Stock Annex: Beaked redfish (*Sebastes mentella*) in subareas 1 and 2 (Northeast Arctic)

Stock specific documentation of standard assessment procedures used by ICES.

Stock:	Beaked redfish
	ACOM considers it not necessary to assess this stock every year since the status of the stock can clearly be deducted from the surveys. No analytical assessment has been made since 2003. New analytical assessment since 2012.
Working Group:	Arctic Fisheries Working Group (AFWG)
Created:	1 March 2012
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A. General

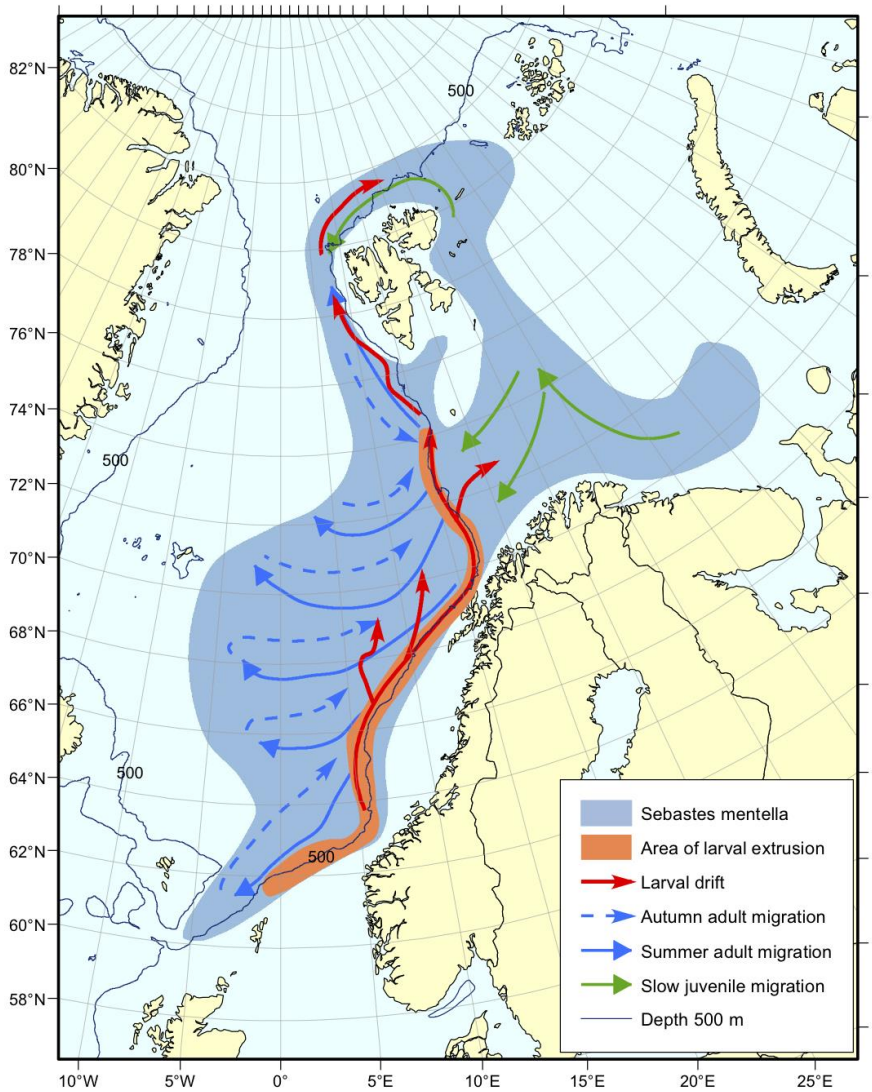
A.1. Biology and Stock definition

Beaked redfish are slow-growing and long-lived. The maximum confirmed length and age of this species in the Barents Sea are 54 cm and more than 40 years, respectively. The age of beaked redfish in the North Atlantic has been validated by radiometric techniques to 75 years. Beaked redfish in the northeast Arctic start maturing at age 7–8 (25–29 cm), and about 50% of the specimens were considered to be mature at age 12–13 years and length 30–34 cm in the 1990s. Recent estimates suggest maturation with 50% mature at age 11 years and length 30–33 cm. Beaked redfish is ovoviviparous. Copulation between males and females takes place several months before mature females aggregate along the continental slope from north of Shetland to the Tromsø Plateau and the Bear Island, where they release larvae in spring (Figure 1).

The stock of *Sebastes mentella* (beaked redfish) in ICES subareas 1 and 2, also called the Norwegian-Barents Sea stock, is found in the northeast Arctic from 62°N in the south to the Arctic ice north and east of Spitsbergen (Figure 1). The south-western Barents Sea and the Spitsbergen areas are first of all nursery areas. Although some adult fish may be found in smaller subareas, the main behaviour of *S. mentella* is to migrate westwards and south-westwards towards the continental slope and out in the pelagic Norwegian Sea as it grows and becomes adult. In the Norwegian Sea and along the slope south of 70°N only few specimens less than 28 cm are observed, and on the shelf south of this latitude *S. mentella* are only found along the slope from about 450 m down to about 650 m depth. The southern limit of its distribution is not well defined but is believed to be somewhere on the slope northwest of Shetland. The stock boundary 62°N is therefore more for management purposes than a biological basis for stock separation,

although the abundance of this species diminishes south of this latitude. The main areas of larval extrusion are along the slope from north of Shetland to west of Bear Island. The peak of larval extrusion takes place during the first half of April. Genetic studies have not revealed any hybridisation with *S. norvegicus* or *S. viviparus* in the area. Recent genetic studies revealed no differentiation between *S. mentella* in the Norwegian Sea and the Barents Sea.

Figure 1. Beaked redfish schematic distribution, area of larval extrusion larval drift and migration routes. Reproduced from Drevetnyak *et al.*, (2011).



