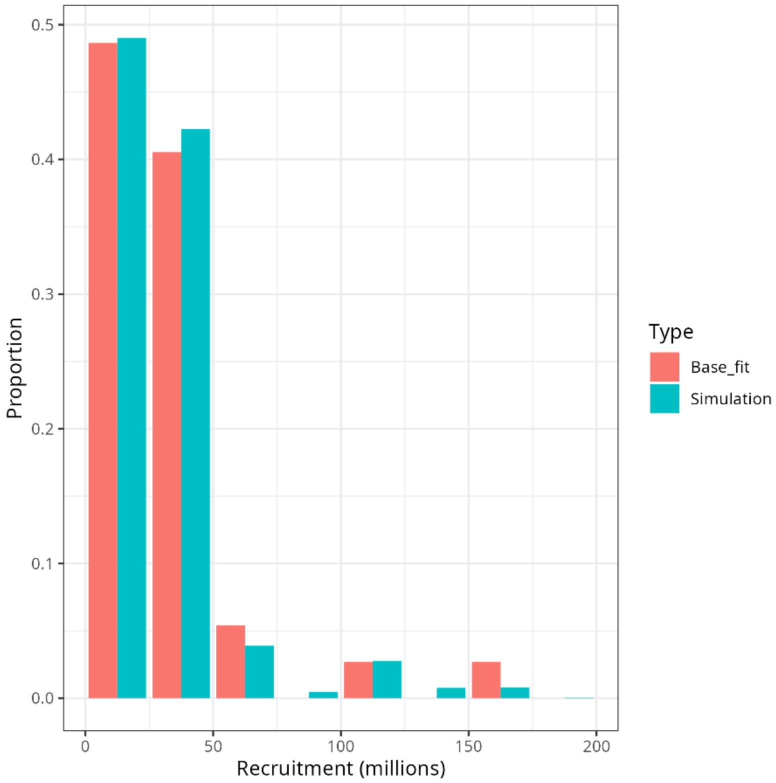


Figure 39: Iceland slope beaked redfish in 5a. Histogram of recruitment from the baseline fit (red bars) and the forward simulations (blue bars). Counts are standardised to proportions.

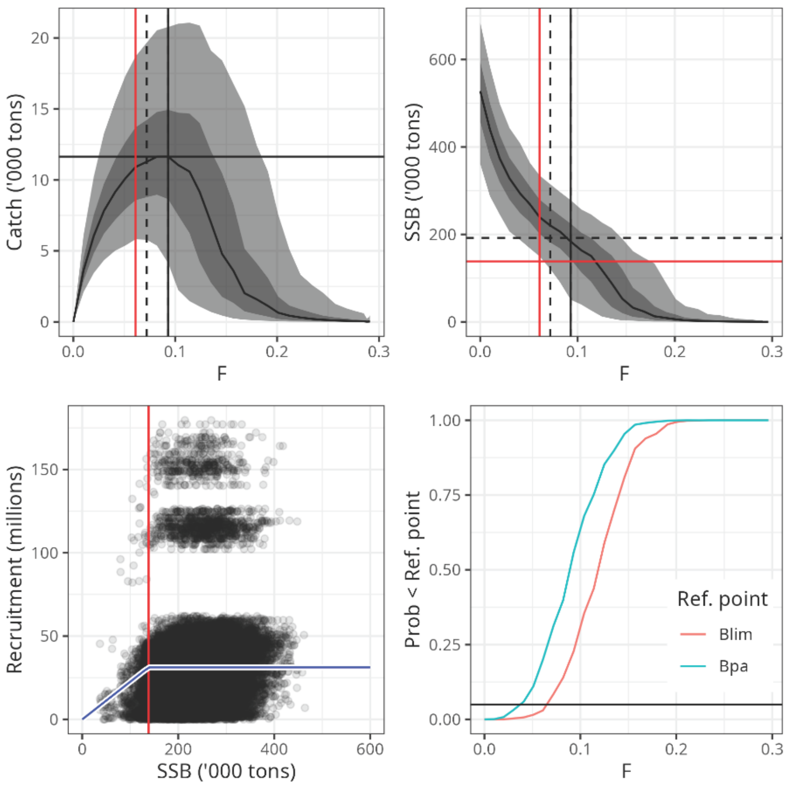


Figure 40: Icelandic slope beaked redfish in 5a. Equilibrium catch, recruitment, SSB and risk from forward projections.

In line with ICES technical guidelines, the MSY $B_{trigger}$ is set as B_{pa} because this is the first time the reference points are evaluated. Maximum sustainable yield is estimated to be obtained at an F of 0.093. F_{p05}, i.e. the maximum F that has less than 5% chance of going below B_{lim} when the advice rule is applied, is 0.061. This value is less than F_{msy}, therefore the suggested F_{target} is set to F_{p05} = 0.061. The equilibrium spawning stock biomass is shown in figure Figure 40.

Icelandic slope beaked redfish in 5a. Overview of estimated reference points.

Reference point	Value	Basis
Blim	138257.000	Median SSB from 2000-2005
Bpa	192118.866	Blim x exp(1.645 sigma_SSB)
Btrigger	192118.866	Bpa
Flim	0.110	F leading to P(SSB < Blim) = 0.5
Fmsy	0.093	F leading to MSY
Fpa	0.061	F, when ICES AR is applied, leading to P(SSB > Blim) = 0.05
HRlim	0.110	HR leading to P(SSB < Blim) = 0.5
HRmsy	0.090	HR leading to MSY
HRpa	0.060	HR, when ICES AR is applied, leading to P(SSB > Blim) = 0.05
MSY	11638.531	MSY

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Survey indices for golden redfish (*Sebastes norvegicus*) in Subareas 5 and 14 (East of Greenland, Iceland and Faroes grounds)

BWKNORTH 2023 13-17 February 2023 MFRI, Hafnarfjörður, Iceland

Kristján Kristinsson

Contents

1 Survey indices

This working document describes the survey index calculation for golden redfish from surveys conducted in the (E)ast (G)reenland , (I)celand and the (F)aroe Ecoregions, hereafter denoted as the EGIF area.

A designed method (Cochran, 1977) is used to calculate the survey indices for golden redfish in Icelandic waters and in East Greenland Sea. For assessment purpose the indices are combined. It was decided to continue to calculate the survey indices based on the Cochran method and include the surveys from the Faroes Ecoregion.

The general approach for calculating the Cochran index: The survey area is split into strata and the index for each stratum is calculated as the mean number (or biomass) in a tow, divided by the area covered multiplied with the size of the stratum. The total index is then a summed estimate from the strata.

1.1 Iceland

Two bottom trawl surveys are conducted in Icelandic waters, the Icelandic spring groundfish survey (IS-SMB) and the Icelandic autumn groundfish survey (IS-SMH). Data from the spring survey is available 1985–2022 and from the autumn survey 1996–2021. The autumn survey was not conducted in 2011.

In previous calculations of the indices, the catch was standardized to 4 NM for the spring survey and 3 NM for the autumn survey. Since 2003, larger part of the survey biomass has been observed to be aggregated in very dense schools west of Iceland, caught on 5–10 stations every year. In some cases these large catch are taken in very few minutes, that is, the trawling distance is shorter than the supposed trawling distance of 3 NM or 4 NM. Standardizing these tows will increase the weight of them. The catch was, therefore, not standardized, but the actual tow length used.

1.1.1 Diel variation

Golden redfish is known for its diel vertical migration, showing semi-pelagic behavior. Usually, the species is in the pelagic area during the night-time and close to the bottom during the daytime. There may also be a size or age difference in this pelagic behavior. This causes diel variation in the catch rates of golden redfish in both the spring and autumn surveys as the surveys are conducted both during the day and the night (24 hours) and can have an effect on the abundance indices. Furthermore, inter-annual variability caused by the time of day when the stations are taken becomes large and hence, can influence the results.

The general model without taking into account length is a linear model:

$$\log(catch) = \alpha_{year} + \beta_{station} + \gamma_{time}$$

The factor α_{year} could be interpreted as abundance index. The factor γ_{time} does on the other hand describe the development during the day.

The data were divided into 17 length groups and fitted for each length group with generalized linear model (GLM).

$$\log(catch) = \alpha_{year}+\beta_{station}+ps(time, df = 7, period = c(0, 24)), family = quasi(link = \log, variance = \mu)$$

where *ps* is the periodic spline with seven degrees of freedom (df) and *period* specifies the dimensions of the basis used for the spline, in this case 24 hours. The periodic spline indicates a cyclic spline, as there should be no discontinuity between 0 and 24. The model uses quasi family with log link and variance proportional to the mean.

Scaled predictions for each length group in the Spring and Autumn Surveys by the model are shown in Figure 1. The smallest redfish has opposite diurnal vertical migration compared to the usual one of larger fish. The model results do also show that much less is caught of the smallest redfish in the survey compared to medium size.

This scaled diurnal variation by length shown in Figure 1 was used for calculating the survey indices for redfish. The difference from the traditional method is that the numbers caught in each length group at each station was divided by the appropriate multiplier.

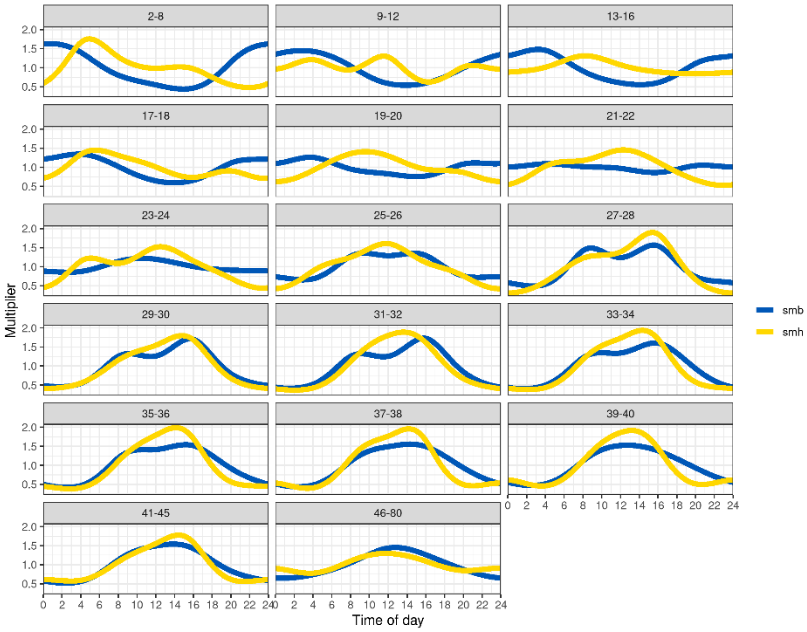


Figure 1: Golden redfish. Dial migration by size groups in the spring survey (smb, blue line) and the autumn survey (smh, yellow line).

1.1.2 Stratification

The strata used for survey index calculation for golden redfish in the Spring Survey are shown in Figure 2 and for the Autumn Survey in Figure 2. The stratification is the same in both surveys, but the area is larger in the Autumn Survey. The stratification is in general based on depth stratification and similar oceanographic conditions within each stratum. The number of strata in the Autumn Survey are 33. The number of strata in the Spring Survey are 24. Total size of the spring survey area is 187,884 km^2 and 279,532 km^2 of the autumn survey.

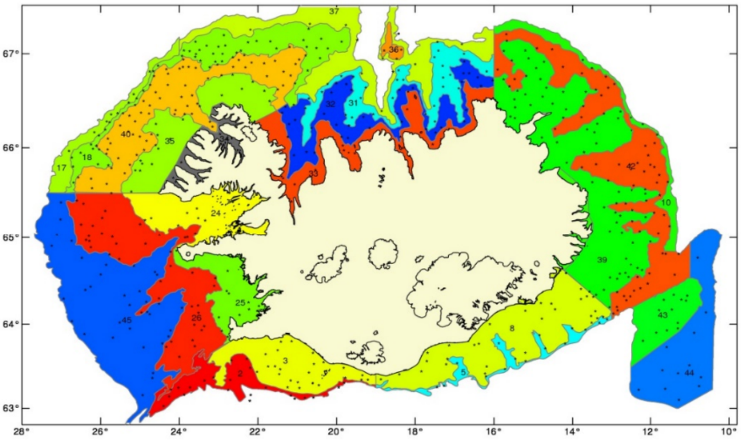


Figure 2: Spring Survey stratification used for calculation of the spring survey index. The dots show the location of the stations. The total number of strata are 24 and the total size is 187,884 km^2

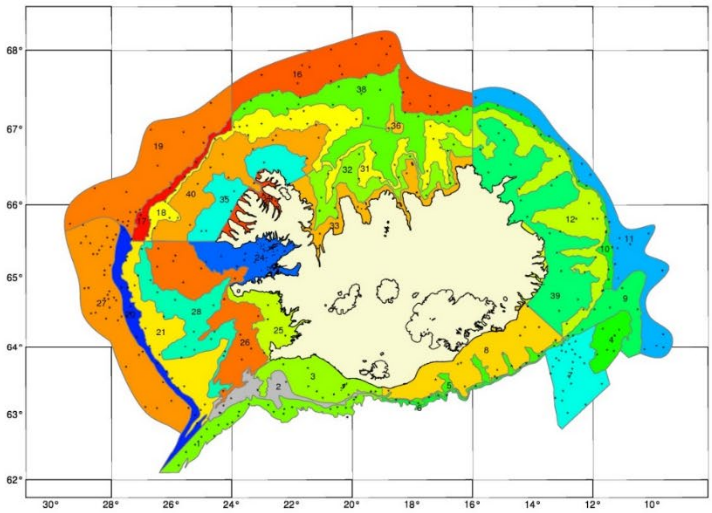


Figure 3: Autumn Survey stratification used for calculation of the spring survey index. The dots show the location of the stations. The total number of strata are 32 and the total size is 279,532 km^2

1.2 Faroe Islands

Two annual groundfish surveys are conducted on the Faroe Plateau by the Faroe Marine Research Institute, the Spring Survey carried out in February-March since 1994 (100 stations per year, down to 500 m depth), and the Summer Survey in August-September since 1996 (200 stations per year, down to 500 m depth). All stations are fixed stations. Half of the stations in the Summer Survey are the same as in the Spring Survey.

The catch was not standardized, but the actual tow length used to reduce the weight of large tows.

1.2.1 Stratification

The surveyed area is divided into 15 strata defined by depth and environmental conditions (Figure 4). The total size of the area is 44,033 km^2.

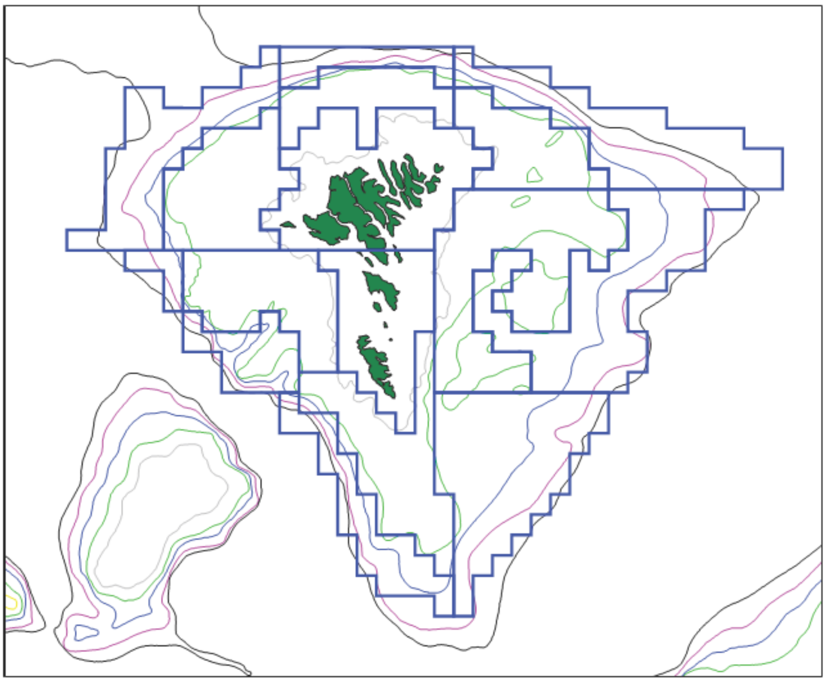


Figure 4: Survey stratification used for calculation of the spring and summer survey indices in the Faeroe ecoregion. The total number of strata are 15 and the total size is 44,033 km^2

1.3 East Greenland

Two surveys conducted in the area, German bottom trawl survey 1981–2022 and the Greenland groundfish survey since 2008. Since the time series of the Greenland groundfish survey is short and there are missing years, the survey was excluded in the index calculations.

The catch was not corrected for diel variability as the towing occurs during the day time.

1.3.1 Stratificaion

The German Survey does not cover the East Greenland continental shelf very well and only the edges of the shelf from 150–450 m are covered. The area used to compile abundance indices from the survey is approximately 35,000 km^2 (Figure 5), a large area compared to the coverage of the survey.

For inclusion of the German Survey in East Greenland waters in the combined survey index, the survey area was reduced. Instead of using the five defined strata shown in @ig-gerstrata, one stratum was defined around the stations taken (Figure 6). This approach was taken to avoid extrapolation to areas not covered by the survey and hence, to reduce the weight of each station. After the changes the area behind each station in the German Survey is 75% larger than of an average station in the Icelandic Spring survey. Results from the Icelandic autumn survey indicate that golden redfish is not common below 500 m depth. Using larger areas in compilation of survey indices leads to substantial extrapolation to areas not covered by the survey.

The size of this region is 24,331 km^2. Outer boundary of the region follows the 500 m contour while the inner boundary is more *ad hoc*.

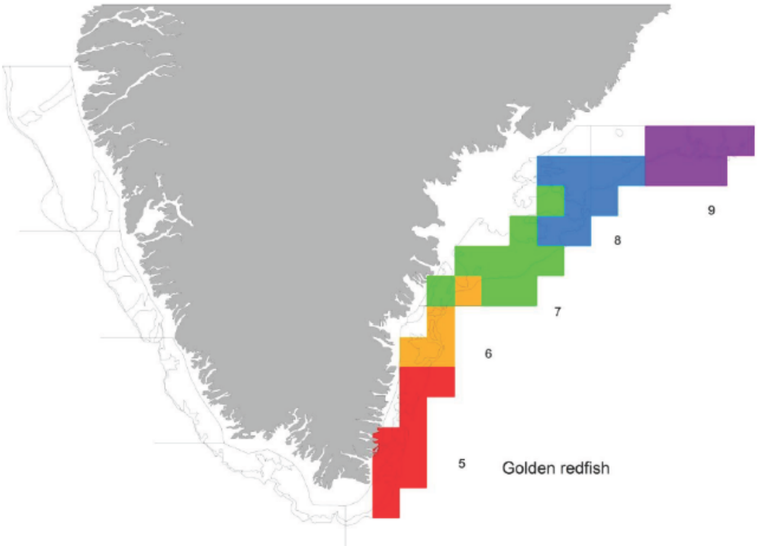


Figure 5: Survey stratification of the German groundfish survey in East Greenland. This stratification is not used in the survey index calculation.

