Stock Annex: Cod (*Gadus morhua*) in Subdivision 5.b.1 (Faroe Plateau)

Stock specific documentation of standard assessment procedures used by ICES.

Stock	Cod
Working Group	North Western Working Group (NWWG)
Created:	
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Last updated:	May 2017
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A. General

A.1. Stock definition.

Extensive tagging experiments on the Faroe Plateau (Strubberg, 1916; 1933; Tåning, 1940; Joensen *et al.*, 2005; unpublished data) during a century strongly suggest that the cod stock on the Faroe Plateau is isolated from other cod stocks, e.g., from cod on the Faroe Bank and cod at Iceland. Only around 0.1% of recaptured tagged cod are recaptured in other areas than the Faroe Plateau (Joensen *et al.*, 2005). The immigration rate from Iceland is even lower. During 1948–86, around 90 000 cod were tagged at Iceland and 11 000 recaptured. Of these, five cod were recaptured in Faroese waters and only three of them on the Faroe Plateau (Jónsson, 1996). Of cod tagged in the North Sea, one specimen has been recaptured at the Faroes (Bedford, 1966).

Icelandic and Faroese tagging experiments suggest that the cod population on the Faroe-Icelandic ridge mainly belongs to the Icelandic cod stock. Faroe Marine Research Institute tagged about 29 000 cod in Faroese waters during 1997–2009 and about 8500 have been recaptured to March 2009. Of these, one individual was caught on the Icelandic shelf and one on the Faroe-Icelandic ridge. In 2002, 168 individuals were tagged on the Faroe-Icelandic Ridge (Midbank). Twelve have been recaptured so far, 6 at Iceland, 3 on the Faroe-Icelandic Ridge and 0 on the Faroe Plateau (3 had unknown recapture position). The Marine Research Institute in Iceland tagged 25 572 cod in Icelandic waters during 1997–2004 and 3708 were recaptured to April 2006. Of these, only 13 individuals were recaptured on the Faroe-Icelandic ridge and none on the Faroe Plateau.

Genetic investigations indicate that Icelandic cod might be composed by two components (Pampoulie *et al.*, 2006): a western component and an eastern component, which, genetically, is indistinguishable from the Faroe Plateau cod stock (Pampoulie *et al.*, 2008). While Faroe Plateau cod is dominated by the Pan I^A allele (above 0.8), the frequency is much lower (between 0.2 and 0.8) for Icelandic populations (Case *et al.*, 2005), especially on the Faroe-Icelandic Ridge (0.2). The cod populations in the North Sea are dominated by the Pan I^A allele (as the populations on the Faroe Plateau and the Faroe Bank) but they have a higher frequency of the HbI(1) hemoglobin allele (Sick, 1965). Hence, Faroe Plateau cod have a rather special combination of genetic traits, as they mainly possess the 'coldwater' hemoglobine allele (Hb-I(2)) and the 'warmwater' PanI^A allele.

Cod spawn in February-March at two main spawning grounds north and west of the islands at depths around 90–120 m. The larvae hatch in April and are carried by the Faroe Shelf residual current (Hansen, 1992) that flows clockwise around the Faroe plateau within the 100–130 m isobath (Gaard *et al.* 1998; Larsen *et al.*, 2002). The fry settle in July-August and occupy the near shore areas, which normally are covered by dense algae vegetation. In autumn the following year (*i.e.* as 1 group), the juvenile cod begin to migrate to deeper waters (usually within the 200 m contour), thus entering the feeding areas of adult cod. They seem to be fully recruited to the fishing grounds as 3 year olds. Faroe plateau cod mature as 3–4 year old. The spawning migration seems to start in January and ends in May. Cod move gradually to deeper waters when they are growing older. The diet in shallow water (< 200 m) is dominated by sandeels and benthic crustaceans, whereas the diet in deeper water mainly consists of Norway pout, blue whiting and a few species of benthic crustaceans.

The geographical areas are presented in Figure 1.

