ICES WKBUT REPORT 2013

ICES ADVISORY COMMITTEE

ICES CM 2013/ACOM:44

Report of the Benchmark Workshop on Greenland Halibut Stocks (WKBUT)

26–29 November 2013

Copenhagen, Denmark

International Council for the Exploration of the Sea

Conseil International pour l'Exploration de la Mer

International Council for the Exploration of the Sea
Conseil International pour l'Exploration de la Mer

H. C. Andersens Boulevard 44–46
DK-1553 Copenhagen V
Denmark
Telephone (+45) 33 38 67 00
Telefax (+45) 33 93 42 15
www.ices.dk
info@ices.dk

Recommended format for purposes of citation:

ICES. 2013. Report of the Benchmark Workshop on Greenland Halibut Stocks (WKBUT), 26–29 November 2013, Copenhagen, Denmark. ICES CM 2013/ ACOM:44. 367 pp.

Contents

1 Executive Summary

WKBUT 2013 met from 26 to 29 November 2013 at ICES Headquarters. The meeting was co-chaired by ICES Chair Jesper Boje (Denmark) and External Chair Joanne Morgan (Canada). David Miller (Netherlands) and Hans Lassen (Denmark) participated in the meeting as invited external experts. A total of 21 participants from eight countries were in attendance.

The main goals and objectives of the meeting were to compile and evaluate data sources for stock assessment, investigate assessment models suitable to provide information on stock status and to update the relevant stock annexes for two stocks. These were Greenland Halibut in Subareas V, VI, XII, and XIV and Northeast Arctic Greenland Halibut in Subareas I and II. A review of the stock in NAFO Subareas 0 and 1 was also undertaken (see ToR in Annex 1). In addition issues related to ageing and maturity staging were discussed.

The main generic results of the meeting were:

1.1 Use of ageing in assessments

A review of the conclusions of WKARGH was presented as well as work on age validation using bomb radiocarbon assays. Although at this time the best method for determining age in Greenland halibut has not been established, it is clear that the traditional method under ages older fish. Validation studies available to WKARGH supported the new methods. The discrepancy in age determination begins somewhere between ages 5 and 10. The issue of age determination has clear implications for any age-based model or any model that relies on a growth assumption. It is likely that growth rates vary between populations. Analyses should use growth assumptions consistent with the new age reading methods as the base case. Further development of the new methods, particularly further age validation, is strongly encouraged.

1.2 Maturity staging

A summary of the findings from ICES Workshop on maturity standardization of redfish and Greenland halibut (WKMSREGH) as they relate to female Greenland halibut was presented. A general agreement during the WKMSREGH was that the maturity cycle lasts at least two years, but females still spawn every year. Primiparous (maturing for the first time) fish are biologically mature, but functionally immature and should not be included in the spawning–stock estimate. Designation of reproductive status should separate immature and maturing, but functionally immature, from adult fish and the primiparous fish should not form part of the spawning–stock biomass. Further the WKMSREGH recommended that maturity data be sampled 2–5 months prior to spawning. This should eliminate the uncertainty of including maturing, but functionally immature females, in the spawning–stock estimates. Maturity ogives should be estimated by sex, due to the sexual dimorphism of the species. Some survey data available for the assessments of Greenland halibut can be split according to the new recommendations.

This is not done so far, but should be done in future assessments. Maturity classification schemes should be in accordance with the recommendations of WKMSREGH.

For the three stocks considered the main results were:

1.3 Northeast Arctic Greenland halibut (ICES Subareas I and II)

The consistency of data from different surveys was examined and formed a large part of the discussion. In addition, preliminary modelling work using GADGET and Bayesian Surplus Production models were presented. Most formulations of both models showed the stock to be at a stable biomass level in recent years. The modelling approaches showed promise, but were not ready for use in the provision of advice at this time. The approaches should be pursued further with presentation during the AFWG. In order to further develop the GADGET model all Norwegian ageing data that are available using the newly developed method should be used.

Uncertainties remain about the appropriate set of indices to use in any modelling exercise. A workshop or similar process is required to examine the indices further and determine which should form the basis of further modelling. This workshop should examine:

Commercial fleet data: all cpue series need to be examined in more detail. The Russian fishing vessel index in 1964–2012 shows a weak reaction to large changes in catch while both this series and the Norwegian low-tonnage trawl vessels show abrupt changes in the level of cpue. These aspects need to be examined, in particular to determine if the time-series need to be split. Also, the sex composition of catches at each fishery should be taken into account. The trawl fleet catches contain more males than the gillnet/longline fleet which catch females primarily. So they may not reflect total-stock biomass dynamics properly if male and female portions of the stock have a different dynamics. Analyses should consider whether adjustments for a 'technology creep' (which often occurs for cpue series) have occurred.

Survey series: the current surveys likely cover different portions of the population both spatially but also different length/ages. Therefore for all indices it should be clarified which part of the NEA Greenland halibut population they cover and if they are appropriate to reflect the dynamics of the modelled population. This will require detailed examination and comparison of the data (total number and weight, length frequencies by sex) for all series at the most disaggregated level possible (preferably on a haul by haul basis).

The workshop should occur in 2014. The agreed indices coming from this workshop will be used in further model development which will be reviewed at a later benchmark. The benchmark could be done via WebEx. ToR for this workshop can be found in Annex 6.

1.4 Northwestern Greenland halibut (ICES Subareas V + XIV + VI + XII)

Input data to the assessment were examined. A new index combining the Icelandic autumn groundfish survey and the East Greenland survey was developed based on a revised stratification scheme covering the area of both surveys. This new combined index was considered to provide a good reflection of stock status and was accepted as the survey index for this stock. The commercial cpue from Va was found to be heavily influenced by catch rates in month 4–6 in the early part of the time-series and an interaction between month and year seems evident. This requires further investigation as this time-series is influential in model results. The results of these analyses should be reviewed in advance of the 2014 NWWG meeting with the aim of providing a new cpue series for use in the assessment.

A variety of analyses were presented using different models and formulations. The focus was on the current assessment model, a state–space surplus production model in a Bayesian framework (SPM), and a length and age-structured model (Gadget). The benchmark concluded that Gadget showed promise but was not yet ready for use as the assessment model. The assessment model should remain the SPM using the new combined survey index and the cpue index as it is revised. Reference points as derived from this model are 30% B_{MSY} as B_{lim}, 1.7 x F_{MSY} as F_{lim} and an $MSYB_{trigger}$ as 50%B_{MSY}.

Gadget should continue to be developed and be reviewed at an inter-benchmark. This work will likely take one to two years and the date of the inter-benchmark should be set two to three months after the work is complete in order to give participants time to review the analyses. The Gadget model should include the anticipated revised cpue, length frequencies representative of all the catch, the new combined survey index, a growth function based on Icelandic tagging data, length selectivities by sex, and iterative reweighting as in the assessment of tusk in Va. Uncertainties on the estimates, tests of sensitivity to the natural mortality assumption, and analyses of possible reference points should be presented.

1.5 Greenland halibut in NAFO Subareas 0+1

The benchmark was asked to consider the best way to analyse the survey data (areas separate and combined) and to comment on a proposed approach to providing advice. The benchmark also reviewed several analyses of the survey, catch and inclusion of environmental data in stock dynamics.

The benchmark suggested that the surveys in the different areas be combined in the provision of advice, provided they are conducted in the same year. They should however, continue to be examined separately as well in order to detect any differences in trends in the different areas. The benchmark considered that an approach similar to the ICES approach for data-limited stocks could be adapted for use in this stock. If surveys are not conducted annually, then it will extend the period required to evaluate stock trends and determine if changes in TAC are warranted.

A range of F_{MSY} estimates from several analyses was provided, however, there is currently no estimate of F for this stock. An index of relative F (catch divided by survey biomass) could be used as a proxy to indicate trends. Since the gillnet fishery catches fish outside the size range in the survey, relative F using gillnet catch is unlikely to be a good index of exploitation rate. In the areas where there are only trawl fisheries, the benchmark suggested that relative F might be a reliable index. Where gillnet fisheries exist, relative F could be calculated using trawl catch only. This would mean that the index of fishing mortality does not include the gillnet portion of the fishery. The performance of the gillnet fishery can be monitored through catch, catch rate and size composition. The proportion of gillnet to trawl catch should also be monitored.

2 Introduction

The present benchmark workshop on Greenland halibut stocks was established because of stock-specific issues. The aims were the improvement of both input data and assessment methodology and to have a common workshop covering more of the Greenland halibut stocks in the North Atlantic to discuss common biological issues such as stock connectivity and growth that are key parameters in assessment methods.

Currently the NAFO stock (SA 0+1) and the ICES Northeast Arctic Greenland halibut stock (SA I+II) are assessed qualitatively based on survey and cpue indices (category 3 stock), while the ICES Northwestern stock (SA V, VI, XII and XIV) is assessed by a stock production model which also provides stochastic forecasts (category 1). The overall objective of the benchmark was therefore to introduce quantitative assessment methods for the category 3 stocks and to improve the present stock assessment model for the category 1 stock. The inclusion of a NAFO stock in an ICES benchmark workshop was mainly suggested for comparative reasons (e.g. choice of central parameters such as growth and maturity) as it is known that connectivity exists between all stocks and since environmental factors at depths where Greenland halibut is distributed are very similar in the North Atlantic. One reason to include NAFO stocks was also to facilitate cooperation in development and implementation of stock assessment models and make use of different scientific schools or traditions that ICES and NAFO constitute.

Prior to the benchmark a data web meeting was held to provide status of ongoing work and data compilation. Especially for the NEA Greenland halibut access to data and compilation of those created problems and as a consequence much of the intended work could not be finalized at the benchmark but were referred to an *ad hoc* meeting scheduled for 2014.

A generic issue was dealt with at the first day of the benchmark workshop, namely ageing and growth. Controversy has arisen on ageing for this species with mainly two perceptions of growth. Since this issue is an important assumption for some of the assessment models suggested for the benchmark meeting, this was discussed on the first day of the meeting. A decision was taken based on available information which includes a recently held ageing workshop.