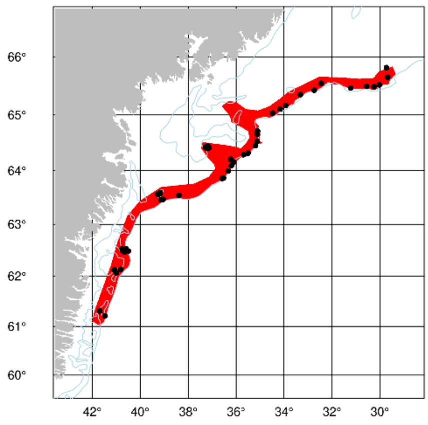


Figure 6: Survey station from the German groundfish survey in East Greenland and stratification (red area) used in the survey index calculation. The size of the area is 24,331 km^2.

1.4 Index calcualation.

The standardized area towed per nautical mile was calculated as the width of the trawl (in m) divided by one nautical mile in m. The standardized area towed is assumed to be 0.00918 NM^2 for the Icelandic and Faeroe trawls (17/1852), but for the German trawl 0.0221 (41/1852).

The following equations are a mathematical representation of the procedure used to calculate the indices for each of the three areas:

$$\overline{Z_i} = \frac{\sum_i Z_i}{N_i}$$

where $\overline{Z_i}$ is the mean catch (number or biomass) in the i-th stratum, Z_i is the total quantity of the index (abundance or biomass) in the i-th stratum and N_i the total number of tows in the i-th stratum. The index (abundance or biomass) of a stratum (I_i) is:

$$I_i = \overline{Z_i}\left(\frac{A_i}{A_{tow}}\right)$$

where A_i is the size of the i-th stratum in NM^2 and A_{tow} is the size of the area surveyed in a single tow in NM^2.

The sample variance in the i-th stratum:

$$\sigma^2 = \left(\frac{\sum_i (Z_i - \overline{Z_i})^2}{N_i - 1}\right)\left(\frac{A_i}{A_{tow}}\right)^2$$

The total biomass in a region is:

$$I_{region} = \sum_{region} I_i$$

and the variance is:

$$\sigma^2_{region} = \sum_{region} \sigma^2_i$$

and the coefficient of variation is:

$$CV_{region} = \frac{\sigma^2_{region}}{I_{region}}$$

1.4.1 Parameters

Golden redfish - Survey parameters

Overview of survey parameters for each survey used in the index calculation. Area size is in km^2.

Variable	Surveys				
	GER(GRL)-GFS-Q4[1]	IS-SMB	IS-SMH[2]	FO-GFS-Q1	FO-GFS-Q3
Time period	1985-2020	1985-2022	1996-2022	1994-2022	1996-2022
Period	Q4	Q1	Q4	Q1	Q3
Stations	6-115	590	375	100	200
Stratas	1	24	32	15	15
Area size	24,331	187,884	279,532	44,033	44,033
Trawl width (m)	41	17	17	17	17
Tow standardiaztion	No	No	No	No	No
Diel variability	No	Yes	Yes	No	No
Length-weight coefficient a	0.0109	0.0109	0.0122	0.0147	0.0147
Length-weight coefficient b	3.0681	3.0681	3.0319	3.0000	3.0000

[1] The survey was not conducted in 2018 and 2021.
[2] The survey was not conducted in 2011.

1.4.2 Combined survey indices

Two combined survey indices were created. The combined areas and stratification is shown in Figure 7:

1. Spring survey index:
    1. Icelandic spring survey 1985–2022.
    2. German autumn survey index 1984–2021, which the year was pushed by one year ($y + 1$). For 2018 (missing) the average of 2017 and 2019 was used, and for 2021 (missing) the index for 2020 was applied.

   3. Faroese spring survey 1994–2022. The indices for 1985–1993 were the averages of 1994–1999.

2. Autumn survey index:

   1. Icelandic autumn survey 1996–2021. For 2011 (missing) the average of 2010 and 2012 was used.
   2. German autumn survey 1996–2021 from East Greenland. For 2018 (missing) the average of 2017 and 2019 was used, and for 2021 (missing) the index for 2020 was applied.
   3. Faroese summer survey 1996–2021.

The German survey in East Greenland waters is conducted in the autumn (September-October) or 4–5 months earlier than the Icelandic Spring survey the following year. When the spring survey index was created, the German survey in year y was added to the Icelandic and Faeroe Spring Surveys conducted the year after $(y + 1)$.

The survey index is mainly driven by the Icelandic survey indices (Figure 8 and Figure 9). No major changes in the survey trends when indices from other areas were added. Total spring and survey indices show similar trends although the decline is sharper of the autumn survey in recent 2–3 years (Figure 10 and Figure 11).

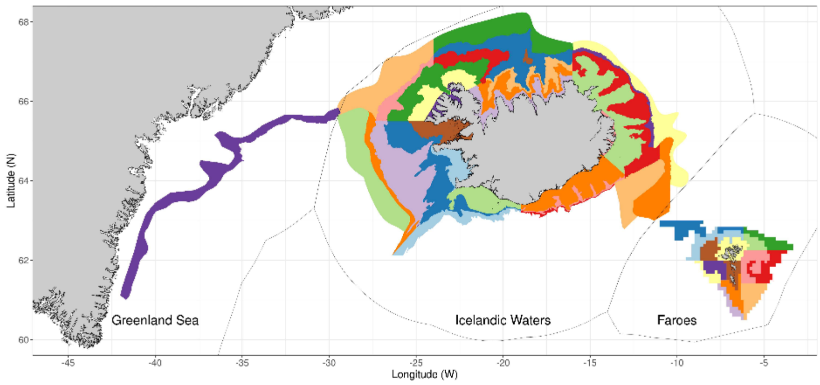


Figure 7: Combined Survey strata of the East Greenland - Iceland - Faroes Ecogretion (EGIF).

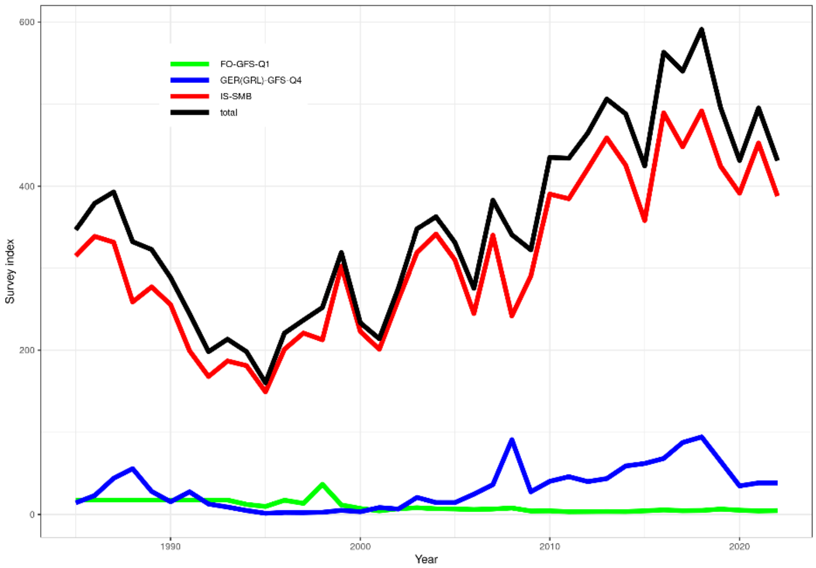


Figure 8: Cochran spring survey indices by area.

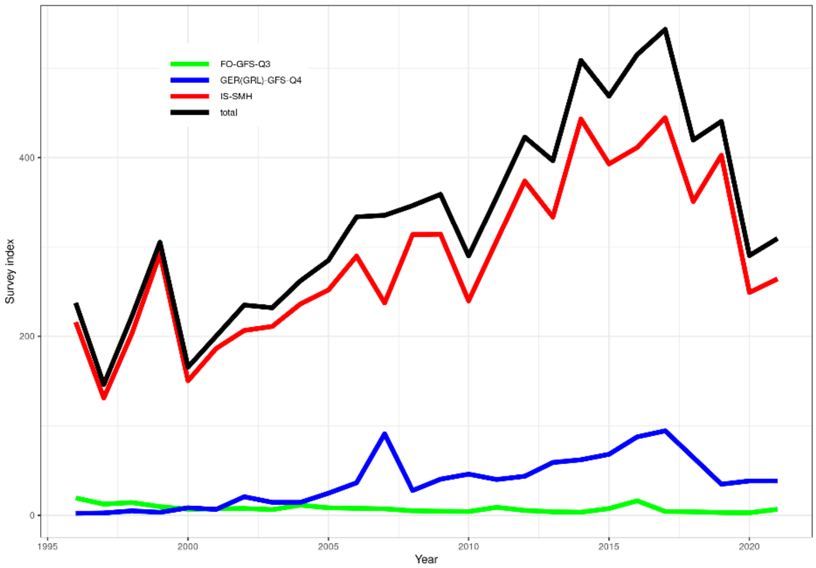


Figure 9: Cochran autumn survey indices by area.

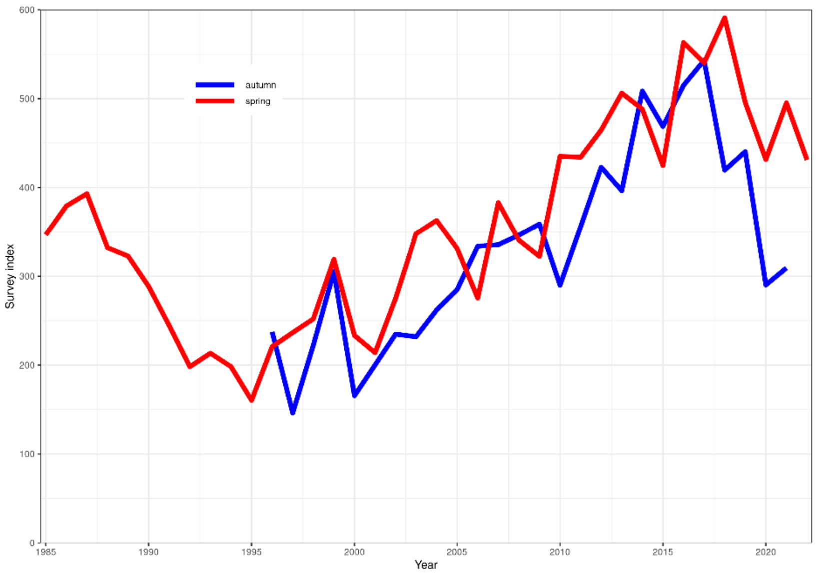


Figure 10: Combined spring and autumn survey indices.

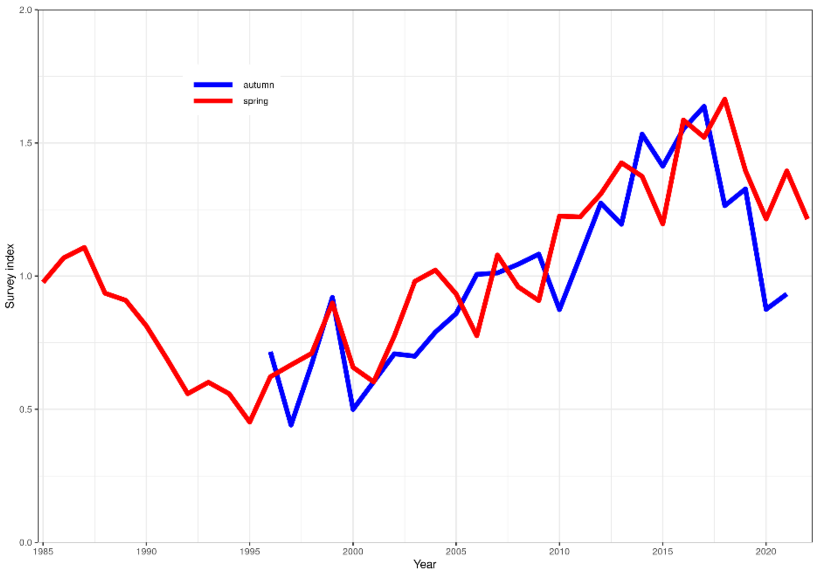


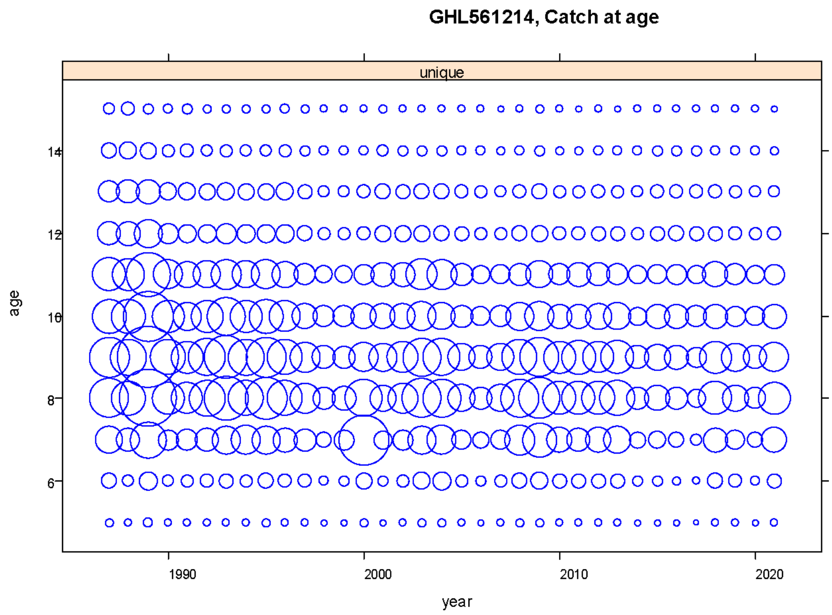
Figure 11: Combined relative survey indices from the EGIF area.

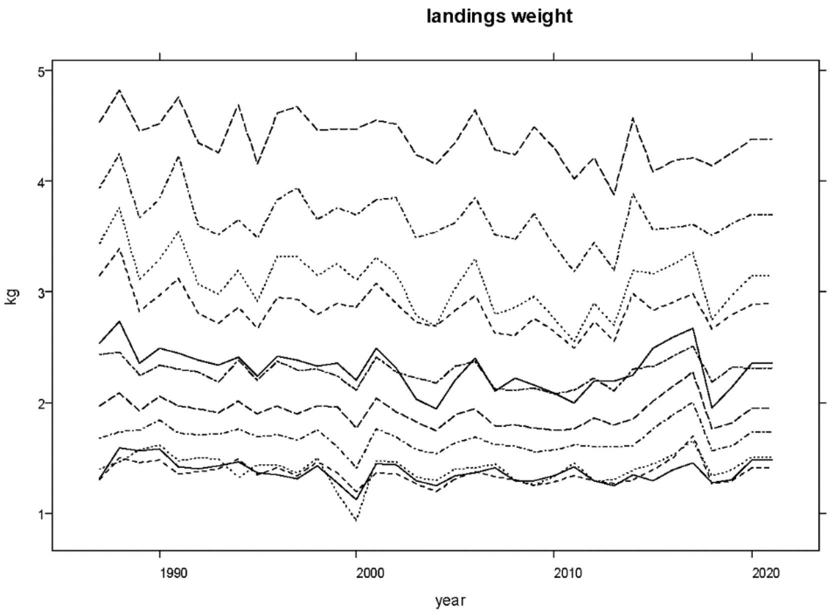
WD 15 Geenland halibut 5,6,12 14 Benchmark February 2023

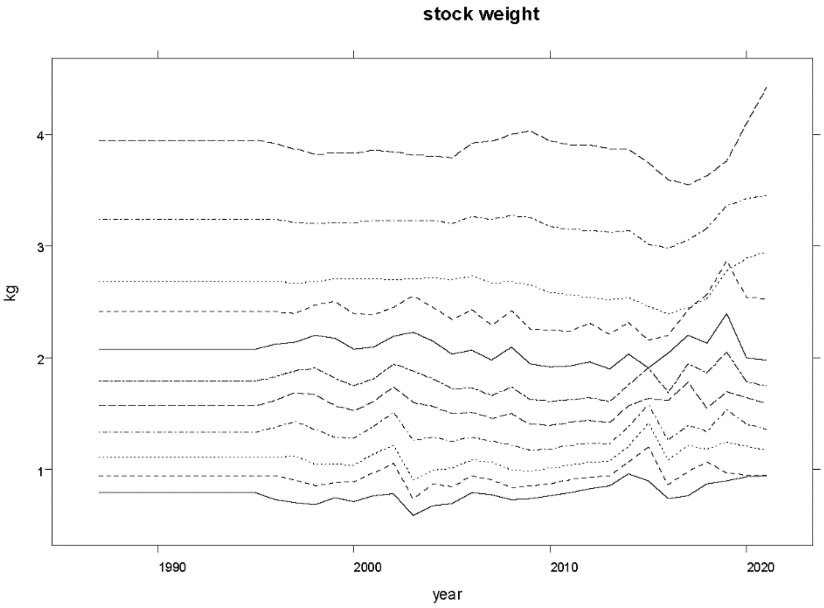
An overview of age-disaggregated data used in an exploratory SAM run.

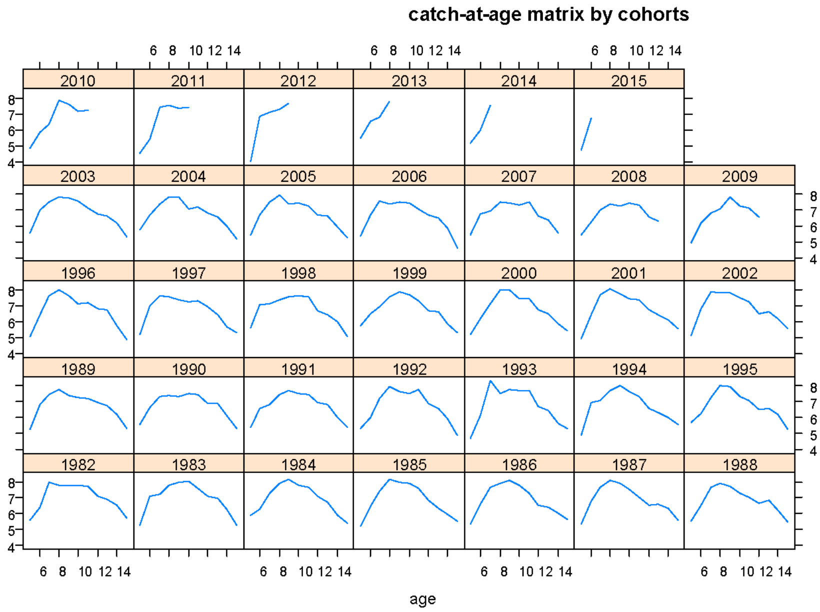
The WD briefly provides information (figures) on the age-based input to an exploratory SAM with few comments. Most figures are self-explanatory. All data are available at the SAM run at https://www.stockassessment.org/results.php?token=088b082205a8867bace15a6d86555624.