A.2. Fishery

The cod fishery on the Faroe Plateau was dominated by British trawlers during the 1950s and 1960s. Faroese vessels took an increasing part of the share during the 1960s. In 1977, the EEZ was extended to 200 nautical miles, excluding most foreign fishing vessels from Faroese fishing grounds. In the 1980s, closed areas (mostly during the spawning time) were introduced and these were extended in the 1990s. Longliners and jiggers fished in shallow (< 150 m) waters, targeting cod and haddock, whereas trawlers exploited the deeper waters, targeting saithe. Small trawlers were allowed to exploit the shallow fishing grounds for flatfish during the summertime. After the collapse in the fishery in the beginning of the 1990s, which contributed to a serious national economic crisis in the Faroes, a quota system was introduced in 1994. It was in charge during 1994–1995, but was replaced by the effort management system in June 1996. The cod stock had by then recovered rapidly, which was in contrast with the scientific expectations.

A.3. Ecosystem aspects

The rapid recovery of the cod stock in the mid-1990s strongly indicated that 'strange things' had happened in the environment. It became clear that the productivity of the ecosystem affected both cod and haddock recruitment and growth (Gaard *et al.*, 2002), a feature outlined in Steingrund and Gaard (2005). The primary production on the Faroe Shelf (< 130 m depth), which took place during May-June, varied interannually by a factor of five, giving rise to low- or high-productive periods of 2–5 years duration (Steingrund and Gaard, 2005). The productivity over the outer areas seems to be negatively correlated with the strength of the Subpolar Gyre (Hátún *et al.*, 2005; Hátún *et al.*, 2009; Steingrund *et al.*,2010), which may regulate the abundance of saithe in Faroese waters (Steingrund and Hátún, 2008).

B. Data

B.1. Commercial catch

When calculating the catch-at-age, the sampling strategy is to have length, length-age, and length-weight samples from all major gears during three periods: January-

April, May-August and September-December. In the period 1985–1995, the year was split into four periods: January-March, April-June, July-September, and October-December. The reason for this change was that the three-period split-up was considered to be in better agreement with biological cycles (the spawning period ends in April). When sampling was insufficient, length-age and length-weight samples were borrowed from similar fleets in the same time period. Length measurements were, if possible, not borrowed. The number of samples in some years (e.g. 2005 and 2007–2008) was not sufficient to allow the traditional three period split-up for all the fleets, and a two period split-up (January-June and July-December) was adopted for those fleets. In recent years the two period split-up has been used.

The landing values were obtained from the Fisheries Ministry and Statistics Faroe Islands. The catches on the Faroe-Iceland ridge were not included in the catch-at-age calculations, a practice introduced in the 2005 WG. Catch-at-age for the fleets covered by the sampling scheme were calculated from the age composition in each fleet category and raised by their respective landings. The catch-at-age by fleet was summed across all fleets and scaled to the correct catch.

Mean weight-at-age data were calculated using the length/weight relationship based on individual length/weight measurements of samples from the landings.

B.2. Biological

B.3. Surveys

The spring groundfish surveys in Faroese waters with the research vessel Magnus Heinason were initiated in 1983. Up to 1991 three cruises per year were conducted between February and the end of March, with 50 stations per cruise selected each year based on random stratified sampling (by depth) and on general knowledge of the distribution of fish in the area. In 1992 the period was shortened by dropping the first cruise and one third of the 1991-stations were used as fixed stations. Since 1993 all stations are fixed stations. The standard abundance estimates is the stratified mean catch per hour in numbers at age calculated using smoothed age/length keys. In last years assessment, the same strata were used as in the summer survey and calculated in the same way (see below). All cod less than 25 cm were set to 1 year old.

In 1996, a summer (August-September) groundfish survey was initiated, having 200 fixed stations distributed within the 500 m contour of the Faroe Plateau. Half of the stations were the same as in the spring survey.

