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Stock Annex: Cod (*Gadus morhua*) in Division 5.a (Iceland grounds)

Stock specific documentation of standard assessment procedures used by ICES.

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A. General

Stock definition

The Icelandic cod stock is distributed all around Iceland, and in the assessment landings of cod within Icelandic EEZ waters it is assumed to be a single homogeneous unit. Spawning takes place in late winter mainly off the southwest coast but smaller, variable regional spawning components have also been observed all around Iceland. The conventional wisdom has been that pelagic eggs and larvae from the main spawning grounds off the southwest coast drift clockwise northwards and eastward along the island to the main nursery grounds off the north coast. The mature stock takes on feeding migration from the spawning grounds to feeding grounds both to deeper waters in the northwest and southeast or within the shallow water realm of the continental shelf proper.

A larval drift to Greenland waters has been recorded in some years and substantial immigrations of mature cod from Greenland which are considered to be of Icelandic origin have been observed in some periods. This pattern was considered to be quite prevalent prior to 1970, when condition in Greenlandic waters were favourable for cod productivity. Periodic immigrations have been estimated in the assessment from anomalies in the catch-at-age matrix with timing and age of such events being based on expert judgement using external information. The most recent of such migration was from the 1984 year class in 1990, the number estimated around 30 million. Recent tagging experiments as well as abnormal decline in survey indices in West Greenlandic waters indicate that part of the 2003 and to some extent the 2002 year classes may have migrated from Greenland to Icelandic waters. In the current assessment the immigration at age 6 in 2009 is estimated around 9.7 million corresponding an additional biomass of around 31 kt in 2009. The influence of this immigration on the current biomass estimate is minimal.

A slight but significant genetic difference has been observed between the cod spawning in the northern waters vs. cod spawning in the southern waters (Pampoulie *et al*., 2007). There are indications that different behavioural type (shallow vs. deep migration) may be found within cod spawning in the same areas (Pampoulie *et al*., 2008). In addition genetic comparisons of cod sample in Greenlandic waters indicate that there is genetic affinity of mature cod in Icelandic and east and southwestern Greenlandic waters.

These research show that management measurements operating on a finer or larger scale than is currently in place may be warranted. However, non-ambiguous methods for splitting up or combining the input measurement of stock assessment among areas (catch-at-age and survey-at-age) have yet been investigated.

Extensive tagging experiments spanning with some hiatuses over the last 100 years indicate that significant emigration of adult cod from Iceland to other areas may be rare. In recent years it has been observed that cod tagged in Iceland has been recaptured inside Faroese waters on the Faroese ridge proper. Anecdotal information from the fishing industry indicate that there may be some exchange of cod across the Denmark Strait. These migrations may be of different nature than the hypothesised net "life-history" immigration of cod described above.

Fishery

Annual landings

Annual estimates of landings of cod from Icelandic waters are available since 1905. The historical information is largely derived from Statistical Bulletin, with unknown degree of accuracy. The more recent landings (from 1980 onward) statistics are from the Directorate of Fisheries (the native enforcement body) as annually reported to ICES.

Landings in Iceland are restricted to particular licensed landing sites, with information being collected on a daily basis. All fish landed has to be weighted, either at harbour or inside the fish processing factory. The information on landing is stored in a centralized database maintained by the Directorate and is available in real time on the Internet (www.fiskistofa.is). The accuracy of the landings statistics are considered reasonable although some bias is likely. In the last years, insignificant amount of cod caught in Icelandic waters have been landed in foreign ports.

Area misreporting after the establishments of 200 miles EEZ in the 1970s has not been regarded as a major problem in the fishery of this stock. This is because the native fleet that accounts for the bulk of the total landings has had very limited access to fishing on other cod stocks. In addition they are not allowed to fish in different management areas in the same trip.

Discarding of fish of economic value is banned in Icelandic waters. Estimates of annual cod discards (Ólafur Pálsson *et al.*, 2010) since 2001 are in the range of 1.4–4.3% of numbers landed and 0.4–1.8% of weight landed. Mean annual discard of cod over the period 2001–2008 was around 2 kt, or just over 1% of landings. In 2008 estimates of cod discards amounted to 1.1 kt, 0.8% of landings, the third lowest value in the period 2001–2008. The method used for deriving these estimates assumes that discarding only occurs as highgrading.

Discarding over the whole time history from 1955 is unknown, but anecdotal information indicates that it may have been substantial even prior to the 1990s. In the absence of any quantifiable data the impact of the discarding on potential bias in dynamics of cod can however not be evaluated.

After WWII the fishery was initially dominated by foreign fleets, mainly English and German trawlers. The former were primarily targeting cod and catching saithe as a bycatch, while the latter were more directly targeting saithe as well as redfish. The domestic fleet has more or less been the sole exploiter of the cod resource since 1978, following the expansion of the Icelandic EEZ from 50 to 200 miles in 1975.

Information on landings by gear is available since 1955. Largest portion of the catch have been taken by trawlers, with gillnet fisheries being secondary in the early part of the period. The importance of the gillnet fishery was around 30% of the landings in beginning of the period but has decline continuously since the 1980s. In recent years it has been around 10% of the total landings. The longline fisheries has increased in importance, in particular at the beginning of the 2000s, and now accounts for 35–40% of the landings.

The spatial distribution of the recent catches based on logbook records show that the bottom-trawl catches are to a large extent confined to outer continental shelf area in the northwest and southeast (400–500 m) while the longline catches are more dispersed on the shelf proper. The distribution of the gillnet and Danish seine fisheries is primarily in shallow waters in the south and the western waters.

Management

Since the establishment of a 200 mile EEZ in 1976 a fishery management system has been under development for the fisheries in Iceland. In the early years various experimental effort control system where tried, but they did not result in reducing fishing mortality, for various reasons. In 1984 a mixture of a TAC and effort control system was introduced for vessels larger than 10 GRT. In the early period the entry into the TAC system for this vessel class was voluntary. Each fishing vessel in the TAC system received a fraction of the TACs, the fraction being based on average share in the catches in the three previous years. The effort options for the size classes larger than 10 GRT was fully abandoned with the Fisheries Management Act in 1990, that first came into full force for the fishing season 1991/1992. Vessels less than 10 GRT in size had until 1990 free access to the fisheries. They were under a mixed ITQ or effort control from 1991–2000. In 2001 boats larger than 6 GRT were all placed under an ITQ system. In 2003 most boast, including those under 6 GRT were under ITQ system, although some specific measures for the smaller vessels has remained in place.

Since the fishing year 1991/1992 the total allowable for cod has been set as follows: Following the annual assessment and advice and prior to the start of the fishing year, the TAC is first set (since 1995/1996 based on a formally adopted harvest control rule). From that a certain amount is set aside for various socio-economic reasons as well that likely to be caught by the effort control fleet. The remainder is then allocated to the vessels in the ITQ system, based on their individual share.

Prior to the 1990s the TAC was most often set considerably higher than that recommended by the Marine Research Institute. In the early 1990s a governmental appointed scientific committee recommended that the TAC should be set based on a formal harvest control rule. The recommended rule was of the form:

$$TAC_{y+1} = 0.22 \times B_{4+,y}$$

where the $B_{4+,y}$ is the reference biomass in the assessment year. A formal harvest control rule was adopted and became the basis for the TAC for the first time for the fishing year 1995/1996. The adopted HCR had however a higher multiplier and was also based on the predicted reference biomass:

$$TAC_{y+1} = 0.25 \times \frac{B_{4+,y} + B_{4+,y+1}}{2}$$

Some amendment to the rule (in the form of catch stabilisers) were done over time but the 0.25 multiplier in place until the mid-2000s. In the fishing year 2007/2008 when the TAC was first set based on the current form of the HCR:

$$TAC_{y+1} = min\left\{1, \frac{SSB_y}{SSB_{trigger}}\right\} \times \frac{0.20 \times B_{4+,y} + TAC_y}{2} \quad (1)$$

The ratio of the landings relative to the catch dictated by the harvest control rule in place at any time has shown that there has been an overshoot in the landings (mean around 8%). These can be largely attributed to various socio-economic measures that were mostly foreseeable and predictable at the time of the decision-making. In the last couple of years a system has been set in place that is supposed to take account of these overshoots, but its effect is still not visible.