A.2. Fishery

The only directed fisheries for *Sebastes mentella* (beaked redfish) are trawl fisheries. By-catches are taken in the cod fishery, occasionally also by longline, and as juveniles in the shrimp trawl fisheries. Traditionally, the fishery for *S. mentella* was conducted by Russia and other East European countries on grounds located south of Bear Island towards Spitsbergen. The highest landings of *S. mentella* were 293 000 t in 1976. This was followed by a rapid decline to about 80 000 t in 1979–1981, and a second peak of 114 000 t in 1982. The fishery in the Barents Sea decreased in the mid-1980s to the low level of 10 500 t in 1987. At this time, Norwegian trawlers showed interest in fishing *S. mentella* and started fishing further south, along the continental slope at approxi-

mately 500 m depth. These grounds had never been harvested before and were inhabited primarily by mature redfish. After an increase to 49 000 t in 1991 due to this new fishery, landings have been at a level of 10 000–15 000 t, except in 1996-1997 when they dropped to 8,000 t. Since 1991 the fishery has been dominated by Norway and Russia. During 1997 to 2012, ICES advised that there should be no directed fishery and that the bycatch should be reduced to the lowest possible level.

Strong regulations were enforced in the fishery in 1997, prohibiting redfish fisheries (both *S. norvegicus* and *S. mentella*) in the Norwegian EEZ north and west of straight lines through the positions:

1. N 7000′ E 0521′
2. N 7000′ E 1730′
3. N 7330′ E 1800′
4. N 7330′ E 3556′

and in the Svalbard area (Division 2.b). When fishing for other species in these areas, a maximum 25% bycatch (in weight) of redfish in each trawl haul is allowed.

To provide additional protection of the adult *S. mentella* stock, two areas south of Lofoten have been closed for all trawl fishing since 1 March 2000. The two areas (A and B) are delineated by straight lines between the following positions:

A	**B**
1. N 6630′ E 0659′	1. N 6236′ E 0300′
2. N 6621′ E 0644′	2. N 6210′ E 0115′
3. N 6543′ E 0600′	3. N 6240′ E 0052′
4. N 6520′ E 0600′	4. N 6300′ E 0300′
5. N 6520′ E 0530′	
6. N 6600′ E 0530′	
7. N 6630′ E 0634.27′	

Area A was shortly afterwards enlarged to include the continental slope north to N 67º10′.

From 1 January 2003 all directed trawl fishery for redfish (both *S. norvegicus* and *S. mentella*) were prohibited in the Norwegian Economic Zone north of 62°N. When fishing for other species it was legal to have up to 20% redfish (both species together) in round weight as bycatch per haul and on board at any time. During 2005–2012 the bycatch percentage was reduced to 15% (both species together), and since 1 January 2013 it has been allowed to have up to 20% redfish (both species together) in round weight as bycatch outside 12 nautical miles and only 10% bycatch inside 12 nautical miles in order to give a higher protection to *S. norvegicus.*

From 1 January 2000 to 31 December 2005 a maximum legal bycatch criterion of 10 juvenile redfish (both *S. norvegicus*, *S. mentella* and *S. viviparus*) per 10 kg shrimp has been enforced in the shrimp fishery. On 1 January 2006 this bycatch criterion was reduced to 3 juvenile redfish (both *S. norvegicus*, *S. mentella* and *S. viviparus*) per 10 kg shrimp. Work is

ongoing to improve the methodology for estimation of bycatch and to aid real-time monitoring of shrimp areas (Breivik *et al.*, 2016[1], 2017[2]).

Landings of *S. mentella* taken in the pelagic fishery for blue whiting and herring in the Norwegian Sea have for some countries for some years been reported to the working group. In 2004–2006 this fishery developed further to become a directed and free fishery in 2006. Faroese and Russian vessels were the first to report large catches in 2004. Since 2007 NEAFC has decided on a TAC to be fished in an Olympic fishery starting in August each year. In 2008, seven countries and 31 trawlers were involved in this fishery. Although single specimens of *S. norvegicus* occasionally may be observed and caught, biological samples of the catches collected by observers and fishers show that the commercial catches are completely dominated by beaked redfish *S. mentella*.

From the first years with a free pelagic fishery, i.e., 2005–2006, it was possible to observe the seasonality and migration pattern of *S. mentella* in the pelagic zone of the Norwegian Sea. During summer, small quantities of redfish were present regularly in catches from the blue whiting and herring fisheries in the international waters of the Norwegian Sea and the Bear Island-Spitsbergen area. Targeted redfish fishery began south of the Mohn Ridge (i.e., the ridge separating the Norwegian Sea into two main basins) in August. The fishery was conducted with gigantic "Gloria" trawls. The fishery finished at the beginning of November after the redfish dispersed and migrated eastwards into the Norwegian EEZ and the Svalbard fishery protection zone.

Some countries have only reported catches taken in Division 2.a, without information whether the fish were caught pelagic or demersal. For these countries, the WG has considered all catches not reported to Norwegian authorities as being caught in international waters outside the EEZ.

Bycatch of herring could be a problem during daytime trawling in these waters at the time of the olympic fishery (August-September). In some catches with the research survey trawl (40 mm mesh size in codend) up to 30% (in weight) herring was caught as bycatch when targeting redfish. Even with a commercial trawl (100 mm mesh size in codend) reports from the fishery show that mixed catches of herring may occur. Even if some of the herring escape through the meshes, mortality through mesh selection may be high. During the 2007 olympic fishery bycatches of blue whiting were small. Best catch-rates of *S. mentella* were usually achieved during daytime. According to the skippers they observed and obtained the best catch-rates of redfish about 50 meters deeper than last year, *i.e.* at about 400 m. Two tons redfish per trawl hour was considered as a very good catch rate. With a common haul duration of 18 hours, catch rates of 30–40 tonnes/day were not uncommon. Even catch rates up to 70 tonnes/day were reported. Sixteen vessels took part in the pelagic Olympic fishery in 2014, compared with 25 in 2013, 32 vessels in 2012, and 58 in 2011. NEAFC have not been able to provide logbook and/or effort information from this fishery in 2015–2017, but 4 000– 7 000 t of *S. mentella* have officially been caught annually (i.e. reported to NEAFC and/or ICES)

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[1] Breivik, O. N., Storvik, G., and Nedreaas, K. (2016). Latent Gaussian models to decide on spatial closures for bycatch management in the Barents Sea shrimp fishery. Canadian Journal of Fisheries and Aquatic Sciences, 73(8): 1271–1280

[2] Breivik, O. N., Storvik, G., and Nedreaas, K. (2017). Latent Gaussian models to predict historical bycatch in commercial fishery. Fisheries Research, 185: 62–72.

in this pelagic fishery during 2015–2017. There is, however, a large discrepancy between the reported landings to NEAFC and ICES, and this must be clearified and harmonized.