3 Age determination, growth and maturity

3.1 Age determination and growth

3.1.1 Status of age reading

The traditional age reading of Greenland halibut was a well-established method agreed on through a NAFO-ICES workshop in 1996 (ICES, 1996). However, in 2003, ICES AFWG first noted that there was an uncertainty in age reading. In 2005 a WD stated that the traditional method underestimates the age of older fish, and this was supported by a NAFO workshop in 2006 as well as through several following studies (Gregg *et al*., 2006; Cooper *et al*., 2007; Treble *et al*., 2008 and Albert *et al*., 2009).

The traditional methods typically indicated an age around 10–12 years for 70 cm fish. The new methods provide much higher longevity and approximately half the growth rate from 40–50 cm onwards compared to the traditional methods. These typically produce age estimates around 20 years of more for 70 cm fish.

An ICES workshop on age reading of Greenland halibut (ICES WKARGH) was consequently arranged in Vigo, Spain, in 2011. Several age reading methods were described and evaluated together with available validation and corroboration results. Validation methods included bomb radiocarbon and mark-recapture of chemically tagged wild fish. Corroboration methods used were modal length analysis and tag recaptures analysis. All validation and corroboration methods were in favour of the new ageing methods.

WKARGH concluded that results from bomb radiocarbon and chemically tagged fish are consistent and show that longevity is much greater and growth rate less than half of that reported based on the traditional ageing method. OTC tagging results show that the left whole otolith, which is commonly used as the basis for the traditional age estimates, apparently shows no growth in surface area for slow growing individuals. Without improved techniques, this prohibits accurate age estimation of these individuals by use of the whole left otolith surface. Based on all available evidence at WKARGH it appears that the traditional method underestimate age for ages above five years, and stock assessments should note that the likelihood that catch-at-age matrices based on the traditional ages are likely to be in error (too low ages). A variety of ageing methods were examined at WKARGH of which several showed improved clarity and interpretation compared to the traditional whole left otolith technique. WKARGH concluded that none of the ageing methods stand out as being ideal, and that there is still work to be done to determine the best methods. Still, WKARGH recommended that based on present knowledge, identification of annual zones in Greenland halibut otoliths should preferably be done along the longest growth axis of the whole right otoliths or towards the proximal edge of the sectioned left otoliths (new methods respectively developed in Norway and Seattle use these approaches).

3.1.2 Age validation using bomb radiocarbon assays

A comparison of ages determined for whole ('traditional' method) vs. thin sectioned otoliths (266 otoliths) was conducted. In addition bomb radiocarbon assays were conducted on 24 pairs of otoliths from fish (57–108 cm) from NAFO SA 2+ Division 3K that were also aged by thin sections to validate the ageing by this method. The results showed that Greenland halibut in the Northwest Atlantic are older and more slow-growing than previously reported. The bomb radiocarbon assays determined that in general sectioned otoliths provide an accurate age for Greenland halibut. Whole and sectioned otolith ages agree until age 9 or 10 (~60 cm), after which age is underestimated using whole otoliths (K.S. Dwyer *et al.*, 2013).

3.1.3 Conclusion on perception on ageing

WKBUT concluded that for potential stock assessment models (Gadget) for the two ICES stocks, assumptions about ageing should be consistent with the results of the new ageing methods.

3.2 Maturity

Previous studies on Greenland halibut reproduction biology have revealed difficulties in interpreting the macroscopic maturity scale. In particular it has been difficult to separate what has previously been termed as resting females from early maturing and females in early maturation. The ICES Workshop on maturity standardization of redfish and Greenland halibut (ICES, 2011) met in Vigo 28th November–1st December 2011 in order to address these issues as well as preparing a standardized maturity classification between marine institutes of the North Atlantic. There was a good general agreement between readers on macroscopic and microscopic assignment of maturity stage during the meeting, and that the main bottleneck is clearly to distinguish between immature – inactive mature and resting females. It has been suggested that the adolescent phase is long - up to four years or more (Junquera *et al.*, 2003) as well as indications of two year period for maturing the eggs (oocytes) for one years' production of off spring (Kennedy *et al.*, 2011). A general agreement during the meeting was that maturity cycle last at least two years, but females still spawn ever year. Primiparous fish are biologically mature, but functionally immature and should not be included in the spawning–stock estimate. The future maturation scale should imply 7 stages: 1- Immature, 2- maturing but functionally immature, 3- maturing eggs 1–2 mm, 4- late maturing eggs 2–4 mm, 5- spawning and 6-spent/recovering. A seventh stage should be used when difficult to distinguish between 1, 2 and 6, and the need of this stage should be considered in future. Main recommendations are further to sample maturity data 2–5 months prior to spawning in order to eliminate the uncertainty of including maturing, but functionally immature females in the spawning–stock estimates, and to estimate maturity ogives on females only, due to the sexual dimorphism of the species. Some survey data available for the assessments of Greenland halibut can be split according to the new recommendations. This is not done so far, but should be done in future assessments. Maturity classification schemes should be in accordance with the recommendations of WKMSREGH.

3.3 References

ICES. 2011. Report of the Workshop on Age Reading of Greenland Halibut (WKARGH). ICES CM 2011/ACOM:41.

K.S. Dwyer, S. E. Campana and M. A. Treble Fisheries and Oceans Canada. 2013. Age validation of Greenland Halibut in the Northwest Atlantic using bomb radiocarbon assays. PPT presentation at WKBUT 2013.

4 Northeast Arctic (NEA) Greenland halibut stock (ICES Subareas I and II)

4.1 Current assessment and issues with data and assessment

An age based assessment (XSA) has been performed for this stock until 2013. However, since 2006 advice has been given based on trends based assessments conducted using surveys and cpues, as the age reading was not found reliable and age data based on the traditional ageing method have not been supplied by Norway after 2005 (see Section 3). The intention is to switch to an assessment model that incorporates uncertainty in estimation of parameters, is more flexible regarding input data, and less dependent on age directly than the XSA.

4.2 Compilation of available data

4.2.1 Biological data– growth

As the new ageing method has been under development in recent years in Norway and routine ageing has newly started, limited amounts of age–length data based on ageing with this method are available (Hallfredsson, WKBUT WD 16). At present in total 1568 specimens of Greenland halibut have been aged with the new method. All were collected at the Norwegian continental slope survey in autumn. As expected, a considerable difference in growth is predicted based on the new ageing method compared to the traditional ageing (Figure 4.2.1.1). Only data from 2009 (N=760) were available for the GADGET model work in advance of the WKBUT, and in the base run for the NEA stock von Bertalanffy's growth was assumed with t_0=0 (Table 4.2.1.1). Through GADGET model work at WKBUT it has become apparent that more age readings are needed by the new ageing method. This is true especially for specimens <40 cm and >70 cm in body length.

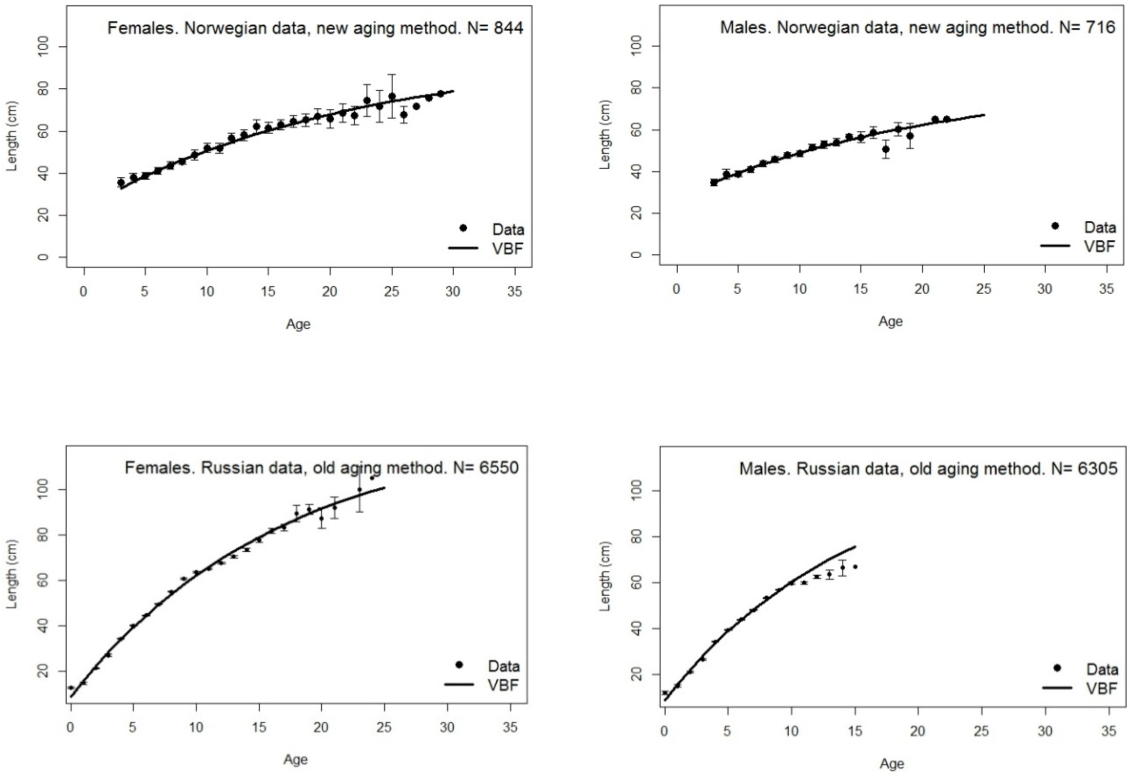


Figure 4.2.1.1. Growth of male Greenland halibut based on all currently available age readings by new ageing method in Norway (upper panels), and based on Russian data from 2008–2012 and old ageing method (lower panel). Also shown are von Bertalanffy's growth functions.

Table 4.2.1.1. Estimates of parameters in von Bertalanffy's growth function as fitted by the NLS function in R. Data from the Norwegian Slope Survey.