A system of instant area closure has been in place since the 1970s. The aim of the system is to minimize fishing on smaller fish. For cod, an area is closed temporarily (for three weeks) for fishing if on-board inspections (not 100% coverage) reveal that more than 25% of the catch is composed of fish less than 55 cm in length. No minimum landing size of any fish species exist in Icelandic waters. The minimum allowable mesh size is 135 mm in the trawl fisheries, with the exception of targeted shrimp fisheries in waters north of the island.

Management measures that aim at reducing incentives or likelihood of discarding have been in place since 1991. These include some allowance for individual vessels for changing quota from one species to another, although this measure does not apply to cod. A 5% overshoot of individual vessel quota in one fishing year is permitted, with the consequences that the vessels ITQ in the next year being reduced equivalently. In addition up to 20% of the quota in one year can be transferred to the next fishing year, without penalty. A quota leasing market is also in place, where individual vessel can lease quota from other vessel owners on a contemporary basis. The system operates in real time, meaning that if overshoot of catch of a particular species occurs during a trip, the captain can at least in theory lease quota prior to landing. The system is however somewhat limited to the supply relative demand at any particular time.

In addition to the above flexibilities additional measures to reduce incentives for discarding were set in place in 2001, by allowing vessels to report up to 5% of annual catches as outside their ITQ allowance. These measures resulted in total landings of around 2 kt, large portion being cod (around 85%).

Observations

Commercial catch

Sampling from the Icelandic fleet

The sampling protocol by the staff of the Marine Research Institute has in the last years been linked to the progression of landings within the year. The system is fully computerized (referred to as “Sýnó” by the natives) and directly linked to the daily landings statistics available from the Directorate of Fisheries. For each species, each fleet/gear and each landing strata a certain target of landings value behind each sample is prespecified. Once the cumulative daily landings value pass the target value an automatic request is made to the sampling team for a specific sample to be taken. The system as such should thus take into account seasonal variability of the landings of any species. The sampling design is not *per se* linked to the geographical distribution of the fisheries. However the fishing location of the fish measured at harbour is known with reasonably accuracy, because fishing date is registered for each fish boxes and can hence be linked to geographic location of the fishing at that date, based on the captain's logbook record.

Calculation of catch in numbers

The calculation of the annual catch in number of the Icelandic cod has since 1980 been calculated in the same way. The base is eight métiers, two areas (northeast and southwest), four gears (longlines, gillnet, Danish seine and gillnets) and two seasons (January–May, June–December). The catch in numbers are calculated for each area, season and gear combination and then combined to total catches in numbers.

Length distributions

Data used are length–frequency samples taken in area **r**, season **t** and gear **g**.

L_l is the number of fishes at length *l*.

One has the option to run the length distributions on 1 cm or 5 cm basis. If the latter one is chosen, a temporary variable *lemultfj* is assigned the value l * L_l to be able to calculate the correct mean length in the length distribution. Then the grouping in 5 cm intervals is done in the way that the numbers get the middle value from the interval. As an example the values in the range 10–14 and 15–19 are assigned 12 and 17 respectively. Lengths are then in fact either

$$l \in \{1,2,3,\ldots\} \text{ or } l \in \{2,7,12,\ldots\}$$

Age-length and maturity keys

Data used are age-determined data from otolith samples in area **r**, season **t** and gear **g**. If no otolith samples exist from this area, season and gear combination, they have to be borrowed from other season or gear for the same area or from other areas.

K_{la} is the number at length *l* and at age *a*, *a*>0.

M_{la} is the number mature at length *l* and at age *a*, *a*>0.

IM_{la} is the number immature at length *l* and at age *a*, *a*>0.

A fish is assigned to IM_{la} if is has a maturity value 1 in the database otherwise it is assigned to M_{la}.

Multiply the age-length and maturity keys with the length distribution

Sum of the numbers at length *l* over all ages:

$$K_{l.} = \sum_a K_{la}$$

Make a new key with the number of fishes:

$$C_{la} = \frac{K_{la}}{K_{l.}} \cdot L_l$$

And new maturity keys:

$$C_{la}^{M} = \frac{M_{la}}{M_{la} + IM_{la}} \cdot C_{la} \quad \text{and} \quad C_{la}^{IM} = \frac{IM_{la}}{M_{la} + IM_{la}} \cdot C_{la}$$

Average length and weight

In this step average length and weight-at-age are calculated. For each area, season and gear the condition factor (*cond*) and the power (*power*) in a length–weight relationship are input data.

$$\tilde{w}_{la} = C_{la} \cdot cond \cdot l^{power}$$ (the weight in each cell)

$$\tilde{l}_{la} = C_{la} \cdot l$$

Note that in the above two equations l is a midpoint if 5 cm grouping has been chosen.

The total frequency in the key is:

$$C_{..} = \sum_l \sum_a C_{la}$$

and total weight

$$\tilde{w}_{..} = \sum_l \sum_a \tilde{w}_{la}$$

So the mean weight in this area, season and gear combination is

$$\bar{w} = \frac{\tilde{w}_{..}}{C_{..}}$$

The ratio of weight and number by age from the total:

$$ratio\_w_a = \sum_l \tilde{w}_{la} / \tilde{w}_{..}$$

$$ratio\_C_a = \sum_l C_{la} / C_{..}$$

The mean weight and mean length-at-age and ratio mature-at-age are:

$$\bar{w}_a = \frac{\sum_l \tilde{w}_{la}}{\sum_l C_{la}}$$

$$\bar{l}_a = \frac{\sum_l \tilde{l}_{la}}{\sum_l C_{la}}$$

$$ratio\_M_a = \frac{\sum_l C_{la}M}{\sum_l (C_{la}M + C_{la}I)}$$

if the denominator >0 otherwise the *ratio_*M_a *is set to -1.*

Catches in numbers

Input data for this module is the landings in tons (*catch*) for each area, season and gear.

The total number of fishes caught are:

$$C_{tot} = \frac{catc}{\overline{w}}$$

The catches in numbers and weight by age is then

$$C_a = C_{tot} \cdot rat\_C_a$$

$$W_a = C_a \cdot \overline{w}_a$$

To derive the total catches in numbers and weight summation is done over all areas, seasons and gears.

Biological data

Weight-at-age

Mean weight-at-age in the landings is available back to 1955. Prior to 1993 mean weight-at-age is compiled using fixed length–weight relationship as weighing of fish was relatively uncommon in that period. Since 1993 weighting of fish has been extensive with large proportion of cod sampled for otholiths weighted gutted and part of it ungutted. The weighting programme has shown that the error in assuming fixed length–weight relationship is relatively small (<3%) and that most of observed changes in mean weight-at-age are really changes in mean length-at-age.

Catch weight estimates in the assessment year (y): The weight-at-age in the catches is used to calculate the reference biomass (B4+). The B4+ in the assessment year (y) is the basis for the calculation of the TAC in the advisory year (y+1). Since weight-at-age in the catches for this year is not available during the annual assessment/advisory cycle, they have to be based on predictions. In the last few years, the estimates of mean weights in the landings of age groups 4–9 in the assessment year (y) have been based on a prediction from the spring survey measurements in the advisory year, using the relationship between survey and landings weights from the terminal year (y-1):

$$cW_{a,y-1} = \alpha + \beta * sW_{a,y-1} \quad (2)$$

and the catch weights in the advisory year then from:

$$cW_{a,y} = \alpha + \beta * sW_{a,y} \quad (3)$$

The weight-at-age for age groups 10–14 in the have however been taken from the terminal year. In assessment done prior to 2005, the mean weights in the landings in the assessment year were predicted from mean weights in the landings one year before and estimated abundance of adult capelin. Prediction of the capelin stock size turned out to be problematic and the survey weights on which predictions are now based are measured 3–4 months before the weights in landings assuming they are on the average in the middle of the year.

Maturity-at-age

Maturity-at-age is based on measurements obtained from spring survey. The survey time is close to the spawning time making visual detection of maturity stages optimal. Maturity-at-age data from surveys are considered to give better estimates of maturity-at-age in the stock than those from landings data, in particular because of limited ungutted samples in the landings.