A new directed demersal and pelagic fishery is permitted in the Norwegian Economic Zone since 2014. Reasonable catch rates and low bycatches of other species were reported for this new fishery. The spatial regulation for this new fishery is illustrated in Figure 2. In 2016, most of the catches of *S. mentella* from the Russian and Norwegian fisheries were taken in the Norwegian Exclusive Economic Zone or as minor bycatches in the Fisheries Protection Zone around Svalbard, while catches in international waters were mainly taken by EU nations. Changes in the total landings and the proportion of landings originating from national and international waters are illustrated in Figure 3.

A minimum legal catch size of 32 cm and 30 cm has been set for *S. norvegicus* (since 14 April 2004) and *S. mentella*, respectively, with the allowance to have up to 10% undersized specimens (in numbers) per haul. For practical reasons and to avoid excuses due to misidentification of the redfish species, this rule has been enforced as a minimum legal catch size of 30 cm for all redfish outside 12 nautical miles, and 32 cm for all redfish inside 12 nautical miles.

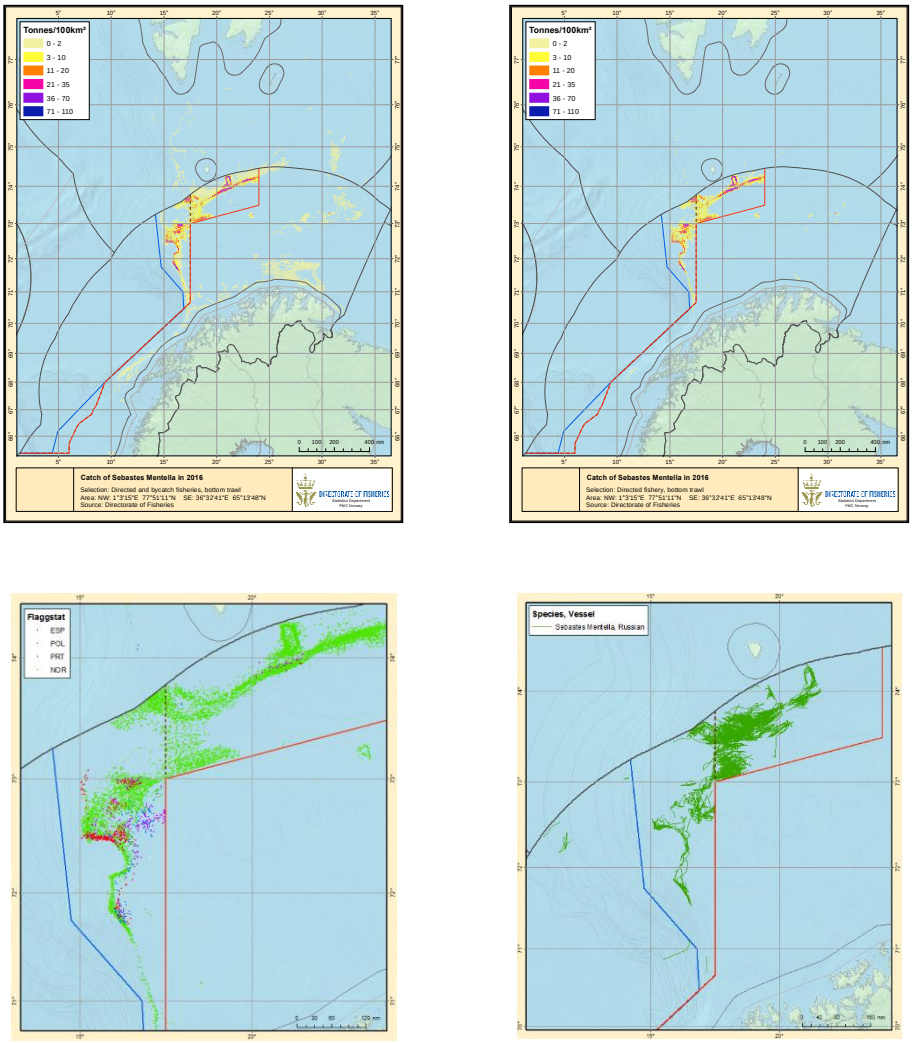

Figure 2. ***Sebastes mentella*** **in subareas 1 and 2. Geographical location, within the Norwegian Exclusive Economic Zone of directed Catches by Norwegian vessesls (top left), directed and bycatches by Norwegian vessels (top right), catches by Spain, Poland, Portugal and Norway (bottom left) and commercial trawl tracks from Russian vessels (bottom right). Directed fishing with bottom trawl is not permitted to the east of the red line. Directed fishing with pelagic trawl is not permitted to the east of the blue line.**

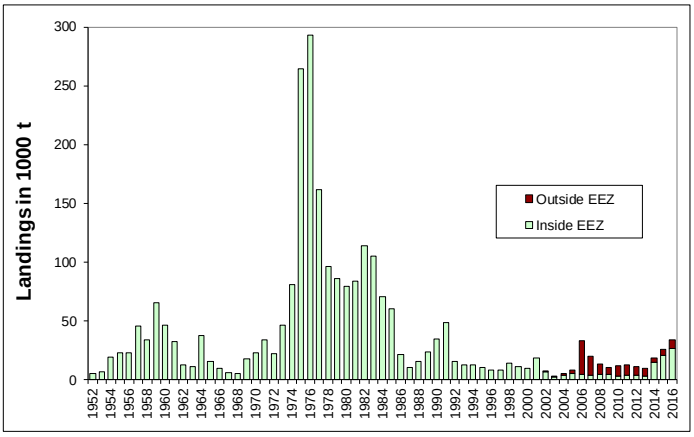

Figure 3. *Sebastes mentella* in subareas 1 and 2. Total international landings 1952–2016 (thousand tonnes).

The redfish population in Subarea 4 (North Sea) is believed to belong to the Northeast Arctic stock. Since this area is outside the traditional areas handled by this Working Group, the catches are tabulated but not included in the assessment. The landings from Subarea 4 have been 1 000–3 000 t per year. Historically, these landings have been *S. norvegicus*, but since the mid-1980s trawlers have also caught *S. mentella* in Subarea 4 along the northern slope of the North Sea. Approximately 80% of the Norwegian catches in Subarea 4 are considered to be *S. mentella*.