			ESTIMATE	STD. ERR	T VALUE	PR(>|T|)	
Norwegian	Females	Linf	98	10	9.5	< 2e-16	***
Slope Survey	N=844	K	0.046	0.011	4.3	1.86E-05	***
2001, 2007, 2009		t0	-5.95	1.19	-5.0	0.000000635	***
and 2011	Males	Linf	83	15	5.7	0.000000021	***
New ageing method	N=716	K	0.049	0.020	2.5	0.013268	*
		t0	-7.95	2.14	-3.7	0.000216	***
	Both sexes	Linf	119	19	6.3	3.96E-10	***
	N=1560	K	0.029	0.008	3.6	0.000336	***
		t0	-8.64	1.25	-6.9	6.07E-12	***
Norwegian	Females	Linf	72	2	45.4	<2e-16	***
Slope Survey	N=844	K	0.151	0.007	21.7	<2e-16	***
2009		---					
t0=0	Males	Linf	54	1	48.2	<2e-16	***
New ageing method	N=716	K	0.272	0.016	16.6	<2e-16	***

	Both sexes	Linf	66	1	58.5	<2e-16	***
	N=1560	K	0.175	0.006	27.0	<2e-16	***

Signif. codes: 0 '*' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1**

4.2.2 Tuning data

Indices from Norwegian and Russian surveys and from a number of cpue series were presented at the meeting. Many of the indices conflicted in the signals and could thus not all reflect the underlying stock trends. Given the time available at the benchmark it was decided to postpone a more detailed analysis of the different stock indices to a workshop in 2014. The main objectives of the workshop should be to describe expected coverage of life stages for each index, and also for the cpue series try to estimate the expected technological creep (increased efficiency of gear) over time and to examine the sex composition of the catches in the cpue series. Present ICES advice for the stock is trend based and mainly on biomass indices from two research surveys (Hallfredsson *et al*., 2013); the Russian Autumn survey in Barents Sea and adjacent waters, and the Norwegian Slope survey. The biomass indices for these surveys showed a similar trend until around 2006, but after that they have shown considerable divergence as the index from the Russian survey shows a profound increase in biomass while the Norwegian survey shows a relative downward trend (Figure 1, 2 and 3). However, the two surveys are not directly comparable due to difference in survey area (Hallfredsson *et al*., 2013). The Russian survey covers both the slope areas down to 900 m depth with high densities of adult Greenland halibut and the shallow central Barents Sea up to 100 m depth with predominantly immature fish. The Norwegian Slope survey covers the adult stock at depths 400–1500 m depth at the continental slope and not the central Barents Sea. One of the main tasks at the scheduled workshop for NEA Greenland halibut in 2014 is to examine their utilization as biomass indicators for the entire NEA stock.

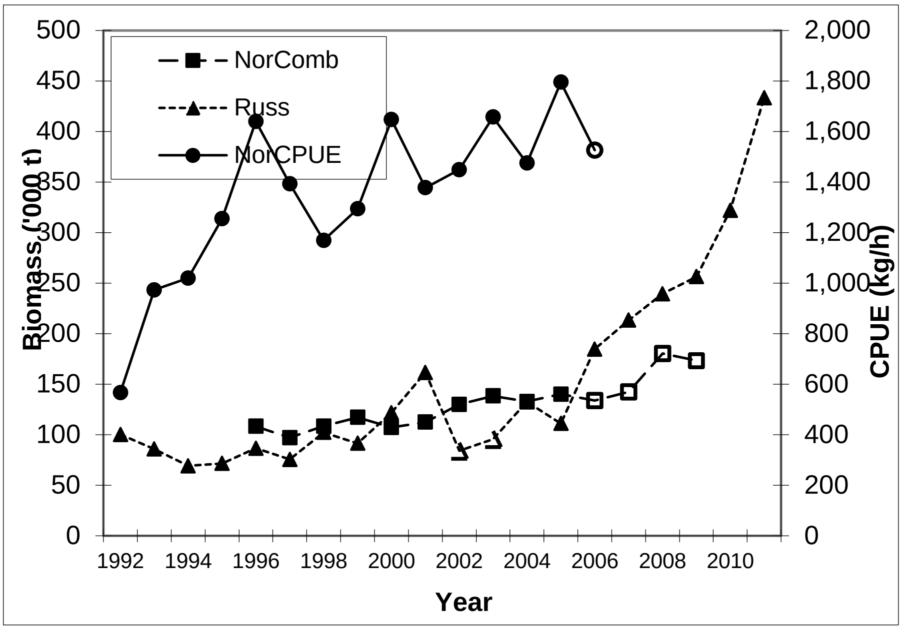


Figure 4.2.2.1. NEA Greenland halibut. Biomass estimates from different tuning series used in the trial XSA at AFWG 2012. Total biomass index (Russ) from the Russian autumn survey is shown. Norwegian cpue index (NorCpue) and Norwegian combined index (NorComb) are currently not updated. Years with open symbols indicate years excluded in the tuning. (Report ICES, AFWG 2012).

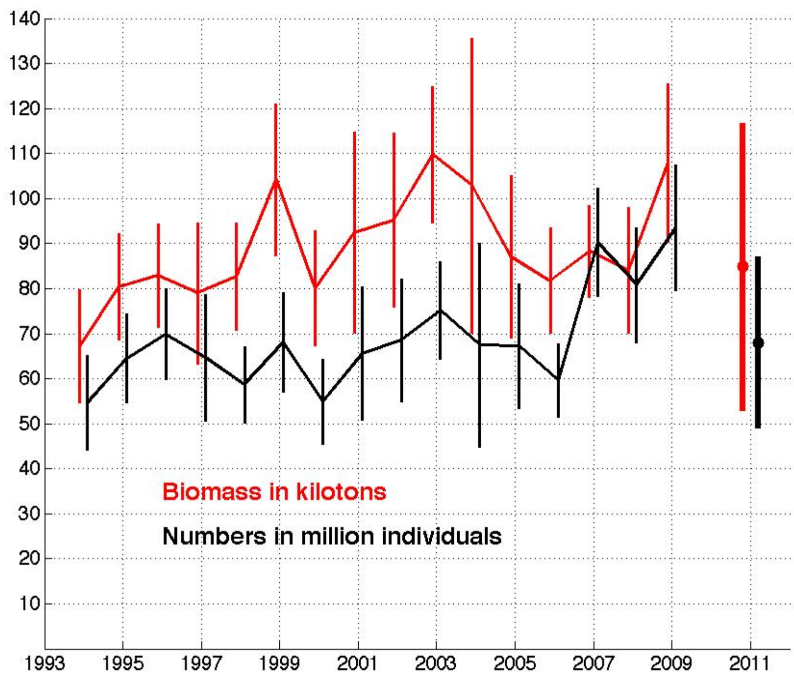


Figure 4.2.2.2. Estimated Greenland halibut total abundance in biomass and by number of individuals from the Norwegian slope surveys 1994–2011. The vertical bars show 95% confidence intervals (Report ICES, AFWG 2012).

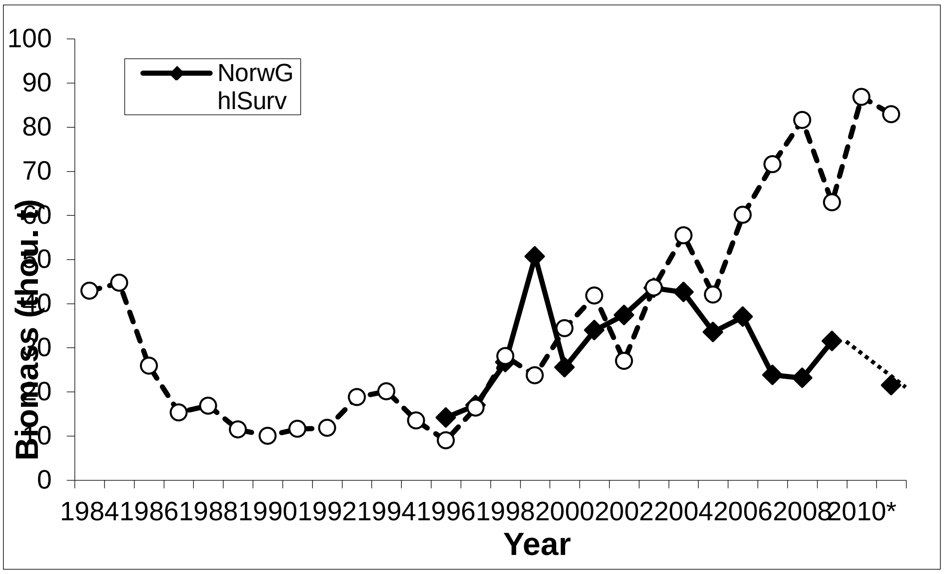


Figure 4.2.2.3. NEA Greenland halibut. Swept-area estimate of the mature female biomass based on the data from the Norwegian Slope Survey in autumn and Russian trawl survey in October–December (Report ICES, AFWG 2012).

4.3 Stock assessment methods

4.3.1 Models

4.3.1.1 Stock production model in Bayesian framework

Results of assessment of the Barents Sea Greenland halibut stock based on a Bayesian surplus production model was provided by Bakanev, WD 14. Different sets of abundance indices were used for tuning the model: cpue of the main Russian fleet; cpue of Norwegian low tonnage and large tonnage vessels; Norwegian and Russian survey indices. The analysis of model run results has showed that K is estimated within the range of 810 to 1139 ktons, B_{MSY} of 405 to 570 ktons and MSY of 23 to 47 ktons. All the calculation variants indicate that, in the last decade, the stock biomass was higher than in the previous one. However, the model was sensitive to the choice of prior on K. Taking into consideration a high probability of the stock size being at the level which was quite a bit above B_{MSY}, the risk of the biomass being below this optimal one was very small in 2002–2012 (<1%). The risk analysis of the stock size in the prediction years (2013–2020) under the catch of 0 to 30 ktons indicated that probability of the stock size being under the threshold levels (B_{MSY}, B_{lim}) was also minor (less than 1%).