Since the spring survey only commenced in 1985, maturity values prior to that were obtained from a relationship between maturity-at-age in the landings and the survey from 1985–2004.

Natural mortality

A fixed natural mortality of 0.2 is used both in the assessment and the forecast. The proportion of natural mortality before spawning (pM) and the proportion of fishing mortality before spawning (pF) are also set as constants:

	AGE	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	pM	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
2	pF	0.00	0.00	0.09	0.18	0.25	0.30	0.38	0.44	0.48	0.48	0.48	0.48	0.48	0.48

Survey indices

Two groundfish surveys, conducted be the Marine Research Institute (MRI) in Iceland, are used directly in assessment of cod, the Icelandic Groundfish Survey conducted annually in March since 1985 (here referred as the March survey or SMB) and the Autumn Groundfish Survey conducted annually in October since 1996 (here referred as the Autumn survey or SMH). Both are bottom-trawl surveys. The March survey is conducted on the continental shelf at depths shallower than 500 m and has a relatively dense station-net (approximately 600 stations towed annually). The Autumn Survey on the other hand has around 380 stations towed annually and covers larger area at depths down to 1500 m, so the density of stations is lower.

Large part of the following text is taken from citation. Where applicable the emphasis has been put on cod. The manual on how the surveys in 2009 were conducted is available in English at MRI website (citation) but the survey protocol has not changed much since 2009 and for cod things related to index have not changed much since 1989, except for weighting of all cod sampled for otoliths since 1993. The weighting has some effect on estimated mean weight-at-age. Still variability of condition only explains 10–20% of variability of mean weight-at-age while variability of length-at-age explains 80–90%.

The spring survey

Timing, area covered and tow location

The optimal time of the year to conduct the survey was considered be in March, or just before and during the spawning of cod in Icelandic waters. During this time of the year, cod is most easily available to survey gear as diurnal vertical migrations are at minimum (citation).

The total number of stations was decided to be 600. The reason of having so many stations was to decrease variance in indices but was within the constraints of what was feasible in terms of survey vessels and workforce available. With 500–600 tow-stations the average coefficient of variation (CV) of the survey indices of cod was estimated to be around 13%.

Allocation of stations and data collection is based on a division between northern and southern areas (Figure 3). The northern area is the colder part of Icelandic waters where the main nursery grounds of cod are located, whereas the main spawning grounds are found in the warmer waters in the southern area. It was assumed that 25–30% of the cod stock (in abundance) would be in the southern area at the survey time but 70–75% in the north. Because of this, 425 stations were located in the colder northern area and 175 stations in the southern area. The two areas were then divided into ten strata, four in the south and six in the north.

Stratification in the survey and the allocation of stations was based on pre-estimated cod density patterns in different "statistical squares" (citation). The statistical squares were grouped into ten strata depending on cod density. The number of stations allocated to each stratum were in proportion to the product of the area of the stratum and cod density. Finally, the number of stations within each stratum were allocated to each statistical square in proportion to the size of the square. Within statistical squares, stations were divided equally between captains chosen stations and the randomly chosen stations for decisions of location. The captains selected their stations from their fishing experience. Up to 16 stations are in each statistical square in the northern area and up to seven in the southern area.

Vessels, fishing gear and fishing method

In the early stages of the planning it was apparent that consistency in conducting the survey on both spatial and temporal scale was of paramount importance. It was decided to rent commercial stern trawlers built in Japan in 1972 and 1973 to conduct the survey. Each year, four or five of these trawlers have participated in the survey. The ten Japanese built trawlers were all built on the same plan and were considered identical for all practical purposes. The trawlers were thought to be in service at least until the year 2000. This has been the case and most of these trawlers still fish in Icelandic waters but have been modified since the start of the survey (see next section).

The survey gear is based on the trawl that was most commonly used by the commercial trawling fleet in 1984–1985. It has relatively small vertical opening of 2–3 m. The headline is 105 feet, fishing line is 63 feet, footrope 180 feet and the trawl weight 4200 kg (1900 kg submerged).

Length of each tow was set 4 nautical miles and towing speed at approximately 3.8 nautical miles per hour. Minimum towing distance of a tow to be considered valid for index calculation is 2 nautical miles.

Later changes and alterations to the survey

Vessels and fishing gear

The commercial trawlers used in the survey have been changed somewhat since the beginning of the survey. The changes include alteration of hull shape (bulbous bow), the hull extended by several meters, larger engines, and some other minor alterations. These alterations have probably changed the qualities of the ships but it is very difficult to quantify these changes.

The trawlers are now considered old and it is likely that they will soon disappear from the Icelandic fleet. Some search for replacements is ongoing. Since 2007, two MRI research vessels have taken part in the Spring Survey after elaborate comparison studies.

The trawl has not changed since the start of the survey. The weight of the otter-boards has increased from 1720–1830 kg to 1880–1970 kg. This increase may have increased the horizontal opening of the trawl and hence decreased the vertical opening. However, these changes should be relatively small as the size (area) and shape of the otter-boards is unchanged.

Trawl-stations

Initially, the numbers of trawl stations surveyed was expected to be 600. However, this number was not covered until 1995 (Table 1). The first year 593 stations were surveyed but in 1989 the stations had been decreased down to 568 mainly due to bottom topography (rough bottom that was impossible to tow), In two years, 1988 and 1998 drift ice caused problems and in 1988 only 545 stations were surveyed. In 1989–1992, between 567 and 574 stations were surveyed annually. In 1993, 30 stations were added in shallower waters to take into account fishermen’s critique that the survey did not cover that area adequately.

In short, until 1995 between 545 to 600 stations were surveyed annually. In 1996, 14 of the 30 stations that were added in 1993 were omitted.

In 1996, the whole survey design was evaluated with the aim of reduce the cost. The number of stations was cut down to 532 stations. The main change was to omit all of the 24 stations on the Iceland-Faroe Ridge southeast of Iceland. This was the state of affairs until 2004 when in response to increased abundance of cod on the Faroe-Iceland Ridge nine stations were added. Since 2005 all of the 24 stations omitted in this area in 1996 have been surveyed.

Since 2008 captains have been asked to take additional tows outside the survey area when substantial amount of fish was caught in the outermost tows. This situation did nearly always apply to cod. The additional tows have not been used directly in index calculations but most of them are anyway outside the stratification scheme used that is drawn around the standard stations. The effect of additional stations near the edges of the continental shelf is usually small as the slopes are steep so the area between 400 and 600 m is relatively small. The additional stations are important for understanding cod distribution in the important fishing area in the slope of the continental shelf although they have not been used for tuning in assessment.

The autumn survey

The autumn survey has been conducted annually since 1996. The objective is to gather fishery-independent information on biology, distribution and biomass of demersal fish species in Icelandic waters, with particular emphasis on Greenland halibut (*Reinhardtius hippoglossoides*) and deep-water redfish (*Sebastes mentella*). This is because the spring survey does not cover the distribution of these deep-water species. Secondary aim of the survey is to have another fisheries-independent estimate on abundance, biomass and biology of demersal species, such as cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*) and golden redfish (*Sebastes marinus*), in order to improve the precision of stock assessment . Having a survey in autumn was also considered desirable if drift ice caused problems with the March survey but the extent of drift ice is much less in autumn.

Timing, area covered and tow location

The autumn survey is conducted in October as it is considered the most suitable month in relation to diurnal vertical migration, distribution and availability of Greenland halibut and deep-water redfish. The research area is the Icelandic continental shelf and slopes within the Icelandic Exclusive Economic Zone to depths down to 1500 m. The research area is divided into a shallow-water area (0–400 m) and a deep-water area (400–1500 m). The shallow-water area is the same area covered in the spring survey. The deep-water area is directed at the distribution of Greenland halibut, mainly found at depths from 800–1400 m west, north and east of Iceland, and deep-water redfish, mainly found at 500–1200 m depths southeast, south and southwest of Iceland and on the Reykjanes Ridge.