A.3. Ecosystem aspect

Beaked redfish is an important plankton eater in the Barents Sea, as 0-group and juvenile fish. 0-group fish have been observed in great abundance in the upper layers utilizing the plankton production. Young (1–6 y) *S. mentella* is also preyed upon by other species, of which its contribution to the cod diet is well documented. High consumption rates were reported in the mid–1980s when the abundance of redfish in the Barents Sea was high. During the 1990's and early 2000's, consumption declined together with the decline in abundance of redfish juvenile. The increase in the number of juvenile redfish in the Barents Sea after 2006 has not been paralleled with a scalable increase in consumption by cod.

Beaked redfish population is distributed over a large geographical area (Figure 1) and, how this distribution may vary in response to changes in environmental conditions is not precisely known.

B. Data

B.1. Commercial catch

The final tables of international landings for beaked redfish (*Sebastes mentella*) and golden redfish (*Sebastes norvegicus*) in ICES subareas 1 and 2 requires a complex collation of data from different sources. The process is described in detail in WKREDFISH-2018 WD 1 Preparation of Norwegian and international landings data for beaked redfish (*Sebastes mentella*) and golden redfish (*Sebastes norvegicus*) (WD Vollen and Nedreaas, 2018). Landings data are gathered from the ICES official and preliminary statistics, ICES InterCatch, data reported directly to the working group, NEAFC statistics and landings from foreign vessels fishing in areas of Norwegian jurisdiction. Discrepancies between the different sources of data are frequent. In such cases, the AFWG

will trust numbers reported directly to the working group more than other sources. In case of discrepancies between other sources, the higher number will often be used. The country's representative may be contacted if discrepancies are large.

Most countries report their redfish landings to species, but there are still some landings reported in the generic category *Sebastes* spp. The AFWG split the landings into *S. mentella* and *S. norvegicus* following some general guidelines: All redfish caught in the NEAFC area are *S. mentella*; All *Sebastes* spp. from ICES Division 2b are *S. mentella*; All *Sebastes* spp. from ICES subarea 1 are *S. norvegicus*. For other areas, *Sebastes* spp. is split using the ratio from the country's own species-specific landings within the same ICES division; or *Sebastes* spp. is split using the ratio from species-specific logbook-reports to Norwegian authorities; or *Sebastes* spp. is split using ratios from earlier years for the same country and division. The Excel spreadsheet files used for collating data and splitting landings of *Sebastes* spp. can be found in the "data" folder in the current year's ICES AFWG SharePoint.

Norwegian commercial catch in tonnes by quarter, Norwegian statistical area and gear are derived from the sales notes statistics of The Directorate of Fisheries. The preparation of the Norwegian landings data is described in detail in WKREDFISH_2018 WD 1 Preparation of Norwegian and international landings data for beaked redfish (*Sebastes mentella*) and golden redfish (*Sebastes norvegicus*) (WD Vollen and Nedreaas, 2018). Data from about 20 subareas are aggregated for the gears gill net, long line, hand line, purse seine, Danish seine, shrimp trawl, pelagic trawl and bottom trawl. For bottom trawl the catches are harmonized with logbooks, *i.e.* the quarterly area distribution of the catches is adjusted by logbook data from The Directorate of Fisheries. No discards are reported or accounted for. Since 2000, the Norwegian landing statistics on redfish is reported to species (*S. norvegicus* or *S. mentella*). However, correct species dentification is challenging and the species composition of the landings is checked and revised by the Institute of Marine Research.

The Norwegian sampling strategy is to have age-length samples from all major gears in each area and quarter. Any unsampled catches will have samples allocated to them manually. Samples to use for length and age are specified independently. Some basic guidelines, in prioritized order, are followed: Use samples from same gear, same quarter, neighboring area or other area that is expected to be similar; Use samples from same gear, same area, neighboring quarter; Use samples from gillnets for longline catches, or vice versa, from same area and quarter; If no appropriate samples are available, overall samples may be used.

For Norway, weights-at-age in the catch are estimated according to the formula which gives the best fit to the length-weight data pairs collected during the year and applied to the mean length-at-age.

B.2. Biological data

Since 1991, the catch in numbers at age of *S. mentella* from Russia is based on otolith readings. The Norwegian catch-at-age is based on otoliths back to 1990. Before 1990, when the Norwegian catches of *S. mentella* were smaller, Russian scale-based age-length keys were used to convert the Norwegian length distribution to age.

As input to analytical assessments, the weight at age in the stock is assumed to be the same as the weight at age in the catch.

A fixed natural mortality of 0.05 y^{-1} is used both in the assessment and the forecast. The mortality is assumed to be constant across ages and years with a value of $M = 0.05$. This

value is derived from earlier calculations based on the Hoenig equation (Hoenig, 1983) which can be used to derive mortality from longevity. This value of *M* is within the range of mortalities estimated using 39 alternative mortality estimates based on the review work by Kenchington (2014) and several additional papers published recently (Then *et al.*, 2014; Hamel 2014; Charnov *et al.*, 2013). Overall, the mode of these natural mortality estimates is 0.058 which departs only slightly from the original estimate of 0.05. Mortality at young ages (< 6 y) is considered to be higher than 0.05 due to higher predation, in particular by cod. Variations in natural mortality by age and year for these young age groups are not currently considered in the model.

Age-based maturity ogives for *S. mentella* (sexes combined) are available for 1986–1993, 1995 and 1997–2001 from Russian research vessel observations in spring and from 1992–present from Norwegian samples (surveys and commercial samples combined). In some years the maturity ogives are imprecise or unrealistic, mainly due to low sampling intensity. The approach taken is to model maturity at age with a double half Gompertz sigmoid[3], using mixed-effect models. In years of poor sampling intensity, the fixed ogive is used, while in years when more data are available, the random (i.e. annual) effects are incorporated.

B.3. Surveys

The results from the following research vessel survey series have been presented to the AFWG:

1) Barents Sea winter survey (BS-NoRu-Q1 (BTr)), annually since 1986 in fishing depths of 100–500 m. Data disaggregated by age only since 1992.

2) The Norwegian Svalbard (Division 2.b) bottom trawl survey (August-September) annually since 1986 (incl.) in fishing depths of 100–500 m. Data disaggregated by age only since 1992. The Norwegian survey initially designed for redfish and Greenland halibut is now part of the Barents Sea Ecosystem survey ((Eco-Noru-Q3 (BTr)) and covers the Norwegian Economic Zone (NEZ) and Svalbard including north and east of Spitsbergen during August 1996–2008 from less than 100 m to 800 m depth.