4.3.1.2 Gadget model

An age–length structured Gadget model has been constructed for the NEA Greenland halibut, and is described in more detail in WD 15 in Annex 6. The model ran from 1992 to 2012, with quarterly time-steps. The stock is split by gender and maturity. Growth is modelled as von Berthanlanffy growth with externally estimated parameters, based on the "new" age reading methodology recommended in WKARGH. Natural mortally is set at 0.1. No SSB–recruitment relationship is used; rather the number of recruits per year is directly estimated. Two combined fleets are used: one for gillnets (and handline and longline) and one for trawl (and other gears). Catch in tonnes by sex was available for both fleets, length distributions by sex were taken from the Norwegian data. Total survey index and length distributions from the Norwegian slope survey were also used as tuning data. No other surveys have so far been included. Examining length distributions indicated that both the survey and the trawl had dome shaped selectivity, and this was modelled using an asymmetric dome. The gillnet fleet was the only fleet to fully select the largest individuals, and an S-shaped curve was assumed for this fleet.

Using all fish of 45+ cm as a proxy for "exploitable biomass", the Gadget model has produced a population rising from around 250 million individuals and 400 thousand tonnes in 1992 to a peak of 650 million individuals and 850 thousand tonnes in 2009, declining to around 450 million individuals and 800 thousand tonnes by 2012. The peak in numbers occurs in 2008, the peak in biomass in 2010. This is slightly higher than scenario 1 from the production model, and slightly lower than scenario 2.

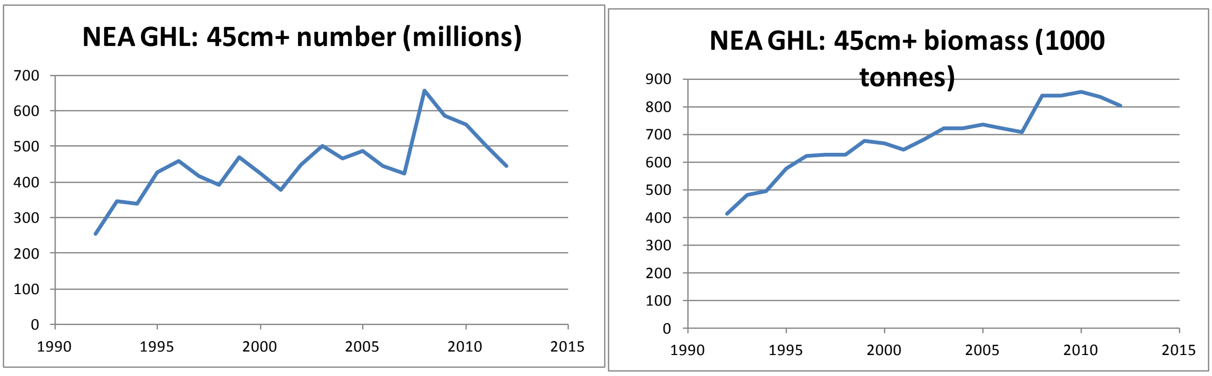


Figure 4.3.1.2.1. Total abundance of NEA Greenland halibut according to base run in GADGET.

The model fit reasonably well to the overall survey index, and to the sex-aggregated length distributions in the commercial catches. However there were discrepancies when examining the sex-disaggregated fit. This indicates that there is a sex-selection effect over that due to length, and this should be incorporated in the model.

An experiment was conducted using growth based on the old age reading, and associated mortality. These results were similar to the XSA run at AFWG using the same age and mortality assumptions.

Further work is required on the model. The fleets need to be split by sex, and Russian length distributions from the commercial fleet should be included. Age–length data should be incorporated to allow for direct estimation of growth rates. Such age data will also help refine the annual recruitment estimate, which is currently rather uncertain. Once this is done the model will be ready to serve both as the basis of an assessment model, and as a tool to examine a range of uncertainties around the model. These include the choice of survey index to include and uncertainties around ageing. Further comparisons between the Gadget model and the production model would also be valuable.

4.4 Conclusion

Both assessment model approaches should be pursued further with presentation during the AFWG. In order to further develop the GADGET model all Norwegian ageing data that are available using the newly developed method should be used.

Uncertainties remain about the appropriate set of biomass indices to use in any modelling exercise. This issue will be of main focus for the coming workshop (WKNDHG) in autumn 2014 (see Annex 4 for ToRs).

Therefore, basis for advice for 2015 will most likely be the DLS approach as developed by ICES in recent years (WKLIFE3). Considering the need for further description and exploration of the different biomass indices (WKNDHG), AFWG clearly need a proper preparation for this prior to their meeting in spring 2014.

Since no changes have been agreed upon in the assessment of this stock, the stock annex is unchanged in this context and accordingly not included in this report.

4.5 References

Hallfredsson, E.H. 2013. A note on growth of Greenland halibut, and status of age readings by new age reading method in Norway. WKBUT 20013 WD 16.

5 Northwestern Greenland halibut stock (ICES Subareas V,VI,XII and XIV)

5.1 Current assessment and issues with data and assessment

Since 2008 assessment and management advice has been derived using a stochastic version of the logistic production model and Bayesian inference (Hvingel *et al.*, 2008 WD 4). Input data are considered to be representative of the three main areas of fishery and stock distribution: East Greenland (Subarea XIV), Iceland (Division Va) and Faroe Islands (Division Vb).

Icelandic cpue series has for a decade in the 1990s been used as a biomass indicator in the assessment of the stock. However, with the appearance of the new fisheries and surveys in XIV and Vb, indices for those areas were compiled. The commercial cpue indices are based on haul by haul data from logbooks, and the fisheries for Greenland halibut in the entire area are clean fisheries with minor bycatches. Thus the quality of these sources is considered good. Despite these qualities, it cannot be ruled out that they are poor biomass indicators due to an assumed scattered distribution of Greenland halibut. Poor knowledge of stock structure and distribution of the life stages in the area prevent interpretation of the indices and also their use in any model framework. Thus, for the present model framework, it was necessary to reject the Greenland cpue series of commercial catches due to a contrasting signal to the other indices, although the quality of the Greenland commercial data is considered similar to the series included in the model. Recently the two surveys shows increasingly contrast, which further increase the uncertainty of the population estimates. The situation with available indicators from Faroe Islands is similar: a survey and standardized cpue from selected trawlers do show trends that conflicts with those used in the stock production model.

Issues for this benchmark are therefore:

- Sensitivity analyses of present assessment model in order to explore its robustness;
- Evaluate alternative assessment methods that utilize age–length information, e.g. GADGET;
- Explore biomass indices that are input to the model;
- Consolidate the MSY estimates from present production model by means of other approaches.

5.2 Compilation of available data

5.2.1 Biological data

5.2.1.1 Growth

Ageing of Greenland halibut from this stock ceased about 2000 due to uncertainty on reliable methods for ageing. Since then otoliths have been sampled by the responsible institutes in Greenland, Iceland and Faroe Island, but no age reading have been conducted. Progress in Norway and Canada on this issue has opened for inclusion of growth assumptions in the modelling. In addition tag–recapture experiments provide new information on growth for this stock.

The growth of 36 tagged and recaptured specimens of Greenland halibut were estimated for the waters around Faroe Islands (Steingrund WD3). The tagged specimens grew on average 3.3 cm per year. The sex was known for 14 of the specimens, four males and ten females. This growth rate was not significantly different from cod at the same temperature (2 C), and was slower than the old otolith ageing method, but faster than the new method.

Growth of Greenland halibut in Icelandic waters was estimated during the meeting based tag recaptures (Va) from the years between 1971 until 1978 (Elvarsson WD 18). The results from that tagging experiment further supported that the growth estimates based on Norwegian age readings were applicable to the stock in Va as they were not significantly different.

5.2.1.2 Maturity

New information from a recent ICES workshop on maturity (WKMSREGH) was available to the group and was presented. The information is summarized as follows.

Previous studies on Greenland halibut reproduction biology have revealed difficulties in interpreting the macroscopic maturity scale. In particular it has been difficult to separate what has previously been termed as resting females from early maturing and females in early maturation. The ICES Workshop on maturity standardization of redfish and Greenland halibut (WKMSREGH) met in Vigo 28th November–1st December 2011 in order to address these issues as well as preparing a standardized maturity classification between marine institutes of the North Atlantic. There was a good general agreement between readers on macroscopic and microscopic assignment of maturity stage during the meeting, and that the main bottleneck is clearly to distinguish between immature/inactive mature and resting females. It has been suggested that the adolescent phase is long - up to four years or more (Junquera *et al.*, 2003) as well as indications of two year period for maturing the eggs (oocytes) for one year's production of offspring (Kennedy *et al.*, 2011). A general agreement during the meeting was that maturity cycle last at least two years, but females still spawn ever year. Primiparous fish are biologically mature, but functionally immature and should not be included in the spawning–stock estimate. The future maturation scale should imply seven stages: 1- Immature, 2- maturing but functionally immature, 3- maturing eggs 1–2 mm, 4- late maturing eggs 2–4 mm, 5- spawning and 6- spent/recovering. A seventh stage should be used when difficult to distinguish between 1, 2 and 6, and the need of this stage should be considered in future. Main recommendations are further to sample maturity data 2–5 months prior to spawning in order to eliminate the uncertainty of including maturing, but functionally immature females in the spawning–stock estimates, and to estimate maturity ogives on females only, due to the sexual dimorphism of the species.

5.2.2 Survey tuning data

Each of the three nations, Greenland, Iceland and Faroe Islands conducts surveys for Greenland halibut in their EEZ. Thus, no overlap or coordination exists currently in the design of the surveys. The Greenland (EG) and the Iceland survey (IAGS) are currently used as biomass indicator in the assessment, while the Faroese survey is not, due to an unconventional design. The surveys are fully described in the respective stock annexes (ICES stocks).