Preparation and later alterations to the survey

Initially, a total of 430 stations were divided between the two areas. Of them, 150 stations were allocated to the shallow-water area and randomly selected from the spring survey station list. In the deep-water area, half of the 280 stations were randomly positioned in the area. The other half were randomly chosen from logbooks of the commercial bottom-trawl fleet fishing for Greenland halibut and deep-water redfish in 1991–1995. The locations of those stations were, therefore, based on distribution and pre-estimated density of the species.

Because MRI was not able to finance a project in order of this magnitude, it was decided to focus the deep-water part of the survey on the Greenland halibut main distributional area. For this reason, important deep-water redfish areas south and west of Iceland were omitted. The number and location of stations in the shallow-water area was left unchanged.

The number of stations in the deep-water area was reduced to 150. A total of 100 stations were randomly positioned in the area. The remaining stations were located on important Greenland halibut fishing grounds west, north and east of Iceland and randomly selected from a logbook database of the bottom-trawl fleet fishing for Greenland halibut in 1991–1995. The number of stations in each area was partly based on total commercial catch.

In 2000, with the arrival of a new research vessel, MRI was able finance the project according to the original plan. Stations were added to cover the distribution of deep-water redfish and the location of the stations selected in a similar manner as for Greenland halibut. A total of 30 stations were randomly assigned to the distribution area of deep-water redfish and 30 stations were randomly assigned to the main deep-water redfish fishing grounds based on logbooks of the bottom-trawl fleet in 1996–1999 (Figure 2).

In addition, 14 stations were randomly added in the deep-water area in areas where great variation had been observed in 1996–1999. However, because of rough bottom which made it impossible to tow, five stations were omitted. Finally, 12 stations were added in 1999 in the shallow-water area, making total stations in the shallow-water area 162. Total number of stations taken 2000–2009 was around 381 (Table 2).

In 2010, the number of stations in deeper waters were reduced by 16 or from 219 to 203. The reduction was mainly west of Iceland where Greenland halibut is mainly found. In this area the density of stations was great and the cut down was considered not to have any effect on biomass and abundance estimates of the species. The number of stations was also cut down southwest and southeast of Iceland, where deep-water redfish are abundant and the station net very dense.

The RV ″Bjarni Sæmundsson″ has been used in the shallow-water area from the beginning of the survey until 2014 when a commercial trawler replace the research vessel as a result of financial engineering exercise. For the deep-water area MRI rented one commercial trawler 1996–1999, but in 2000 the commercial trawler was replaced by the RV ″Árni Friðriksson″ until 2014 when financial engineering exercises cause a trawler being used instead of the research vessel (Table 2).

The survey was not conducted in 2011 due to strike by the crew of research vessels.

Fishing gear

Two types of the bottom survey trawl “Gulltoppur” are used for sampling: “Gulltoppur” is used in the shallow water and “Gulltoppur 66.6 m” is used in deep waters. The shape of the trawls are the same but the trawl used in deep waters is larger. The trawls were common among the Icelandic bottom-trawl fleet in the mid-1990s and are well suited for fisheries on cod, Greenland halibut and redfish.

The towing speed is 3.8 knots over the bottom. The trawling distance is 3.0 nautical miles calculated with GPS when the trawl touches the bottom until the hauling begins (i.e. excluding setting and hauling of the trawl).

B. Data sampling

The data sampling in the spring and autumn surveys are similar. The difference is that more emphasis is on stomach content analysis in the autumn survey than in the spring survey.

Length measurements and counting

All fish species are measured for length. For the majority of species, including cod, total length is measured to the nearest cm from the tip of the snout to the tip of the longer lobe of the caudal fin. At each station, the general rule is to measure at least four times the length interval of cod in both the surveys.

Example: If the continuous length distribution of cod at a given station is between 15 and 80, the length interval is 65 cm and the number of measurements needed is 260. If the number of cod caught at this station exceeds 260 individuals, the rest is counted.

Care is taken to ensure that the length measurement sampling is random so that the fish measured reflect the length distribution of the haul in question.

Otolith sampling

Otoliths for age reading are sampled from cod in both surveys. In the spring survey the sampling protocol changes between north and south (Figure 3) with 25% of cod caught in the south sampled for otoliths and 5% in the north. In both areas minimum of five cod are sampled for otoliths and a maximum of 30. Cod are selected randomly for otolith sampling, in recent years the electronic scales used for punching in the data blink when the next cod is to be taken for otolith sampling.

The sampling for otoliths is the March survey has been similar since 1989 but from 1985–1988 the sampling was stratified with area split into five strata. Within each strata certain number of fish in each length group were sampled for otolith.

In the autumn survey, the minimum is 25 otoliths extracted and the maximum is 50 otoliths. Otoliths are sampled at ten fish interval so that if in total 300 cod are caught in a single haul, 30 otoliths are sampled. The same proportion of fish is sampled for otoliths in the whole survey area.

In both surveys, each cod taken in the otolith sampling is sex and maturity determined, and weighed ungutted and gutted. Liver is also weighed and roes/gonads of mature fish in the March survey. The stomach content is also analysed in both surveys, first 15 in the March survey and 25 in the autumn survey (citation).

Data processing

Information on tow, gear and environmental factors

At each station/haul relevant information on the haul and environmental factors, are filled out by the captain and the first officer in cooperation with the cruise leader.

Abundance and biomass estimates at a given station

As described above the normal procedure is to measure at least four or five times the length interval of a given species. The number of fish caught of the length interval L_1 to L_2 is given by:

$$P = \frac{n_{measured}}{n_{counted}+n_{measured}} \quad (4)$$

$$n_{L_1-L_2} = \sum_{i=L_1}^{i=L_2} \frac{n_i}{P} \quad (5)$$

where $n_{measured}$ is the number of fished measured and $n_{counted}$ is the number of fish counted. Biomass of a given species at a given station is calculated as:

$$B_{L_1-L_2} = \sum_{i=L_1}^{i=L_2} \frac{n_i \alpha L_i^{\beta}}{P} \quad (6)$$

where L_i is length and α and β are coefficients of the length–weight relationship.

Number and biomass by age at each station

The first step is to calculate age–length key $P_{a,L}$ that describes the proportion of each age in a length group that is 5 cm. The age–length key for cod is calculated separately for the north and south area (Figure 3) due to difference in mean weight-at-age in the areas and also much higher sampling percent in the March survey.

In the March survey maturity stage is registered (and used) for each fish sampled for otoliths. In the age–length keys mature fish are treated like it was a separate age group.

Age–length keys are calculated as follows. Look at length group L with min length l_1 and max length l_2 let $N_{a,L}$ be the number of fish of age a and length group L. The age–length key is defined as.

$$P_{a,L} = \frac{N_{a,L}}{\sum_a N_{a,L}} \quad (7)$$

The number of fish at age a in each station is calculated from the length distribution at the station and the age–length key for the area where the station is:

$$n_{a,st} = \sum_L P_{a,L} n_{L,st} \quad (8)$$

Where L means length group, n_L total number of fish in length group L, a age group st station and the age–length key is calculated by equation 7.

Biomass of age group a at station st is computed from the length distribution at the station, the age–length key for the area where the station is and mean weight of length L in the area W_L (condition). Condition is calculated for the same areas as the age–length keys, since 1993 based on weighting of fish in the survey. Function of the form $W = \alpha L^{\beta}$ was found to have too little flexibility so a smoothing spline with 3 degrees of freedom is used.

$$B_{a,st} = \sum_L P_{a,L} n_{L,st} W_L \quad (9)$$

Mean weight of fish of age a at station st is obtained by dividing the result from equation 9 by the result from equation 8.

To be able to calculate mean length and standard deviation of length by age group the values $L \times n$ and $L^2 \times n$ must be kept track of. To calculate the same values by age the following equations are used.

$$nL_{a,st} = \sum_L P_{a,L} nL_{L,st} \quad (10)$$

$$nL^2_{a,st} = \sum_L P_{a,L} nL^2_{L,st} \quad (11)$$

In the March survey maturity-at-age and mean length by age of mature fish is calculated in addition to number, mean length and mean weight by age. Those calculations are done in similar way as shown before, except mature age in each age group is treated like a separate age group and mean length and mean weight are calculated for that group.

As mentioned earlier different age–length keys are used for the northern and southern area when compiling number and other values by age and station for cod.