3) The Russian bottom trawl survey (RU- Q4 (BTr)) in the Svalbard and Barents Sea areas in October-December annually since 1978 in fishing depths of 100–900 m.

4) The International pelagic survey in the Norwegian Sea in Summer for years 2008, 2009, 2013 and 2016.

5) The international 0-group survey (Eco-NoRu-Q3), annually (since 2004 part of the Ecosystem survey) in the Svalbard and Barents Sea areas in August-September since 1980.

6) The Russian acoustic survey in April-May from 1992 to 2001 (except 1994, 1996) on spawning grounds in the western Barents Sea.

7) Norwegian northern autumn and southern spring slope surveys (NO-GH-Btr-Q3/no ICES acronym) which take place every alternate year since 2011.

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[3] the double half sigmoid equation is of the form 0.5 * ((1+tanh(age- a50)/w1)) for age < a50 and 0.5 * ((1+tanh(age- a50)/w2)) for age > a50. a50 equals the age at 50% maturity.

A schematic illustration of these survey series and their use in the analytical assessment is provided in Figure 2.

Further information on the surveys may be found in WKREDFISH_2018 WD 2 Description of scientific surveys used for the assessment of beaked and golden redfishes in ICES subareas 27.1 and 27.2 (WD Planque *et al.,* 2018).

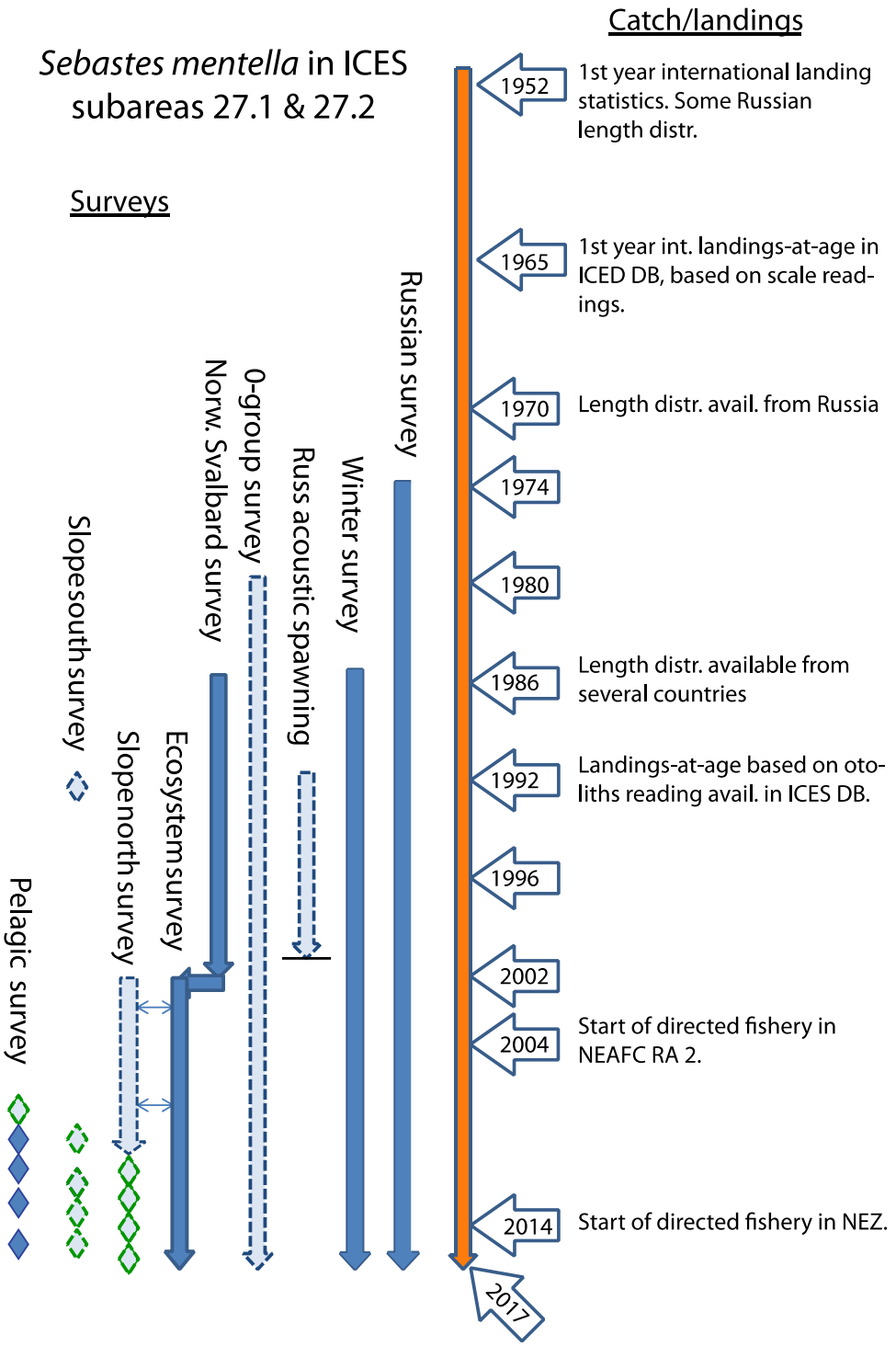

Figure 2. Illustration of the available time series of surveys and catch/landings data. Solid blue arrows and lozenges show the scientific surveys currently used in the SCAA model, while the dotted light blue arrows and dotted lozenges show available surveys for which data are available, but are currently not used as inputs to the assessment models.

B.4. Commercial CPUE

No such data are used at present

B.5. Other relevant data

Estimates of predation by cod on redfish juveniles in the Barents Sea, derived from the ecosystem survey, are provided to the assessment working group. The series covers the period 1984 to present.

C. Analytical assessment model <-Benjamin

Model used: Statistical Catch-at-Age (SCAA).

Software used: R, TMB.

In the 2012 benchmark assessment for beaked redfish, GADGET and Schaefer models where used for validation in addition to the SCAA. This are no longer in use. The model version presented below is the one evaluated during the benchmark assessment in 2018 (ICES, 2018).

C.1. Statistical catch-at-age model structure

The assessment model used is a statistical catch-at-age model. The model runs for the period 1992–2016 (or later). A complete description of the model structure, equations, input data, parameters and options is provided in Working Document 4 of the Benchmark Workshop on Redfish in Northeast Arctic Waters (ICES, 2018).