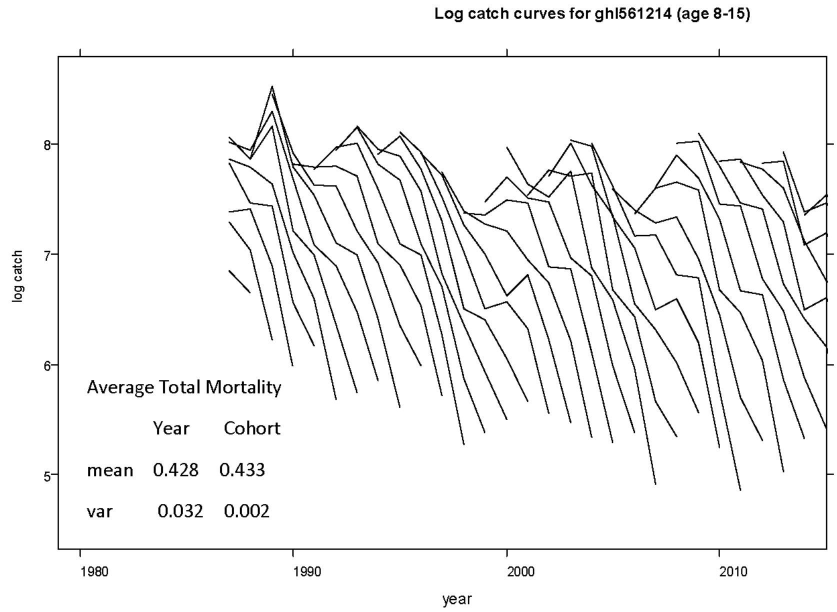
An ALK based on Iceland readings are unique for the years 2016-2021 and for the years prior to 2016 a fixed key (pooled) are applied to length distributions.

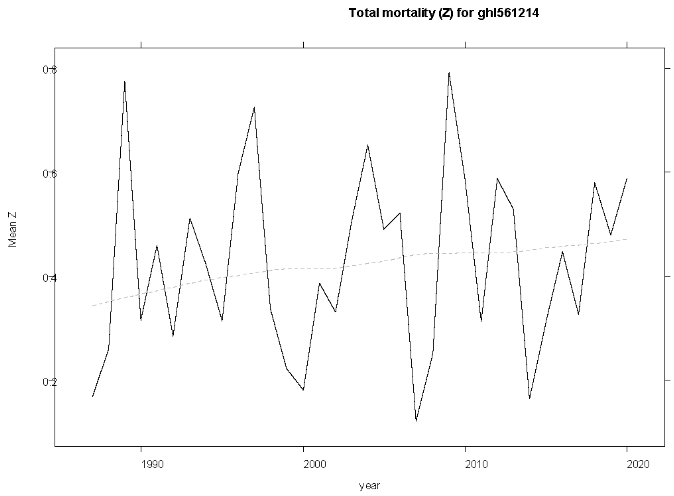


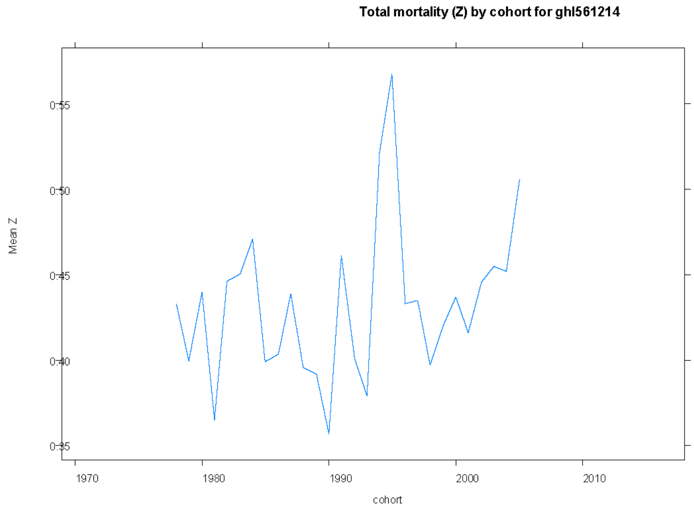

landings weight
kg
year
1
2
3
4
5
1990
2000
2010
2020

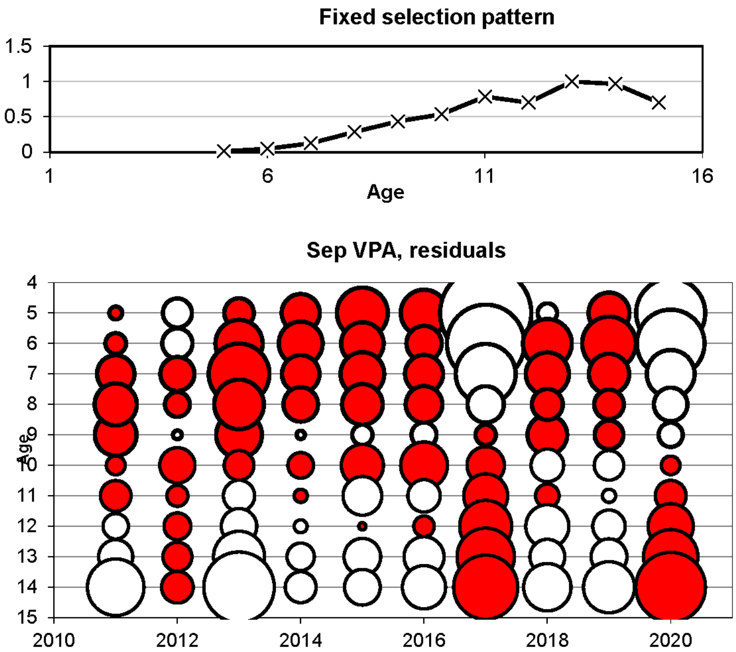

stock weight
kg
4
3
2
1
1990
2000
2010
2020
year


catch-at-age matrix by cohorts
2010
2011
2012
2013
2014
2015
2003
2004
2005
2006
2007
2008
2009
1996
1997
1998
1999
2000
2001
2002
1989
1990
1991
1992
1993
1994
1995
1982
1983
1984
1985
1986
1987
1988
age


Log catch curves for ghl561214 (age 8-15)
log catch
8
7
6
5
1980
1990
2000
2010
year
Average Total Mortality
Year Cohort
mean 0.428 0.433
var 0.032 0.002

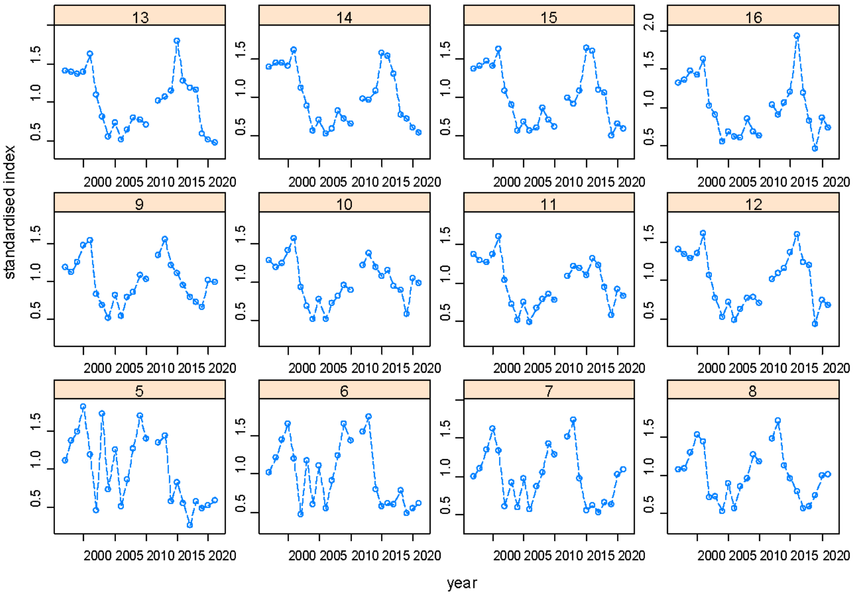

Total mortality (Z) for ghl561214
Mean Z
0.8
0.6
0.4
0.2
1990
2000
2010
2020
year

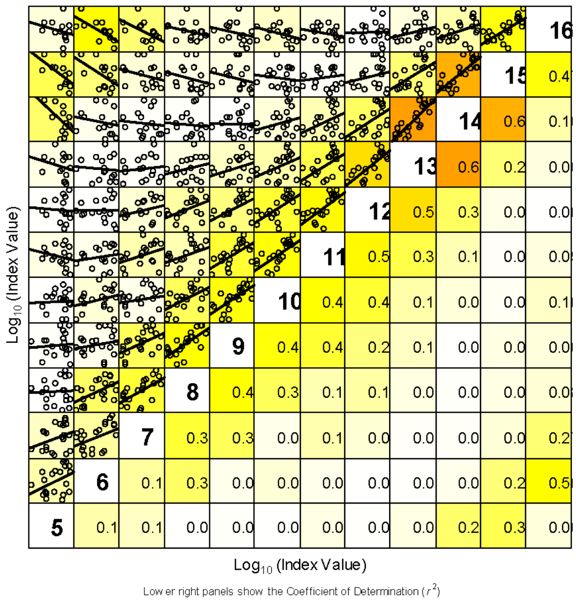

Total mortality (Z) by cohort for ghl561214
Mean Z
0.55
0.50
0.45
0.40
0.35
1970
1980
1990
2000
2010
cohort



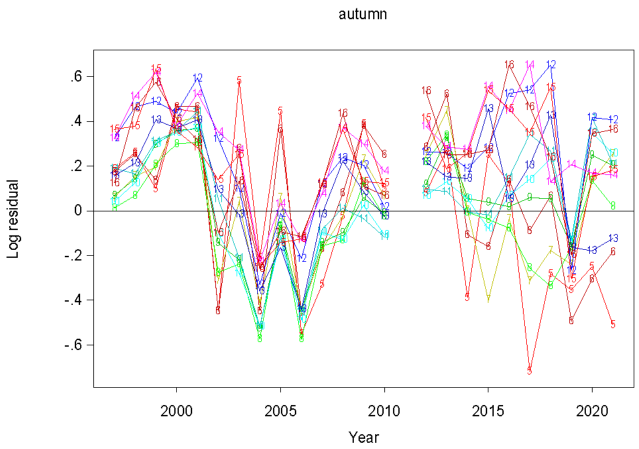
Exploration of the catch matrix by a seperable VPA with best fit of selection.

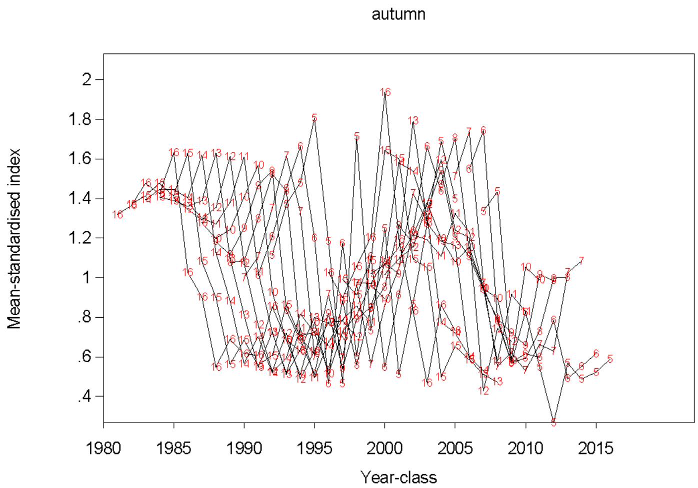
SURVEY (combined Iceland autumn and Greenland)

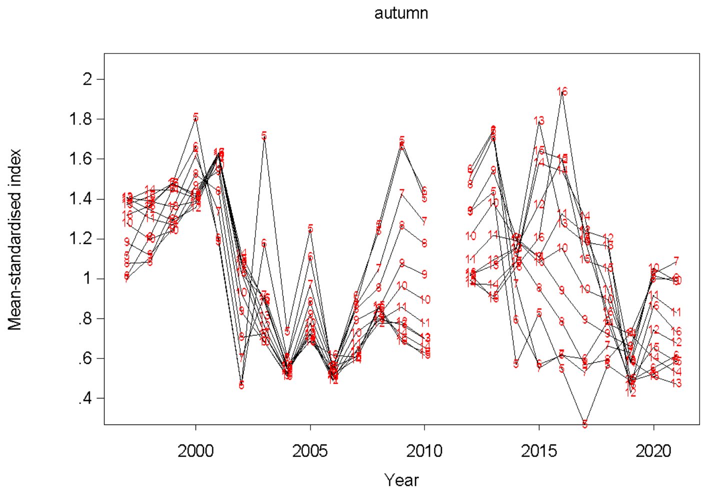




Internal consistency plot of survey

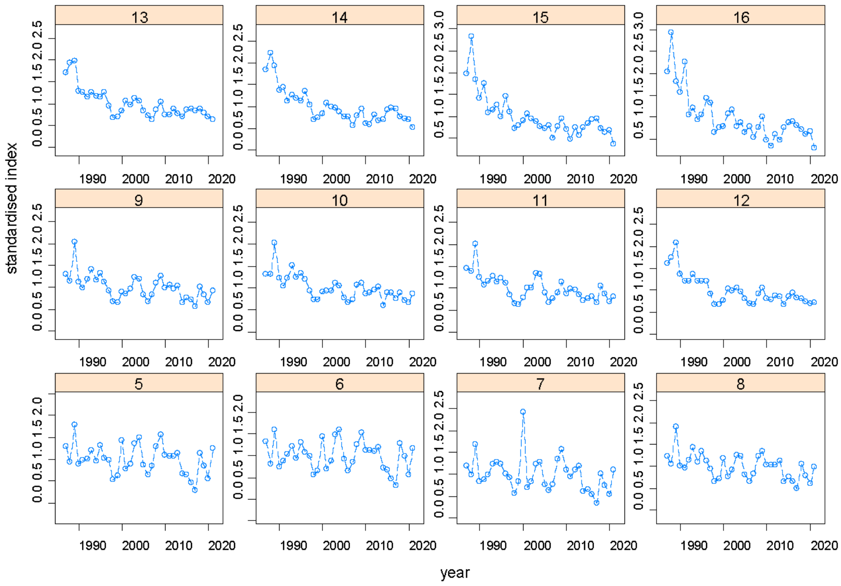

autumn
Log residual
.6
.4
.2
0
-.2
-.4
-.6
2000
2005
2010
2015
2020
Year

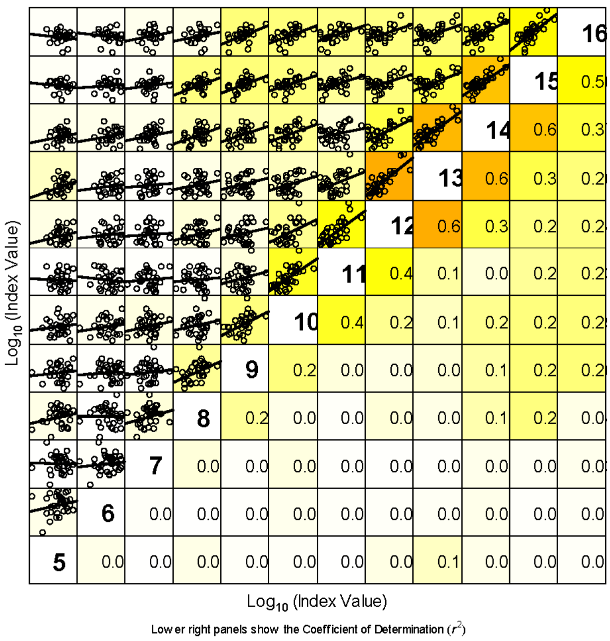

autumn
Mean-standardised index
2
1.8
1.6
1.4
1.2
1
.8
.6
.4
1980
1985
1990
1995
2000
2005
2010
2015
Year-class



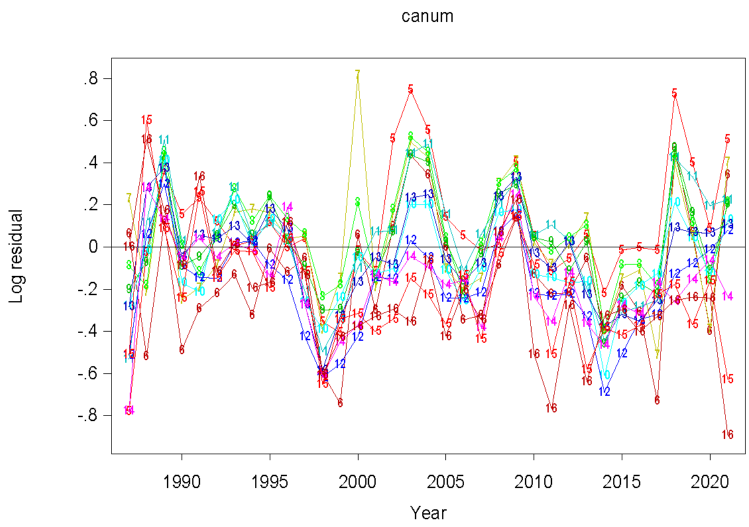
The year-class plot and the internal consistency clearly demonstrate the lack of ability to track cohorts.

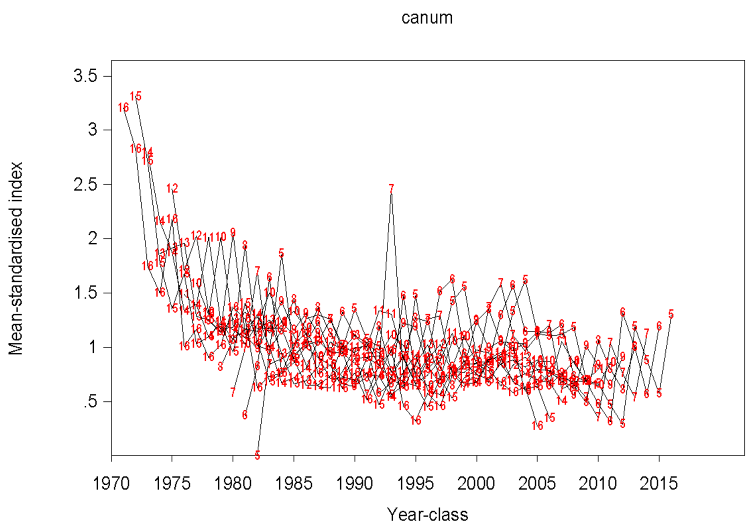
CANUM

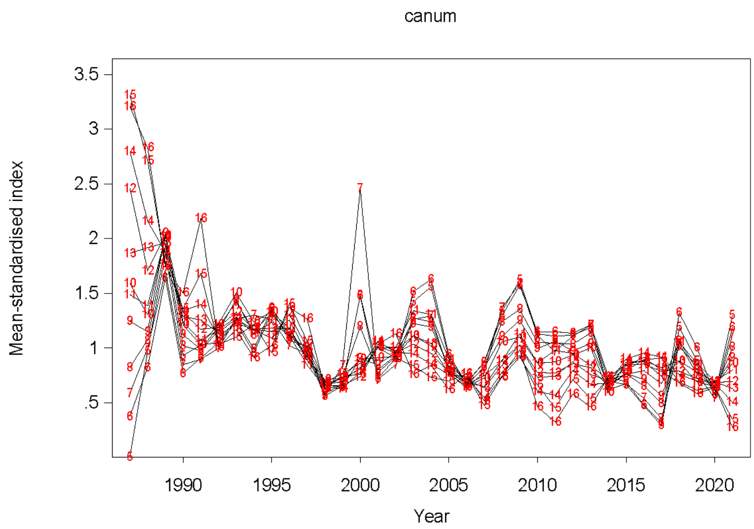

13
14
15
16
9
10
11
12
5
6
7
8
standardised index
year
1990
2000
2010
2020



Internal consistency of catch matrix

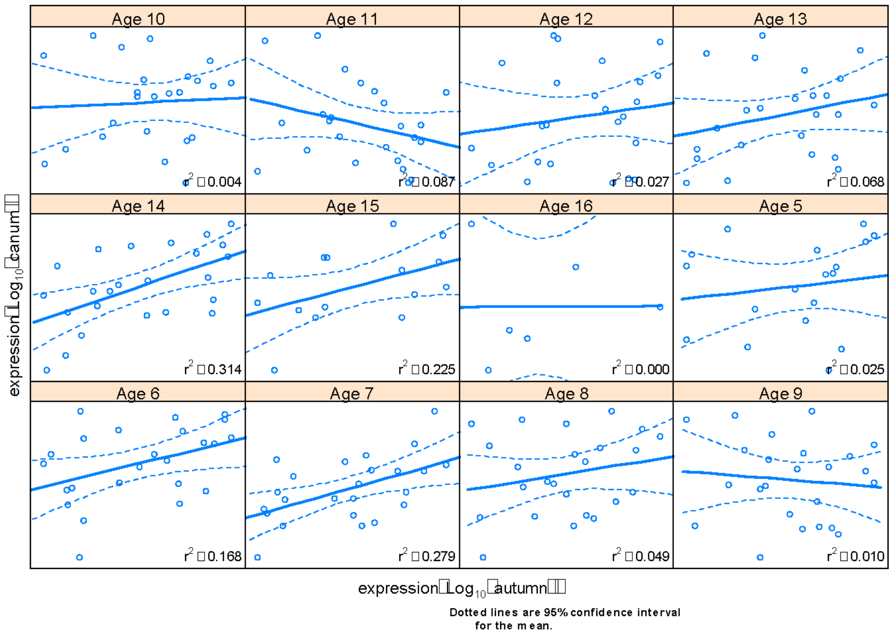

canum
Log residual
Year
1990
1995
2000
2005
2010
2015
2020


canum
Mean-standardised index
Year-class
1970
1975
1980
1985
1990
1995
2000
2005
2010
2015



As for the survey data also the catch data lack consistency and the ability to track cohorts.