Stratification

The strata used for survey index calculation for most species in the spring survey is shown in Figure 5 and for the autumn survey in Figure 4. The stratification is in general based on depth stratification and similar oceanographic conditions within each stratum.

The stratification used in the March survey was set up as part of the BORMICON multispecies project. The number of strata is quite large but so is the number of stations. When indices from the autumn survey started to be tested in assessment work it soon appeared that the number of strata should be reduced but the density of stations in the autumn survey is much lower than in the March survey. Indices for most species from both the surveys are available for both stratifications.

For cod assessment was based on indices from the March survey, using the old stratification scheme (Figure 5). Since 2009 indices from the autumn survey have also been used but they are based on the new stratification. The number of strata in the autumn survey is 33 (Figure 4) and the March survey 45. Extending the old stratification scheme to cover the autumn survey leads to 68 strata, and the subset of the new stratification scheme Figure 4 covering the March survey has 24 strata.

Some of the stations are near/at the boundary between strata and random changes in positions can lead to the stations not being in the same stratum each year. This is not desirable as the weight of each station varies between strata. Therefore a station is allocated into the strata that it has most often been calculated to be in.

Index calculation

For calculation of indices the Cochran method is used (citation) The survey area is split into strata (see the section above). Index for each stratum is calculated as the mean number in a standardized tow divided by the area covered multiplied with the size of the stratum. The total index is then a summed up estimates from the strata. A 'tow-mile' is assumed to be 0.00918 square nautical mile. That is the width of the area covered is assumed to be 17 m (17/1852=0.00918). When calculating the area of the strata closest to shore the part closest to the coast is excluded where it is not surveyed.

The same width of the trawl is used for the March survey and the smaller trawl in the autumn survey while 25% greater width is used for the large trawl in the autumn survey. As q is estimated separately for each survey the ratio of the values used does not matter. In the autumn survey the catch in the large trawl needs to be 25% higher than in the small trawl to get the same contribution to the index.

The following equations are a mathematical representation of the procedure used to calculate the survey indices:

$$\overline{Z}_i = \frac{\sum_i Z_i}{N_i} \qquad (12)$$

where $\overline{Z}_i$ is the mean catch (number or biomass or any other value available on station basis) in the i-th stratum, Z_i is the total quantity of the index (abundance or biomass) in the i-th stratum and N_i the total number of tows in the i-th stratum. The index (abundance or biomass) of a stratum (I_i) is:

$$I_i = \overline{Z}_i \left(\frac{A_i}{A_{tow}}\right) \qquad (13)$$

and the sample variance in the i-th stratum:

$$\sigma_i^2 = \left(\frac{\sum_i (Z_i - \overline{Z}_i)^2}{N_i - 1}\right)\left(\frac{A_i}{A_{tow}}\right)^2 \qquad (14)$$

where A_i is the size of the i-th stratum in NM ^{2} and A_{tow} is the size of the area surveyed in a single tow in NM ^{2}.

The index in a given region

$$I_{region} = \sum_{region} I_i \qquad (15)$$

the variance is

$$\sigma_{region}^2 = \sum_{region} \sigma_i^2 \qquad (16)$$

and the coefficient of variation is

$$CV_{region} = \frac{\sigma_{region}}{I_{region}}. \qquad (17)$$

When compiling the age disaggregated indices for March survey the Indices are compiled based on the following values at each stations.

1) Biomass per station and age group. $I_{B,a}$

2) Number per station and age group. $I_{N,a}$

3) Biomass of mature fish per station. $I_{Bmat,a}$

4) Number of mature fish per station. $I_{Nmat,a}$

5) Number times mean length at each station. $I_{N\times\bar{L},a}$

6) Number times mean length squared at each station. $I_{N\times\bar{L}^2,a}$

These indices with associated variance estimate are available for each stratum, and specific combinations of strata (including the whole area).

When the indices are have been calculated following derived quantities can be compiled from the indices, also available for each stratum, and specific combinations of strata (including the whole area).

1) Mean weight-at-age $W_a = \frac{I_{B,a}}{I_{N,a}}$

2) Mean weight-at-age of mature fish $W_{mat,a} = \frac{I_{Bmat,a}}{I_{Nmat,a}}$

3) Proportion mature $P_a = \frac{I_{Nmat,a}}{I_{N,a}}$

4) Mean length-at-age $\overline{L_a} = \frac{I_{N\times\bar{L},a}}{I_{N,a}}$

5) Standard deviation at age $\sigma_{L,a} = \sqrt{(\frac{I_{N\times\bar{L}^2,a}}{I_{N,a}} - \overline{L_a})^2}$

Computing the quantities in this way will give more weight to stations where density of stations is low.

The variance of the derived quantities is not calculated but it will in the end mostly depend on the number of fish in that age group sampled for otoliths and best be estimated by bootstrap.

C. Assessment: data and method

The Marine Research Institute's three main gadoid stocks have been assessed based on ADMB modules that were designed and written by Höskuldur Björnsson. Three modules have been in use:

- **adcam**: A forward running statistical catch-at-age model where fishing mortality-at-age is allowed to change gradually in time. The fishing mortality is allowed to deviate from separability using a random walk penalty in the objective function. This module has been used as the basis for the calculation of the annual TAC according to the HCR since 2002. Resembles the method called "correlated random walk" in SAM, but the correlation matrix has different structure and not as many variances can be estimated as the Adcam model is not a real state–space model, rather what has been Referred to as Error in Variables approach.
- **separ**: A statistical catch-at-age model were selection pattern are fixed over any given period. This module has been used in the HCR evaluations of the Icelandic cod (2009) and haddock and saithe (2013).
- **adapt**: A tuned VPA type of model, were no error is assumed in the catch-at-age.

All the models are stock assessment models with possibilities for short- and long-term predictions according to a number of HCR. Some of the predictions are adapted to the

Icelandic fishing year and the HCR used for Icelandic stocks. The Separable model and the Adapt model use the same input files and 90% of the code is the same.

Evolution of the stock and fisheries

$$\hat{N}_{1,y} = f(SSB_{y-1}) \tag{18}$$

$$N_{1,y} = \hat{N}_{1,y} e^{\xi_y} \tag{19}$$

$$N_{a+1,y+1} = N_{a,y} e^{-(F_{a,y}+M_{a,y})} + \Delta a, y \tag{20}$$

Where $\Delta a, y$ are estimated migrations of specified age groups in specified years For Icelandic cod these are imports from Greenland.

For the VPA model the stock is projected backwards

$$N_{a,y} = (N_{a+1,y+1}\, \Delta_{a,y}\, e^{0.5M_{a,y}} + C_{a,y}) e^{0.5M_{a,y}} \tag{21}$$

The migration $\Delta a, y$ are here multipliers limited to the range 0–1, assuming that the migration is at the beginning of the year.

The VPA model can only estimate migrations in periods where survey indices are available but the catch-at-age models can use anomalies in catch-at-age for estimation of migrations.

If the oldest age group A is a plus group, then its numbers develop according to.

$$N_{A,y+1} = N_{A-1,y} e^{-(F_{A-1,y}+M_{A-1,y})} + N_{A,y-1} e^{-(F_{A,y-1}+M_{A,y-1})} \tag{22}$$

For Icelandic cod the oldest age group A is not a plus group, so the equation changes to:

$$N_{A,y+1} = N_{A-1,y} e^{-(F_{A-1,y}+M_{A-1,y})} \tag{23}$$

The Adapt model is not designed for plus group.

Natural mortality was assumed fixed at the value of 0.2 The values used for prerecruits that are not in the fisheries, age 1–2 for cod do of course not matter and the value 0.0 would be the best choice, helping to relate number of prerecruits to the number of those entering the catches (age 3 for cod).

Catches removed from the stocks are estimated from stock number by Baranov's equation.

$$\hat{C}_{a,y} = \frac{F_{a,y}}{Z_{a,y}} (1 - e^{-Z_{a,y}}) N_{a,y} \tag{24}$$

In the separable model the fishery is simulated as a single fleet modelled as a non-parametric separable model:

$$F_{a,y} = F_y S_a \tag{25}$$

More than one separable period can be specified.

