Stock Annex: Beaked redfish (*Sebastes mentella*) in ICES subareas 6, 12, and 14 (Iceland and Faroes grounds, North of Azores, East of Greenland) and NAFO subareas 1 and 2 (deep pelagic stock > 500 m)

Stock specific documentation of standard assessment procedures used by ICES.

Stock: Beaked redfisj

Working Group: North-Western Working Group (NWWG)

Created:

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A. General

A.1. Stock definition

The deep pelagic beaked redfish (*Sebastes mentella*) stock is distributed mostly in pelagic habitats within NAFO divisions 1–2, and ICES Subareas 5, 12, 14 at depths >500 m, but it is also found in demersal habitats west of the Faroe Islands (ICES, 2010).

The Workshop on Redfish Stock Structure (WKREDS) reviewed the stock structure of beaked redfish in the Irminger Sea and adjacent waters (ICES, 2009a). For this, it used genetic information (i.e. microsatellite information), supported by analysis of allozymes, fatty acids and other biological information on stock structure, such as some parasite patterns. ICES Advisory Committee (ACOM) concluded, based on the outcome of the WKREDS meeting, that there are three biological stocks of the species in the Irminger Sea and adjacent waters:

- a **Deep Pelagic stock** (NAFO 1-2, ICES 5, 12, 14 >500 m)primarily pelagic habitats, and including demersal habitats west of the Faroe Islands;
- a **Shallow Pelagic stock** (NAFO 1-2, ICES 5, 12, 14 <500 m)extends to ICES 1 and 2, but primarily pelagic habitats, and includes demersal habitats east of the Faroe Islands;
- an **Icelandic Slope stock** (ICES 5.a, 14) primarily demersal habitats.

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 *S. mentella* in this region. WKREDS also suggested that the East-Greenland shelf is most likely a common nursery area for the three biological stocks they distinguished.

Based on this new stock identification information, ICES recommended in 2009 the use of three potential management units that are geographic proxies for the newly defined biological stocks, which are partly limited by depth and whose boundaries are based on the spatial distribution pattern of the fishery to minimize mixed-stock catches. Thus the newly described deep pelagic stock corresponds to the management unit in the northeast Irminger Sea: NAFO Areas 1 and 2, ICES areas 5.b, 12 and 14 at depths greater than 500 m, including demersal habitats west of the Faroe Islands.

The decision to classify pelagic redfish as two stocks rather than one stock was not unanimous among ACOM members. Russia's position regarding the structure of the redfish stock in the Irminger Sea and adjacent waters remains unchanged, i.e. that there is a single-stock of *S. mentella* in that area (ICES, 2011c).

A.2. Fishery

The fishery for deep pelagic redfish started in the early 1990s and grew quickly, with vessels from Iceland, Faroese, Germany, Norway, Portugal and Russia (Sigurðsson *et. al*, 2006). In 1995, 17 nations participated in the fishery, but nine of them retired soon or have participated occasionally.

In the period 1992-1996, the fishery gradually shifted from the traditional redfish fishing grounds towards greater depths, developing a clear seasonal spatial pattern. The fleets moved systematically to different areas and depths as the season progressed, fishing the deep component in the north-eastern Irminger Sea (north of 61°N and east of 32°W) during the first months of the fishing season, or from April to mid-June, and moving to the shallow fishing grounds later in the season. Fishing is scarce between November and late March or early April.

As more nations joined the fishery, annual landings increased quickly from 59 tonnes in 1991 to nearly 140,000 t in 1996, stabilizing at 85,000- 105,000 t during the period 1997-2004, when some countries ceased fishing (Figure A.2.1). From 2005 onwards, annual landings have declined, being in the range 23,00068,000 t. From 1997 onwards, logbook data from Russia, Iceland, Faroe Islands, Norway and Germany have been used to calculate landings by stock within each ICES Division. It is assumed that catches by other nations have the same spatial distribution. However, the figures for total catch are probably underestimated due to incomplete reporting of catches. A large percentage of annual landings (66% on average) were taken in ICES division 14 in 1991-2015.Total catches have fluctuated without trend between 23,000 and 70,000 t since 2005, and the percentages of catch taken in ICES division 14.b for these years are among the highest, reaching 86% in 2010 and being practically 100% in 2012 (Figure A.2.1.).

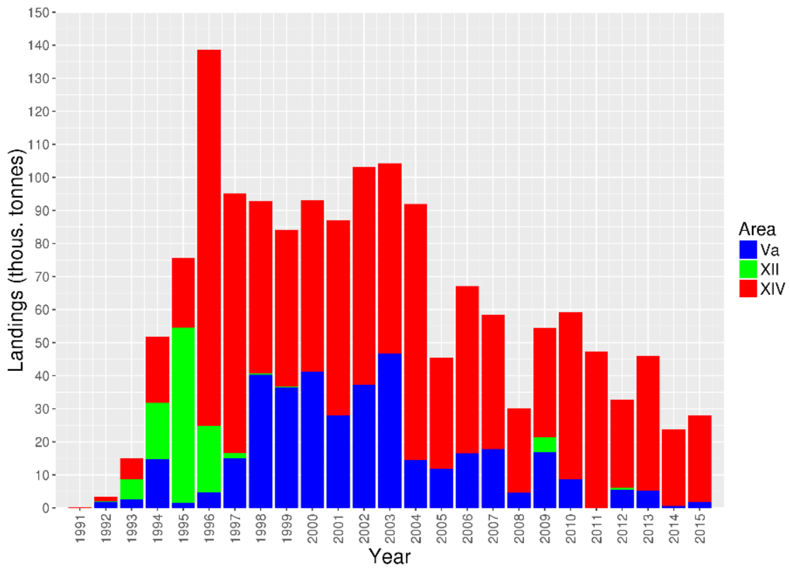

Figure A.2.1. Nominal landings of deep pelagic beaked redfish 19912015 by ICES areas.

The fleets participating in this fishery keep updating their fishing technology, and most trawlers now use large pelagic trawls ("Gloria"-type) with vertical openings of 80-150 m.

A.3. Ecosystem aspects

Beaked redfish is an ovoviviparous fish species, in which eggs are fertilized, develop and hatch internally. The male and female mate several months before the female extrudes the larvae. The females carry sperm and non-fecundated eggs for months before fertilization takes place in spring (Sorokin, 1961). Females are thought to have a determinate fecundity. Beaked redfish produce many small larvae that are extruded soon after they hatch from eggs and disperse widely as zooplankton. The extrusion of larvae may take place over several days or weeks in a number of batches. It occurs in large areas of the Irminger Sea during April and May, peaking in late April and early May (Noskov *et al*. 1984; Shibanov *et al*. 1984; Pavlov *et al*. 1989). The main area of extrusion is found south of 65°N and east of 32°W (Magnússon and Magnússon 1977; Magnússon 1980, Zakharov 1964, 1966; Shibanov *et al*. 1995). The location of the mating grounds is unknown, but mating adults are found in the slopes. Knowledge of the biology, behaviour and dynamics of redfish reproduction is very scarce (Magnusson and Magnusson, 1995).