The abundance index was calculated as the stratified mean number of cod at age. The age length key was based on otolith samples pooled for all stations. Due to incomplete otolith samples for the youngest age groups, all cod less than 15 cm were considered being 0 years and between 15 and 34 cm 1 year (15–26 cm for 2005 because of abnormally small 2 year old fish). Since the age length key was the same for all strata, a mean length distribution was calculated by stratum and the overall length distribution was calculated as the mean length distribution for all strata weighted by stratum area. Having this length distribution and the age length key, the number of fish at age per station was calculated, and scaled up to 200 stations.

The proportion mature was obtained from the spring survey, where all aged individuals were pooled, i.e., from all stations, being in the spawning areas or not. The average maturity at age for 1983 to 1996 was used in years prior to 1983. Some of the 1983–1996 values were revised in 2003 but not the maturities for the 1961–1982 period. At the benchmark in 2017 the actual data were investigated and revised and al-most changed back to the values used before the revision in 2003. The average maturities 1983 to 1996 changed slightly.

B.4. Commercial CPUE

Two/three commercial cpue series (longliners and pair trawlers) are updated every year, but the WG decided in the benchmark assessment in 2004 not to use them in the tuning of the VPA. The cpue for the longliners was shown to be highly dependent upon environmental conditions whereas the cpue for the pair trawlers could be influenced by other factors than stock size, for example the price differential between cod and saithe. These two/three cpue series are presented in the report although they were not used as tuning series.

B.5. Other relevant data

C. Historical Stock Development

An XSA has been performed during a number of years. The use of tuning indices has, however, varied quite a lot since the mid-1990s. The Faroese spring groundfish survey was excluded as a tuning series in the mid-1990s because the catch-curves in the survey showed an anormal pattern. Two commercial tuning series (single trawlers 400–1000 HP and longliners > 100 GRT) were used during 1996–1998 where the effort was in number of days. In 1999, the tuning series constituted the pairtrawlers > 1000 HP (effort in the number of trawl hours) and the longliners > 100 GRT (effort in the number of hooks set). In 2002, the Faroese Summer Groundfish Survey was used as the only tuning series, as was the case in 2003. A benchmark assessment was performed in the 2004 NWWG, where the Faroese Spring Grounfish Survey was reintroduced, albeit with a modified stratification, i.e., the two surveys were used as the only tuning series.

At the benchmark meeting in February 2017 it was decided to replace the traditional XSA model with a SAM model as the assessment tool, although it was noted that the assessment results were data-driven and not so much by model choice. One benefit of using SAM was that the model provided uncertainty estimates. SAM also provided a short term forecast that carried the trends from the assessment into the forecast. Yet another benefit was that the assessment could be stored on the website (www.stockassessment.org) making it readily accessible for the site users.

SAM is a state-space assessment mode (Nielsen and Berg, 2014). The current implementation (https://github.com/fishfollower/SAM) is an R-package that is based on the Template Model Model Builder (TMB) (Kristensen *et al*., 2016). The states (α) are the log-transformed stock sizes (log of population numbers N at age) and fishing mortalities (log of fishing mortalities F at age). For cod it is assumed that the fishing mortalities for ages 7 years and older are the same. In any given year the state is the combined vector of population numbers and fishing mortalities. The transition equation describes the distribution of the next years' state from a given state in the current year. The transition equation is technically composed of a transition function (T) and an error term (actually the prediction noise or process error).

$$\alpha_y = T(\alpha_{y-1}) + \eta_y$$

The transition function is actually a set of equations that are outlined verbally below (but not that prediction noises are added to the equations):

Equation 1: LogN of age 1 = the logN of age 1 the previous year.

Equation 2a: LogN of ages 2-9 = LogN – F – M for the same cohort the previous year.

Equation 2b: LogN of age 10 = LogN – F – M for the same cohort the previous year PLUS the LogN – F – M for the same age the previous year.

Equation 3: LogF = LogF for the same cohort (ages 2–7) the previous year.