CANUM VS SURVEY – EXTERNAL CONSISTENCY



External consistency between canum and survey.

The SAM run GHL561214_2022 (see link above) provides and exploratory assessment for the stock in parallel to the suggested assessment framework in Gadget (see WD6+13.

ICES WKBNORTH WD17: Assessment model for the Northeast Atlantic Greenland halibut stock (ghl.27.1-2)

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Version: 16 May, 2023

1 Introduction

We used Globally applicable Area Disaggregated General Ecosystem Toolbox (gadget3) to create the assessment model for Northeast Arctic Greenland halibut. The model and data are available on GitHub. This document has been created using the f1d6019 commit. This model is an updated version of the gadget2 model used for the stock. The model is set up to use four sub-stocks (immature/mature, female/male) from 1980 to 2021 using a single time-step per year. There are five fishing fleets: TrawlNor, TrawlRus, OtherNor, OtherRus and Internat. Internat shares selectivity (selectivity and suitability are synonyms in gadget terminology) parameters with TrawlNor and OtherRus with OtherNor due to lack of sufficient length and sex distribution data for these fleets. In addition, there are 4 survey fleets (EggaN, EcoS, WinterS, RussianS) all with separate suitability parameters.

The gadget3 model has been developed with transparency, reproducibility and automation of data acquisition in mind. The differences in fleets, data acquisition, survey indices and other details have been explained in the previous sections of this report. The most fundamental differences to the previous assessment model setup are starting the model from 1980 instead of 1992, using only one time step per year instead of four, and using exact catches in tonnes instead of estimating catches through effort in likelihood. Further, data are no longer allocated to females and males externally, but the model considers sexual dimorphism internally through sub-stocks and likelihood components. These chances make data flow more transparent and possible to automise. The following sections explain model settings, fit, and results.

2 Settings

The model uses centimeters as length unit, years as age unit, kilograms as individual fish weight unit, and kilotons (kt, 1000 metric tonnes) as catch unit. These units have been harmonized using internal model scalars and parameters. The model was set up using 1 cm length bins (delta-length, dl) and maximum length group growth of 20 cm per time-step (year). Sub-stocks were set up using parameters shown in Table 1. Data were cleaned following the min/max data lengths in the table because passing inconsistent data into the model caused issues. Immature sex ratio was forced to 50/50 for fish smaller than 31 cm.

Table 1: Model sub-stock setup: min/maxage and length columns give the minimum and maximum possible age and length (in cm), respectively. Higher ages/lengths than the maximum are assigned to plus groups. The mindatalength and maxdatalength columns give limits for data. Any values exceeding these boundaries were cleaned away from the data before passing them into the model.

substock	minage	maxage	minlength	maxlength	mindatalength	maxdatalength
female_mat	3	25	1	120	40	
female_imm	1	25	1	100		75
male_mat	3	25	1	90	31	80
male_imm	1	20	1	65		60

2.1 Sub-stock related parameters

We used fixed recruitment length and standard deviation parameters combined for both sexes, and fixed Linf VBGF parameter for males (Table 2). The Linf parameter for males was estimated from all age data using the new method including surveys and catches (see WD2). The model was forced to stay within the parameter bounds using the g3experiments::g3l_bounds_penalty() function, and optimization (optim() through g3_optim()) was done using parameter scaling (`parscale` argument). The model split recruitment 50/50 to females and males. Recruitment occurred year before actual recruitment in data due to internal model dynamics. Consequently, juvenile indices were adjusted back by one year.

Table 2: Model growth parameters: switch column gives the parameter name, value the optimised/fixed parameter value, optimise indicates whether the parameter was optimised (TRUE) or fixed (FALSE), the lower and upper bounds, and the parameter scaling for optimised parameters. The K parameters have been multiplied by 1000 due to internal model behaviour, which will be corrected later. The bbin parameter indicates beta-binomial variation around the VBGF.

switch	value	optimise	lower	upper	parscale
ghl.rec.sd	2.00	FALSE	1	8	7
ghl.recl	14.00	FALSE	12	20	8
ghl_female.K	64.22	TRUE	20	500	480
ghl_female.Linf	103.43	TRUE	80	120	40
ghl_female.bbin	6.40	TRUE	0	10	10
ghl_male.K	135.55	TRUE	20	500	480
ghl_male.Linf	68.00	FALSE	40	100	60
ghl_male.bbin	9.99	TRUE	0	10	10

Natural mortality was fixed to 0.12 for females and to 0.12, 0.16 for males. Initial F was optimized (Table 3). Initial population was set up using 50/50 split to females/males at age 1, M and initial F acting over ages, and a scalar that was optimised. In addition, we used standard deviations for initial age groups from previous model runs (Figure 1).

Table 3: Model mortality parameters together with optimised scalar for initial population. The scalar numbers are in 10 millions (check with Will). See previous tables for a detailed caption.

switch	value	optimise	lower	upper	parscale
ghl.init.F	0.029	TRUE	0.001	0.8	0.799
ghl.init.scalar	2.203	TRUE	1.000	100.0	99.000
ghl_female.M	0.120	FALSE	0.001	0.4	0.399
ghl_male.M	0.160	FALSE	0.001	0.4	0.399

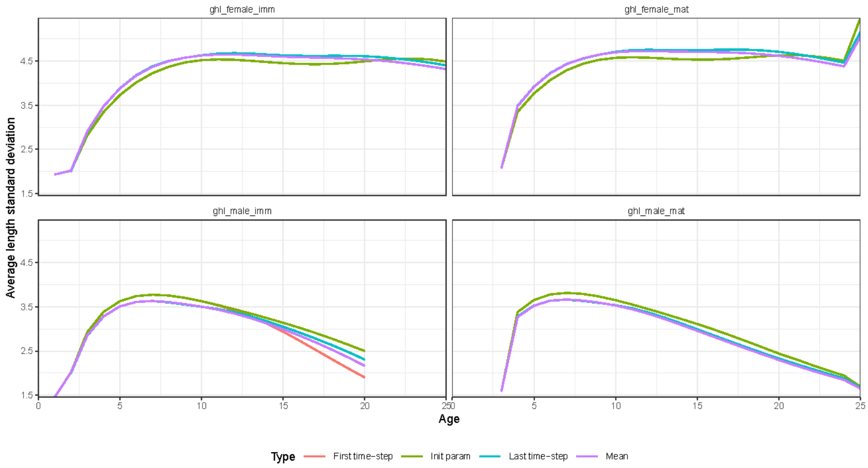

Figure 1: Average length standard deviations (cm) of age groups (a).

Maturity parameters were fixed for initial population and optimized for other model populations (Table 4).

Table 4: Model maturity parameters. See previous tables for a detailed caption.

switch	value	optimise	lower	upper	parscale
ghl__female.mat__alpha	125.554	TRUE	10.000	300.000	290.000
ghl__female.mat__initial__a50	14.520	FALSE	3.000	25.000	22.000
ghl__female.mat__initial__alpha	0.421	FALSE	0.001	3.000	2.999
ghl__female.mat__l50	58.288	TRUE	46.005	76.674	30.670
ghl__male.mat__alpha	115.242	TRUE	10.000	300.000	290.000
ghl__male.mat__initial__a50	7.340	FALSE	3.000	25.000	22.000
ghl__male.mat__initial__alpha	0.449	FALSE	0.001	3.000	2.999
ghl__male.mat__l50	39.045	TRUE	32.722	54.537	21.815

Parameters relative to their bounds have been shown in Figure 2. See the Appendix Table 12 for all model parameters.

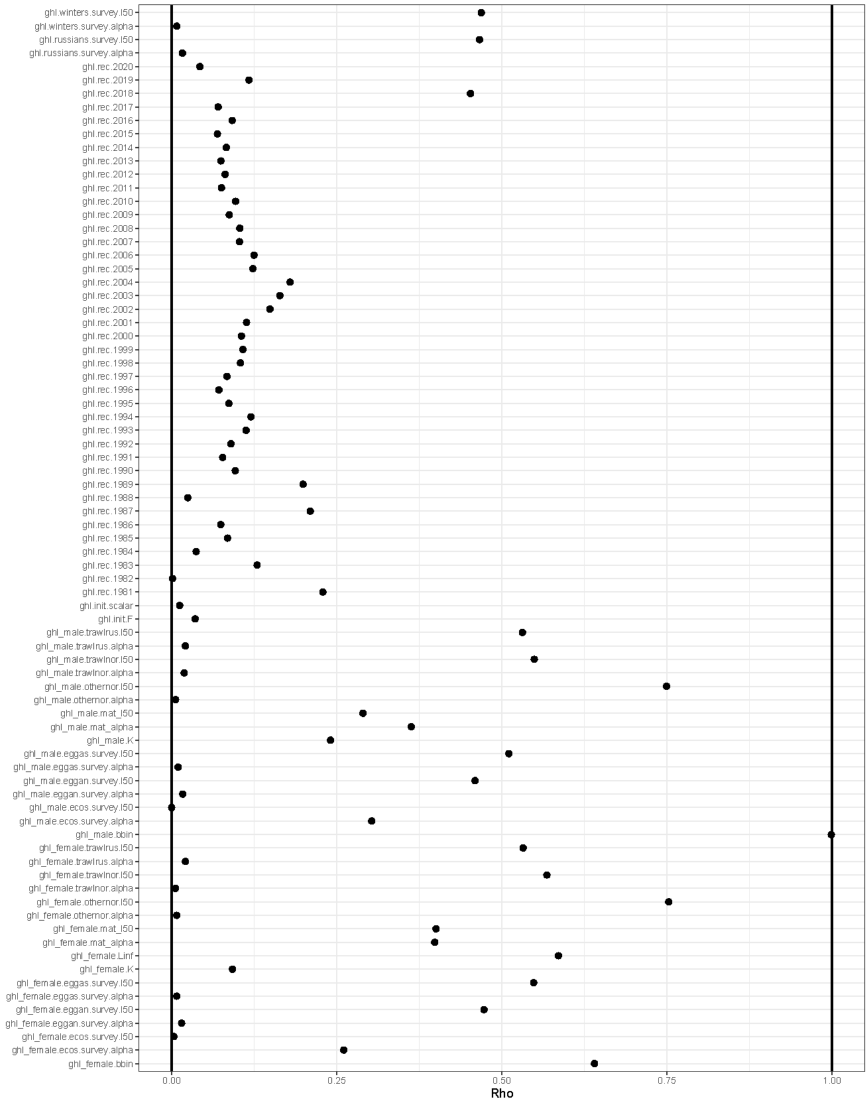

Figure 2: Optimised parameters relative to their bounds.

2.2 Fleet related parameters

Within the fisheries in the Barents Sea and associated slope, fish have a tendency to move to the slope as they mature. This means that fisheries on the shelf tend to fewer of the large mature fish. The Barents Sea Greenland halibut Gadget model was designed to be a "fleets as areas model", where fleet selectivity would take care of the issue of the larger fish moving out of the areas covered by some fleets and surveys. However, the dome shaped selectivity required for this was problematic. The model employing the dome shaped selectivity was unstable, with a large pattern in the jitter analysis indicating that the model was unable to converge to a single solution. The reasons for this are unclear, but it was clear that the dome-shaped selectivity model cannot be used at present as the basis for advice. The model presented here therefore uses exponential ("flat topped", "S-shaped") selectivity curves using the exponential L50 function (expL50) for all fleets and surveys. The ecosystem survey index is expected to be affected by this issue, and the survey index has been computed over a range of sizes (28-65cm) to avoid this and ensure that the movement of fish does not cause undue bias. It is clear in the data, that the trawl fleets catch fewer large fish than the other gears (which are more concentrated along the slope) and there is therefore a slight mismatch here between model and data. The fits to the length distributions is otherwise good for these fleets, and the issue of dome shaped selectivity is therefore a research recommendation for future improvements in the model.

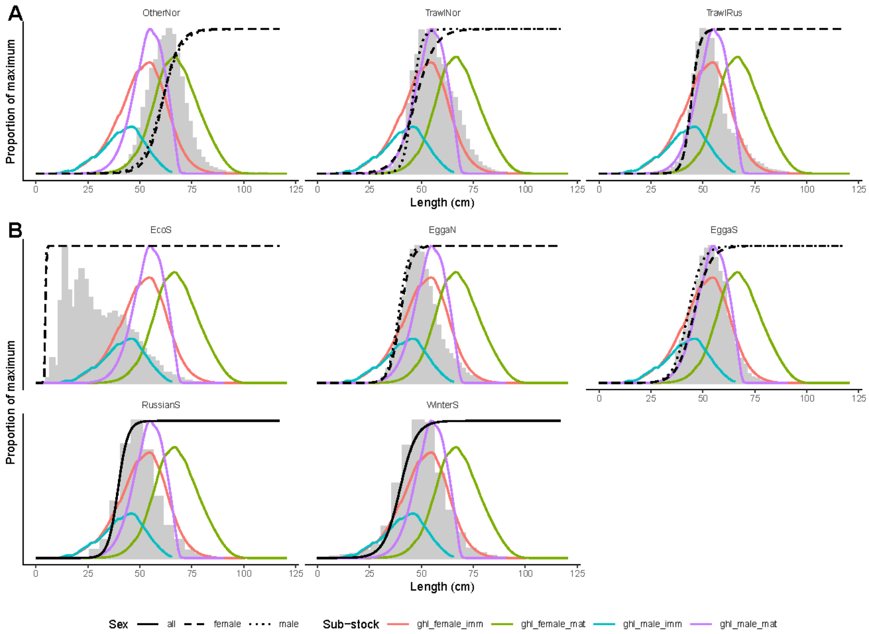

Figure 3: Modelled suitability for fishing (A) and survey (B) fleets shown as black lines. The line type refers to sex. Grey histogram on the background shows annually averaged length distributions for each likelihood component. Colored lines indicate the available model biomass of each sub-stock. All datasets are scaled to maximum value.

Suitabilities were optimized separately for males and females for fleets that contained sex distribution data (Table 5, Figure 3). Sex specific suitabilities did not work as intended as there was generally no separation between sexes. Males arrive the spawning grounds along the continental slope, that are also major fishing grounds, smaller and earlier than females. Our current model does not manage to incorporate this sexual dimorphism. This may stem from an issue how model was set up using separate sex-distribution length distributions stratified by length or a problem in how gadget3 fits the suitability parameters. These issues must be solved eventually.

Table 5: Optimised fleet suitability parameters. See previous tables for a detailed caption.

switch	value	optimise	lower	upper	parscale
ghl_female.ecos.survey.alpha	5.289	TRUE	0.1	20	19.9
ghl_female.ecos.survey.l50	5.149	TRUE	5.0	50	45.0
ghl_male.ecos.survey.alpha	6.130	TRUE	0.1	20	19.9
ghl_male.ecos.survey.l50	5.002	TRUE	5.0	50	45.0
ghl_female.eggan.survey.alpha	0.401	TRUE	0.1	20	19.9
ghl_female.eggan.survey.l50	40.485	TRUE	5.0	80	75.0
ghl_male.eggan.survey.alpha	0.436	TRUE	0.1	20	19.9
ghl_male.eggan.survey.l50	39.473	TRUE	5.0	80	75.0
ghl_female.eggas.survey.alpha	0.255	TRUE	0.1	20	19.9
ghl_female.eggas.survey.l50	46.125	TRUE	5.0	80	75.0
ghl_male.eggas.survey.alpha	0.295	TRUE	0.1	20	19.9
ghl_male.eggas.survey.l50	43.315	TRUE	5.0	80	75.0
ghl_female.trawlnor.alpha	0.213	TRUE	0.1	20	19.9
ghl_female.trawlnor.l50	47.625	TRUE	5.0	80	75.0
ghl_male.trawlnor.alpha	0.479	TRUE	0.1	20	19.9
ghl_male.trawlnor.l50	46.193	TRUE	5.0	80	75.0
ghl_female.othernor.alpha	0.257	TRUE	0.1	20	19.9
ghl_female.othernor.l50	61.465	TRUE	5.0	80	75.0
ghl_male.othernor.alpha	0.220	TRUE	0.1	20	19.9
ghl_male.othernor.l50	61.220	TRUE	5.0	80	75.0
ghl.russians.survey.alpha	0.426	TRUE	0.1	20	19.9
ghl.russians.survey.l50	39.974	TRUE	5.0	80	75.0
ghl_female.trawlrus.alpha	0.515	TRUE	0.1	20	19.9
ghl_female.trawlrus.l50	44.932	TRUE	5.0	80	75.0
ghl_male.trawlrus.alpha	0.513	TRUE	0.1	20	19.9
ghl_male.trawlrus.l50	44.854	TRUE	5.0	80	75.0
ghl.winters.survey.alpha	0.256	TRUE	0.1	20	19.9
ghl.winters.survey.l50	40.176	TRUE	5.0	80	75.0

3 Likelihood components

3.1 Weighting

The model was run through g3_iterative() to acquire iteratively reweighted estimates for likelihood component weights. These iterated weights where then adjusted manually to give more weight for survey indices and sex distributions (Table 6, Figure 4). Adjusting the weights manually improved sex distribution fit and stabilized model trends. While the manual adjustment of weights was not entirely objective process, different weights did generally not influence the estimated biomass trends except the last model years: since all survey indices have a negative trend the recent years, giving more weight for them increased the negative trend in model biomass. See more discussion about model stability in the Jitter section.