The adults of the deep pelagic stock move northwards and are found in MayJuly close to and within the Icelandic EEZ and on the continental shelf of Iceland. The international fishing fleet targets this adult population, with the main fishing areas being both close to the Icelandic-Greenland EEZ's and within Icelandic waters.

The larvae are pelagic and drift northward in the surface layer and to the continental slope of West- and East-Greenland. The nursery areas are believed to be on the continental shelf of East-Greenland and to some extend of West-Greenland. It is unknown to what extend juveniles recruit to the different stocks.

Early life history stages are described in Magnusson and Magnusson (1995). Larvae drift to the continental shelf of East Greenland and to some extent to West Greenland, where they settle to the bottom. It is difficult to distinguish from the sibling species golden redfish (*S. norvegicus*), which occupies the same nursery areas.

Young redfish dwell at the bottom at different depths, the youngest ages preferring lesser depths than older fish. Juveniles are predominantly distributed on the continental shelf of West- and East Greenland. Adults are found in the open ocean.

Age of recruitment to the fishery of both stocks is believed to be near maturity, maybe between ages 812 years. The causes for variability of recruitment are unknown.

Little is known about the trophic interactions in the Irminger Sea. However, a study by Petursdottir et al. (2008) shows that Euphausiids (*M. norwegica*) and *Calanus spp.* appear to play an important role in the diet of beaked redfish in pelagic ecosystem on the Reykjanes ridge. Pedersen and Riget (1993) investigated stomach contents of beaked redfish in West Greenland waters and found planktonic crustaceans such as hyperiids, copepods and euphausiids to be the main food items in small redfish (5-19cm). Among shallow stock adults, the main food items are dominant plankton crustaceans such as amphipods, copepods and euphausids. Cephalopods (small squids), shrimp (*P. borealis*) and small fish (redfish included) are also important food items (Pedersen and Riget, 1993; Magnusson and Magnusson 1995).

There are indication that *Sebastes spp.* play an important role as a prey item for Greenland halibut (Orr and Bowering, 1997; Solmundsson, 2007) and adult harp and hooded seals during pelagic feeding (Haug *et al*., 2007; Tucker *et al*., 2009). The prey items in these studies were, however, not species-specific observations.

Research is needed to get a better understanding of the following issues:

- migrations and locations of the different life stages,
- recruitment success,
- determination of population age structure,
- species identification for young specimens,
- standardization of maturity determination,
- natural mortality.

There has already been some effort conducted to validate and harmonize the methodologies used for age determination at an international level (ICES, 2006, 2009b). This should be further pursued, since there are still non-standard methodologies used by some Russian teams which forbid data compilation at an international level.

A maturity scale has been agreed at an international level (ICES WKMSREGH, 2011, unpublished report), but it is necessary to carry out workshops to guarantee that this scale is well understood and used in a standardized fashion across nations and research laboratories.

Regarding the impact of the fishery on pelagic redfish in the Irminger Sea and adjacent waters, it is generally regarded as having negligible impact on the habitat and other fish or invertebrate species due to very low bycatch and discard rates, characteristic of fisheries using pelagic gear.

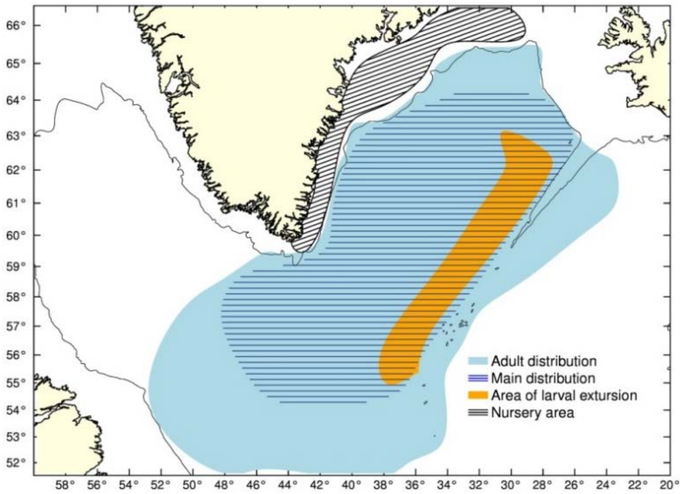

Figure A.3.1. Distribution of both pelagic redfish stocks (shallow and deep) in the Irminger Sea and adjacent waters at different stages of the life cycle.

A.4. Management

NEAFC is the responsible management body, and ICES the advisory body. Management of fisheries on pelagic redfish is based on setting total allowable catches (TAC) since 1996 and technical measures.

No harvest control rule exists for the stock and there has been no agreement on stock structure (see A.1) and the TAC and allocation key between contracting parties in NEAFC for several years. Some countries have set autonomous quotas. This has led to total annual catches far above the NEAFC TAC.

In March 2011, NEAFC agreed on interim measures for the deep pelagic beaked redfish fisheries until the end of 2014. These measures were agreed by all members of NEAFC except Russia. It is therefore expected that the total catch will exceed the TACs set by NEAFC. The objective of these measures is to gradually decrease the catches until they comply with the ICES advice, and to establish harvest control rule in the long term.

The following main measures were applied in 2011 and are still in force (see detailed agreement on http://www.neafc.org/system/files/postalvote_redfish_Irminger-sea_april2011.pdf):

1. The Contracting Parties are allocated the following quota shares of the established TACs for the period 2011 to 2014. These percentage shares are agreed on an *ad hoc* basis for the period 2011 to 2014 and do not prejudice quota allocation schemes for subsequent periods.

a.	Denmark, in respect of the Faroe Islands and Greenland	28.98 %
b.	European Union	15.45 %
c.	Iceland	31.02 %
d.	Norway	3.85 %
e.	Russian Federation	20.70 %

2. From 2011, each Party may transfer to the following year unutilized quantities of up to 5% of the quota allocated to that Party for the initial year. The quantity transferred shall be in addition to the quota allocated to the Party concerned

in the following year. This quantity cannot be transferred further to the quotas for subsequent years. No transfers may be made from unfished quantities of quotas established for 2010 or for any earlier fishing seasons.

3. Each Party may authorize fishing by its vessels of up to 5% beyond the quota allocated to that Party in any one year. All quantities fished beyond the allocated quota for one year shall be deducted from that Party's quota allocated for the following year.