In the random walk model all the fishing mortalities $F_{a,y}$ are estimated and the random walk implemented through constraint in the likelihood function (see notes on likelihood function below). The estimation is done in two phases, first a separable model is estimated and later deviations from the separable model.

More than one stock–recruitment function is implemented in the model. Recruitment is not generated directly from the selected stock–recruitment model except in predictions. They do enter the assessment as residuals from stock–recruitment functions are used in the likelihood function to estimate the parameters. For stocks with good data the effects of the stock–recruitment function on historical assessment is small, but in predictions the stock–recruitment function is important although the parameters are often poorly estimated.

The functions allowed in the model are.

Hockey stick:

$$R_y = min\left\{R_{max}, R_{max}\frac{SSB_{y-1}}{SSB_{break}}\right\} \tag{26}$$

Ricker model:

$$R_y = R_{max}e^1\frac{SSB_{y-1}}{SSB_{max}}e^{\frac{-SSB_{y-1}}{SSB_{max}}} \tag{27}$$

and Beverton–Holt model:

$$R_y = R_{max}\frac{SSB_{y-1}}{SSB_{y-1}+SSB_{50}} \tag{28}$$

Constant recruitment

$$R_y = R_{max} \tag{29}$$

As seen from the equations R_y refers to recruitment-at-age 1 that is the first age group used in the cod assessment. The model can use other age groups as first age.

R_{max} is always estimated and also the second parameter called SSB_{break}, SSB_{max} or SSB_{50}, depending on the function specified.

R_{max} is set so that it can change in 1985 by a value that can be estimated. The reason for this setup is the 30–40% reduction in recruitment of Icelandic cod around before and after 1985. This option can be turned off by specifying the change to be zero.

In the evaluations of Harvest Control Rule for Icelandic cod in 2009 a number of other SSB–Recruitment functions were investigated, some of which are found in the code. Emphasis has also been put on statistical properties of the residuals from the SSB–recruitment function as described below.

Likelihood function

In the random walk model the error in catch in numbers is split in two parts.

- Process error i.e. the error between this years and last year's fishing mortality.
- The measurement error i.e. the difference between observed and modelled catches.

The model cannot estimate standard deviation of the total error (process + measurement error) independently for each age group. The pattern standard deviation of the total error with is specified and a multiplier estimated. The pattern is obtained from a Shephard–Nicholson model. Estimating a smooth function of age described with 2–3 parameters is also a possibility but the estimation is sometimes unstable.

The split of the total error into process error and measurement error is specified in the input file. The number given specify the proportion of the variance for each age group assigned as process error. The split is 50–50 of for ages 6–8 which are the ages with the least total error. For older fish higher proportion is allocated to measurement error and for younger age groups higher proportion is allocated to process error.

Difference in $log(F)$ between adjacent years follows multivariate normal distribution with correlation between ages.

$$\Gamma_{a_1,a_2} = \sigma_{p,a_1}\tau^{\left|\frac{(a_1-2)^{0.3}-(a_2-2)^{0.3}}{2^{0.3}-1^{0.3}}\right|}\sigma_{p,a_2} \tag{30}$$

$\Gamma_{a_1,a_2} = 1$ when $a_1 = a_2$. Where σ_{p,a_1} is standard deviation of the process error of age a_1. τ is an estimated parameter in the model called process correlation there. Equation 30 leads to more correlation between adjacent old age groups than adjacent young age groups i.e. the relative difference in age matters.

Measurement error in catch-at-age

The error in the catch-at-age is assumed to be lognormal and hence the likelihood is calculated as:

$$L_C = \sum_y \sum_a \left\{\frac{\left(log[C_{a,y}+\varepsilon_C]-log[\hat{C}_{a,y}+\varepsilon_C]\right)^2}{2\sigma_{aC}^2} + log(\sigma_{aC})\right\} \tag{31}$$

where ε_C is to reduce the effect of very small catches that are poorly sampled. Typical value of ε_c would be catches corresponding to 2–4 sampled otoliths. The standard deviations σ_{aC} are estimated as a multiplier on prespecified pattern. The pattern was generated from a Shephard–Nicholson model run based on the data from 1980–2008.

In the random walk model, σ_{aC} is generated from the total standard deviation and the split of the total variance between process and measurement error as described above.

Total landings

As described above catch in numbers-at-age is one component in the objective function to be minimized. This does in many cases guarantee that the modelled catch in tonnes is close to the landed catch but in some years this is not the case. In all cases one has:

$$Y_y = \sum_a C_{a,y}\, cW_{a,y} \tag{32}$$

$$\hat{Y}_y = \sum_a \hat{C}_{a,y}\, cW_{a,y} \tag{33}$$

To let the model follow the "real" landed catch the following term is added to the objective function.

$$L_Y = \sum_y \left[\frac{\left(logY_y - log\hat{Y}_y\right)^2}{2\sigma_Y^2} + log\sigma_Y\right] \tag{34}$$

where σ_Y is input from a file and is typically rather low (≈ 0.05). The statistical properties of this term as an addition to catch-at-age are somewhat questionable, but this formulation has often been used in statistical catch-at-age models.

Survey at-age

The predicted survey index $\hat{I}_{ay}$ is calculated from:

$$\hat{I}_{a,y} = q_a N_{a,y}^{\beta_a} \tag{35}$$

where α_a and β_a are estimated parameters. For cod the β_a is set equal to 1 for age 6 and older. The error in the survey at-age is assumed to be lognormal and hence the likelihood is calculated as:

$$L_I = \sum_y \sum_a \left\{ \frac{\left(log[I_{a,y}+\varepsilon_I]-log[\hat{I}_{a,y}+\varepsilon_I]\right)^2}{2\sigma_{aI}^2} + log(\sigma_{aI}) \right\} \tag{36}$$

where ε_I is externally set to reduce the effect of very small survey indices based on few otoliths . Typical value of ε_I would be indices that correspond to 2–4 sampled otoliths. The standard deviations σ_{aI} are estimated by the model by giving the pattern, estimating a multiplier. The pattern is estimated in the Adapt type model, the only type of model that can estimate σ_{aI} independently for each age group.

Since correlation between indices of different age groups is modelled the equation is changes to:

$$\Gamma = log\left[I_{a,y} + \varepsilon_I\right] - log\left[\hat{I}_{a,y} + \varepsilon_I\right] \tag{37}$$

$$L_I = \sum_y \left\{0.5 log\left(det\, \Theta_I \right) + \Gamma^T\, \Theta_I^{-1}\, \Gamma\right\} \tag{38}$$

Where $Gamma$ is the vector of residuals and Θ the correlation matrix.

In the model runs conducted here the matrix Θ_I is generated by a 1st order AR model.

$$\Theta_{Iij} = \sigma_{Ii}\sigma_{Ij}\kappa^{|i-j|} \tag{39}$$

where κ is an estimated parameter which has been estimated in the range 0.2 to 0.7 for cod, haddock and saithe in the March groundfish survey. High value of κ indicates that the residuals in the survey approach a year factor. The estimate of the parameter for cod is 0.42 for the March survey and 0.53 for the autumn survey. The effect of modelling this correlation on estimated biomass varies from year to year but the effect is to take less notice of survey abundance indices.

In the random walk model the equation for Θ_I is similar to what is used to model the correlation in process error (equation 30).

$$\Theta_{Iij} = \sigma_{Ii}\sigma_{Ij}\kappa^{\left|\frac{i^{0.7}-j^{0.7}}{2^{0.7}-1^{0.7}}\right|} \tag{40}$$

Compared to equation 39 this equation increases the correlation between age groups of old fish compared to young fish, i.e. it is more the relative difference in age that matters.

Stock–recruitment likelihood function

This component involves discrepancy between observed and modelled recruitment. The model allows for autocorrelation in residuals and CV of residuals can be a function of spawning stock size. The likelihood is calculated by the equations.

$$\hat{N}_{1,y} = f(SSB_{y-1}) \quad (41)$$

$$\Gamma_{SSB-R} = log[N_{1,y}] - log[\hat{N}_{1,y}] \quad (42)$$

$$\sigma_{3y} = \sigma_3 \left(\frac{SSB_y}{SSB_{ref}}\right)^{\beta_3} \quad (43)$$

$$\Theta_{SSB-Rij} = \sigma_{3i}\sigma_{3j}\kappa_3^{|i-j|} \quad (44)$$

$$L_{SSB-R} = \sum_y \left\{0.5log(det\,\Theta_{SSB-R}) + \Gamma_{SSB-R}^T \Theta_{SSB-R}^{-1} \Gamma_{SSB-R}\right\} \quad (45)$$

σ_3 standard deviation of the residuals, κ_3 autocorrelation and β_3 dependence on SSB, usually not included.