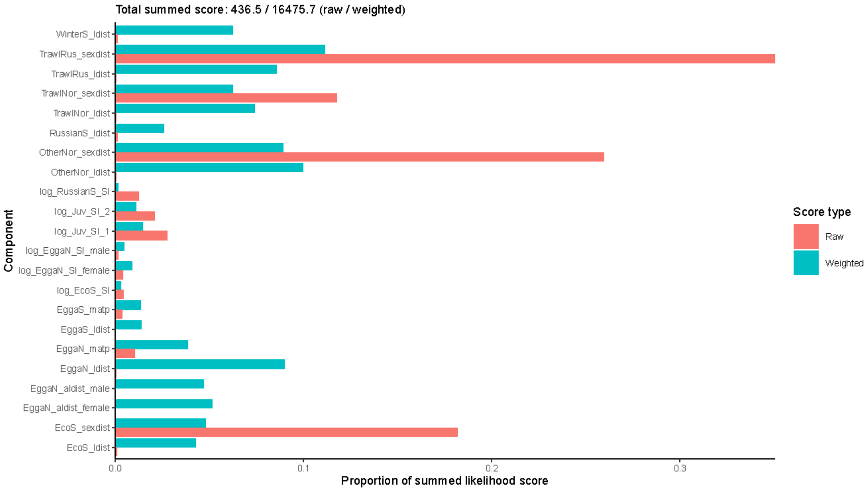

Figure 4: Proportion of likelihood for weighted and unweighted (raw) likelihood components.

Table 6: Likelihood component weights. Values rounded to 0 decimals have been set manually after iterative reweighting.

switch	value
adist_surveyindices_log_EcoS_SI_weight	25.5
adist_surveyindices_log_EggaN_SI_female_weight	80.0
adist_surveyindices_log_EggaN_SI_male_weight	120.0
adist_surveyindices_log_Juv_SI_1_weight	20.0
adist_surveyindices_log_Juv_SI_2_weight	20.0
adist_surveyindices_log_RussianS_SI_weight	5.2
cdist_sumofsquares_EcoS_ldist_weight	2382.3
cdist_sumofsquares_EcoS_sexdist_weight	10.0
cdist_sumofsquares_EggaN_aldist_female_weight	10430.1
cdist_sumofsquares_EggaN_aldist_male_weight	6322.2
cdist_sumofsquares_EggaN_ldist_weight	10000.0
cdist_sumofsquares_EggaN_matp_weight	139.1
cdist_sumofsquares_EggaS_ldist_weight	5880.4
cdist_sumofsquares_EggaS_matp_weight	142.2
cdist_sumofsquares_OtherNor_ldist_weight	9851.7
cdist_sumofsquares_OtherNor_sexdist_weight	13.0
cdist_sumofsquares_RussianS_ldist_weight	913.6
cdist_sumofsquares_TrawlNor_ldist_weight	5724.3
cdist_sumofsquares_TrawlNor_sexdist_weight	20.0
cdist_sumofsquares_TrawlRus_ldist_weight	7196.4
cdist_sumofsquares_TrawlRus_sexdist_weight	12.0

cdist_sumofsquares_WinterS_ldist_weight	1718.9

3.2 Fit to survey indices

While the survey indices shared the trend of stock decrease during the last decade, the signals in them were conflicting resulting in gadget3 being unable to fit any survey index well (Figure 5).

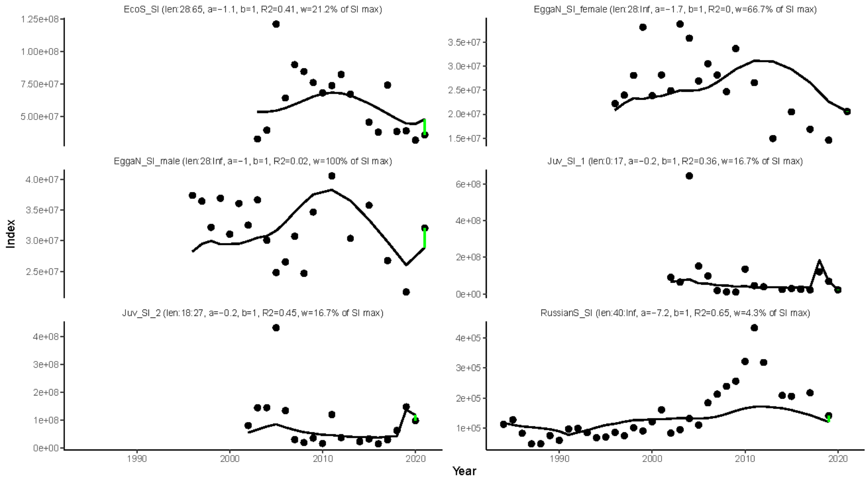

Figure 5: Model fit (black line) to survey indices (black dots). Name of the survey index, flat length selectivity (min:max in cm), intercept (a), slope (b), coefficient of determination (R2) and weight (w) as a percentage of maximum assigned for any survey index are given as panle headers.

3.3 Fit to length distributions

There is a mismatch between the signals concerning the recruitment pattern in the early 2000s. The EggaN and the EcoS length distributions both indicate a recruitment peak. There is, however, a mismatch between the year that is estimated as the year of peak recruitment (c. 2002 for the EggaN and 2005 for the EcoS index). In contrast, the age data indicates a much smoother recruitment pattern, with a run of three moderately good recruitment years 2000-2002. There is currently no data to distinguish which of these possibilities is more accurate. The current model uses the smoother version, although at points in model development a higher spike was found. There is little difference in the overall stock development, it is simply the degree to which the stock has erratic recruitment that is unclear.

3.3.1 Fishery

There was no sufficient data to estimate OtherRus and Internat selectivities.

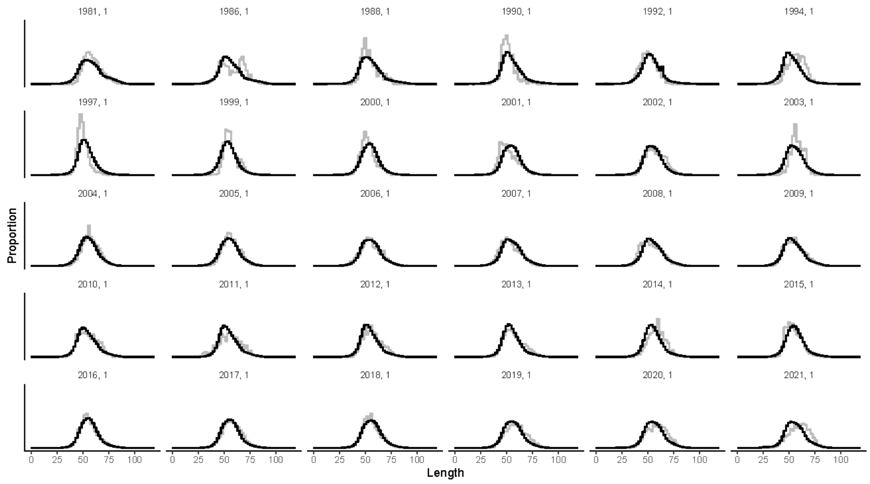

Figure 6: Model fit (black lines) to TrawlNor length distributions (grey lines).

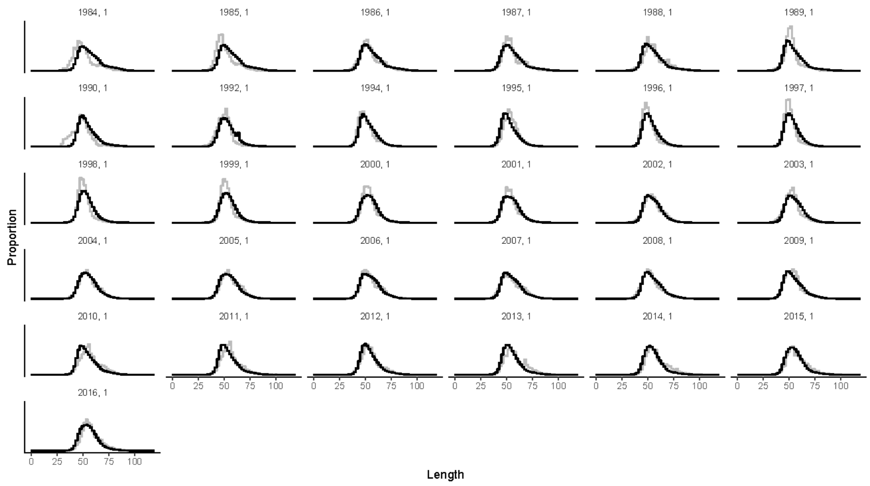

Figure 7: Model fit (black lines) to TrawlRus length distributions (grey lines).

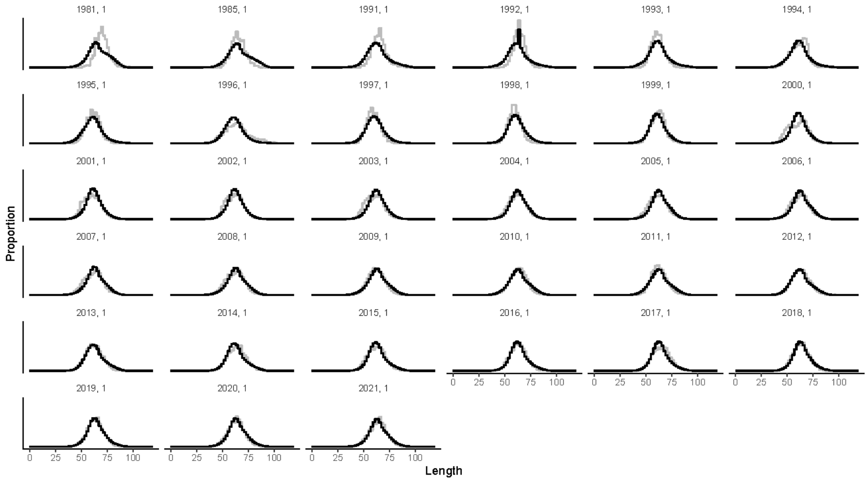

Figure 8: Model fit (black lines) to OtherNor length distributions (grey lines).

3.3.2 Surveys

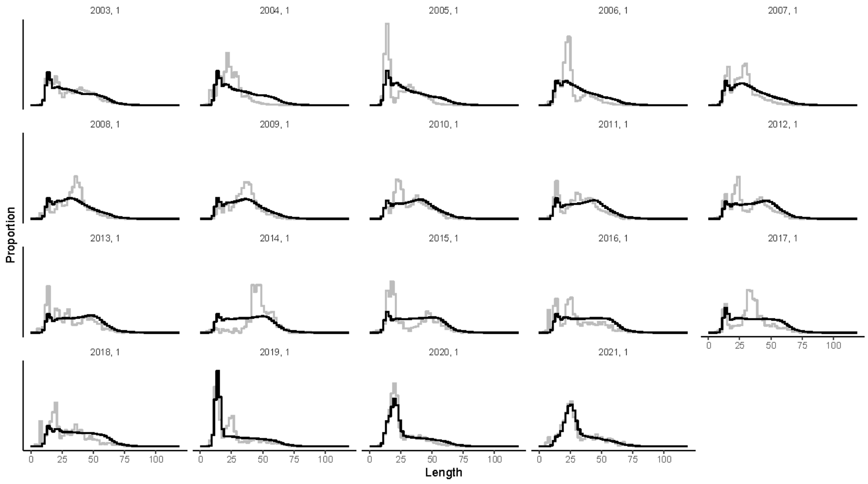

Figure 9: Model fit (black lines) to EcoS length distributions (grey lines).

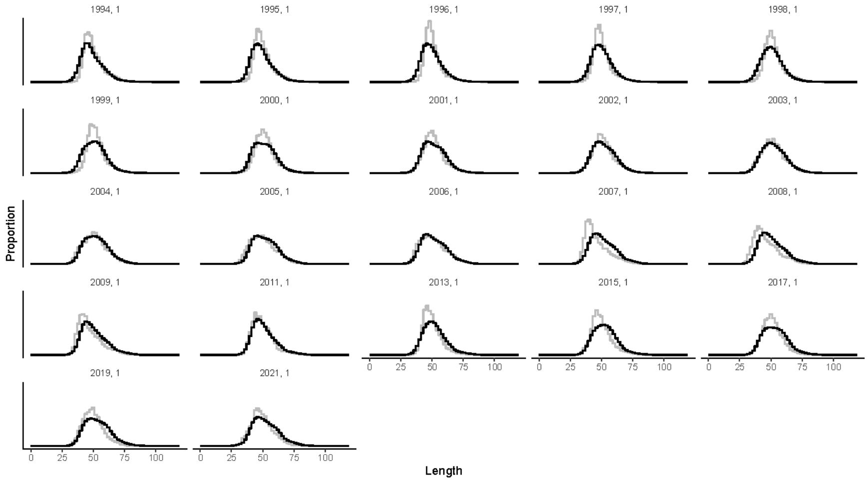

Figure 10: Model fit (black lines) to EggaN length distributions (grey lines).

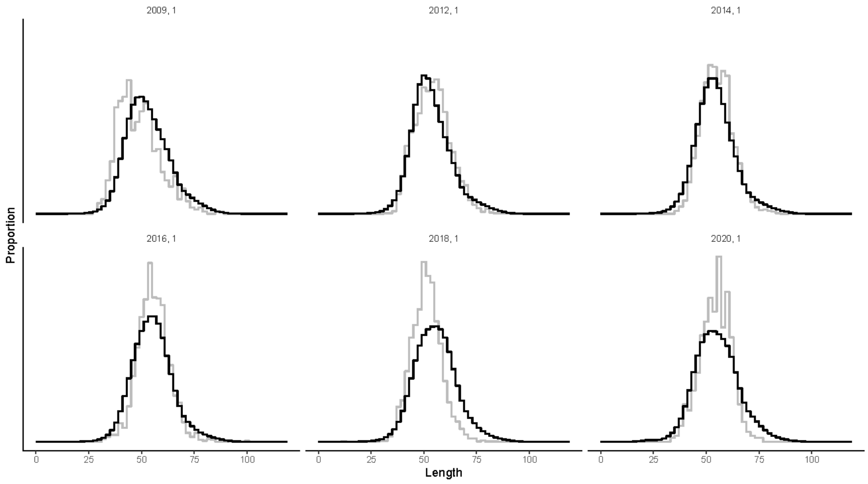

Figure 11: Model fit (black lines) to EggaS length distributions (grey lines).

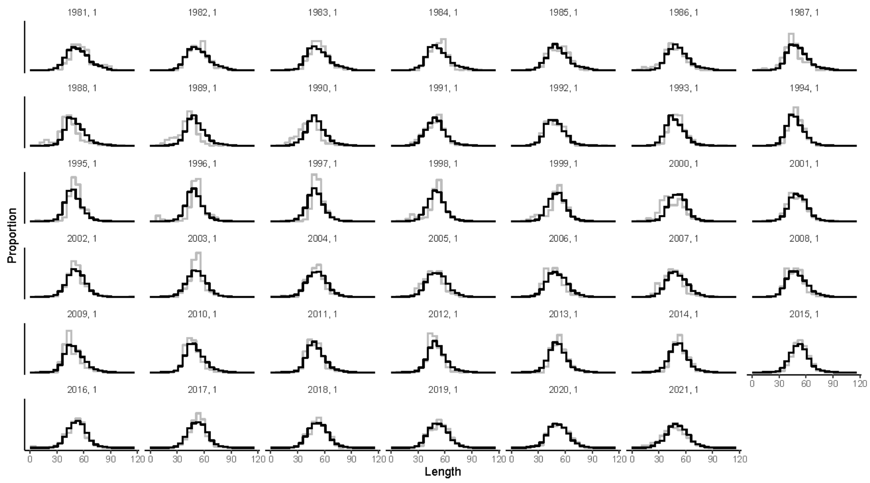

Figure 12: Model fit (black lines) to WinterS length distributions (grey lines).

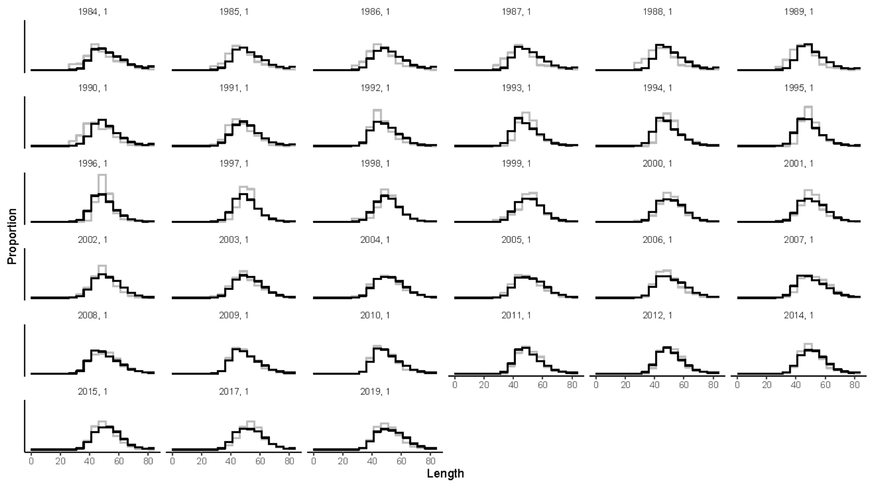

Figure 13: Model fit (black lines) to RussianS length distributions (grey lines).

3.4 Fit to maturity distributions

Maturity (substock) and sex distribution data were cleaned and smoothed before passing them into the model. The data manipulation has been documented on GitHub.

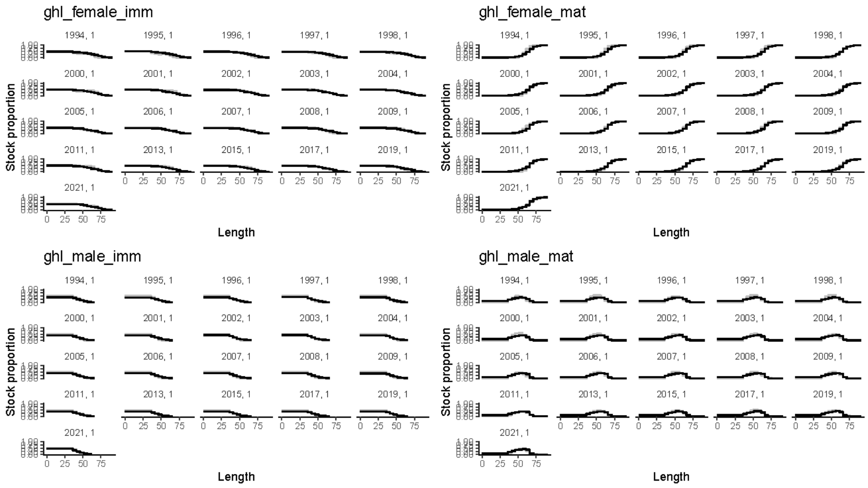

Figure 14: Model fit (black lines) to EggaN sub-stock distribution data (grey lines).