4. The fisheries shall not commence prior to 10 May each year to enhance the protection of areas of larval extrusion.

5. Catches in the deep pelagic fishery in the Irminger Sea and adjacent waters referred to in paragraph 1 shall be conducted from 2011 to 2014 within an area bounded by the lines joining the following coordinates (Area 1 in Figure A.4.1):

Point no.	Latitude	Longitude
1	64° 45' N	28° 30' W
2	62° 50' N	25° 45' W
3	61° 55' N	26° 45' W
4	61° 00' N	26° 30' W
5	59° 00' N	30° 00' W
6	59° 00' N	34° 00' W
7	61° 30' N	34° 00' W
8	62° 50' N	36° 00' W
9	64° 45' N	28° 30' W

6. The minimum mesh size of the trawl is 100 mm.

7. Finally, NEAFC will seek to establish a long-term management plan for redfish in the Irminger Sea and adjacent waters during the period of implementation of these interim management measures. This includes appropriate harvest control rule.

   The objective of any such management plan shall be to establish such levels of catches and fishing effort, which will result in the sustainable exploitation of pelagic redfish in the Irminger Sea and adjacent waters. This long-term management plan should take due account of the interim management measures as set out in this recommendation.

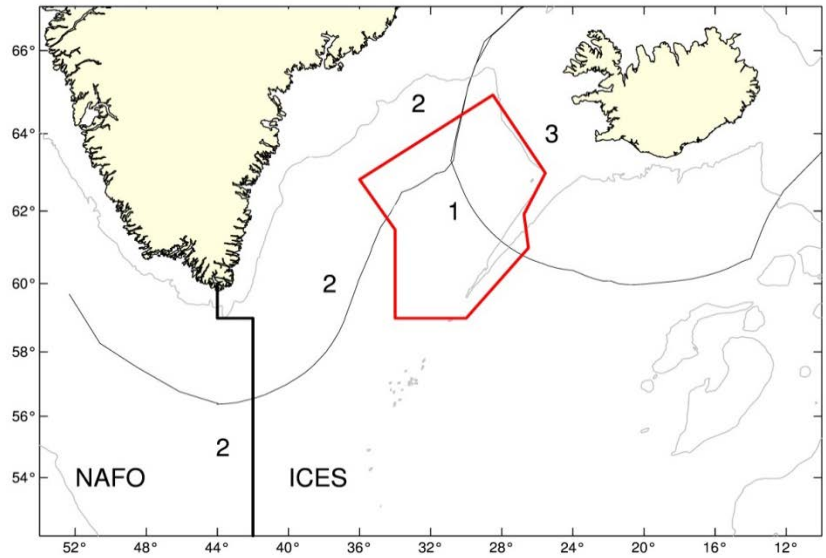

Figure A.4.1. Management unit boundaries for beaked redfish (*S. mentella*) in the Irminger Sea and adjacent waters. The polygon bounded by red lines, i.e. 1, indicates the region of the deep-pelagic management unit in the northwest Irminger Sea, 2 is the shallow-pelagic management unit in the Irminger Sea and adjacent waters including within the NAFO Convention areas, and 3 is the Icelandic slope management unit which is within the Icelandic EEZ.

B. Data

B.1. Commercial catch

Iceland, Greenland, Faroe Islands, Norway, Germany and Russia are the nations providing the most complete databases, including detailed vessel and gear information, as well as catch data on a haul by haul basis. The rest of the countries supply catch in weight and the length composition of the catch.

The preliminary official landings data are provided to the ICES North-Western Working Group (NWWG) by the ICES Secretariat, NEAFC and NAFO, and various national data are reported to the Group. The Group faced problems in obtaining reliable data in 2002–2007 due to unreported catches of pelagic redfish. There are indications that reported effort (and consequently landings) could represent only around 80% of the real effort in certain years (see Chapter 19.3.3 in the 2008 NWWG report). No new data in IUU have been available since 2008.

Splitting of catches: In the period 1992-1996, the redfish fishery gradually shifted towards greater depths and developed a clear seasonal spatial pattern. The fleets fished first the deep stock and moved to the southwestern Irminger Sea (south of 60°N and west of about 32°W) from mid-June to October, to fish the shallow stock. Landings from these years have been assigned to the different biological stocks according to several criteria, such as landings by ICES statistical areas, ICES divisions, by nation, and logbook data. When a nation lacked data, the average from the other nations was used instead. Landings data disaggregated by biological stock from this period are considered to be the most unreliable and must be regarded as the WG’s best estimates (guesstimates). This task was carried out according to the NWWG meeting celebrated in 2004, Bergen (ICES, 2004).

B.2. Biological

Biological information is collected from commercial catches (Iceland, Russia, Spain and other EU countries). For Iceland and Spain, the data consist of length measurements, weight, sex, maturity stage, and otolith collection. Otoliths have not been age read.

B.3. Surveys

The surveys provide valuable information on the biology, distribution and relative abundance of oceanic redfish, as well as on the oceanographic conditions of the surveyed area. Until 1999, oceanic redfish was only surveyed by acoustics down to an approximate depth of 500 m. Attempts to obtain reliable stock size estimates and map the stock distribution below that depth did not succeed (Shibanov *et al*., 1996; ICES, 1998; Sigurðsson and Reynisson, 1998), mostly due to the "deep scattering layer" (DSL), which is a mixture of many vertebrate and invertebrate species mixed with redfish (Magnússon, 1996). However, since the fishery had moved towards greater depths it was very important to expand the vertical coverage of the survey. The 1999 survey provided for the first time an estimate of the abundance of the deep pelagic *S. mentella* deeper than 500 m depth, showing that the highest concentrations of redfish below 500 m. were associated with eddies and fronts.

Since 1999, an international trawl-acoustic survey has been conducted biennially by Iceland, Germany and Russia (with Norway participating in 2001) with two to five research vessels (ICES 2002, 2003, 2005, 2007b, 2009c, 2011b; 2013; 2015; Sigurdsson et. al 1999). In this survey, the deep pelagic beaked redfish stock is measured with the so-called "trawl method". The surveys in 2005 and 2007 are not comparable with the other surveys due to changes in the depth range covered in 2005 and 2007. Attempts were made to get an approximate biomass estimate of the deep pelagic stock in 2005 and 2007 (ICES 2014).

The Working Group on International Deep Pelagic Ecosystem Surveys (WGIDEEPS, formerly as WGRS, SGRS and then PGRS) has organized and planned these international surveys since 1999, and distributed survey area and time among the participants.

Table 1. Deep pelagic redfish surveys carried out in the Irminger Sea and adjacent waters. Th. NM2; thousand square nautical miles surveyed, Depth: depth stratum reached during survey, above or below 500 m depth, Country: GER=Germany, ICE=Iceland, NOR=Norway, RUS=Russia.