The natural mortality M of 0.2 for all ages was not changed at the benchmark, although tagging studies indicated that M could be slightly higher. M of the age 1 was also set at 0.2 realising the use of a higher value would not have any effect on the assessment results or forecast.

The prediction noise is assumed to be Gaussian (i.e., normally distributed) with zero mean and three separate variance parameters: one recruitment, one for survival and one for fishing mortality at age. The N-part of the prediction noise is assumed to be uncorrelated. The F-part is assumed to be correlated according to an ar(1) correlation structure, such that $cor(\Delta\log(F_{a,y}), \Delta\log(F_{\tilde{a},y})) = \rho^{|a-\tilde{a}|}$.

The observation part of the state-space model describes the distribution of the observations for a given state α_y. Here the vector of all observations from a given year y is denoted x_y. The elements of x_y are age-specific log-catches $\log C_{a,y}$ and age-specific log-indices from scientific survey $\log I_{a,y}$. The combined observation equation is:

$$Xy = O(\alpha_y) + \varepsilon_y.$$

The observation function 'O' consists of the catch equations for total catches and scientific surveys. The measurement noise term ε_y is assumed to be Gaussian. An expanded view of the observation equation becomes:

$$\text{Log } (C_{a,y}) = \log(F_{a,y} / Z_{a,y} (1\text{-e-}Z_{a,y}) + \text{catch } \varepsilon_{a,y}$$

$$\text{Log (survey } I_{a,y}) = \log(\text{survey}Q_a\, e^{-Z_{a,y}D/365}\, N_{a,y}) + \text{survey } \varepsilon_{a,y}$$

Here Z is the total mortality rate $Z_{a,y} = M_{a,y} + F_{a,y}$, D is the number of days into the year where the survey is conducted, Q_a are model parameters describing catchability coefficients. It is assumed that the catchability is the same for ages 8 and 9 within each of the two surveys. The variance of ε_y is the same for ages 8 and 9 within each of the two surveys. The variance of ε_y is set up in such a way that each data source (catch and the two scientific surveys) have their own covariance matrix.

Observation uncertainty is important e.g. to get the relative weighting of the different information sources correct, so a lot of effort has been invested in getting the optimal options into SAM. In Berg and Nielsen (2016) different covariance structures are compared for four ICES stocks.

The options used for Faroe Plateau cod are the following. The logarithm of the total catches at age are assumed independent Gaussian with the same variance for all ages. The logarithm of the age specific indices from the spring survey are assumed to be independent Gaussian with a separate variance for age one and a common variance for ages 2–9. The logarithm of the age specific indices from the summer survey are assumed to follow a multivariate Gaussian distribution with order 1 auto-regressive correlation structure, a separate variance for age one, and a common variance for ages 2–9.

The residual calculation procedure in state-space assessment models can be difficult, but is extremely important when evaluating the assumed covariance structure. The standard practice of calculating the residuals (as 'observed' minus 'predicted' divided by an estimate of the standard deviation) is strictly only valid for models with purely independent observations. It is not valid for state-space models, where an underlying unobserved process is introducing a correlation structure in the (marginal) distribution of the observations. It is not valid if the observations are directly assumed to be correlated (e.g. multivariate normal, or multinomial for age compositions). The problem is that the resulting residuals will not become independent.

To get independent residuals the so-called 'one-observation-ahead' residuals are computed. The residual for the n'th observation is computed by using the first n-1 observations to predict the n'th. Details can be found in Thygesen *et al.*, (2017).