For the East Greenland bottom-trawl survey a number of sensitivity analyses were conducted (Hedeholm *et al.*, WD 9); stratification was altered in several ways to estimate the effect on the overall biomass trend. This included removing certain areas with highly variable estimates and/or altering the area to which the swept-area density estimates were extrapolated to. It was also attempted to stratify solely by depth, assuming it was a better predictor of depth and area. Finally, survey estimates were recalculated following deletion of the largest hauls (removing sequently.). Besides different scaling of the survey estimates, the trend did not change as a consequence of any single change or the combined effect of them all and it was concluded that the survey estimates are robust. In addition given the current fishery locations and the inconsistency with survey stations allocation it was suggested that the survey to a higher degree should include important fishing grounds.

Greenland halibut in Subareas V, VI, XII, and XIV is surveyed by three surveys aimed at this stock. The Icelandic Autumn survey (IAGS), the Greenlandic Greenland halibut survey (EG) and the Faroe Greenland halibut survey. In many aspects the Icelandic and Greenland Survey are similar and combined they cover most of the known distribution of Greenland halibut in that management area. Apart from the northern most fishing area in the Greenland EEZ the Faroe survey covers the rest of the area. However the Faroe survey design is very different as it is not standardized.

In order to construct a combined index from the Greenland and the Iceland survey (EG and IAGS) a single stratification scheme was constructed that covers both survey areas. The main objectives were to have a fairly large number of stations in each strata (>6) and to have the strata so small that biomass is not being extrapolated over large unsurveyed areas. The first objective was not reached in all strata for the EG as it has fairly few stations (40–55) whereas the IAGS has around 177 stations at depths greater than 400 m.

The calculated combined index shows much stronger correlation to the original IAGS index than to the original EG index (Figure 5.2.2.1.). The reason is that the IAGS part of the combined survey region is much larger, more than compensating for slightly lower average catch rates. The indices for each of the survey regions using the combined stratification scheme are comparable to those indices normally presented for each of the survey.

The group concluded that the combined index was an improvement and should be used as input data in the assessment of the Greenland halibut stock in the NWWG.

For surveys and commercial indices in Faroese waters, analyses were conducted to explore the possibility of compiling these into one single index that better reflected the stock biomass development (Steingrund, WD 19). Two surveys (spring and autumn groundfish surveys), one less standardized survey (Greenland halibut trip in May–June) and one commercial index (trawlers) were considered. Most of the indices were positively correlated. The trawler index was also extended back to 1983 by a correlation with the spring survey. This extended index corresponded well with the cpue for trawlers at Iceland, but there were some differences. These differences seemed to correlate with the extent of the Subpolar Gyre, so that the Faroe index was higher when the gyre was in a retracted state (warm waters at the Faroes) whereas the Faroe index was lower when the Subpolar Gyre was in an extended state. This preliminary exercise indicates that hydrographical conditions may, either directly or indirectly, affect the distribution of Greenland halibut in the east Greenland/Iceland/Faroe area. Hence, a combined biomass index of Greenland halibut may be more appropriate in a stock assessment model than using separate indices for each area or selecting one of them.

The group encouraged that further work be carried out on this issue to explore inclusion of environmental parameters and the use of Faroese indices in the assessment model.

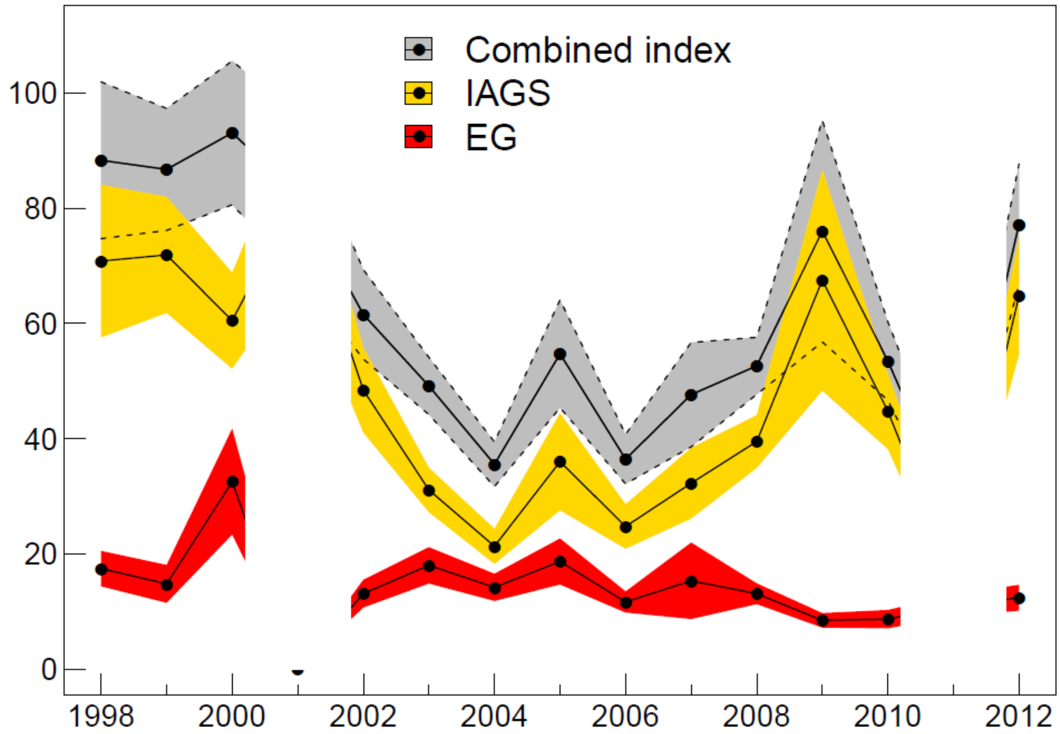


Figure 5.2.2.1. Iceland survey (IAGS), Greenland survey (EG) and the combined swept-area total biomass index.

5.2.3 Data from the fishery

Cpue series from the commercial fisheries in East Greenland, Iceland and at the Faroe Islands are available as biomass indicators for the stock. Currently only the Iceland cpue series is used as input to the assessment model due to conflicting signals by the remaining two series. The cpue series from Iceland has been driving the Bayesian stock production model and there is concern about the early part of the time-series with very high values. Analyses of the cpue series (Thordarson, WD 20), showed that the high cpue in the early part of the time-series was mainly due to high cpues in 2nd quarter, while this pattern is not a feature of the remaining part of the series, e.g. from mid-1990s and onwards. The reason for these seasonal spikes according to Dr Einar Hjörleifsson (IMR, Iceland) is what fisherman claimed to be fishing on spawning aggregations in spring at fishing grounds known in Iceland as 'Hampiðjutorgið'. The trawlers would search for the boundary of the Greenland current where the fish would aggregate, and consequently trawlers concentrated their effort in those spots. In reality the trawlers cued in line and did go over the spot one after another. A similar phenomenon has been seen in the redfish fishery in the Irminger Sea with very high catch rates. **The group agreed that work should be conducted to consider this phenomenon in standardization of the index for use in the assessment model at the NWWG 2014.**

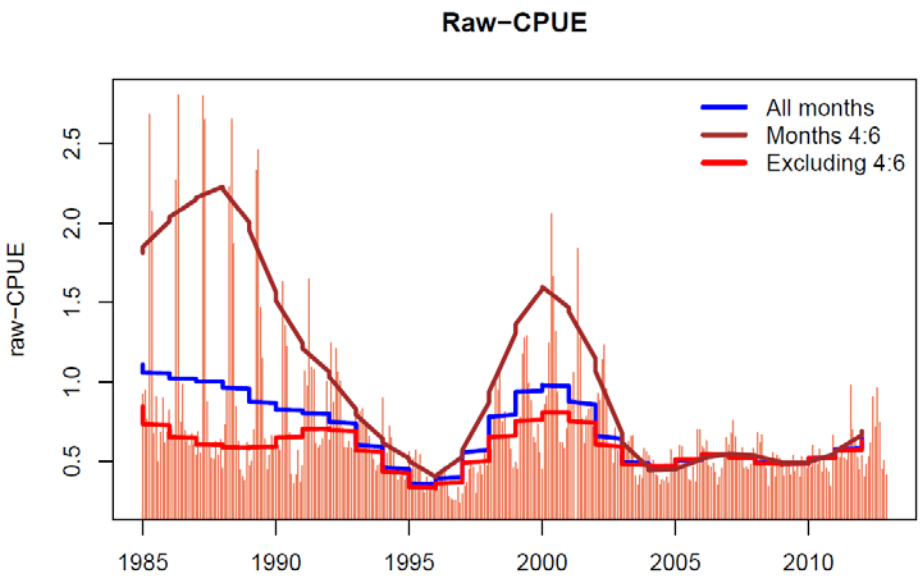


Figure 5.2.3.1. Average catch per haul in Va (Iceland) of Greenland halibut by month in 1985 to 2012 (bars), the lines are a loess smoother added on various subset of the data (see legends).

5.3 Stock assessment methods

5.3.1 Models

5.3.1.1 Stock production model

Currently a stock production model in Bayesian framework is the assessment model for the stock. A number of issues have been raised by reviewers and NWWG members over time on the behaviour of this model, most in connection with sensitivity to prior settings. Under this workshop analyses were therefore presented to address these issues. These are described under sensitivity analyses in Section 5.8.2.

5.3.1.2 Gadget Model

Gadget is an age–length structured forward-simulation model, coupled with an extensive set of data comparison and optimization routines. Processes are generally modelled as dependent on length, but age is tracked in the models, and data can be compared on either a length and/or age scale. The model is designed as a multi-area, multifleet model, capable of including predation and mixed fisheries issues; however it can also be used on a single-species basis, which is the case here.

At the present meeting a Gadget stock assessment of Greenland halibut in Subareas V, VI, XII, and XIV was presented (Thordarson and Elvarsson, WD 4). The model is able to follow trends in the tuning data and the fit to other datasets is acceptable. The main challenges identified during the meeting are the growth assumptions and sensitivities for the various parameters, which therefore were analysed as time allowed at the meeting.