Year	Country	# of vessles	Th. NM2	Depth	Ref
1999	GER/ICE/ RUS	3	296	> 500	Sigurðsson et al., 1999
2001	GER/ICE/RUS/NOR	5	420	> 500	ICES, 2002
2003	GER/ICE/ RUS	3	405	> 500	ICES, 2003
2005	GER/ICE/RUS	3	386	>350	ICES 2005
2007	ICE/ RUS	2	349	>350	ICES 2007b
2009	GER/ICE	2	360	> 500	ICES 2009c
2011	GER/ICE/ RUS	3	343	> 500	ICES 2011b
2013	GER/ICE/ RUS	3	341	> 500	ICES 2013b
2015	GER/ICE	2	201	> 500	ICES 2015

Technical description

The technical details and description of the equipment used are described in (ICES, 2015). Here a brief summary of the sampling methodology of the surveys 1999-2015 is given.

Acoustics

In the 2015 survey, 38 kHz Simrad EK60 split-beam echosounder was used for the acoustic data collection on RV "Árni Friðriksson" RV "Walther Herwig III". The settings of the acoustic equipment used during the survey are given in Table 2 in ICES (2015). During the survey on board of the Icelandic and German vessels the post-processing system (EchoView V5.3) was used for scrutinising the echograms. Mean integration values of redfish per 5 NM were used for the calculations.

The integration threshold of 80-84 dB/m^3 was used. A length based target

$$TS = 20\log L - 71.3 \text{ dB}$$

has been used for the estimation of the number of pelagic redfish in the survey area.

Earlier investigations (Magnússon *et al.*, 1994; Magnússon *et al.*, 1996; Reynisson and Sigurðsson, 1996) have shown that the acoustic values obtained from oceanic redfish exhibit a clear diurnal variation, due to a different degree of mixing with smaller scatter and to changes in target strength. In order to compensate for these effects, the acoustic data obtained when mixing is most pronounced (i.e. during the darkest hours of the night), are discarded and the values within the missing sections are estimated by interpolation.

In further data processing, the number of fish was calculated for statistical rectangles, the size of which was 1 degree in latitude and 2 degrees in longitude. Changes in the length range of redfish in the past acoustic surveys are taken into account by changing the length-based target strength formula accordingly (Reynisson, 1992; ICES, 2011a for details).

The total number of fish within the subareas A-F in which the survey area is divided (Figure B.3.1) is then obtained by summation of the individual rectangles. The acoustic results were further divided into the number of individuals, and biomass based on the biological samples representative for each subarea.

For the entire survey area, single-fish echoes from redfish are expected to be detectable down to 350 m. In order to include all echoes of interest, a low integration threshold is chosen (i.e. -80 dB//m^3 for the 2011 survey). Based on the depth distribution of redfish observed during the survey and the expected target strength distribution, the method outlined by Reynisson (1996) is used to estimate the expected bias due to thresholding. The results of the biomass calculations were adjusted accordingly.

The measurements of echosounders can be disturbed by noise (from the ambient and the vessel) and reverberation (echoes reflected from unwanted targets). Because the amplitude of the signal decreases with depth whereas the amplitude of noise increases due to time varied gain, very small noise can prevent the measurements. Thus, to improve the signal to noise ratio, a threshold is usually applied (Bethke, 2004).

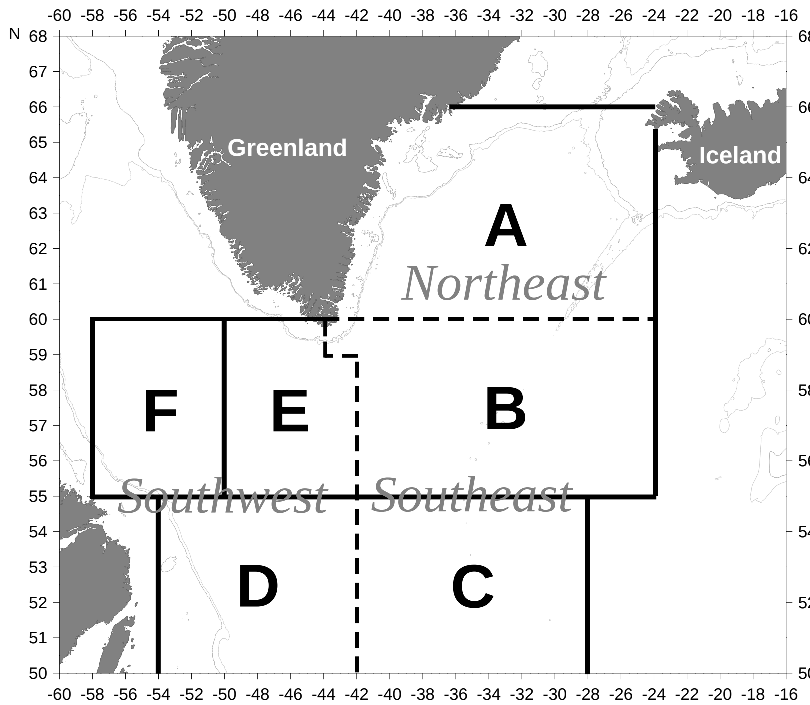

Figure B.3.1. Sub-areas A-F used on international surveys for redfish in the Irminger Sea and adjacent waters, and divisions for biological data (Northeast, Southwest and Southeast; boundaries marked by broken lines).

When the redfish appears mixed with other deep-sea species, or the weather is bad and disturbs the measurements, echo counting is preferred over echo integration, as described in Bethke (2004). The counting procedure is based on the fact that fish are recognized as single targets according to the parameter settings of the echosounder. However, if redfish is found in dense aggregations, echo integration is more accurate. Switching between methods may be necessary during the survey (ICES, 2011a).

Trawling

The classic method of continuous echo integration deeper than 350 m (within and deeper than DSL) is applicable only under very specific conditions. The need for the vertical expansion of the survey led to the use of the trawl method since 1999. This method is based on a combination of standardized survey catches and the acoustic data, where the correlation between catch and acoustic values during trawling in the layer shallower than the DSL is used to obtain acoustic values for the deeper layer. There are three types of trawling depths (ICES, 2015):

1. The depth zones shallower than the DSL, in which redfish could be acoustically identified. Trawling distance is 4 NM.
2. The depth shallower than 500 m depth, where acoustic redfish registration is hampered by the DSL: from the top of the DSL down to 450m. Trawling distance is 2 NM in each depth layer.
3. The depth zones deeper than 500 m depth, trawling at different depth layers. The deep identification covered the following three depth layers: 550 m, 700 m, 850 m. Trawling distance at each depth layer was 2 nautical miles.

In the 2005 and the 2007 surveys (ICES, 2005, 2007b) trawling was carried out within the depth range 350–950 m, i.e. within and deeper than the DSL. Thus, the abundance estimates by the trawl method are not comparable with the other years, as both stocks were sampled simultaneously.