The basic equation SCA relates numbers N in the population in year y and age a to numbers in the previous year (y-1) for the previous age (a-1):

(1) $$N_{y,a} = N_{y-1,a-1} e^{-Z_{y-1,a-1}}, a = 2, \dots, A.$$

$Z_{y,a}$ can be decomposed into 2 components: the natural mortality $M_{y,a}$ and the fishing mortality $F_{y,a}$. In SCA the fishing mortality is derived from two quantities: the fishing mortality in year y, F_y, and the fleet selectivity at age, $F_a \in [0,1]$. The simple multiplicative relation between F_y and F_a relies on the assumption that these are independent of each other. The resulting fishing mortality-at-age a in year y is given as $F_{y,a} = F_y F_a$. The resulting equation becomes:

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

Fitting the model requires estimating F_a's, F_y's, the number of fish in year 1, for all ages ($N_{1,.}$) and the number of fish of age 1 for all years ($N_{.,1}$). The natural mortality cannot be estimated for each year and age, since such estimates would be confounded with the fishing mortalities. However, it is in principle possible to estimate a fixed mortality term $M_{y,a} = M_0$ identical for all years and all ages. r_{ix}

The SCA model uses a population matrix expanded into a right trapezoid version in which the definition of the +group changes with time (Figure 1).

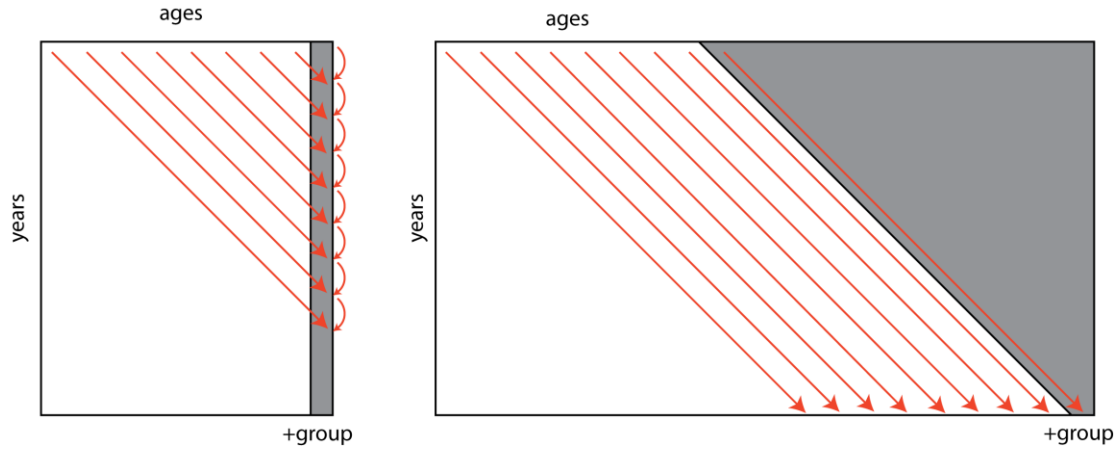

Figure 1. Left: the rectangular population matrix. Individual cohorts (red arrows) are followed until they merge into the +group. Right: the right trapezoid population matrix. Individual cohorts are followed throughout the modelling time period. The age of the +group increases with time.

Because age determination for older individuals is uncertain and because the number of individuals observed in older cohorts may be rather small, older age groups are combined into pre-defined age-blocks instead of being represented as individual ages (Figure 2).

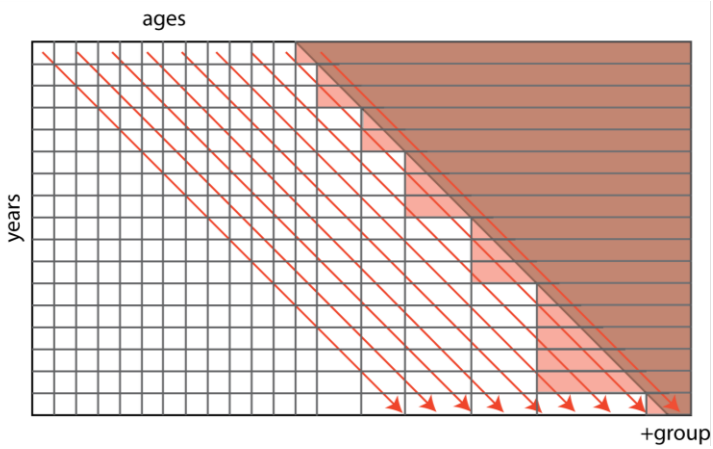

Figure 2. the right trapezoid population matrix with illustration of the age-blocks (vertical grey lines). In his example, age-blocks for young ages are individual years-of-age, but for older ages, numbers are grouped by block of several years-of-age. The +group in the data and model output follows the block structure (pink).

To estimate the temporal variation of the log recruitment, $\log(N_{y,1})$, a stochastic model for the log recruitment is integrated with the population model. Starting in year y0 a first order auto-regressive (AR) process is used

(4) $$\log(N_{y,1}) = \upsilon_1 + \alpha_1 \log(N_{y-1,1}) + u_y^{(1)}.$$

Here α_1 is the AR parameter, υ_1 is the intercept and $u_y^{(1)}$ is a zero mean normally distributed random variable with standard deviation σ1, i.e., $u_y^{(1)} \sim \mathcal{N}(0, \sigma_1)$. Instead of estimating the recruitment pointwise for each year the model estimates two parameters α_1 and σ_1.

To estimate the temporal variation of the log-fishing mortality, log F_y, a stochastic model for the log-fishing mortality is used, in the form of a first order auto-regressive process:

(5) $\log F_y = \upsilon_2 + \alpha_2 \log F_{y-1,} + u_y^{(2)}$.

Here α_2 is the AR parameter, υ_2 is the intercept, and $u_y^{(2)}$ is a zero mean normally distributed random variable with standard deviation σ2, i.e., $u_y^{(2)} \sim \mathcal{N}(0, \sigma_2)$. Instead of estimating the log-fishing mortality pointwise for each year, the model estimates four parameters υ_2, α_2, σ_2, and the initial value of the log fishing mortality in year y0, i.e. the $\log F_{y0}$.

The selectivity of fleets F_a is approximated by a sigmoid function following the Gompertz sigmoid equation:

(6) $F_a = \frac{1}{2}\left(1 + tanh\left(\frac{(a-a50)}{w}\right)\right)$

Two parameters need to be estimated: *a50* (the age of 50% selectivity) and w (smoothness/inverse slopes parameter).