3.5 Fit to sex distributions

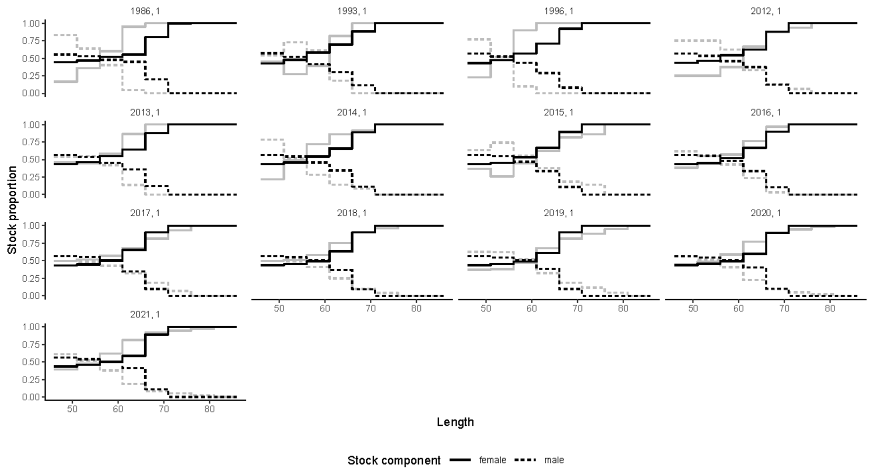

Figure 15: Model fit (black lines) to TrawlNor sex distribution data (grey lines). Females are plotted using solid and males with dashed lines.

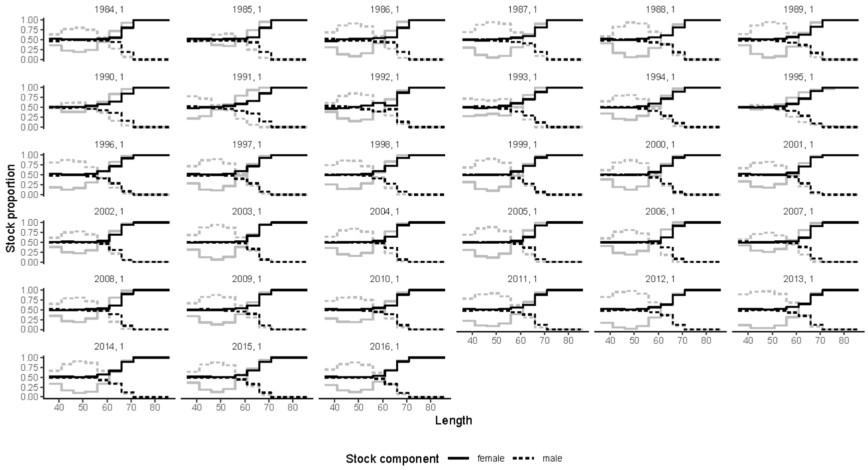

Figure 16: Model fit (black lines) to TrawlRus sex distribution data (grey lines). Females are plotted using solid and males with dashed lines.

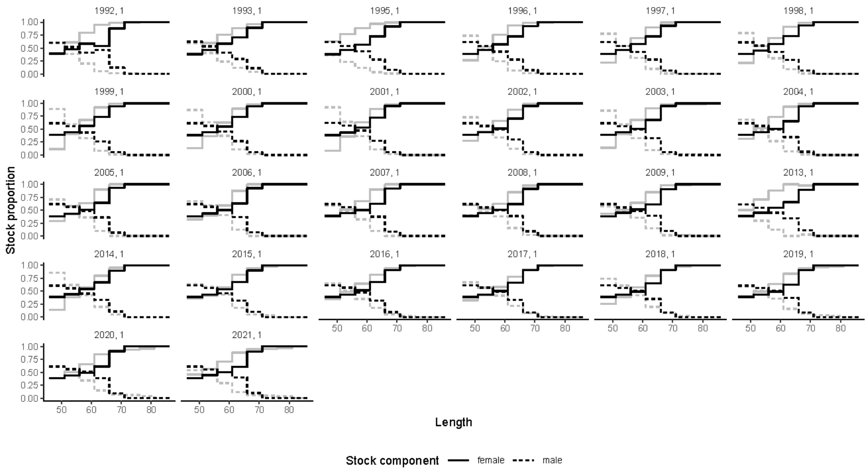

Figure 17: Model fit (black lines) to OtherNor sex distribution data (grey lines). Females are plotted using solid and males with dashed lines.

3.6 Fit to age data

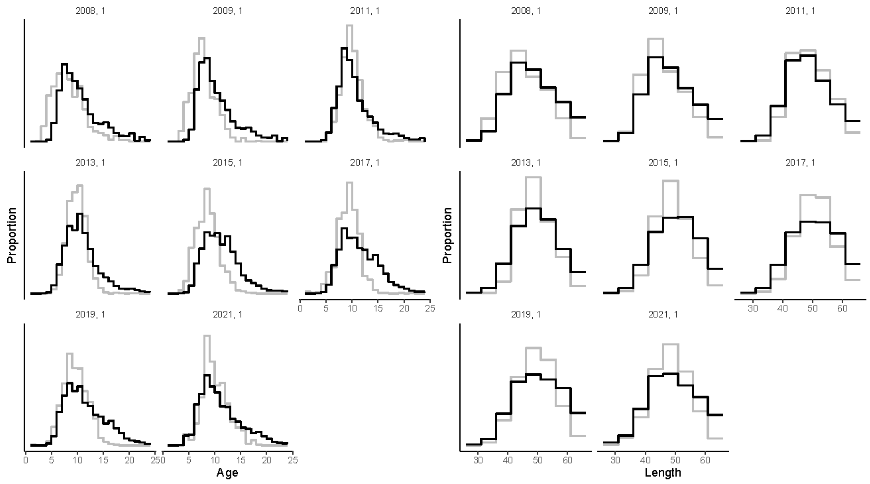

Figure 18: Model fit (black lines) to EggaN male age-length distribution data (grey lines).

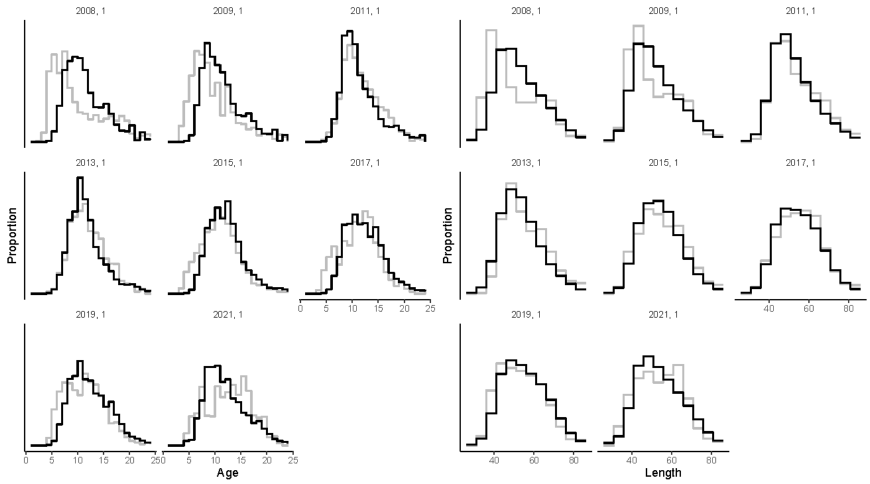

Figure 19: Model fit (black lines) to EggaN female age-length distribution data (grey lines).

4 Results

The estimated population biomass trends are very similar to those in the previous gadget2 assessment model (Figures 20-21, Table 7, ICES (2020)). However, the overall biomass level has been revised significantly downwards, and the HR estimates revised up accordingly (Figure 21). The revision has minimal effect on the advice, with the higher HR applied to a lower stock giving similar catch advice. It should be noted that the previous assessment model did not include age data, and did not extend far enough back in time to cover the lowest point for the stock. The overall biomass level (as opposed to trends) in the previous model was therefore considered highly uncertain. The last few years of recruitment did not have enough data to scale to and should be ignored (Figure 20B). The last trustworthy peak in recruitment occurred almost two decades ago in 2003-2005. Population biomass demonstrated a clear downward trend due to harvest rates exceeding the sustainable levels (Figure 20C-D). Harvest rate for $\geq$ 45 cm fish increased from 0.09 in 2009 to 0.26 in 2021 (Figure 20C).

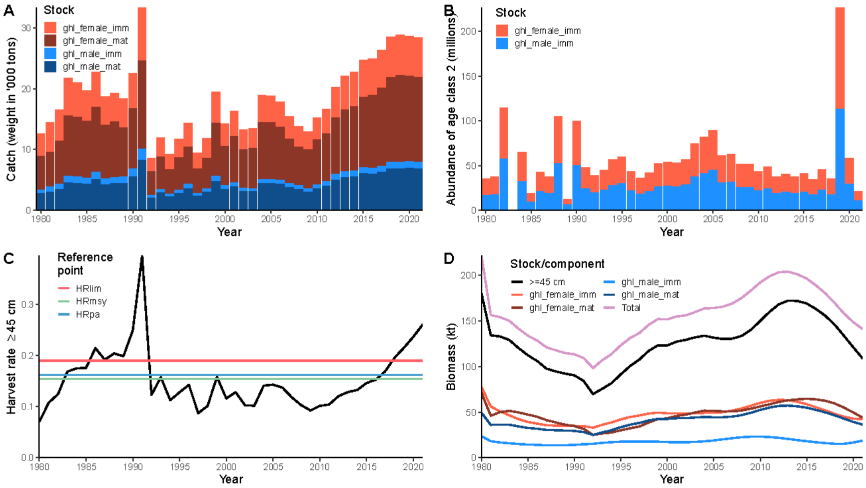

Figure 20: Catches (A), recruitment (B, considered as age class 2 in the model), harvest rate (C) and population biomass (D) estimated by the assessment model. Colors refer to substocks and summed up components explained in legends. Horizontal lines indicate reference points explained later in this chapter.

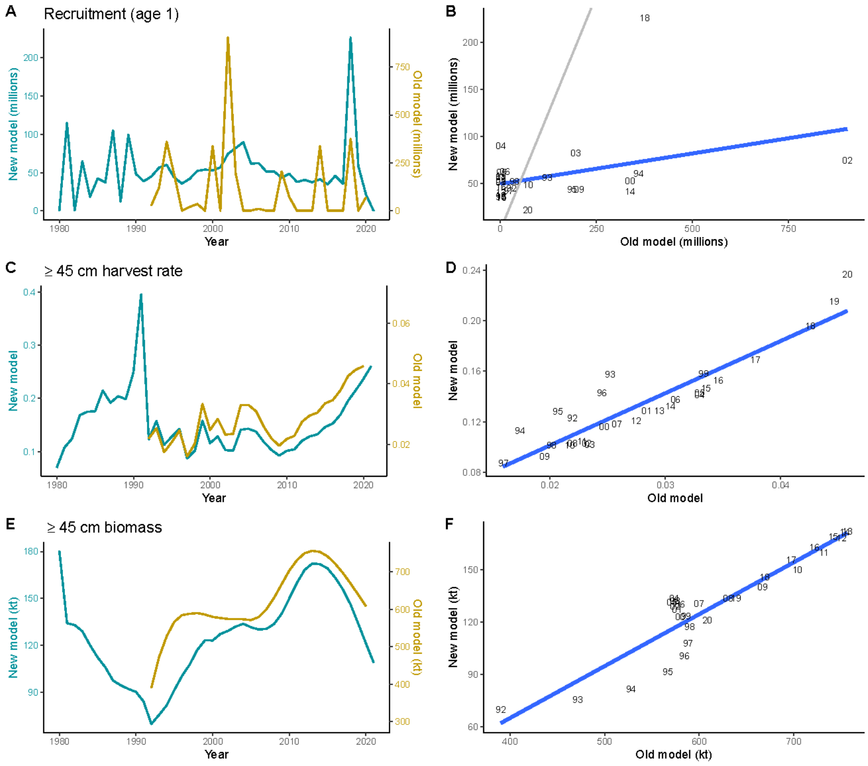

Figure 21: Comparison between the old gadget2 assessment model (yellow) and the new gadget3 model (turquoise) results for recruitment at age 1 (A-B), >= 45 cm harvest rate (C-D) and >= 45 cm biomass (E-F). Left panels (A, C, E) show the time series. Note different scales on y-axes for old and new model estimates. Right panels (B, D, F) show scatter plots with blue line indicating the best fitting linear regression and grey line a reference line with slope of 1 and intercept of 0.

Table 7: Gadget assessment model output: year, estimated number of recruits, spawning stock biomass (mature females), and harvest rate of the spawning stock

year	recruits (millions)	SSB (kt)	HR
1980	0.00	71.06	0.08
1981	114.51	46.11	0.13
1982	0.65	50.05	0.15
1983	64.77	51.46	0.20
1984	18.58	49.69	0.21
1985	42.29	47.36	0.21
1986	37.22	44.97	0.25

1987	104.98	41.20	0.23
1988	12.22	38.79	0.26
1989	99.55	36.28	0.24
1990	48.20	34.68	0.32
1991	38.66	31.70	0.52
1992	44.94	25.03	0.19
1993	56.38	26.64	0.24
1994	60.10	27.65	0.18
1995	43.33	30.15	0.23
1996	35.78	32.32	0.24
1997	41.90	34.37	0.15
1998	52.17	38.60	0.16
1999	53.95	42.39	0.26
2000	52.83	43.23	0.18
2001	56.74	45.83	0.21
2002	74.47	47.31	0.16
2003	81.98	49.70	0.16
2004	89.74	51.77	0.22
2005	61.53	51.45	0.22
2006	62.42	50.92	0.20
2007	51.37	50.80	0.16
2008	51.62	51.80	0.14
2009	43.65	53.85	0.14
2010	48.45	56.32	0.15
2011	37.79	58.68	0.15
2012	40.52	61.19	0.17
2013	37.35	63.00	0.19
2014	41.41	64.06	0.19
2015	34.68	64.64	0.20
2016	45.88	64.05	0.22
2017	35.25	62.47	0.23
2018	226.30	59.57	0.26
2019	58.59	55.06	0.29
2020	21.44	49.75	0.32
2021	0.02	44.10	0.36

4.1 Model exploration

During the model development and at the benchmark, we conducted different investigations and variations of model setups. Priority was given to settings which provided stable models as well as those which best fit the available data. A partial list of the issues examined is given below:

- Different methods of treating sex split and length distribution data in the fleets
- Examination of data to identify outliers (either years for some surveys or small length classes with erratic data)
- Different M estimates by sex
- Different length of tuning series and possible starting dates
- Different functional form for selectivity in fleet and surveys
- Fixing or freeing starting length and standard deviation and L infinity
- Different methods of estimating the distribution of number at age in the model initial conditions
- Including different survey series

- Worked on the weights for different data sets in the likelihood sum

4.2 Analytical testing

4.2.1 Jitter

Model stability was assessed using a jitter analysis by letting optimized model parameters randomly vary 10% of their bound range and repeating the jittering 50 times (Figure 22). There is still a bug in the jitter code either in gadget3 or in the current model which makes jitter optimisation to crash sometimes. In the current jitter run, 40 out of 50 did not crash. One jitter run out of the non-crashed ones had slightly different (1.7% compared to the mean) negative log-likelihood score than the rest, but total biomass, harvest rate nor recruitment were not visibly influenced by this. Recruitment was unstable before 1994 because we did not have juvenile indices nor age data going that far back in time. This variation did not influence the estimated model biomasses.

The benchmark model appears stable and warrants the use of ICES category 1 rules. Nevertheless, during the model development, absolute model biomass level tended to be unstable, while the biomass trends varied little. Hence, caution should be taken when modifying the model and adding new years of data as any changes may make the absolute levels unstable.

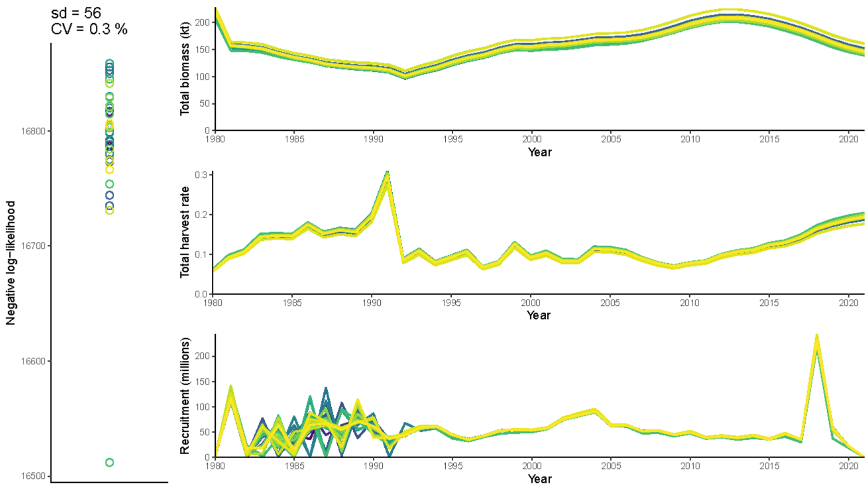

Figure 22: Jitter results for the model. Negative log-likelihood scores of jitter runs are shown on the left together with standard deviation and CV (in percentage). Total biomass, harvest rate and recruitment are on top of each other on the right. Color indicates the run number and is standardized across all panels.

The beta-bin parameters that define the variation around growth functions varied considerably during the jitter runs (Figure 23). Other variables, such as the above mentioned recruitment and suitability parameters for EcoS did not matter for the model results. EcoS suitability tried to include all fish, also the smallest ones, and there were multiple ways to achieve it explaining the variation.

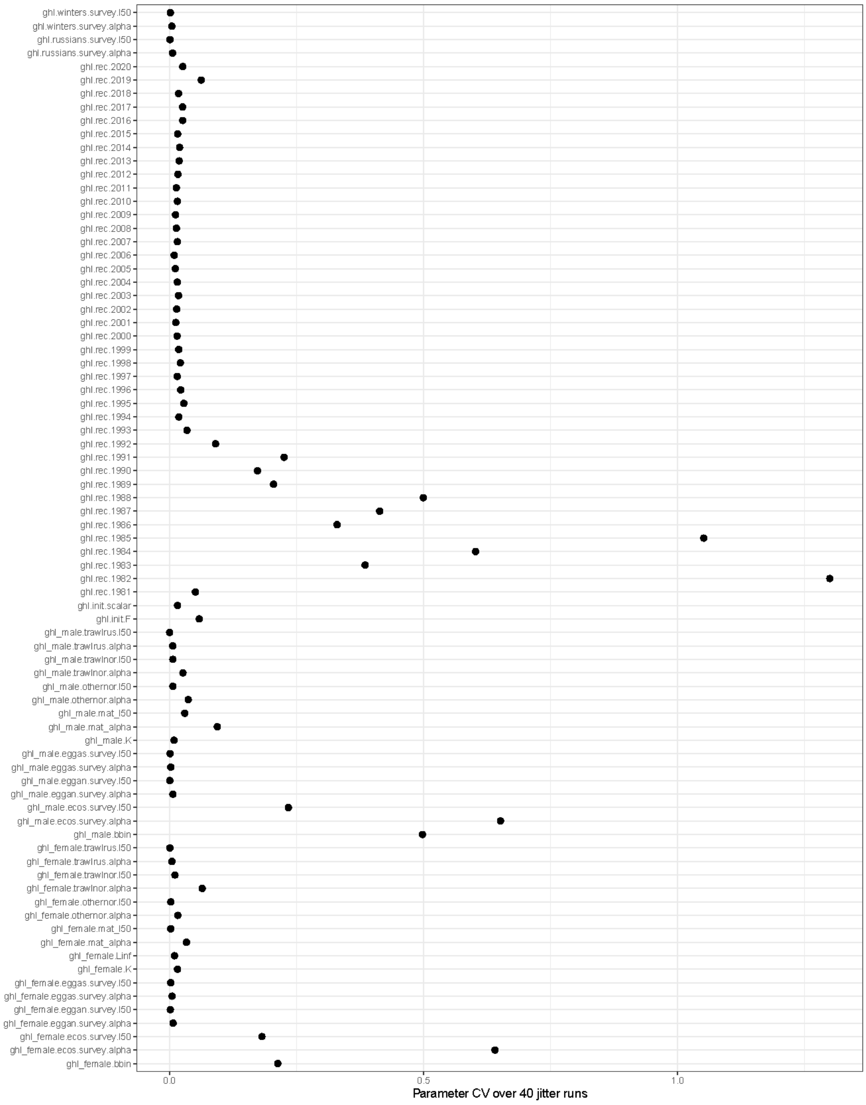

Figure 23: Coefficient of variation for the model parameters during the jitter runs.