A likelihood function is set up by first defining the joint likelihood of both random effects (here collected in the α_y states), and the observations (here collected in the x_y vectors). The likelihood function, $L(\theta,\alpha,x)$ is a function of e.g. a vector of model parameters (θ). Since the random effects α are not observed inference must be obtained from the marginal likelihood $L_M(\theta,x)$ = integral of $L(\theta,\alpha,x)$ over α. Since the integral is difficult to calculate directly, the Laplace approximation is used. The Laplace approximation is derived by first approximating the joint log likelihood by a second order Taylor approximation around the optimum $\hat{\alpha}$ with regards to α. The resulting approximated joint log likelihood is then integrated by regarding it as a constant term and a term where the integral is known as the normalizing constant from a multivariate Gaussian distribution. The approximation is obtained by a complex formula and taking the logarithm give the Laplace approximation of the marginal log likelihood (another complex formula).

The input data (see below) were only slightly changed at the benchmark meeting in February, i.e., the age 1, both in the March survey and the August survey were included in the tuning, but having its own variance – and lower weight in the assessment model.

The SAM model is run from the website (www.stockassessment.org). The input files are uploaded to the website on beforehand. The SAM model may also be run from the laptop. The R-package is used on the webpage as well as on the laptop.

Configuration in the SAM-run was the following (as obtained by the R-package):

```
> conf

$minAge

[1] 1
```

```
$maxAge
[1] 10

$maxAgePlusGroup
[1] 1

$keyLogFsta
     [,1] [,2] [,3] [,4] [,5] [,6] [,7] [,8] [,9] [,10]
[1,]   -1    0    1    2    3    4    5    5    5     5
[2,]   -1   -1   -1   -1   -1   -1   -1   -1   -1    -1
[3,]   -1   -1   -1   -1   -1   -1   -1   -1   -1    -1

$corFlag
[1] 2

$keyLogFpar
     [,1] [,2] [,3] [,4] [,5] [,6] [,7] [,8] [,9] [,10]
[1,]   -1   -1   -1   -1   -1   -1   -1   -1   -1    -1
[2,]    0    1    2    3    4    5    6    7    7    -1
[3,]    8    9   10   11   12   13   14   15   15    -1

$keyQpow
     [,1] [,2] [,3] [,4] [,5] [,6] [,7] [,8] [,9] [,10]
[1,]   -1   -1   -1   -1   -1   -1   -1   -1   -1    -1
[2,]   -1   -1   -1   -1   -1   -1   -1   -1   -1    -1
[3,]   -1   -1   -1   -1   -1   -1   -1   -1   -1    -1

$keyVarF
     [,1] [,2] [,3] [,4] [,5] [,6] [,7] [,8] [,9] [,10]
[1,]    0    0    0    0    0    0    0    0    0     0
[2,]   -1   -1   -1   -1   -1   -1   -1   -1   -1    -1
[3,]   -1   -1   -1   -1   -1   -1   -1   -1   -1    -1

$keyVarLogN
 [1] 0 1 1 1 1 1 1 1 1 1
```

```
$keyVarObs
     [,1] [,2] [,3] [,4] [,5] [,6] [,7] [,8] [,9] [,10]
[1,]    0    0    0    0    0    0    0    0    0     0
[2,]    1    2    2    2    2    2    2    2    2    -1
[3,]    3    4    4    4    4    4    4    4    4    -1

$obsCorStruct
[1] ID AR ID
Levels: ID AR US

$keyCorObs
     1-2 2-3 3-4 4-5 5-6 6-7 7-8 8-9 9-10
[1,]  NA  NA  NA  NA  NA  NA  NA  NA   NA
[2,]   0   0   0   0   0   0   0   0   -1
[3,]  NA  NA  NA  NA  NA  NA  NA  NA   -1

$stockRecruitmentModelCode
[1] 0

$noScaledYears
[1] 0

$keyScaledYears
numeric(0)

$keyParScaledYA
<0 x 0 matrix>

$fbarRange
[1] 3 7

$keyBiomassTreat
[1] -1 -1 -1

$obsLikelihoodFlag
```

[1] LN LN LN

Levels: LN ALN

$fixVarToWeight

[1] 0

Input data types and characteristics:

Type	Name	Year range	Age range	Variable from year to year Yes/No
Caton	Catch in tonnes	1959–last data year		Yes
Canum	Catch at age in numbers	1959–last data year	2–10+	Yes
Weca	Weight at age in the commercial catch	1959–last data year	2–10+	Yes
West	Weight at age of the spawning stock at spawning time.	1959–last data year	2–10+	Yes, the same data as for the commercial catch
Mprop	Proportion of natural mortality before spawning	1959–last data year	1–10+	No, set to 0 for all ages in all years
Fprop	Proportion of fishing mortality before spawning	1959–last data year	1–10+	No, so to 0 for all ages in all years
Matprop	Proportion mature at age	1983–last data year +1	1–10+	Yes, but constant values used prior to 1983, i.e., average maturities during 1983–1996
Natmor	Natural mortality	1959–last data year	1–10+	No, set to 0.2 for all ages in all years

Tuning data:

Type	Name	Year range	Age range
Tuning fleet 1	Summer Survey	1996– last data year	1–8
Tuning fleet 2	Spring Survey	1994– last data year+1	1–9

D. Short-Term Projection

Model used: Age structured. The SAM model was adopted at the benchmark in February and used as the assessment tool and for short-term and long-term forecast.

Maturity ogives: The maturity in the assessment year +1 and year +2 was taken as the average of the 1983 up to the assessment year.

Weight at age in the stock: The same values as weight-at-age in the catch. This procedure was investigated and confirmed at the benchmark meeting in February 2017. The reason was that the stock biomass using survey weights for all ages was very similar to the current procedure to use catch weights as stock weights.

Weight at age in the catch: The procedure was changed at the benchmark meeting in February 2017. Instead of using the January-February weights in the catches in combination with survey weights in the spring, the January-February weights in the catches were not used, because it was expected that these data would probably not be available in the future. The weights in the catch in the assessment year (WCy) were predicted by a regression model having the weights in the March survey (WCy) and the weight in the catch of the same cohort in the catch the year before (WCy-1): WCy = a*WCy-1 + b*WSy. This is done for ages 3–8 years. The weight of age 2 is estimated by a regression with age 3 the same year, age 9 and age 10+ is estimated by a regression with age 8 the same year.

The forecast procedure used starts from the last year's (assessment year) estimate of the state (log(N) and log(F) at age). One thousand replicates of the last state are simulated from its estimated joint distribution. Each of these replicates are then simulated forward according to the assumptions and parameter estimates found by the assessment model. In the forward simulations a 5 year average (years up to the assessment year) is used for catch mean weight, stock mean weight, proportion mature, and natural mortality. Recruitment is re-sampled from the last 10 years (up to the year before the assessment year). In each forward simulation step the fishing mortality is scaled, such that the median of the distribution is matching the requirement in the scenario (e.g. hitting a specific Fbar value or a specific catch).

E. Medium-Term Projections

F. Long-Term Projections

The yield per recruitment calculations are performed in the SAM model and were based on the last 20 years (up to the year before the assessment year).

G. Biological Reference Points

Since the assessment model was replaced at the benchmark in February 2017, it was necessary to recalculate reference points at the NWWG meeting in 2017 (this was not finally conducted during the benchmark).

The Blim was kept unchanged at 21 thousand tons, since this previously defined Bloss was the lowest spawning biomass from which the stock had made a recovery. The bio-mass has been lower in recent years but the stock has not recovered yet.

The Bpa = Btrigger = 29 226 tons (changed from 40 000 tons). The uncertainty in the SAM assessment one the final year of SSB was found to be $\sigma = 0.20$ and the Bpa was found by using the formula Bpa = Blim × exp(σ × 1.645). The Btrigger was, according to ICES guidelines, set equal to Bpa since the stock had not been fished at Fmsy for five or more years.

Flim = 0.90 (changed from 0.68). Flim was derived from Blim. A stock was simulated with a segmented regression on the spawning stock – recruitment function having the point of inflection at Blim. Flim was set to the F that, in equilibrium, gave a 50% probability that SSB > Blim. This simulation was based on a fixed F, i.e., without inclusion of a Btrigger and without inclusion of assessment/advice errors.