In order to capture temporal variations in demersal fleet selectivity the age at 50% parameter, a50, as well as the inverse slope parameter w are modelled as stochastic variables. A first order auto-regressive process is used in both cases, i.e.,

(7) $a_{50,y} = \upsilon_3 + \alpha_3 a_{50,y-1} + u_y^{(3)}$

and

(8) $w_y = \upsilon_4 + \alpha_4 w_{y-1} + u_y^{(4)}$,

where α_3 and α_4 are the AR parameters, υ_3 and υ_4 are the intercepts, and $u_y^{(3)}$ and $u_y^{(4)}$ are zero mean normally distributed random variables with standard deviations σ_3 and σ_4, respectively.

Catch-at-age is modelled as:

(9) $\hat{C}_{y,a,f} = \frac{F_{y,a,f}}{M_{y,a}+F_{y,a,f\cdot}} N_{y,a}\left(1 - e^{-(M_{y,a,\cdot}+F_{y,a,f\cdot})}\right)$

where f is the fleet index. Two commercial fleets are considered. The bycatch fleet mostly operating in national waters are using bottom trawl, and the pelagic fleet operating in international waters and using very large pelagic trawls. The selectivity-at-age of the two fleets are different (due to differences in gear and in the geographical distribution of age groups of redfish). The fishing mortality for each year is also different, and the pelagic fleet only started to operate in 2006. Typically, the model is fitted on the log of the catch-at-age, $\log(C_{y,a,f})$, assuming a normal error distribution on the log-scale.

(10) $\log \hat{C}_{y,a,f} = \log F_{y,a,f} - \log\left(M_{y,a} - F_{y,a,f}\right) + \log\left(1 - e^{-(M_{y,a}+F_{y,a,f})}\right) + \log N_{y,a} + \varepsilon$,

where $\varepsilon \sim \mathcal{N}(0, \sigma_5)$.

Survey indices, i.e. numbers-at-age in each survey, are modelled as:

(11) $\hat{I}_{y,a,s} = q_s \theta_{a,s} N_{y,a} e^{-\tau(M_{y,a}+F_{y,a})}$,

where $\hat{I}_{y,a,s}$ is index for survey s, year y and age a, q_s is a survey scaling coefficient and $\theta_{a,s}$ is the survey selectivity-at-age. Note that θ_a not only contains gear selectivity, but also fish availability, being small if fish of a certain age is poorly presented at the fishing field though the gear selectivity is high. The input parameter τ is the fraction of the year before the time of the survey, assuming stationary fishing activity throughout the year.

In the Norwegian Sea, data from the pelagic survey (WGIDEEPS) is not believed to produce estimates of numbers-at-age that can be compared from year-to-year. However, the age distribution derived from this survey, i.e. proportions-at-age, is considered robust. The proportions at age are modelled as:

(12) $$\hat{P}_{y,a} = \frac{\theta_a N_{y,a}}{\sum_a \theta_a N_{y,a}} e^{-\tau(M_{y,a}+F_{y,a})}$$

Ages in the WGIDEEPS survey are reported beyond 19 y and the data is provided in predefined age-blocks. The corresponding age-blocks are used in the model to predict proportions-at-age.

The selectivity of surveys (θ_a) can be estimated for each individual age or can alternatively be approximated by a function. Survey selectivity can increase or decrease with age due to a combination of gear-selectivity effects and ontogenetic migrations in/out of the survey area. The following piecewise polynomial function for survey selectivity is used:

(13) $$\log \theta_a = \begin{Bmatrix} \beta_1 a^2 + \beta_2 a + \gamma_1 \; if \; a < a_0 \\ \beta_1' a^2 + \beta_2' a + \gamma_2 if \; a \geq a_0 \end{Bmatrix},$$

where β's, and γ's are the polynomial parameters for the increasing and decreasing part of the selectivity curve. The two parts of the polynomial share the same inflexion point and the maximum value (at the inflexion point) of $\log(\theta_a)$ is zero (so that maximum selectivity is unity). Therefore, only three parameters are required: a_0, b_1 and b_2 with:

(14) $$\begin{Bmatrix} \beta_1 = \frac{-b_1}{2a_0} \\ \beta_2 = b_1 \\ \gamma_1 = \frac{b_1^2}{4a_0} \end{Bmatrix} \text{and} \begin{Bmatrix} \beta_1' = \frac{-b_2}{2a_0} \\ \beta_2' = b_2 \\ \gamma_2 = \frac{b_2^2}{4a_0} \end{Bmatrix},$$

where a_0 is the age at maximum selectivity and b_1, b_2 are the two slope parameters. For each survey, a set of selectivity parameters is estimated.

Model parameters are estimated by maximizing the likelihood of the model given the data. There are up to nine likelihood components: Catch numbers-at-age, Survey numbers-at-age, Survey proportions-at-age, Total catch in weight and the likelihood components of the random effects.

C.3. Model Options chosen:

	SCAA
Year-span	1992–2016
Population characteristics	Single population
Maximum age	75 y
Genders	1
Number of maturity stages	2
Population lengths (cm)	N/A
Summary biomass (mt)	Immature/SSB/Total
Data characteristics	
Data lengths	N/A

Data ages	2–19+ (catches), 2–11/15 (BS surveys), 7–75 (WGIDEEPS survey)
First mature age	From fitted annual maturity ogives
Starting year of estimated recruitment	1992

Fishery & surveys characteristics	2 fleets: international (pelagic) and in EEZ (demersal)
Fishery timing	Annual
Fishery ages	6–19+
Winter survey timing (year fraction or quarter)	0.12
Winter survey ages	2-15
Ecosystem survey timing	0.75
Ecosystem survey ages	2–15
Russian survey timing	0.90
Russian survey ages	2–11
Fishing mortality	Separable, age x year
Fishery selectivity	Gompertz sigmoid
Winter & ecosystem survey selectivities	Piecewise-parabolic
Russian groundfish survey selectivity	Piecewise-parabolic

C.4 Data sources

Fisheries data sources:

Type	Name	Year range	Age range	Variable from year to year
Caton	Total catch in tonnes	1992–2016	NA	yes
Canum1	Catch-at-age in numbers for the demersal fleet	1992–2016	6–19+	yes
Canum2	Catch-at-age in numbers for the pelagic fleet	2006–2016	6–19+	yes
Weca	Weight-at-age in the population/catch	1992–2016	6–19+	yes
Matprop	Proportion mature-at-age in the population/catch	1992–2016	6–19+	yes
Natmor	Natural mortality		6-19+	Constant = 0.05