4.2.2 Retrospective

The retrospective analysis for model biomass had slightly negative Mohn's rho (Hurtado-Ferro et al. 2015) values (Figure 24). The retro patterns with years removed got clumped following the availability of survey data: 2021 EggaN (0 years removed), 2019 EggaN and RussianS (1 and 2 years removed), 2017 EggaN and RussianS (3 and 4 years removed), and 2015 EggaN (5 years removed). As a result of this pattern, and the fact that the EggaN survey is run every two years, it is strongly recommended that the assessment be run every two years rather than annually.

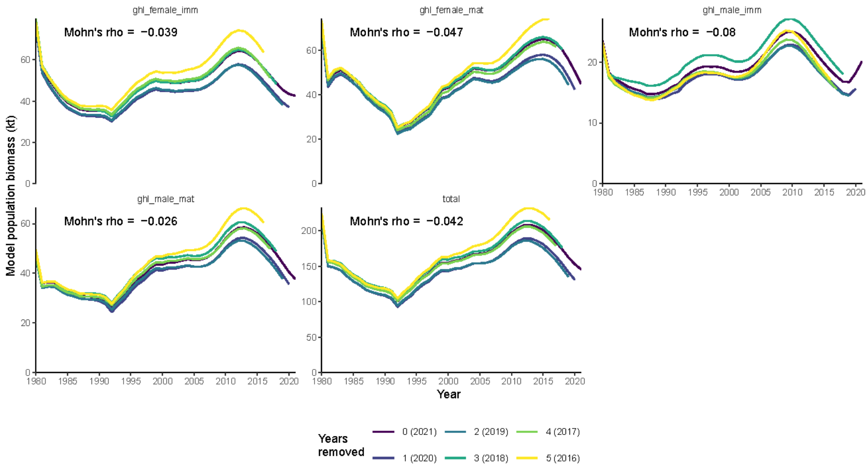

Figure 24: Retrospective analysis using model biomass for each sub-stock and total biomass. Colors are scaled to the number of years removed

Harvest rates for >45 cm fishable stock showed similar patterns to model biomass with a Mohn's rho of 0.06 (Figures 24 and 25)

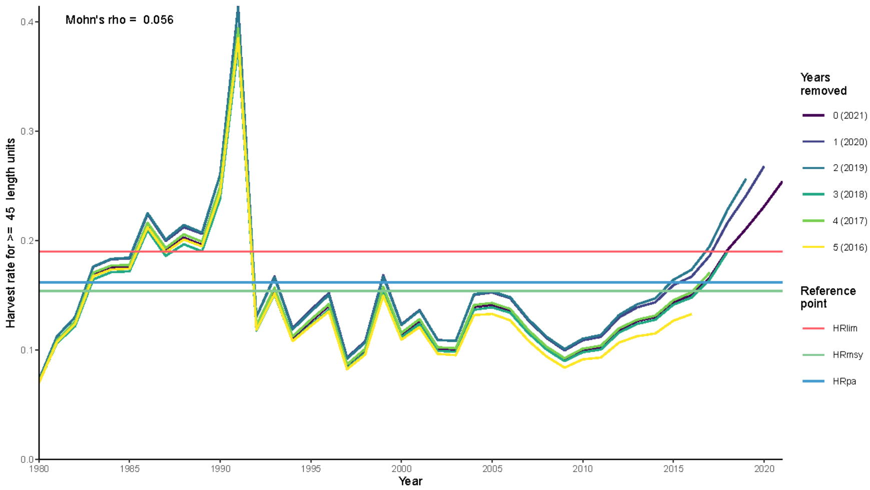

Figure 25: Retrospective analysis using harvest rate for >45 cm fish. Colors are scaled to the number of years removed

4.3 Reference points

Due to relative model stability, we suggest assessing the stock as ICES category 1 (ICES 2022) and using the maximum sustainable yield (MSY) principle.

4.3.1 Stock recruitment relationship, B_{lim} and B_{pa}

We define the mature female substock in the model at the beginning of an (annual) time-step as spawning stock biomass and 1-year old fish at the end of an (annual) time-step as recruitment, except for projections where we use SSB at the end of a time-step. There was no linear relationship between spawning stock biomass and recruitment year later (Figure 26). The lowest spawning stock biomass with sufficient recruitment (i.e. the lowest biomass in the model) occurred in 1992 and was 25.03 kt according to the current model run. This value should be treated as the limit reference point for spawning stock biomass (B_{lim}). Since we did not bootstrap the model to estimate uncertainty, we suggest using the ICES rule of multiplying B_{lim} by 1.4 as the precautionary reference point for spawning stock biomass (B_{pa}).

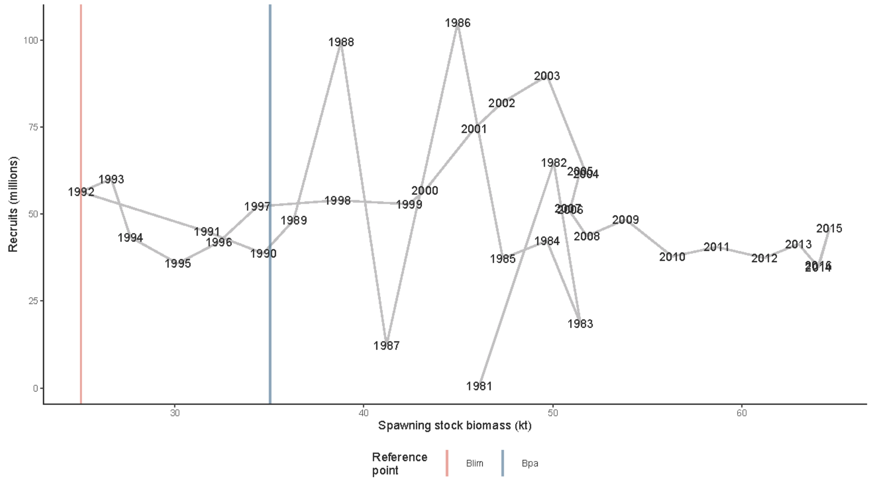

Figure 26: Spawning stock biomass (mature females; ghl_female_mat) against recruitment the following year. The last four recruitment and hence five spawning stock years have been cut to exclude the model artefact recruitment spikes.

4.3.2 Long-term projections

The hindcast model (see Settings) was used to project stock status 100 years into the future with following modifications and assumptions:

- Catch proportions by fleet were fixed to the average of last four years.
- Fleets had the same selectivity than in the hindcast model
- The ICES advice rule was implemented via catchability as a multiplier to effort level: catchability was replaced by a hockey stick variant with identical catchability to the hindcast model for SSB values $> B_{trigger}$ and a linearly declining value for SSB values $\leq B_{trigger}$.
- The value of SSB triggering a management action ($B_{trigger}$) was set equal to B_{pa}.
- Model target harvest rates from 0 to 1 were used with 0.01 increments.
- Seven year periods of recruitment were bootstrapped from model estimates for 1-year old fish at the end of an (annual)time-step between 1990 and 2017. The block bootstrap was used to maintain autocorrelation.
- Due to model technical reasons, recruitment was directed to a dummy stock which transferred the recruits 50/50 to immature female and male substocks.
- Harvest rate (HR) using fleet selectivities was used to model fishing mortality.
- Assessment error was incorporated into the projections for bootstrapped annual projected harvest rates assuming a log-normal AR(1) process with CV of 0.212 (`advice_cv`) and autocorrelation (`advice_rho`) of 0.423.
- Probabilities were calculated using 100 replicates for each target harvest rate.

4.3.2.1 Estimation of HR_{lim}, HR_{pa} We used harvest rate for $\geq$ 45 cm Greenland halibut as the reported harvest rate, but run all simulations using harvest rates assuming fleet selectivities from the model. We separate these harvest rates by using HR^{target} notation for harvest rates with model fleet selectivities and $HR^{\geq 45cm}$ (or just HR) for derived harvest rates for $\geq$ 45 cm fish. The reference points were calculated using the last 50 projection years (50-100 years from the end of the hindcast model 2021).

The limit reference point for harvest rate ($HR^{\geq 45cm}_{lim}$) was calculated using the maximum HR^{target} (precautionary closest to SSB) giving 50% probability (=quantile) for SSB > B_{lim} without assessment error (`advice_cv` and `advice_rho` = 0) and $B_{trigger}$ (Figure 27, Table 8). Precautionary reference point for harvest rate ($HR^{\geq 45cm}_{pa}$) was calculated using the maximum HR^{target} giving 5% probability for SSB < B_{lim} with assessment error and $B_{trigger}$ (Figure 27D). $HR^{\geq 45cm}_{pa}$ was also close to $HR^{\geq 45cm}$ yielding 50% probability for SSB > B_{pa} even though B_{pa} was not used in the calculations (but it was used as $B_{trigger}$ in the model simulations).

4.3.2.2 Maximum sustainable yield Maximum sustainable yield (MSY) was estimated using the 50% quantile of catches for the last 50 projection years providing maximum catch (Figure 27A). The corresponding harvest rate, $HR^{\geq 45cm}_{msy}$, was an average $HR^{\geq 45cm}$ over the 100 bootstrap repetitions providing MSY. Uncertainty for $HR^{\geq 45cm}_{msy}$ was estimated as minimum and maximum HR^{target} yielding catches that were 95% of the MSY.

Table 8: Suggested reference points. Reference point name is given in the first column and explanation in the last column. SSB and Catch columns list mature female substock and total catch based values in kilotons, respectively. HR column indicates harvest rate for >45 cm Greenland halibut.

Reference point	SSB	Catch	HR	Basis
Blim	25.031			Lowest modelled mature female substock biomass
Bpa	35.043			Blim x 1.4
Btrigger	35.043			Bpa
MSY		18.938		Maximum sustainable yield
HRlim			0.190	HR(>=45cm) leading to P(SSB < Blim) = 0.5
HRmsy			0.154	HR(>=45cm) leading to MSY
HRpa			0.162	HR(>=45cm), when ICES AR is applied, leading to P(SSB > Blim) = 0.05

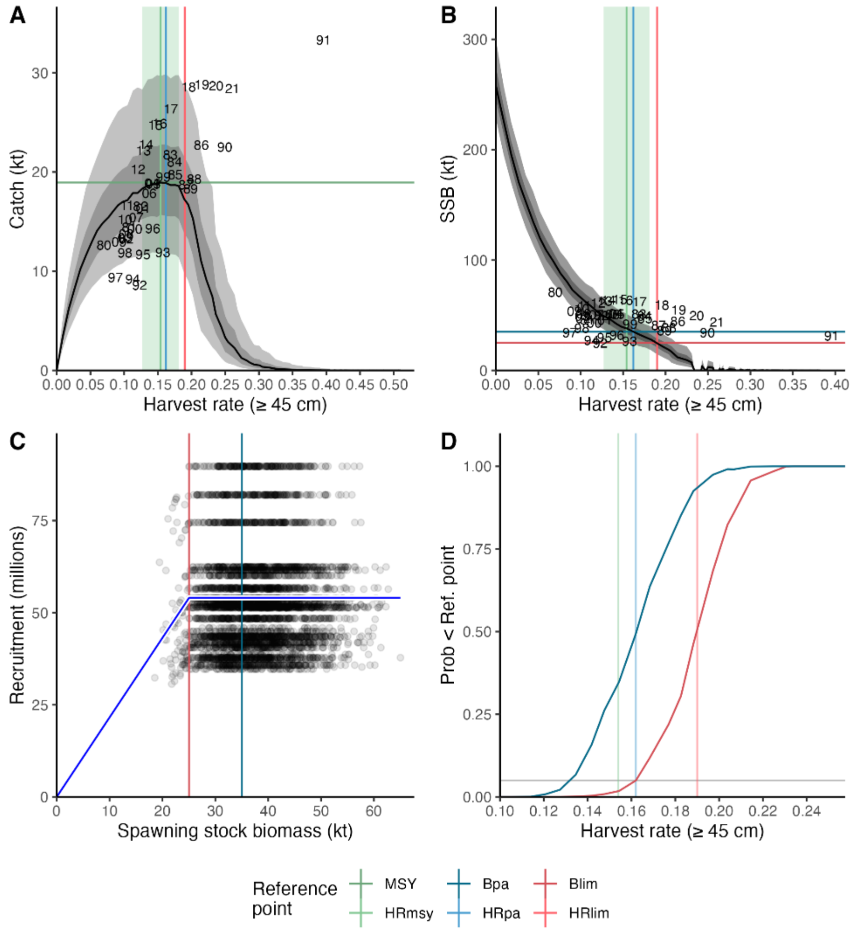

Figure 27: Simulation plot showing the reference points. A) Yield figure showing catch and harvest rates under constant effort in 50 to 100 years. Black line indicates the median, and dark and light grey shading 25/75% and 5/95% quantiles, respectively. Colored lines indicate the reference points (see the legend and table below). Green shading presents 95% uncertainty for HRmsy. Numbers indicate annual catches (y-axis) and model-estimated HR(>45cm) (x-axis) for modeled years. B) Simulated effect on spawning stock biomass (SSB) with a constant target harvest rate in 50 to 100 years. C) Recruitment related to SSB for simulations with targeted harvest rate (0.2) leading to MSY in 50 to 100 years. D) Probability of ending up with an SSB under the corresponding biomass reference point indicated by color (green = Blim, red = Bpa) given a constant target harvest rate in 50 to 100 years. Grey horizontal line indicates 0.05 probability tolerance for the precautionary approach and vertical lines the HR reference points. Simulations have been done using constant target harvest rates and x-axis values in A, B, and D represent realized harvest rates for >45 cm fish.

4.4 Short-term projections: advice simulation

Note that the numbers presented in this section are for comparison only and do not present actual advice. The harvest control rule for the species has to be set in the future. We run a simple forward simulation for three years using the long-term projection model described above with following assumptions:

- Equal catches to the last year of the hind-cast model for the assessment (intermediate) year.
- Catch proportions by fleet were fixed to the average of last three years.
- Constant recruitment using the model average between 1990 and 2017 (has no effect for three-years simulation).

The forward simulation was run using the model target harvest rate yielding MSY in long-term projections ($HR_{msy}^{target} = 0.2$), $HR^{target} = 0$, and last year's HR.

Summary figure for the advice reference sheet using outdated catches (2022 not included) is shown in Figure 28 and the code can be copied for the advice sheet once the model has been updated. Further work includes weighting the model using the updated Russian survey indices.

Figure 28: Summary figure for the advice reference sheet. From top left to bottom right: Catches included to the model with estimated MSY; Recruitment at age 1; Harvest rate for ≥ 45 cm fish with estimated HRmsy; and biomass of ≥ 45 cm fish (solid black line) and spawning stock (dashed black line) together with Bpa for SSB (solid horizontal blue line).

Basis for the short-term scenatios is shown in Table 9 and simulation advice tables populating automatically in Tables 10 and 11. It appears that the SSB will go below B_{pa} in 2023 (Figure 29).

Table 9: The basis for the catch scenarios table (Table 1 in the advice sheet).

Variable	Value	Notes
Harvest rate >= 45 cm (2022)	0.292	Based on expected catch (2022); for >= 45 cm
Biomass >= 45 cm (2022)	97.217	Beginning of 2022; kilotonnes
SSB (2022)	38.237	Beginning of 2022; kilotonnes. Bpa = 35.043

Recruitment (2022-2024)	50.825	Average 1990-2017 recruitment in millions. Does not influence short-term forecast
Expected catch (2022)	28.433	Based on catch in 2021; kilotonnes

Table 10: Annual catch scenarios for 2023 (Table 2a in the advice sheet). The advice basis using HRmsy and other two scenarios are listed in the first column. Columns there after: total allowable catch (TAC) in tonnes, harvest rate (HR) for >= 45 cm fish, spawning stock biomass (SSB) in tonnes (SSB < Bpa given using red letters), SSB change in percentages relative to 2022, and TAC change in percentages relative to the last advice in 2021 (19094 tonnes). Note this is an automatic advice table template, NOT a real advice table.

Basis	TAC	HR	SSB	SSB change	TAC change
ICES advice basis for 2023					
HRmsy = 0.2	17310	0.2	31982	-16	-9
Other scenarios for 2023					
HR = 0	0	0	38044	-1	-100
Catch2022	22557	0.261	30147	-21	18

Table 11: Annual catch scenarios for 2024 (Table 2a in the advice sheet). The advice basis using HRmsy and other two scenarios are listed in the first column. Columns there after: total allowable catch (TAC) in tonnes, harvest rate (HR) for >= 45 cm fish, spawning stock biomass (SSB) in tonnes (SSB < Bpa given using red letters), SSB change in percentages relative to 2022, and TAC change in percentages relative to the last advice in 2021 (19094 tonnes). Note this is an automatic advice table template, NOT a real advice table.

Basis	TAC	HR	SSB	SSB change	TAC change
ICES advice basis for 2024					
HRmsy = 0.2	17822	0.199	32292	-16	-7
Other scenarios for 2024					
HR = 0	0	0	44692	17	-100
Catch2022	22131	0.259	28994	-24	16

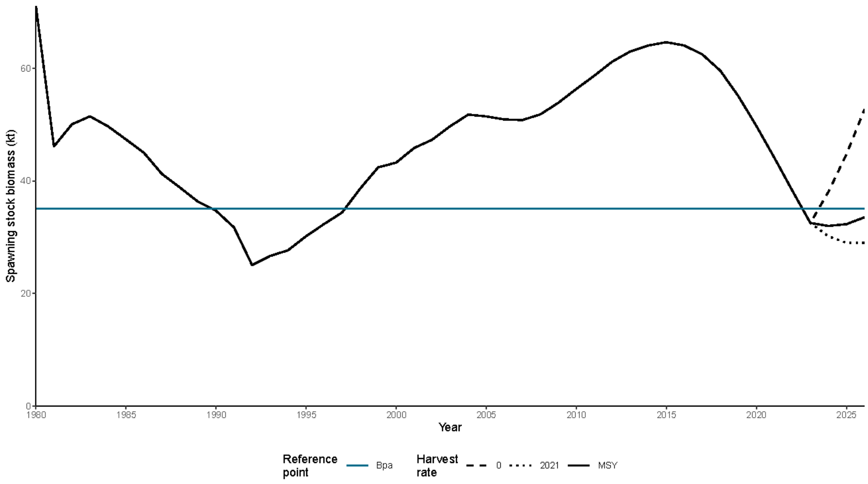

Figure 29: Spawning stock biomass following the three harvest rate scenarios indicated using line type. The biological reference point Bpa is indcated using a horizontal line.