The general setup of the model as follows:

Modelled age range between 2–25 and natural mortality (*M*) was set at 0.1.The model starts in 1961 and has four time-steps per year. Recruitment is estimated by a SSB–R relationship between 1961 and 1984; then recruitment is estimated annually. The model has two 'stocks', namely females and males. The tuning data in the base model is length aggregated indices (20–45 cm, 45–65 cm and 65–120 cm) split by sex from the Icelandic autumn survey (IAGS) and the cpue from commercial catches Va. Catches in the model are taken by three fleets; i.e. Icelandic which has the only available length data, Faroese and Greenlandic.

As there are no length distributions from Greenland and Faroe Islands, the selection for these fleets is assumed to be the same as the selection estimated for Iceland. Additionally the model has data on the sex-ratio from Icelandic catches as a likelihood component. Growth information in the base model comes from Norwegian survey data. However as the growth of females was too low compared to the available data the growth curve for the females was adjusted slightly i.e. faster growth (See WD 2 and WD 4 this meeting). The model estimates that SSB was around 62 Kt in 2012 and F at 0.19. Fishing at $F_{0.1}$ would result in catches of around 19 kt in 2014. The advice would therefore be very similar to the advice from the current assessment model. Comparisons of stock trajectories from Gadget using either the IAGS index or the combined index (Figure 5.2.2.1) to two variants of the current stock production model are shown in Figure 5.3.1.2. The difference in behaviour of the two models is evident: Gadget is less fluctuating in perceived biomass development than the stock production model and in addition more conservative in its estimation of biomass for the entire time-series. Especially the biomass decrease estimated by both models from the late 1980s to mid-1990s is less prominent for the GADGET than the production model, and the peak estimated by the production model in the early 2000s is estimated insignificant by the GADGET. The trend for the last decade is similar for the two models.

At the meeting in total ten variants (including the base model) of the Gadget model were presented, that is five growth scenarios and using both the IAGS index and the combined index. The growth scenarios were:

1) Norwegian mean length-at-age.
2) Norwegian mean length-at-age scaled to fit length distributions in Va catches.
3) Icelandic age-structured data collected between 1969 and 2002. Aged using the old ageing method that has been rejected.
4) Icelandic age-structured data (as in 4) scaled using a von Bertalanffy growth curve to the Norwegian data.
5) No age data/information included.

The rationale and explanations of growth scenarios 1 to 4 are given in Thordarson and Elvarsson (WD 4) and the combined index is explained in Thordarson (WD 10). The results from the different growth scenarios indicated that, although notably different in scale, appear to broadly follow similar biomass trends. In more recent years the estimated biomass by the different model alternatives appear to converge. However, based on $F_{0.1}$ as the proxy for F_{MSY} the projected short-term catches ranged between 16 ktons to 30 ktons, a variation that is attributed to growth assumptions.

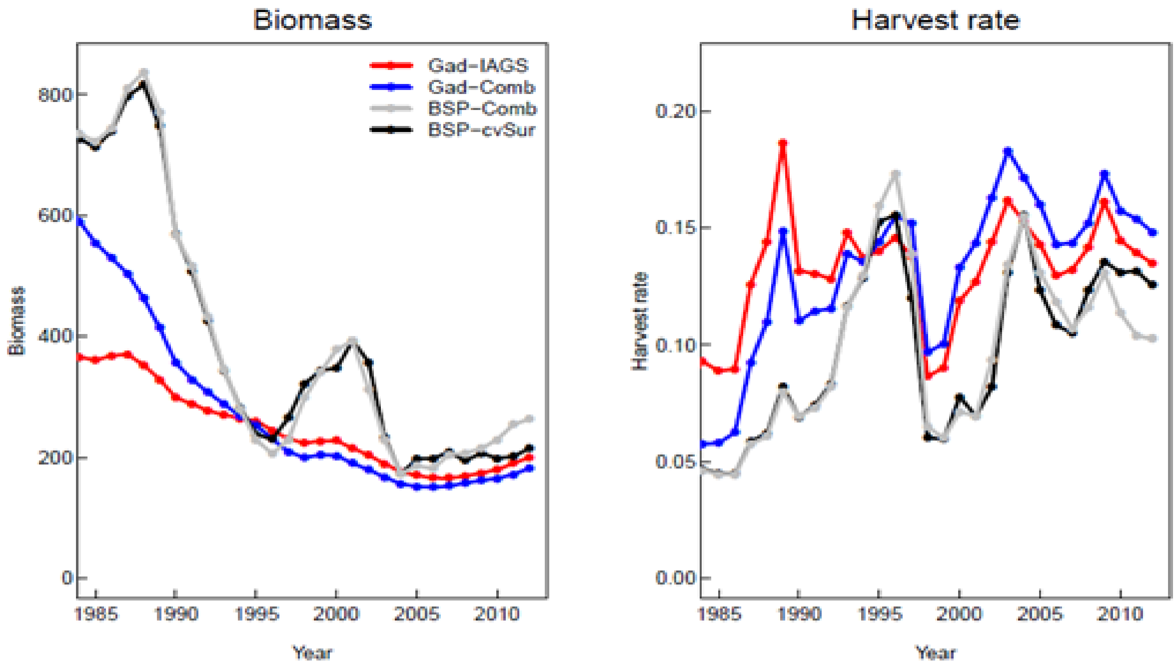


Figure 5.3.1.2. Comparison of biomass and harvest rate estimates from two Gadget variants (Gad) and the Bayesian stock production model (BSP).

5.3.1.3 Stock production model for Faroe Islands (Division Vb)

In addition to the Gadget model and the currently used stock production model, both aiming to assess the entire stock, a simple production model for the population of Greenland halibut in Faroese waters was presented (Steingrund, WD 13). Two cpue series were used for tuning the assessment model, the Greenland halibut survey (or trip) and the commercial trawlers. Data storage tags showed that Greenland halibut occupied the 400–600 m depth interval most of the time, and only tows at those depths were used. Both these series were treated by a general linear model (GLM). The cpue from the Greenland halibut survey was probably more reliable, because the cpue depended only on the depth (not statistical square), whereas the trawler cpue depended on many factors, and exclusion of any of them changed the modelled cpue. In the production model, the growth rate (r) was obtained from the tagging study in Faroese waters (Steingrund, WD 3). The model fitted well with the Greenland halibut survey catch rates as well as the cpue for the trawlers. The two runs of the assessment model gave nearly exactly the same results. The model suggested that the biomass 1995–2012 fluctuated between 15 and 29 thousand tonnes and that the exploitation ratio fluctuated between 0.05 and 0.25. When the trawler cpue series was extended back to 1983 (Steingrund, WD 19) as an attempt to cover a period of high abundance of Greenland halibut, the model gave slightly higher estimates of biomass and lower estimates of exploitation. An overall assumption for the exercise was that Greenland halibut in Faroese waters is a well-defined population entity.

5.3.2 Sensitivity to priors for stock production model, BSP (from Section 5.3.1.1)

In the Bayesian approach a hypothesis about what the model parameters should look like (their probability density distribution) can be included as "priors". These priors are developed before the data are analysed and is thus based on any ancillary information available. In Hvingel (WD 11) the influence of the setting of the priors evaluated for the models results. The sensitivity of the different options for all priors is illustrated in Figure 5.3.2.1 and summarized as follows:

P0, biomass of the initial year; Overall the setting of the P0 prior has little influence on model results and very little or no influence on determining current stock status.

qx, the catchabilities of biomass index series; Priors alternative to the ones used (uniform in log space) would by definition be informative and was therefore not investigated.

σ_x, the error terms; the medians are not sensitive to the choice of priors for the observation errors. However, the uncertainties of stock status estimates did change slightly. To avoid having to choose the priors for the observation error it could be considered to use the series of observed uncertainties calculated for biomass series as a direct data input to the model.

K, carrying capacity; there is not a lot of information in the data regarding *K* and its posterior is therefore sensitive to the prior. The model is thus somewhat sensitive to whether the informative prior used is a sensible/realistic one. However, stock status and *MSY* are fortunately not particularly sensitive to the setting of the prior for *K*.

MSY, Maximum Sustainable Yield; a non-informative uniform prior was given to MSY and was therefore not investigated further. The upper limit was chosen high enough not to truncate the posterior distribution or have any influence on other parameters.

Process errors

The Model assumes time-independent process error. This assumption was investigated by examining annual process errors standardized to the estimated relative biomass (P_t) (Figure 5.3.2.2). The process errors were variable with maximum values around 30%P_i and a serial correlation of 0.6. This indicated that there are factors other than those included in the model that affects stock dynamics. The autocorrelated error might cause underestimates of uncertainty in model predictions. This is however partly compensated for by the increase in the estimate of the error variance caused by the autocorrelation itself. Furthermore, the observed errors for the most recent period (since 2006) have not been correlated (Figure 5.3.2.2).