The net used on RV "Árni Friðriksson" and RV "Walther Herwig III" was a Gloria type #1024, with a vertical opening of approximately 50 m. The net used on RV "Vilnyus" was a Russian pelagic trawl (design 75/448) with a circumference of 448 m and a vertical opening of 47-50 m. Russia used a mesh opening of 40 mm in the codend, while Iceland and Germany used a mesh opening of 23 mm in the codend. The trawls used on RV "Árni Friðriksson" and RV "Walther Herwig III" were fitted with a multiple codend sampling device: the 'multisampler' (Engås *et al.*, 1997). This allowed for successive sampling at three distinct depth zones within one trawl haul and without 'contamination' from one depth to the next, as well as no sampling during shooting or heaving of the trawl. The catches were standardized by 1 NM and converted into acoustic values using a linear regression model between catches and acoustic values at depths shallower than the DSL.

A linear regression model between the acoustic values and catches (in kg/NM) of type 1 trawls (shallower than the DSL) was applied to predict the acoustic values (SA) for trawls type 2 and 3. The obtained sA values were then adjusted for the vertical coverage of the trawls and the depth range of each haul (ΔD/Htr; where ΔD is the difference between maximum and minimum depth of each haul, and Htr is the vertical opening during each tow). The S_A value for each trawl ($S_A$tr) is:

$$\mathrm{SAtr} = C * K * K_H$$

where C is the catch in kg per NM of each type 2 and 3 trawl, K is the coefficient of the trawl obtained from the linear regression of type 1 trawls for each vessel and KH is the width of the depth range towed defined as:

$$K_H = (H_{MAX} - H_{MIN} + \mathrm{d}H_{TR}) / \mathrm{d}H_{TR}$$

where H_{MAX} and H_{MIN} of the headline of the trawl during the tow and $\mathrm{d}H_{TR}$ is mean vertical opening of the trawl.

Based on the regressions, confidence limits for the estimates are also calculated. After having calculated the S_A values from the catches of each haul, the estimation of the abundance and biomass was calculated using the same target strength equation for redfish (20logL – 71.3 dB) and the same algorithm as used for the acoustic estimation. The area coverage was considered to be the same as for the acoustic results and applied to all subareas.

Inclusion of the 2005 and 2007 surveys

In the 2005 and the 2007 surveys (ICES, 2005, 2007b) trawling was carried out within the depth range 350–950 m, i.e. within and deeper than the DSL. Thus, the abundance estimates by the trawl method are not comparable with the other years, as both stocks were sampled simultaneously. To get an approximate biomass estimate of the deep pelagic stock in 2005 and 2007 the following was done (detailed description is found in ICES 2014):

- Biomass indices are calculated after each survey for six areas shown in Figure B.3.1) for both T3 tows (deep pelagic stock) and T2 tows (shallow pelagic stock).
- For the surveys conducted in 2001, 2009, 2011, and 2013 biomass estimates from the T2 and T3 tows were combined to get a total biomass estimates from

350-950 m depths and are similar estimates as were done in 2005 and 2007. No T2 tows in the 1999 and 2003 were taken.

- For each subarea and year a proportion of the deep pelagic stock of the total biomass was calculated. Then, for each area a mean was calculated.
- The mean for each subarea was finally multiplied with the 2005 and 2007 estimates.
- This gives estimates of 392 and 522 thousand tonnes for 2005 and 2007 respectively.

Biological sampling

Catch weight and number of all species are be recorded for each haul. The individual biological sampling of deep-water redfish is as follows (taken from ICES (2011a)):

1. The total length (cm below), individual weight, sex and maturity stage are measured on at least 300 redfish from each haul type.
2. Otolith sampling is carried out at each station. Sampling is conducted on 50 individuals following a random sampling procedure (i.e. not stratified by length).
3. Observations on the stomach fullness, the location and size of skin/muscular pigments as well as infestation with *Sphyrion lumpi* and its remnants are investigated on at least 50 randomly sampled fish (usually collected on individual fish from which otoliths are sampled).

B.4. Commercial cpue

It is not known to what extent the cpue reflects changes in the stock status of pelagic *S. mentella*. Since the fishery focuses on aggregations, the cpue series might not indicate or reflect actual trends in stock size.

B.5. Other relevant data

C. Historical Stock Development

Deep pelagic beaked redfish in the Irminger Sea and adjacent waters has previously been assessed based on trends in survey biomass indices from the international redfish survey about the ICES “trends based assessment” approach. Supplementary data used includes relevant information from the fishery and length distributions from the commercial catch and the international redfish survey.

C.1. Description of GADGET

Gadget is a shorthand for the "Globally applicable Area Dis-aggregated General Ecosys-tem Toolbox", which is a statistical model of marine ecosystems. Gadget is an age-length structured forward-simulation model, coupled with an extensive set of data comparison and optimization routines for model fitting. Processes are generally modelled as dependent on length, but age is tracked in the models, and data can be compared on either a length and/or age scale. The model is designed as a multi-area, multifleet, multistock model, capable of including predation and mixed fisheries issues, however it can also be used on a single species basis. Gadget models can be both very data- and computationally- intensive, with optimization in particular taking a large amount of time. Worked examples, a detailed manual and further information on Gadget can be found on www.hafro.is/gadget. In addition the structure of the model is described in Stefánsson and Pálsson (1997) and Begley and Howell (2004), and a formal mathematical description is given in Frøysa *et al*. (2002).

Gadget is a forward simulation model and is structured around both age and length. It therefore requires direct modelling of growth within the model. The plus groups (in both age and length) should be chosen to be large enough that they contain few fish, and the exact choice of plus group does not have a significant impact on the model.

C.1.1. Setup of a gadget run

There is a separation of model and data within Gadget. The simulation model runs with defined functional forms and parameter values, and produces a modelled population, with model-predicted surveys and catches. These surveys and catches are compared against the available data to produce a weighted likelihood score. Optimization routines then attempt to find the best set of parameter values (Figure C.1).