5 References

Hurtado-Ferro, Felipe, Cody S. Szuwalski, Juan L. Valero, Sean C. Anderson, Curry J. Cunningham, Kelli F. Johnson, Roberto Licandeo, et al. 2015. "Looking in the Rear-View Mirror: Bias and Retrospective Patterns in Integrated, Age-Structured Stock Assessment Models." *ICES Journal of Marine Science* 72 (1): 99–110. https://doi.org/10.1093/icesjms/fsu198.

ICES. 2020. "Arctic Fisheries Working Group. ICES Scientific Reports 2:52." https://doi.org/10.17895/ices.pub.6050.

———. 2022. "ICES Fisheries Management Reference Points for Category 1 and 2 Stocks (2021)," June. https://doi.org/10.17895/ices.advice.7891.

6 Appendix A: model parameters

Table 12: All parameters used in the Gadget3 assessment model for Greenland halibut.

switch	value	optimise	lower	upper	parscale
retro__years	0.00	FALSE			
ghl.init.scalar	2.20	TRUE	1.00	100.00	99.00
ghl__female.M	0.12	FALSE	0.00	0.40	0.40
ghl.init.F	0.03	TRUE	0.00	0.80	0.80
ghl__female.mat__initial__alpha	0.42	FALSE	0.00	3.00	3.00
ghl__female.mat__initial__a50	14.52	FALSE	3.00	25.00	22.00
ghl__female.Linf	103.43	TRUE	80.00	120.00	40.00
ghl__female.K	64.22	TRUE	20.00	500.00	480.00
ghl.recl	14.00	FALSE	12.00	20.00	8.00
ghl__female__imm.init.sd.1	1.93	FALSE	0.00	20.00	20.00
ghl__female__imm.init.sd.2	2.02	FALSE	0.00	20.00	20.00
ghl__female__imm.init.sd.3	2.82	FALSE	0.00	20.00	20.00
ghl__female__imm.init.sd.4	3.34	FALSE	0.00	20.00	20.00
ghl__female__imm.init.sd.5	3.73	FALSE	0.00	20.00	20.00
ghl__female__imm.init.sd.6	4.01	FALSE	0.00	20.00	20.00
ghl__female__imm.init.sd.7	4.22	FALSE	0.00	20.00	20.00
ghl__female__imm.init.sd.8	4.37	FALSE	0.00	20.00	20.00
ghl__female__imm.init.sd.9	4.46	FALSE	0.00	20.00	20.00
ghl__female__imm.init.sd.10	4.51	FALSE	0.00	20.00	20.00
ghl__female__imm.init.sd.11	4.53	FALSE	0.00	20.00	20.00
ghl__female__imm.init.sd.12	4.52	FALSE	0.00	20.00	20.00
ghl__female__imm.init.sd.13	4.50	FALSE	0.00	20.00	20.00
ghl__female__imm.init.sd.14	4.47	FALSE	0.00	20.00	20.00
ghl__female__imm.init.sd.15	4.45	FALSE	0.00	20.00	20.00
ghl__female__imm.init.sd.16	4.43	FALSE	0.00	20.00	20.00
ghl__female__imm.init.sd.17	4.42	FALSE	0.00	20.00	20.00
ghl__female__imm.init.sd.18	4.43	FALSE	0.00	20.00	20.00
ghl__female__imm.init.sd.19	4.45	FALSE	0.00	20.00	20.00
ghl__female__imm.init.sd.20	4.49	FALSE	0.00	20.00	20.00
ghl__female__imm.init.sd.21	4.52	FALSE	0.00	20.00	20.00
ghl__female__imm.init.sd.22	4.55	FALSE	0.00	20.00	20.00
ghl__female__imm.init.sd.23	4.55	FALSE	0.00	20.00	20.00
ghl__female__imm.init.sd.24	4.53	FALSE	0.00	20.00	20.00
ghl__female__imm.init.sd.25	4.48	FALSE	0.00	20.00	20.00
ghl__female.walpha	0.00	FALSE	0.00	1.00	1.00
ghl__female.wbeta	3.41	FALSE	2.00	4.00	2.00
ghl__female__mat.init.sd.3	2.07	FALSE	0.00	20.00	20.00
ghl__female__mat.init.sd.4	3.35	FALSE	0.00	20.00	20.00
ghl__female__mat.init.sd.5	3.76	FALSE	0.00	20.00	20.00
ghl__female__mat.init.sd.6	4.07	FALSE	0.00	20.00	20.00
ghl__female__mat.init.sd.7	4.29	FALSE	0.00	20.00	20.00
ghl__female__mat.init.sd.8	4.43	FALSE	0.00	20.00	20.00
ghl__female__mat.init.sd.9	4.52	FALSE	0.00	20.00	20.00
ghl__female__mat.init.sd.10	4.57	FALSE	0.00	20.00	20.00
ghl__female__mat.init.sd.11	4.58	FALSE	0.00	20.00	20.00

ghl_female_mat.init.sd.12	4.57	FALSE	0.00	20.00	20.00
ghl_female_mat.init.sd.13	4.55	FALSE	0.00	20.00	20.00
ghl_female_mat.init.sd.14	4.54	FALSE	0.00	20.00	20.00
ghl_female_mat.init.sd.15	4.53	FALSE	0.00	20.00	20.00
ghl_female_mat.init.sd.16	4.53	FALSE	0.00	20.00	20.00
ghl_female_mat.init.sd.17	4.55	FALSE	0.00	20.00	20.00
ghl_female_mat.init.sd.18	4.57	FALSE	0.00	20.00	20.00
ghl_female_mat.init.sd.19	4.60	FALSE	0.00	20.00	20.00
ghl_female_mat.init.sd.20	4.62	FALSE	0.00	20.00	20.00
ghl_female_mat.init.sd.21	4.63	FALSE	0.00	20.00	20.00
ghl_female_mat.init.sd.22	4.61	FALSE	0.00	20.00	20.00
ghl_female_mat.init.sd.23	4.57	FALSE	0.00	20.00	20.00
ghl_female_mat.init.sd.24	4.50	FALSE	0.00	20.00	20.00
ghl_female_mat.init.sd.25	5.46	FALSE	0.00	20.00	20.00
ghl_male.M	0.16	FALSE	0.00	0.40	0.40
ghl_male.mat_initial_alpha	0.45	FALSE	0.00	3.00	3.00
ghl_male.mat_initial_a50	7.34	FALSE	3.00	25.00	22.00
ghl_male.Linf	68.00	FALSE	40.00	100.00	60.00
ghl_male.K	135.55	TRUE	20.00	500.00	480.00
ghl_male_imm.init.sd.1	1.46	FALSE	0.00	20.00	20.00
ghl_male_imm.init.sd.2	2.02	FALSE	0.00	20.00	20.00
ghl_male_imm.init.sd.3	2.93	FALSE	0.00	20.00	20.00
ghl_male_imm.init.sd.4	3.38	FALSE	0.00	20.00	20.00
ghl_male_imm.init.sd.5	3.63	FALSE	0.00	20.00	20.00
ghl_male_imm.init.sd.6	3.74	FALSE	0.00	20.00	20.00
ghl_male_imm.init.sd.7	3.77	FALSE	0.00	20.00	20.00
ghl_male_imm.init.sd.8	3.75	FALSE	0.00	20.00	20.00
ghl_male_imm.init.sd.9	3.70	FALSE	0.00	20.00	20.00
ghl_male_imm.init.sd.10	3.63	FALSE	0.00	20.00	20.00
ghl_male_imm.init.sd.11	3.54	FALSE	0.00	20.00	20.00
ghl_male_imm.init.sd.12	3.45	FALSE	0.00	20.00	20.00
ghl_male_imm.init.sd.13	3.35	FALSE	0.00	20.00	20.00
ghl_male_imm.init.sd.14	3.24	FALSE	0.00	20.00	20.00
ghl_male_imm.init.sd.15	3.14	FALSE	0.00	20.00	20.00
ghl_male_imm.init.sd.16	3.03	FALSE	0.00	20.00	20.00
ghl_male_imm.init.sd.17	2.91	FALSE	0.00	20.00	20.00
ghl_male_imm.init.sd.18	2.78	FALSE	0.00	20.00	20.00
ghl_male_imm.init.sd.19	2.64	FALSE	0.00	20.00	20.00
ghl_male_imm.init.sd.20	2.50	FALSE	0.00	20.00	20.00
ghl_male.walpha	0.00	FALSE	0.00	1.00	1.00
ghl_male.wbeta	3.09	FALSE	2.00	4.00	2.00
ghl_male_mat.init.sd.3	1.58	FALSE	0.00	20.00	20.00
ghl_male_mat.init.sd.4	3.38	FALSE	0.00	20.00	20.00
ghl_male_mat.init.sd.5	3.65	FALSE	0.00	20.00	20.00
ghl_male_mat.init.sd.6	3.78	FALSE	0.00	20.00	20.00
ghl_male_mat.init.sd.7	3.81	FALSE	0.00	20.00	20.00
ghl_male_mat.init.sd.8	3.79	FALSE	0.00	20.00	20.00
ghl_male_mat.init.sd.9	3.73	FALSE	0.00	20.00	20.00
ghl_male_mat.init.sd.10	3.65	FALSE	0.00	20.00	20.00
ghl_male_mat.init.sd.11	3.55	FALSE	0.00	20.00	20.00

ghl_male_mat.init.sd.12	3.45	FALSE	0.00	20.00	20.00
ghl_male_mat.init.sd.13	3.34	FALSE	0.00	20.00	20.00
ghl_male_mat.init.sd.14	3.23	FALSE	0.00	20.00	20.00
ghl_male_mat.init.sd.15	3.11	FALSE	0.00	20.00	20.00
ghl_male_mat.init.sd.16	2.99	FALSE	0.00	20.00	20.00
ghl_male_mat.init.sd.17	2.86	FALSE	0.00	20.00	20.00
ghl_male_mat.init.sd.18	2.72	FALSE	0.00	20.00	20.00
ghl_male_mat.init.sd.19	2.58	FALSE	0.00	20.00	20.00
ghl_male_mat.init.sd.20	2.44	FALSE	0.00	20.00	20.00
ghl_male_mat.init.sd.21	2.32	FALSE	0.00	20.00	20.00
ghl_male_mat.init.sd.22	2.19	FALSE	0.00	20.00	20.00
ghl_male_mat.init.sd.23	2.06	FALSE	0.00	20.00	20.00
ghl_male_mat.init.sd.24	1.95	FALSE	0.00	20.00	20.00
ghl_male_mat.init.sd.25	1.70	FALSE	0.00	20.00	20.00
ghl_female.ecos.survey.alpha	5.29	TRUE	0.10	20.00	19.90
ghl_female.ecos.survey.l50	5.15	TRUE	5.00	50.00	45.00
ghl_male.ecos.survey.alpha	6.13	TRUE	0.10	20.00	19.90
ghl_male.ecos.survey.l50	5.00	TRUE	5.00	50.00	45.00
ghl_female.eggan.survey.alpha	0.40	TRUE	0.10	20.00	19.90
ghl_female.eggan.survey.l50	40.49	TRUE	5.00	80.00	75.00
ghl_male.eggan.survey.alpha	0.44	TRUE	0.10	20.00	19.90
ghl_male.eggan.survey.l50	39.47	TRUE	5.00	80.00	75.00
ghl_female.eggas.survey.alpha	0.25	TRUE	0.10	20.00	19.90
ghl_female.eggas.survey.l50	46.13	TRUE	5.00	80.00	75.00
ghl_male.eggas.survey.alpha	0.29	TRUE	0.10	20.00	19.90
ghl_male.eggas.survey.l50	43.31	TRUE	5.00	80.00	75.00
ghl_female.trawlnor.alpha	0.21	TRUE	0.10	20.00	19.90
ghl_female.trawlnor.l50	47.62	TRUE	5.00	80.00	75.00
ghl_male.trawlnor.alpha	0.48	TRUE	0.10	20.00	19.90
ghl_male.trawlnor.l50	46.19	TRUE	5.00	80.00	75.00
ghl_female.othernor.alpha	0.26	TRUE	0.10	20.00	19.90
ghl_female.othernor.l50	61.46	TRUE	5.00	80.00	75.00
ghl_male.othernor.alpha	0.22	TRUE	0.10	20.00	19.90
ghl_male.othernor.l50	61.22	TRUE	5.00	80.00	75.00
ghl.russians.survey.alpha	0.43	TRUE	0.10	20.00	19.90
ghl.russians.survey.l50	39.97	TRUE	5.00	80.00	75.00
ghl_female.trawlrus.alpha	0.51	TRUE	0.10	20.00	19.90
ghl_female.trawlrus.l50	44.93	TRUE	5.00	80.00	75.00
ghl_male.trawlrus.alpha	0.51	TRUE	0.10	20.00	19.90
ghl_male.trawlrus.l50	44.85	TRUE	5.00	80.00	75.00
ghl.winters.survey.alpha	0.26	TRUE	0.10	20.00	19.90
ghl.winters.survey.l50	40.18	TRUE	5.00	80.00	75.00
ghl_female.bbin	6.40	TRUE	0.00	10.00	10.00
ghl_female.mat_alpha	125.55	TRUE	10.00	300.00	290.00
ghl_female.mat_l50	58.29	TRUE	46.00	76.67	30.67
ghl_male.bbin	9.99	TRUE	0.00	10.00	10.00
ghl_male.mat_alpha	115.24	TRUE	10.00	300.00	290.00
ghl_male.mat_l50	39.05	TRUE	32.72	54.54	21.81
ghl.rec.scalar	1.00	FALSE	1.00	100.00	99.00
ghl.rec.1980	0.00	FALSE	0.00	100.00	100.00

ghl.rec.1981	5725.70	TRUE	0.10	25000.00	24999.90
ghl.rec.1982	32.27	TRUE	0.10	25000.00	24999.90
ghl.rec.1983	3238.43	TRUE	0.10	25000.00	24999.90
ghl.rec.1984	928.87	TRUE	0.10	25000.00	24999.90
ghl.rec.1985	2114.68	TRUE	0.10	25000.00	24999.90
ghl.rec.1986	1861.22	TRUE	0.10	25000.00	24999.90
ghl.rec.1987	5249.02	TRUE	0.10	25000.00	24999.90
ghl.rec.1988	610.76	TRUE	0.10	25000.00	24999.90
ghl.rec.1989	4977.49	TRUE	0.10	25000.00	24999.90
ghl.rec.1990	2409.98	TRUE	0.10	25000.00	24999.90
ghl.rec.1991	1932.93	TRUE	0.10	25000.00	24999.90
ghl.rec.1992	2247.24	TRUE	0.10	25000.00	24999.90
ghl.rec.1993	2819.18	TRUE	0.10	25000.00	24999.90
ghl.rec.1994	3005.17	TRUE	0.10	25000.00	24999.90
ghl.rec.1995	2166.64	TRUE	0.10	25000.00	24999.90
ghl.rec.1996	1788.79	TRUE	0.10	25000.00	24999.90
ghl.rec.1997	2095.15	TRUE	0.10	25000.00	24999.90
ghl.rec.1998	2608.43	TRUE	0.10	25000.00	24999.90
ghl.rec.1999	2697.37	TRUE	0.10	25000.00	24999.90
ghl.rec.2000	2641.60	TRUE	0.10	25000.00	24999.90
ghl.rec.2001	2837.00	TRUE	0.10	25000.00	24999.90
ghl.rec.2002	3723.58	TRUE	0.10	25000.00	24999.90
ghl.rec.2003	4098.76	TRUE	0.10	25000.00	24999.90
ghl.rec.2004	4487.03	TRUE	0.10	25000.00	24999.90
ghl.rec.2005	3076.75	TRUE	0.10	25000.00	24999.90
ghl.rec.2006	3121.08	TRUE	0.10	25000.00	24999.90
ghl.rec.2007	2568.26	TRUE	0.10	25000.00	24999.90
ghl.rec.2008	2581.07	TRUE	0.10	25000.00	24999.90
ghl.rec.2009	2182.51	TRUE	0.10	25000.00	24999.90
ghl.rec.2010	2422.34	TRUE	0.10	25000.00	24999.90
ghl.rec.2011	1889.72	TRUE	0.10	25000.00	24999.90
ghl.rec.2012	2026.13	TRUE	0.10	25000.00	24999.90
ghl.rec.2013	1867.67	TRUE	0.10	25000.00	24999.90
ghl.rec.2014	2070.62	TRUE	0.10	25000.00	24999.90
ghl.rec.2015	1733.79	TRUE	0.10	25000.00	24999.90
ghl.rec.2016	2293.87	TRUE	0.10	25000.00	24999.90
ghl.rec.2017	1762.43	TRUE	0.10	25000.00	24999.90
ghl.rec.2018	11314.76	TRUE	0.10	25000.00	24999.90
ghl.rec.2019	2929.28	TRUE	0.10	25000.00	24999.90
ghl.rec.2020	1072.20	TRUE	0.10	25000.00	24999.90
ghl.rec.2021	1.00	FALSE	0.00	100.00	100.00
ghl.rec.sd	2.00	FALSE	1.00	8.00	7.00
adist_surveyindices_log_EcoS_SI_weight	25.47	FALSE			
adist_surveyindices_log_EggaN_SI_female_weight	80.00	FALSE			
adist_surveyindices_log_EggaN_SI_male_weight	120.00	FALSE			
adist_surveyindices_log_Juv_SI_1_weight	20.00	FALSE			
adist_surveyindices_log_Juv_SI_2_weight	20.00	FALSE			
adist_surveyindices_log_RussianS_SI_weight	5.18	FALSE			
cdist_sumofsquares_EcoS_ldist_weight	2382.30	FALSE			
cdist_sumofsquares_EcoS_sexdist_weight	10.00	FALSE			

cdist_sumofsquares_EggaN_aldist_female_weight	10430.10	FALSE
cdist_sumofsquares_EggaN_aldist_male_weight	6322.20	FALSE
cdist_sumofsquares_EggaN_ldist_weight	10000.00	FALSE
cdist_sumofsquares_EggaN_matp_weight	139.07	FALSE
cdist_sumofsquares_EggaS_ldist_weight	5880.35	FALSE
cdist_sumofsquares_EggaS_matp_weight	142.24	FALSE
cdist_sumofsquares_OtherNor_ldist_weight	9851.70	FALSE
cdist_sumofsquares_OtherNor_sexdist_weight	13.00	FALSE
cdist_sumofsquares_RussianS_ldist_weight	913.58	FALSE
cdist_sumofsquares_TrawlNor_ldist_weight	5724.30	FALSE
cdist_sumofsquares_TrawlNor_sexdist_weight	20.00	FALSE
cdist_sumofsquares_TrawlRus_ldist_weight	7196.40	FALSE
cdist_sumofsquares_TrawlRus_sexdist_weight	12.00	FALSE
cdist_sumofsquares_WinterS_ldist_weight	1718.90	FALSE
project_years	0.00	FALSE