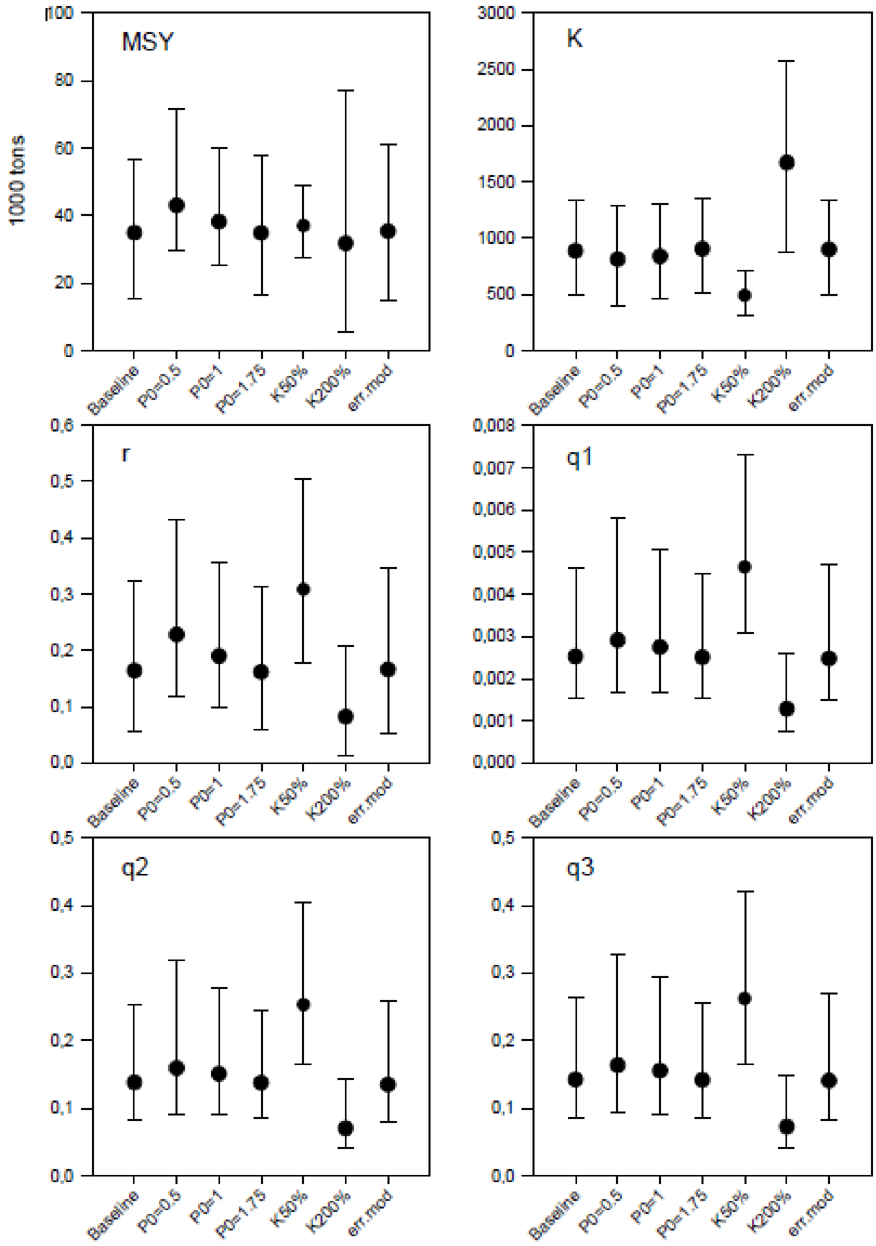


Figure 5.3.2.1. Distributions of model parameters (one panel for each parameter: dot is the median and error bars is 90% confidence interval) in response to selected variations of the informative priors. "Baseline" is the 2013 assessment model; "P0=0.5, 1, 1.75" is priors with a variance similar to that of the 2013 model but with means set to 0.5, 1, 1.75 respectively; "K50%, 200%" is a prior equal to 0.5 and 2 times the prior used in the 2013 model; err.mod is slightly less informative priors on observation error equal to those used in Hvingel, 2012.

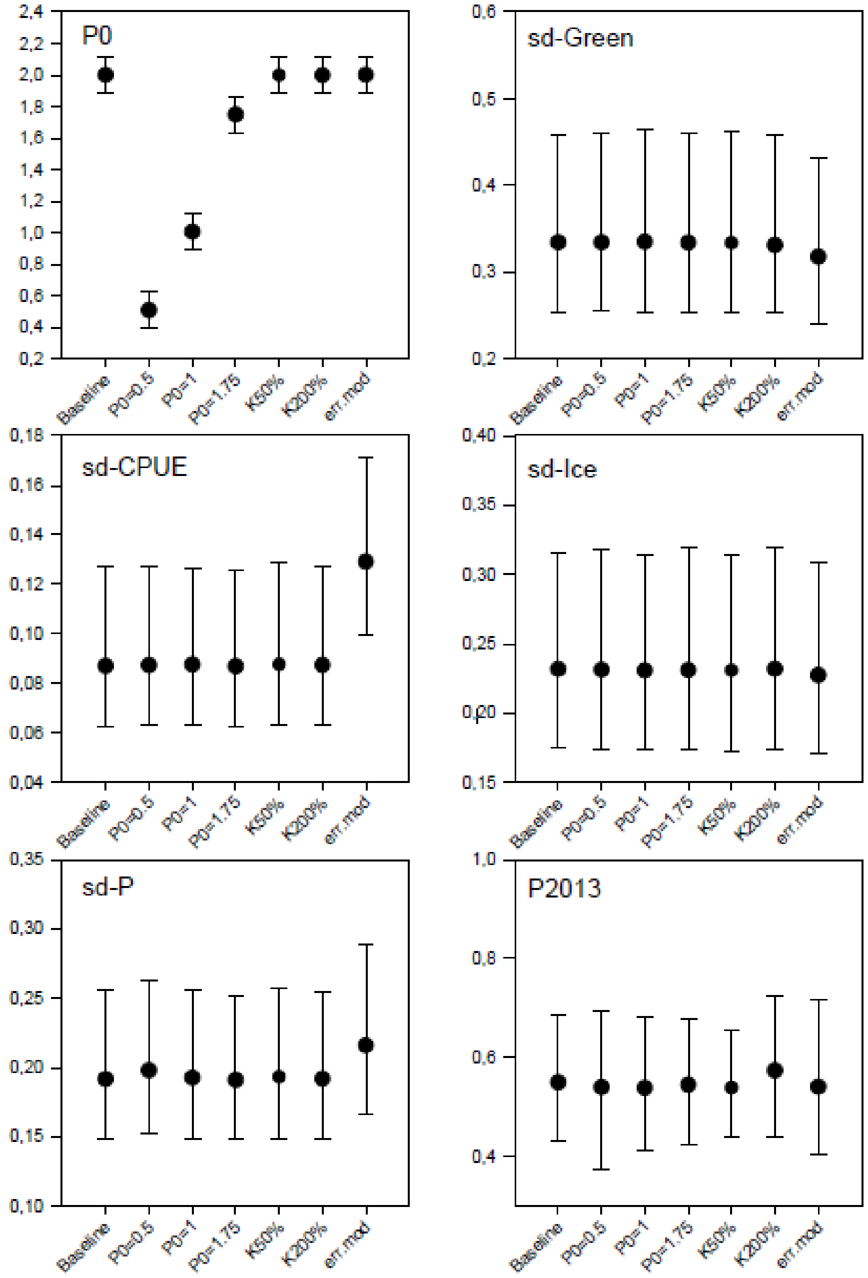


Figure 5.3.2.1. Continued.

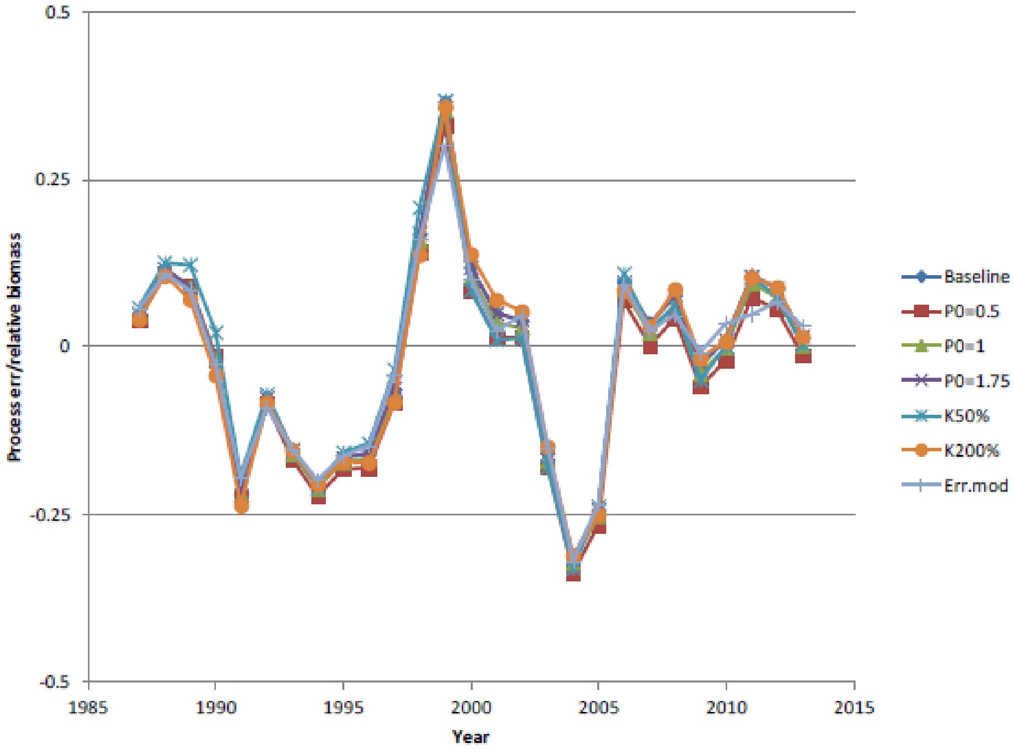


Figure 5.3.2.2. Process error standardized to annual estimated stock biomass. "Baseline" is the 2013 assessment model; "P0=0.5, 1, 1.75" is priors with a variance similar to that of the 2013 model but with means set to 0.5, 1, 1.75 respectively; "K50%, 200%" is a prior equal to 0.5 and 2 times the prior used in the 2013 model; err.mod is slightly less informative priors on observation error equal to those used in Hvingel, 2012.

5.4 Biological reference points

Approaches to estimate MSY alternative to the present model framework was presented at the benchmark (Boje, WD 7). Both methods only used catch data input back to start of the fishery in 1961. Using Catch-MSY method by Martell and Froese (2013) and Depletion corrected average catch (DCAC), MSY for Greenland halibut in V,VI, XII and XIV was estimated in the range 20–28 kt. The Catch-MSY approach was sensitive to estimation constraints of the population growth parameter r, so where restricting r to the interval 0.05-0.3 MSY was estimated 20–25 kt, while restricting r to 0.15–0.4 gave MSY estimates 25–30 kt. The DCAC approach gave relatively consistent estimates of MSY at 20–23 kt depending on assumptions on M, depletion of stock in total time range and definition of B_{MSY} in relation to B_0.