The parameters σ_3, κ_3 and β_3 are all among parameters that can be estimated. Estimating them all in addition to the three parameters of the SSB–rec function requires a very long time-series. The SSB–rec function has three parameters due to the change in R_{max} observed in 1985. In the work here 3–4 parameters are estimated, 2–3 parameters of the SSB–rec function and the parameter σ_3. The parameters κ_3 and β_3 were set to low values in the estimation part but a fixed value of the autocorrelation parameter, estimated external to the model is used in stochastic simulations. Anyone trying to estimate parameters of a simple AR model from 50 years of data discovers that the estimate is very poor except the autocorrelation is small.

The choice of stock–recruitment function has minor effects on the results of stock assessment but is of course of importance in future simulations.

Estimated parameters

Estimated parameters in the random walk assessment model are

- Initial numbers in stock.
- Recruitment-at-age 1 each year.
- Parameters of the stock–recruitment function.
- Fishing mortality each year and age.
- q_a and β_a for the surveys. (equation 35)
- σ_c, σ_I and σ_3, i.e. multiplier on standard deviation of catch residuals, multiplier on standard deviation of survey residuals and multiplier on SSB–recruitment residuals.
- Correlation parameters κ in the survey likelihood and τ in the process error.

Estimated parameters in the separable model are

- Initial numbers in stock.
- Recruitment-at-age 1 each year.
- Parameters of the stock–recruitment function.

- Effort for each year.
- Selection pattern for each age and selection period.
- q_a and β_a for the surveys. (equation 35)
- σ_C, σ_I and σ_3, i.e. multiplier on standard deviation of catch residuals, multiplier on standard deviation of survey residuals and multiplier on SSB–recruitment residuals.
- Correlation parameters κ in the survey likelihood.

In the Adapt type model the estimated parameters are

- Number in stock in the assessment year.
- Parameters of the stock–recruitment function.
- q_a and β_a for the surveys. (equation 35)
- σ_I and σ_3, i.e. multiplier on standard deviation of catch residuals, multiplier on standard deviation of survey residuals and multiplier on SSB–recruitment residuals.
- Correlation parameters κ in the survey likelihood.

As described at the beginning the inverse Hessian matrix of the parameter estimates is used as a proposal distribution in MCMC runs. The number of runs was usually 1.0 million with the parameter set from every 500th run saved. Probability distribution of spawning stock, reference biomass and other parameters is obtained by printing the respective values to a file in each of the stochastic simulations.

The exact settings of the historical assessment model do affect the estimate of stock in the assessment year (±20%) but have less effect on the results of the long-term simulation where the stock–recruitment parameters have most effect. If the simulation were run in a closed loop with assessment model in the feedback loop those settings would have more effect, but to used it to infer about "correct" model settings would require a realistic observation model.

Short-term deterministic prediction

The prediction occurs in few steps.

1) Calculate mean weight and maturity-at-age from the March survey in the assessment year.
2) Estimate true reference biomass and spawning stock.
3) Calculate recruitment from SSB–Recruitment relationship.
4) Calculate the TAC for next fishing year from equation 1.
5) Calculate catch in the assessment year $C_y = \frac{2}{3}TAC_{y-1/y} + \frac{1}{3}TAC_{y/y+1}$.
6) Calculate selection-at-age, based on the average of last five years.
7) Calculate F_y for the assessment year by iterating the equations $F_{a,y} = F_y S_{a,y}$ and $\hat{C}_y = \sum_a \frac{F_{a,y}}{Z_{a,y}}(1 - e^{Z_{a,y}})N_{a,y}cW_{a,y}$. The two equations are solved for F_y by Newton's method until $C_y - \hat{C}_y = 0$.
8) Project the stock forward one year.

If projection for more than one year is to be done, the steps are repeated. What is then required are catch weight, SSB weights and maturity-at-age for those years. The default is to use the values for the assessment year.

Mean weight-at-age, maturity-at-age, recruitment, selection-at-age and maturity-at-age can be multiplied with stochastic noise.

The current model used in the annual stock assessment is **adcam**. The input is as follows:

	Type	Year.range	Age.range	Variable
1	Caton	1955 onwards		Yes
2	Canum	1955 onwards	3–14	Yes
3	Weca	1955 onwards	3–14	Yes
4	West	1955 onwards	3–10	Yes
5	Mprop	1955 onwards	1–14	No
6	Fprop	1955 onwards	1–14	No
7	Matprop	1955 onwards	1–14	Yes
8	Natmor	1955 onwards	1–14	No
9	Spring survey (SMB)	1985 onwards	1–10	Yes
10	Fall survey (SMH)	1996 onwards	1–10	Yes

D. Short-term projections

Short-term prediction for Icelandic cod is rather simple as the TAC next fishing year does depend on TAC in the current fishing year and biomass 4+ and SSB in the assessment year. Maturity-at-age, mean weight-at-age and mean weight-at-age in the SSB in the assessment year are all available at the time of assessment, the only missing values for the TAC are mean weight-at-age in the catches that are obtained from equations 2 and 3.

E. Biological reference points

		Type	Value	Technical basis
1	Management plan	MP $B_{trigger}$	220 000	Set by managers, consistent with ICES MSY framework
2		Harvest rate MP	0.2	Set by managers, consistent with ICES MSY framework
3	MSY framework	MSY $B_{trigger}$	220 000	Trigger point in HCR considered consistent with ICES MSY framework
4		F_{MSY}	Not relevant	
5	Precautionary approach	B_{lim}	125 000	Bloss
6		B_{PA}	Not defined	
7		F_{lim}	Not defined	
8		F_{PA}	Not defined	

Table 1: Number of vessels used and the number of stations taken in the Spring Groundfish Survey 1985-2014.

Year	Number of vessels	Number of stations	Year	Number of vessels	Number of stations
1985	5	593	2000	4	532
1986	5	585	2001	4	532
1987	5	566	2002	4	526
1988	5	545	2003	4	536
1989	5	568	2004	4	538
1990	5	567	2005	5	550
1991	5	570	2006	5	555
1992	5	574	2007	5	548
1993	5	597	2008	5	566
1994	5	596	2009	5	595
1995	5	600	2010	5	594
1996	4	540	2011	5	595
1997	4	533	2012	5	597
1998	4	506	2013	5	594
1999	4	530	2014	4	591

Table 2: Vessels used in the Autumn Groundfish Survey 1996-2010, their survey areas, and the number of stations taken. The survey was not conducted in 2011.

	Shallow waters		Deep waters		
Year	Vessel name	Number of stations	Vessel name	Number of stations	Total stations
1996	r/v Bjarni Sæmundsson	146	Múlaberg ÓF32	144	290
1997	r/v Bjarni Sæmundsson	150	Brettingur NS50	149	299
1998	r/v Bjarni Sæmundsson	153	Brettingur NS50	144	297
1999	r/v Bjarni Sæmundsson	166	Brettingur NS50	149	315
2000	r/v Bjarni Sæmundsson	160	r/v Árni Friðriksson	219	382
2001	r/v Bjarni Sæmundsson	160	r/v Árni Friðriksson	219	380
2002	r/v Bjarni Sæmundsson	162	r/v Árni Friðriksson	221	383
2003	r/v Bjarni Sæmundsson	162	r/v Árni Friðriksson	220	382
2004	r/v Bjarni Sæmundsson	162	r/v Árni Friðriksson	220	382
2005	r/v Bjarni Sæmundsson	162	r/v Árni Friðriksson	219	381
2006	r/v Bjarni Sæmundsson	162	r/v Árni Friðriksson	219	381
2007	r/v Bjarni Sæmundsson	162	r/v Árni Friðriksson	219	381
2008	r/v Bjarni Sæmundsson	181	r/v Árni Friðriksson	219	400
2009	r/v Bjarni Sæmundsson	178	r/v Árni Friðriksson	219	397
2010	r/v Bjarni Sæmundsson	179	r/v Árni Friðriksson	203	382
2011	No survey conducted				
2012	r/v Bjarni Sæmundsson	178	r/v Árni Friðriksson	202	381
2013	r/v Bjarni Sæmundsson	179	r/v Árni Friðriksson	201	379
2014	Jón Vídalín VE-82	179	Ljósafell SU-70	201	380