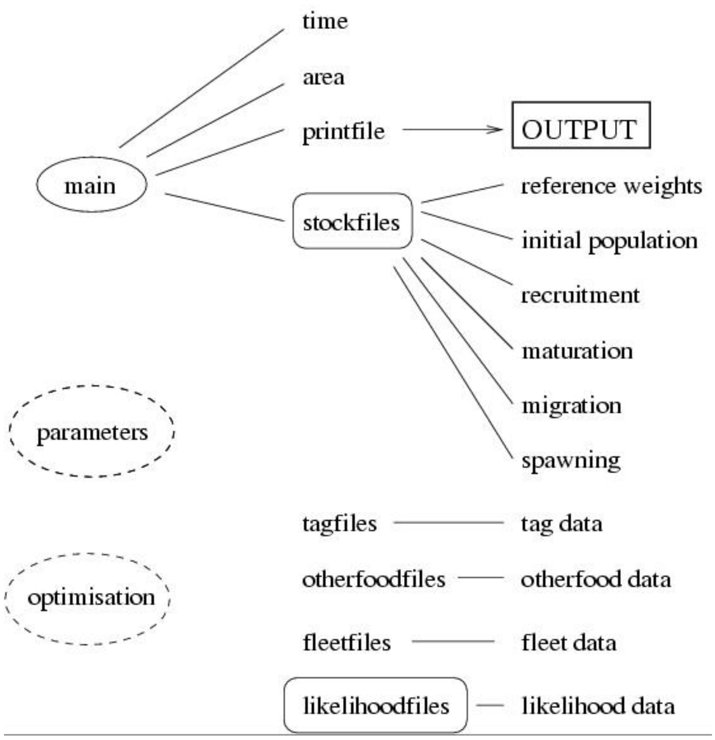

Figure C.1: Schematic description of a Gadget model

C.1.2. Simulation model

In a typical Gadget model the simulated quantity is the number of individuals, N_{alyt} at age a, in length-group l, at the start of time-step t within year y. The length of the time-step is denoted Δt. For deep pelagic redfish age classes are $a = 5 \ldots 39, 40+$, length l ranges between 10 and 50+ cm in 1 cm length-groups, and t represents the 4 quarters of the year. The population is governed by the following equations:

$$
\begin{aligned}
N_{aly,t+1} &= \sum_{l'} G_{l'}^{l}\left[(N_{al'yt} - \sum_{f} C_{fal't})e^{-M_a \Delta t}\right] && if\ t < 4 \\
N_{a,l,y+1,1} &= \sum_{l'} G_{l'}^{l}\left[(N_{a-1,l'y,4} - \sum_{f} C_{f,a-1,l',4})e^{-M_{a-1}\Delta t}\right] && if\ t = 4\ and\ 6 < a < 40 \\
N_{al,y+1,1} &= \sum_{l'} G_{l'}^{l}(N_{al'y,4} - \sum_{f} C_{fal'y,4} + N_{a-1,l'y,4} - \sum_{f} C_{f,a-1,l'y,4})e^{-M_a \Delta t} && if\ t = 4\ and\ a = 40
\end{aligned}
\tag{1}
$$

where $G_{l'}{}^{l}$ is the proportion in lengthgroup l' that has grown l-l' length groups during the time interval Δt, C_{falyt} denotes the catches by fleet f (i.e. survey and commercial fleets[1]) and M_a the natural mortality-at-age a.

C.1.2.1. Growth

Growth in length is modelled as a two–stage process, an average increase in length during the time interval Δt and a growth dispersion around the mean increase (as described in Stefansson 2005). The average increase in length is modelled by calculating the mean growth for each length group for each time-step, using a parametric growth function. In the current model a simplified form of the Von Bertanlanffy function has been employed to calculate this mean length increase starting from length l:

$$\Delta l = (l_{\infty} - l)(1 - e^{-k\Delta t}) \tag{2}$$

where l_{∞} is the terminal length and k is the annual growth rate.

The length distributions are updated according to the calculated mean growth by allowing some portion of the fish to have no growth, a proportion to grow by one length group, a proportion two length groups etc. How these proportions are selected affects the spread of the length distributions but these two equations must be satisfied:

$$\sum_{i} p_{il} = 1$$

and

$$\sum_{i} i p_{il} = \Delta l$$

Here Δl is the calculated mean growth given in equation (2) and p_{il} is the proportion of fish in length group l growing i length groups. The growth is dispersed according to a beta–binomial distribution resulting in the following equation for the proportion of fish growing from length group l to length group l':

$$G_{l}^{l'} = \frac{\Gamma(n+1)}{\Gamma((l'-l)+1)} \frac{\Gamma((l'-l)+\alpha)\Gamma(n-(l'-l)+\beta)}{\Gamma(n-(l'-l)+1)\Gamma(n+\alpha+\beta)} \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)} \tag{3}$$

where α is subject to

$$\alpha = \frac{\beta \Delta l}{n - \Delta l} \qquad (4)$$

where n denotes the maximum number of length groups that a fish may growth during a time interval Δt.

C.1.2.2. Recruitment and initial abundance

Gadget allows for a number of relationships between stock recruitment and the size of the spawning stock to be defined. However, in the model for deep pelagic redfish the number of recruits each year, R_y is estimated directly from the data as part of the stock assessment and without using an SSB-Recruitment relationship.

Recruitment enters the population at age 5 in the end of the first time-step according to:

$$N_{5ly1} = R_y p_l \qquad (5)$$

where p_l is the proportion of recruits in length-group l (determined by a normal density with mean L_0 and variance σ_0^2).

A simple formulation of the population abundance in numbers in the initial year of the assessment is used:

$$N_{al11} = \nu_a q_{la} \qquad (6)$$

where ν_a is the abundance at age a and q_{la} the proportion of age a fish in length group l, which is determined by a normal density function with mean according to the growth model in equation (2) taking into account the mean length at recruitment L_0, and with variance σ_a^2. The initial population enters the model at the beginning of the first time-step

C.1.2.3. Fleet operation

Catches are simulated based on reported total landings and a length based suitability function for each of the fleets (commercial fleets and surveys). Total catches by fleet in biomass are assumed to be known exactly and the total-stock biomass is simply offset by those catches. The catches for age group a, length group l, fleet f at year y and time-step t are calculated as:

$$C_{falyt} = E_{ft} \frac{S_f(l) N_{alyt} W_l}{\sum_{a'} \sum_{l'} S_f(l') N_{a'l'yt} W_{l'}} \qquad (7)$$

where E_{fyt} is the landed biomass (assumed to be known by time-step, survey given a nominal catch of 1 kg at the time of survey) and $S_f(l)$ the suitability of length group l for fleet f (either survey or commercial) defined as:

$$S_f(l) = \frac{1}{1+e^{-b_f(l-l_{50,f})}} \qquad (8)$$

The weight at length group l is calculated according to the following length – weight relationship:

$$W_l = \mu\, l^{\omega} \qquad (9)$$

C.1.3. Observation model

A significant advantage of using an age-length structured model is that the modelled output can be compared directly against a wide variety of different data sources. It is not necessary to convert length into age data before comparisons. Gadget can use various types of data that can be included in the objective function. Length distributions, age length keys, survey indices by length or age, cpue data, mean length and/or weight at age, tagging data and stomach content data can all be used.

Importantly this ability to handle length data directly means that the model can be used for stocks where age data are sparse, as is the case with the deep pelagic beaked redfish. Length data can be used directly for model comparison. The model is able to combine a wide selection of the available data by using a maximum likelihood approach to find the best fit to a weighted sum of the datasets.

In Gadget, data are assimilated using a weighted log–likelihood function. Typically three types of data enter the likelihood, length based survey indices, length distributions from survey and commercial fleets and age – length distribution from the survey and commercial fleets. Additionally other types of data, and other likelihood functions, could be used, see Begley (2005) for further details.