Fpa = 0.69 (changed from 0.35). Fpa was derived from Flim in the reverse of the way Bpa was derived from Blim, i.e., Fpa = Flim × exp(−σ × 1.645), where σ = 0.16.

The calculations were conducted using EQSIM following ICES guidelines. Decisions made involved the spawning stock – recruitment relationship, the weights at age, the selection pattern and the level of advice error. The full time series (1959–2015) was used as basis for the spawning stock – recruitment relationship where the S-R function was based on the segmented regression (weight 0.61), Ricker (weight 0.36), and Beverton and Holt (weight 0.03). The Ricker curve was included because recruitment at very large stock sizes was low according to extension of stock biomass back to 1710 (ICES, 2016). The autocorrelation between SSB-R data points was approximately 0.55. The weights at age were based on the last 10 years (2007–2016). The selection pattern was also based on the last 10 years. The selection pattern has been very stable over time, so the use of the last 20 years would not make any big difference for the Fmsy. The advice error was estimated from advice sheets back to 1999: cvF = 0.44, phiF = 0.47, cvSSB = 0.38, phiSSB = 0.24. In total 2000 iterations were performed that projected the stock 200 years into the future, of which, the last 50 years were kept to calculate 'equilibrium' values.

The result of the analyses was that Fmsy = 0.23 (changed from 0.32). The fishing mortality that is associated with a risk of 5% to fall below Blim, Fp0.5, was estimated to be 0.42, greater than Fmsy.

H. Other Issues

I. References

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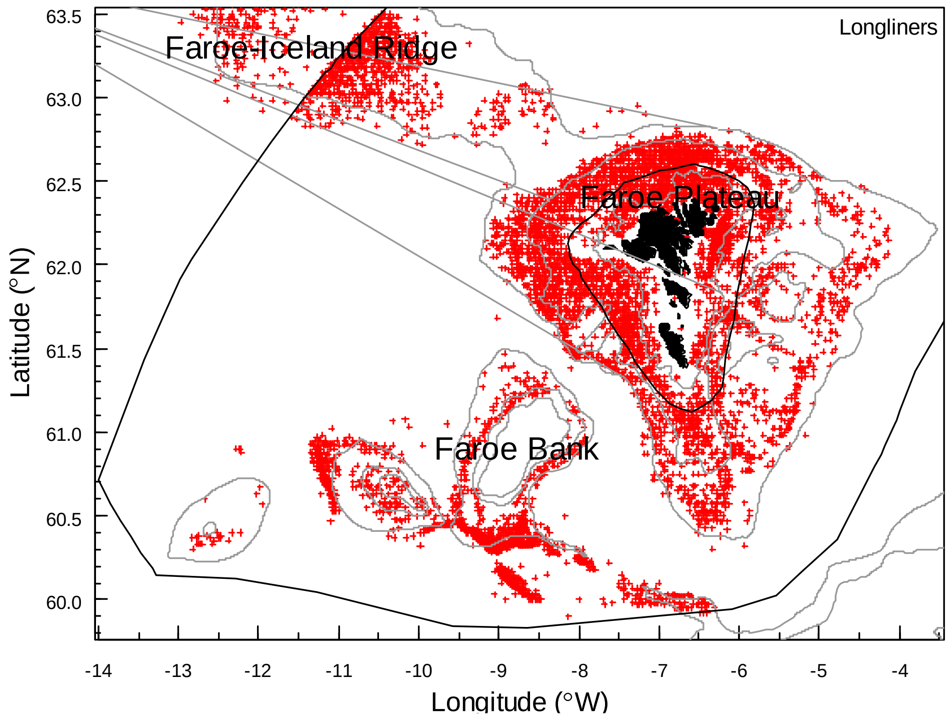

Figure 1. Map of geographical areas often used in the report. The red crosses show the start positions of all longliner settings in 2011.