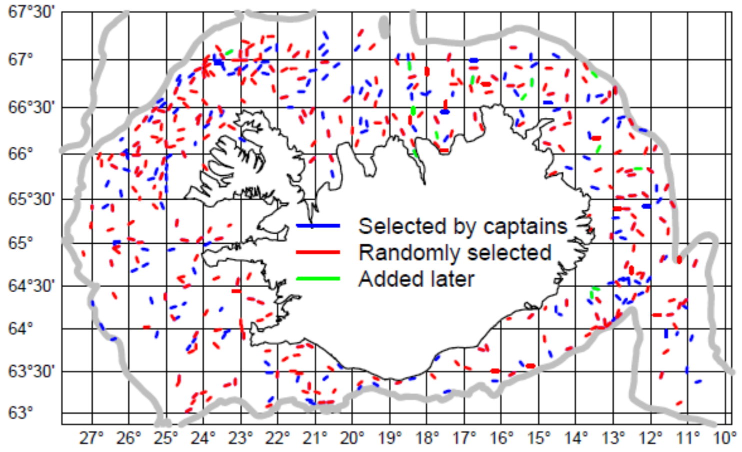

Figure 1: Stations in the spring survey. The picture shows the 1995 survey.

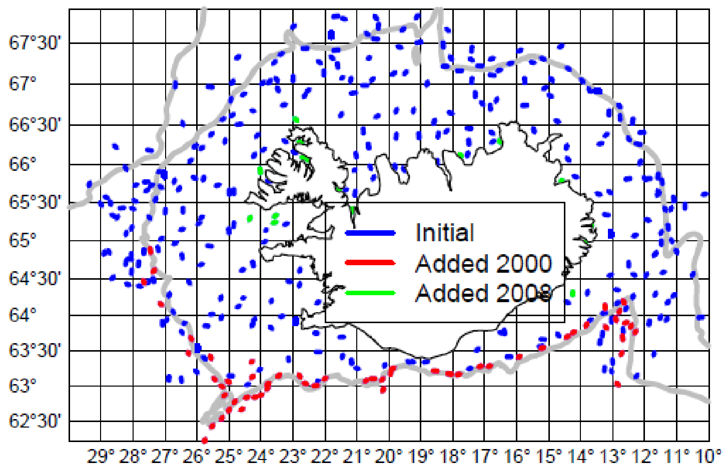

Figure 2: Stations in the autumn survey showing the 2013 survey.

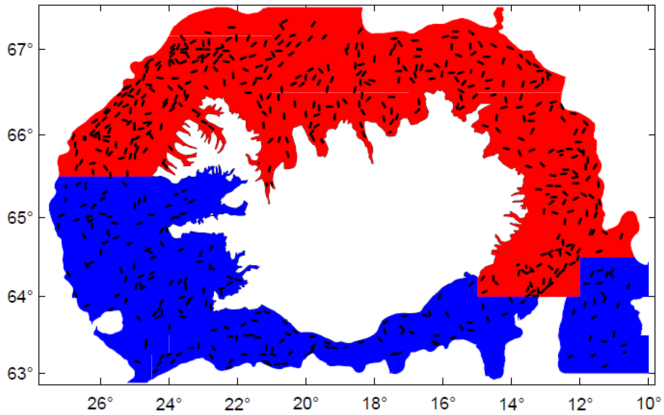

Figure 3: Division of the survey area into north and south. Stations from the March survey 2014 shown for comparison

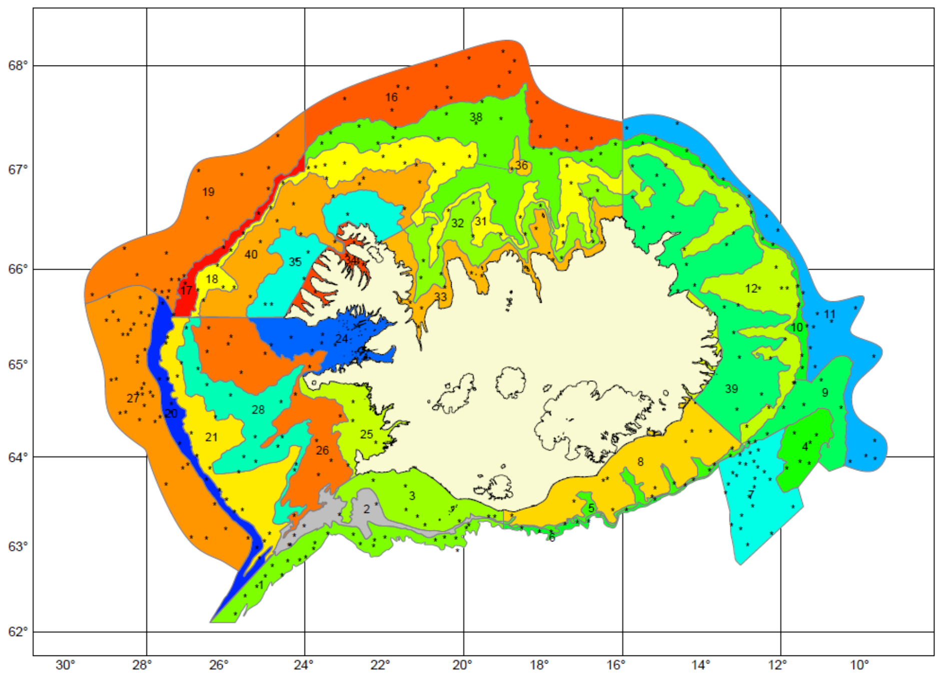

Figure 4: Sub-areas or stratas used for calculation of cod survey indices of the Autumn Survey in Icelandic waters. The dots show the stations

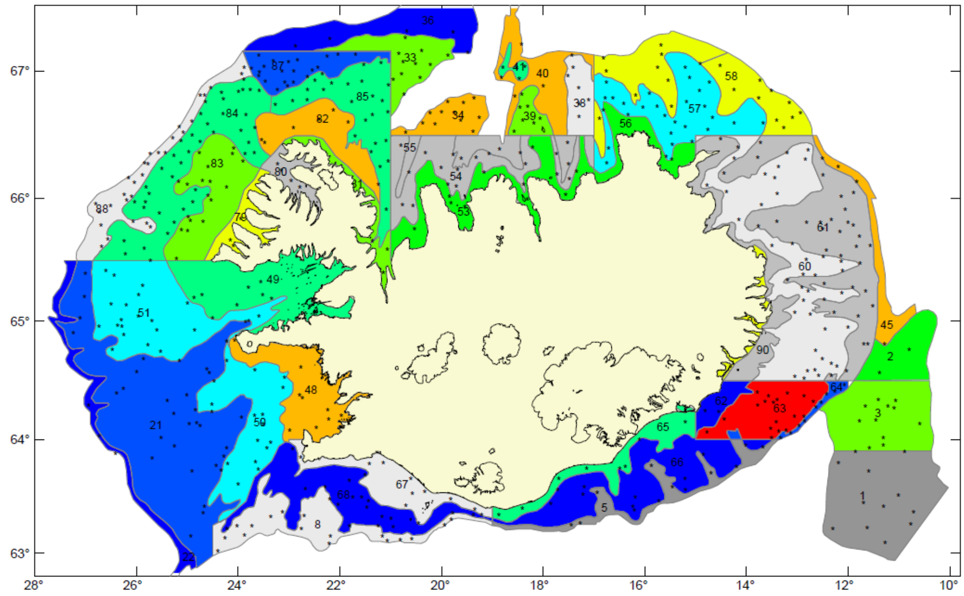

Figure 5: The old stratification that is used to calculate survey indices of cod in spring survey. The dots show the stations