Numbers/proportions-at-age from surveys

Type	Name	Year range	Age range
Survey 1	Winter survey	1992–2016	2–15
Survey 2	Ecosystem survey	1996–2016	2–15
Survey 3	Russian survey	1992–2016	2–11
Survey 4	WGIDEEPS	2008, 2009, 2013, 2016	7–75

D. Biological Reference Points: B_{lim}, B_{pa}, F_{MSY}

The stock-recruit scatterplot is classified as a type 1 according to ICES nomenclature: no clear evidence of relation between recruitment and spawning stock biomass but rather trends in recruitment and SSB over time (Figure 10). B_{lim} is thus approximated by the lowest observed SSB: 324 000 t (95% CI = [250 000;420 000]).

B_{pa} is then be estimated from B_{lim} taking into account the uncertainty in estimating SSB in the most recent year: $B_{pa} = B_{lim}e^{(1.645\times\sigma)}$ = 450 000 t, with $\sigma = 0.2$.

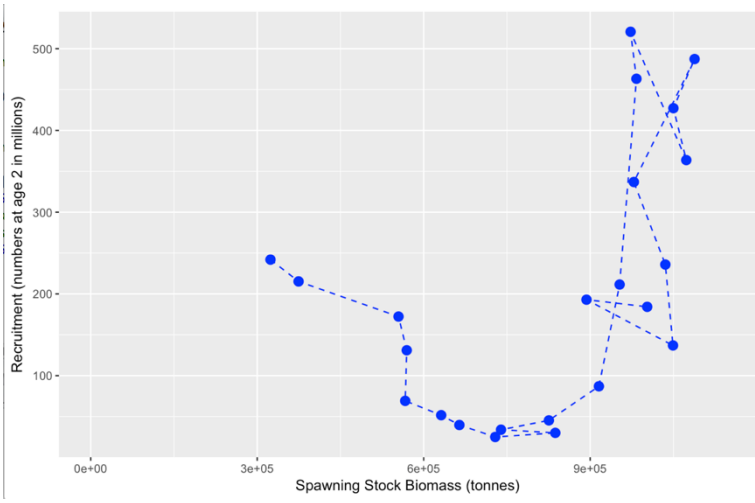

Figure 10: Recruitment at age 2 y against Spawning-Stock Biomass for *S. mentella* in subareas 27.1 and 27.2 estimated by the SCA model. Each point is a year and dotted lines connect consecutive years (starting from left) for the period 1992–2014.

F_{MSY} is approximated by $F_{0.1}$. Since the bulk of the biomass targeted by the fishery is older than 19 y, the 19+ group is chosen as the age range over which $F_{0.1}$ is calculated. Change in yield-per-recruit as a function of F are illustrated in Figure 11.

$F_{0.1}$ (19+) = 0.080

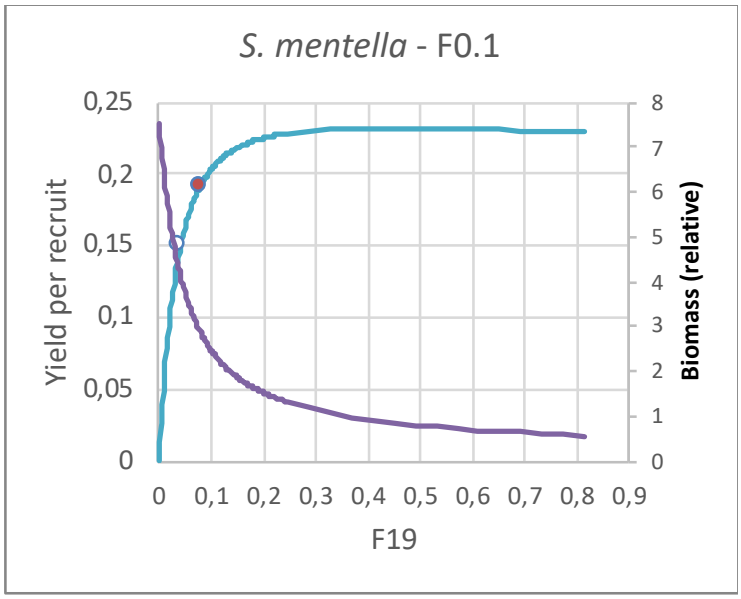

Figure 11. Blue line: yield-per-recruit against fishing mortality for the 19y+ group for *S. mentella* in subareas 27.1 and 27.2. The open white circle indicates the fishing mortality in 2016 estimated from the baseline run of the SCA model. The red circle indicates the fishing mortality at $F_{0.1}$. Relative biomass is indicated in purple.

E. Other Issues

There has been a recurrent limitations in age determination of *S. mentella* specimens from survey or fisheries in recent years, which seriously undermines the use of the statistical catch-at-age model which requires 'age'.

The expected termination of the Russian groundfish survey in Autumn will have a limited impact on the assessment of *S. mentella*, provided that the Winter and Ecosystem surveys are maintained with appropriate geographical coverage and biological sampling.

The inadequacy of the geographical coverage of the WGIDEEPS survey in the Norwegian Sea is a serious issue that should be addressed in conjunction with other pelagics surveys operating in the area (see WGIPS).

While 'numbers-at-age' are reported for catch and surveys in the Barents Sea, it is 'proportions-at-age' that are reported for the survey in the Norwegian Sea. This should be harmonised in the future. Preferably by reporting proportions at age one one side and total numbers (or total biomass) on the other, for all catch and survey data.

The work on mortality estimates started at the benchmark (ICES, 2018) should be pursued and completed in order to provide the most robust mortality estimate for *S. mentella* in the northeast Atlantic, to be used in the SCA model. The mortality at young ages is likely higher than the mean population mortality rate and this should be revised in the model to provide better quantitative estimates of recruitment at age 2 y.

Most random processes in the SCA model (section C.1) can be approximated by random walks (alpha parameters ≈ 1) and the corresponding parameters could be provided as input rather than being estimated.

Changes in the regulations and the dynamics of the fleets operating to catch redfish must be closely monitored as these affect the assumptions behind the numerical model used and, if not adequately considered, could result in biased estimates of stock size, structure and trajectory.

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