C.1.3.1. Survey indices

For the deep pelagic beaked redfish an acoustic survey has been conducted, biennially, in the Irminger Sea. The acoustic survey produces an absolute biomass number for the stock and is assimilated to the likelihood using the following formulation:

$$l^{SI} = \sum_y \left(\log(I_y) - \log(\widehat{B_y}) - \alpha\right)^2 \qquad (10)$$

where I is the biomass index and

$$\widehat{B_y} = \widehat{\sum_{l=30}^{50} \sum_a \mu\, l^{\omega}\, N_{aly2}}$$

i.e. the modelled biomass for all ages, between lengths 30 to 50 cm in time-step 2 in year y.

C.1.3.2. Fleet data

Length distributions are compared to predictions using

$$l_f^{LD} = \sum_y \sum_t \sum_l ({}^L\pi_{lyt} - {}^L\hat{\pi}_{lyt})^2 \qquad (11)$$

where

$$\pi_{lyt} = \frac{\sum_a O_{alyt}}{\sum_a \sum_{l'} O_{alyt}}$$

and

$$\hat{\pi}_{lyt} = \frac{\sum_a N_{alyt}}{\sum_a \sum_{l'} N_{alyt}}$$

i.e the observed and modelled proportions in lengthgroup l respectively at year y and time-step t. Similarly age – length data are compared using 1 cm length groups:

$$l_f^{AL} = \sum_y \sum_t \sum_a \sum_l (\pi_{falyt} - \hat{\pi}_{falyt})^2 \qquad (12)$$

where

$$\pi_{alyt} = \frac{O_{alyt}}{\sum_a \sum_{l'} O_{alyt}}$$

and

$$\hat{\pi}_{alyt} = \frac{N_{alyt}}{\sum_a \sum_{l'} N_{alyt}}$$

C.1.3.3. Penalty functions

A penalty weight is given to parameters that have moved beyond the bounds, as specified in the parameter file. If a value exceeds the bounds a penalty of the following form is given:

$$B = 1000 * (1_{]u,\infty[}(x)(x-u)^2 + 1_{]\infty,l[}(x)(x-l)^2) \qquad (13)$$

Where x denotes the parameter value, u the upper bound, l the lower bound and $1_{]a,b[}$ is the indicator function for the statement $x \in]a,b[$.

An additional penalty, the understocking likelihood, is applied if there are an insufficient number of a particular prey to meet the requirements of the predators. In the case of a fleet, this means that the landings data indicates that more fish have been landed than there are fish in the model, for that time-step. A well-defined model will have a zero likelihood score from this component. The likelihood component that is used is the sum of squares of the overconsumption, given by the equation below:

$$\boldsymbol{U} = \sum_y \sum_t \boldsymbol{D_{yt}}^2 \tag{14}$$

where$D_{yt} = \sum_a \sum_l 1_{]\infty,0[}(N_{alyt} - C_{alyt})(C_{alyt} - N_{alyt})$, i.e. the amount of fish that is "over-consumed".

C.1.3.4. Iterative re-weighting

The total objective function used in the model fitting process combines equations 10 to 14 using the following formula:

$$l^T = w^{SI} l^{SI} + \sum_{f \in \{S,C\}} \left(w_f^{LD} l_f^{LD} + w_f^{AL} l_f^{AL} \right) + 100U + B/2 \tag{15}$$

where *f* denotes the fleet, either survey (*S*) or commercial (*C*), and *w*'s are the weights assigned to each likelihood components.

The weights, w_i, are necessary for several reasons. First of all they are used to prevent some components from dominating the likelihood function. Another would be to reduce the effect of low quality data. It can be used as an a priori estimates of the variance in each subset of the data.

Assigning likelihood weights is not a trivial matter. Often this is done using some form of 'expert judgement'. For Gadget models the so called iterative re–weighting heuristic, introduced by Stefansson (2003), and subsequently implemented in Taylor *et al*. (2007), has become standard practice.

The general idea behind the iterative re-weighing is to assign the inverse variance of the fitted residuals as component weights. The variances, and hence the final weights, are calculated according the following algorithm:

1. Calculate the initial sums of squares (SS) given the initial parameterization for all likelihood components. Assign the inverse SS as the initial weight for all likelihood components.
2. For each likelihood component, do an optimization run with the initial SS for that component set to 10000. Then estimate the residual variance using the resulting SS of that component divided by the degrees of freedom (df^*), i.e. $\hat{\sigma}^2 = \frac{SS}{df^*}$.
3. After the optimization set the final weight for each component as the inverse of the estimated variance from the step above (weight $= 1/\hat{\sigma}^2$).

The number of non-zero data-points (df^*) is used as a proxy for the degrees of freedom. While this may be a satisfactory proxy for larger datasets it could be a gross overestimate of the degrees of freedom for smaller datasets. In particular, if the survey indices are weighed on their own while the yearly recruitment is estimated they could be overfitted. In general problem such as these can be solved with component grouping, that is, in step 2, the likelihood components that should behave similarly, such as survey indices representing similar age ranges, should be heavily weighted and optimized together.

C.1.4. Optimization

The model has three alternative optimizing algorithms linked to it: a wide area search simulated annealing (Corana *et al.* 1987), a local search Hooke and Jeeves algorithm (Hooke and Jeeves 1961) and finally one based on the Boyden-Fletcher-Goldfarb-Shanno algorithm hereafter termed BFGS.

The simulated annealing and Hooke-Jeeves algorithms are not gradient based, and there is therefore no requirement on the likelihood surface being smooth. Consequently neither of the two algorithms returns estimates of the Hessian matrix. Simulated annealing is more robust than Hooke and Jeeves and can find a global optima where there are multiple optima but needs about 2-3 times the order of magnitude number of iterations than the Hooke and Jeeves algorithm.

BFGS is a quasi-Newton optimization method that uses information about the gradient of the function at the current point to calculate the best direction to look for a better point. Using this information the BFGS algorithm can iteratively calculate a better approximation to the inverse Hessian matrix. Compared with the two other algorithms implemented in Gadget, BFGS is very local search compared to simulated annealing and more computationally intensive than the Hooke and Jeeves. However the gradient search in BFGS is more accurate than the stepwise search of Hooke and Jeeves and may therefore give a more accurate estimation of the optimum. The BFGS algorithm used in Gadget is derived from that presented by Bertsekas (1999).

The model is able to use all three algorithms in a single optimization run, attempting to utilize the strengths of all. Simulated annealing is used first to attempt to reach the general area of a solution, followed by Hooke and Jeeves to rapidly home in on the local solution and finally BFGS is used for fine-tuning the optimization. This procedure is repeated several times to attempt to avoid converging to a local optimum.

The total objective function to be minimized is a weighted sum of the different components. The estimation can be difficult because some parameters or groups of parameters are correlated and, therefore, the possibility of multiple optima cannot be excluded. The optimization was started with simulated annealing to make the results less sensitive to the initial (starting) values and then the optimization was changed to Hooke and Jeeves when the 'optimum' was approached and then finally the BFGS was run in the end.

C.2. Model settings

As is common with redfish species the deep pelagic beaked redfish is assumed to be a long lived species with the maximum age set at 39, 40 being a plus group, and simulation goes back to 1970. An overview of the datasets and model parameters used in the model study is shown in Tables 1 and 2 respectively.

Table C.1: Overview of the likelihood data used in the model. Survey indices are calculated as described in NWWG2015:WD28. Number of data-points refer to aggregated data used as inputs in the Gadget model and represent the original dataset. All data can obtained from the Marine Research Institute, Iceland.

ORIGIN	TIME-SPAN	LENGTH	NUM. DATA-	LIKELIHOOD
		group size	points	function
Length distributions:				
Combined Survey	2nd quarter, 1999 – 2015	1 cm	152	See eq. 11
	(biennially)			

Trawl	All quarters, 1994 – 2015	1 cm	833	See eq. 11
Age – length frequencies				
Trawl	All quarters, 1994 – 2016	1 cm	1515	See eq. 12
Survey indices				
Acoustic survey	2nd quarter, 1999 – 2015	20–60	9	See eq. 10

C.2.1. Natural mortality

Choice of natural mortality (*M*) is problematic as is normally the case in stock assessments. Here *M* is assumed to be constant with age, at 0.05, as age readings suggest a long lived species.

C.2.2. Fleets and selection

In the model there is one commercial fleet and one survey fleet. The selection is described by a logistic function and total catch in kilograms is specified for each timestep.

C.2.3. Iterative re-weighting, initial parameter- and optimization settings

In order to assign weights to the individual likelihood components the iterative re-weighting process described in C.1.3.4 was used. The datasets were grouped when over-weighting them, the rationale was that similar datasets should contain similar information. The grouping of the likelihood components is shown in Table C.3.

All runs were started from the same initial values. The values and the boundaries, and the settings for the optimizing algorithms are stored in the software section on the SharePoint. All runs, both individual weighting and final runs converged.

Table C.2: An overview of the estimated parameters in the model.

Description	Notation	Comments	Formula
Natural mortality	Ma	Fixed to 0.05	See eq. 1
Growth function	K, L∞	Estimated from age–length frequencies, L∞ is fixed to 50 cm	See eq. 2
Recruitment length	L0, σ0	Estimated	See eq. 5
Growth implementation	B,n	Estimated, n is fixed to 15	See eq. 3
Fleet selection	bf , l50,f	One set for each of the fleets	See eq. 8
Number of recruits by year	Ry	y ϵ [1970, 2015]	See eq. 5
Initial abundance at ages a0 – a∞ in Y0	ηa	a ϵ [5,40]. σ_a^2, i.e. variance in initial length-at-age a, based on length distributions obtained from the commercial catches.	See eq. 6
Length–weight relationship	μs, ωs	Estimated outside the model to 9.36*10-6 and 3.07 respectively	See eq. 9
Catchability coefficient	α	Estimated using regression in log-space	See eq. 10

Table C.3: Deep pelagic beaked redfish in the Irminger Sea and adjacent waters. Likelihood components in the re-iterative process.

Grouping	Likelihood component	Data type
SI	SI	Survey indices
LDs	LDs	Survey data
LDc	LDc	Data from trawls
ALDc	ALDc	-

D. Short-Term Projection

Projection settings:

WKDEEPRED agreed the following settings to conduct short-term projections:

Model used: Same age-length structured population dynamics model used in the stock assessment (implemented in Gadget)

Software used: Gadget and RGadget (see github.com/hafro/gadget and github.com/hafro/rgadget)

Initial stock size:

As estimated from the stock assessment with the following modifications (see Section 5.2):

Recruitment (at age 5) in the last 10 years in the assessment is replaced by the geometric mean of the recruitment estimated for the years ranging from 1985 to (last year included in the assessment – 9); for example, for an assessment based on data until 2015, recruitment for years 2007 and onwards is replaced by the geometric mean of the recruitment estimates for the years 1985-2006. Fishing mortality and stock abundance in the last 10 years in the assessment are recalculated according to the replaced recruitment values so as to match the observed catches (in overall tonnage) in each of those years.

Recruitment (at age 5): in the intermediate year (the year following the last year included in the assessment) and any subsequent forecast years uses the same geometric mean value applied for the replaced recruitments in the assessment (described in previous paragraph).

Maturity: The projections use the same maturity ogive at length applied in the stock assessment (assumed constant over time).

F and M before spawning: SSB is calculated on January 1st; therefore, the proportion of F and M before spawning is 0.

Weight at age in the stock: The model uses weight-at-length. The weight-at-length relationship used for the projections is the same one used in the stock assessment (assumed constant over time)

Weight at age in the catch: The model uses weight-at-length. The weight-at-length relationship used for the projections is the same one used in the stock assessment (assumed constant over time)

Exploitation pattern: The projections the selection-at-length pattern estimated in the stock assessment (assumed constant over time)

Intermediate year assumptions: Recruitment in intermediate year has been explained above. An assumption about either catch or F in the intermediate year is also necessary in order to project the stock to the start of the year(s) for which catch options are provided; the intermediate year assumption should be based on the most reliable information available to NWWG experts.

Stock recruitment model used: Recruitment in the forecast years has been explained above.

Procedures used for splitting projected catches: Total catches are not split into any components. Discards are considered to be negligible.

E. Medium-Term Projections

Medium-term projections are not regularly carried out for this stock

F. Long-Term Projections

Long-term projections are not regularly carried out for this stock

G. Biological Reference Points

Note: Although the table here presents reference points as absolute values, as this is a Category 2 stock, reference points are presented in ICES advice sheets relative to the average of the F and SSB estimates over the stock assessment series.

Framework	Reference point	Value	Technical basis
MSY approach	MSY Btrigger	782 kt	Bpa
	FMSY	0.041	F that maximizes median long-term catch in stochastic simulations with recruitment drawn from 19852006 estimates while incorporating a factor to gradually reduce recruitment when SSB < SSB(2001) (where SSB(2001) is the Bloss from the converged stock–recruitment period). FMSY is constrained not to exceed Fpa.
Precautionary approach	Blim	559 kt	Bpa / 1.4
	Bpa	782 kt	SSB(2001), corresponding to Boloss from the years with converged SSB and recruitment estimates (year classes 1990-2001)
	Flim	0.057	F corresponding to 50% long-term probability of SSB > Blim.
	Fpa	0.041	Flim / 1.4

H. Other Issues

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