These alternative methods gave MSY estimates somewhat lower than estimated for the currently used stock production model (34 kt) and slightly higher than the Gadget approach (~23 kt at $F_{0.1}$).

5.5 Conclusions

The benchmark concluded that the Gadget model showed promised but was not yet ready for use as the assessment model. The assessment model should remain the stock production model using the new combined survey index and the Icelandic cpue index as it is revised. Reference points as derived from this model are 30% B_{MSY} as B_{lim}, 1.7 x F_{MSY} as F_{lim} and an $MSYB_{trigger}$ defined as 50%B_{MSY}.

Gadget should continue to be developed and be reviewed at an inter-benchmark. The Gadget model should include the anticipated revised cpue, length frequencies representative of all the catch, the new combined survey index, a growth function based on Icelandic tagging data, length selectivity's by sex, iterative reweighting as in the assessment of tusk in Va. Uncertainties on the estimates, tests of sensitivity to the natural mortality assumption, and analyses of possible reference points should be considered at the inter-benchmark. The decisions above are described in the relevant sections of the stock annex and included in this report (Annex 3).

5.6 References

Boje, J. 2013. MSY approximations for Greenland halibut in V+XIV WKBUT 2013. WKBUT 2013 WD 7.

Elvarsson, B. 2013. A note on the growth based on tag–recapture experiments on Greenland halibut (*Reinhardtius hippoglossoides*) in Subarea Va. WKBUT 2013 WD 18.

Elvarsson, B. 2013. A study on the possible scenarios for the exploratory gadget stock assessment model for Greenland halibut (*Reinhardtius hippoglossoides*) in Subareas V, VI, XII, and XIV. WKBUT 2013 WD 12.

Hedeholm, R., Post, S.L. and J. Boje. 2013. A new look at the Greenland halibut survey on the East Greenland shelf 1998–2012 WKBUT 2013 WD 9.

Hvingel, C. 2013. Some investigations on the Bayesian assessment model for GHL in ICES Division V+XIV. WKBUT 2013 WD 11.

Junquera, S., Román, E., Morgan, J., Sainza, M., and Ramilo, G. 2003. Time scale of ovarian maturation in Greenland halibut (*Reinhardtius hippoglossoides*, Walbaum). ICES Journal of Marine Science, 60: 767–773.

Kennedy, J., A.C. Gundersen, Å. S. Høines, O. S. Kjesbu. 2011. Greenland halibut (*Reinhardtius hippoglossoides*) spawn annually but successive cohorts of oocytes develop over two years, complicating correct assessment of maturity. Canadian Journal of Fisheries and Aquatic Science.

Steingrund, P. 2013. A production model of Greenland halibut (*Reinhardtius hippoglossoides*) in Faroese waters. WKBUT 2013 WD 13.

Steingrund, P. 2013. Biomass indices of Greenland halibut ((*Reinhardtius hippoglossoides*) in Faroese waters. WKBUT 2013 WD 19.

Steingrund, P. 2013. Growth of Greenland halibut (*Reinhardtius hippoglossoides*) in Faroese waters based on mark–recapture experiments. WKBUT 2013 WD 3.

Thordarson, G. 2013. A note on the Greenland halibut (*Reinhardtius hippoglossoides*) CPUE estimates from Va. WKBUT 2013 WD 20.

Thordarson, G. 2013. Constructing a combined index for Greenland halibut (*Reinhardtius hippoglossoides*) in Subareas V, VI, XII, and XIV from the Icelandic autumn survey and the Greenland deep-water survey WKBUT 2013 WD 10.

Thordarson, G. 2013. Surveys on Greenland halibut (*Reinhardtius hippoglossoides*) in Va. WKBUT 2013 WD 1.

Thordarson, G. and B. Elvarsson. 2013. Exploratory gadget stock assessment of Greenland halibut (*Reinhardtius hippoglossoides*) in Subareas V,VI, XII, and XIV. WKBUT 2013 WD 4.

Thordarson, G. 2013. A note on growth assumptions used in the Gadget model for Greenland halibut (*Reinhardtius hippoglossoides*) in Subareas V,VI, XII, and XIV. WKBUT 2013 WD 2.

6 Greenland halibut in NAFO Subareas 0+1

6.1 Current assessment and issues with data and assessment

No analytical assessment is currently conducted for this stock. Previously, attempts have been made to assess the stock by various methods. An Extended Survivors Analysis (XSA) stock assessment model fitted to the stock data from SA 0+1 was presented in 2003. The analysis was considered to be provisional due to problems with the catch-at-age data and the short time-series, but the outcome was considered to reflect the dynamics of the stock. The XSA has not been updated in recent years due to lack of catch-at-age data.

A Greenland halibut age determination workshop in 2011 concluded that there is considerable uncertainty about accuracy in the current age reading methods (see Section 3) and the age reading procedure is currently under revision hence no age-based analyses are presented.

A stock production model (ASPIC) was attempted in 2012, but results were not tabled as the outcome of the analysis did not improve significantly over previous attempts. The ASPIC fails primarily because of lack of contrast in the input data and short time-series.

The input to the present assessment is mainly based on bottom-trawl surveys conducted biannually in Division 0A since 1999 and annually in Division 1CD since 1996. Sporadic surveys in the remaining part of the assessment area are, however, also taken into consideration, together with a recruitment index (age 1) from a survey conducted along the cost of West Greenland. Further, standardized cpue series from the trawl fishery and the gillnet fishery are evaluated. A relative F is estimated from the caches and the biomass estimated from Division 1CD. A proxy B_{lim} has been estimated based on survey results for Division 0A + Division 1AB and Division 0B + 1C–F, respectively.

Since 2001 advice has been given separately for the northern area (Division 0A + Division 1AB) and the southern area (Division 0B + 1C–F) in order to avoid concentration of fishing effort. Biomass and cpue indices have shown an overall increasing trend and the advice TAC has been increased stepwise mainly in Division 0A + Division 1AB but also in Division 0B + Division 1C–F (Jørgensen and Treble, WD 5).

The above information presented to the benchmark was the basis for an evaluation of improvement in input data as well as suggestions for analytical approaches to be considered in future.

6.2 Survey tuning data

Currently, surveys conducted by Greenland and Canada which cover different areas are examined separately in the assessment. The benchmark suggested that the surveys in the different areas be combined in the provision of advice, provided they are conducted in the same year. They should however, continue to be examined separately as well in order to detect any differences in trends in the different areas. The benchmark considered that an approach similar to the ICES approach for data-limited stocks could be adapted for use in this stock. If surveys are not conducted annually, then it will extend the period required to evaluate stock trends and determine if changes in TAC are warranted.

6.3 Influence of environmental drivers on the stock dynamic

Analyses of the dynamics of the NAFO 0+1 Greenland halibut stock was presented to the benchmark (Solari *et al.*, WD 8).

The input data to the analyses was Abundance, Biomass and Mean Catch Per Tow, MCPT (years 1997–2011) and Age class 1 (years 1991–2011) are analysed in relation to the winter (December–March) North Atlantic Oscillation (NAO) and monthly Optimum Interpolated Sea Surface Temperature (SST, years 1982–2013) sampled for the area (Latitude 62.5–64.5 o N and Longitude 55.5–57.5 o W) of the Age class-0 pelagic drift. Environmental variables (External Forcing) were aggregated to a temporal resolution of a yearly mean, maximum, minimum and Standard Deviation, SD. All data were log-transformed and standardized.

It was both observed and assumed that: Environmental forcing (EF): (i) The population variables were significantly correlated ($p<0.05$); MCPT was selected for further analysis as it may be regarded as a proxy for both abundance and catch/effort/area; (ii) NAO and SST means and minima (N=33) were inversely correlated ($p<.05$) indicating that positive and negative winter NAO values may imply colder and warmer surface/mixing layer (winter) conditions, respectively: it is considered that this mesoscalar mechanism may have an impact on the juvenile halibut pelagic drift area implying a relatively higher survival rate of Age class 1 during negative NAO (milder winters) and (iii) Correlation between SSTSD and MCPT lagged six years was significant ($p<0.05$), being the inverse of one another from which it is suggested that (c1) the SST oscillations around the mean may be a key factor affecting Age class 1 strength (lagged one year) and subsequently overall Abundance six years after (biased by recruitment-at-age 6); (iv) we may expect floor and ceiling values in abundance in 2014/2018 and 2017, respectively and (v) the positive and negative trends and amplitudes determined by the peak values may be useful to propose a range of sustainable catches adapted to the variable carrying capacity of the environment (as reflected by the SST variation and other system wide external variables contributing to the forcing such as upwelling strength and overlapping between primary production and halibut Age class 1 drift); (vi) A multi resolution decomposition (MRD) wavelet analysis on the SST minima and Age class 1 series showed the signals are the inverse of one another as a one year lag is considered and periodicities of approximately ten year cycles (five in each compensatory or depensatory phase) were detected.

Multi-oscillatory System Approach (MOSA): (i) Correlations were significant ($p<0.05$) between both Age class 1, Abundance and Mean Catch Per Tow (MCPT). It is assumed that Abundance can be biased by Age class 6 (recruits); (ii) The phase plane between age class 1 and Abundance (lagged five years, $p<0.05$) showed two orbits of stability for which two singular points on equilibrium values were detected by nonlinear (locally weighted) fitting. Although Age class 1 series can be relatively noisy, Abundance can be estimated assuming the appropriate lags; (iii) A Multi-oscillatory System Approach (MOSA) is proposed for the halibut dynamics: in this framework, recruitment (R) to the population, area and fishery, production per Spawning–Stock Biomass (R/SSB) and Abundance are considered as a system or summation of nonlinear functions with dynamic features ranging from chaos (the ceiling, when external conditions are extremely benign), going through a range of relatively stable, converging cycles (as external stress increases), to a quasi-standstill state with no clear oscillations (when the minimum viable population is being approached) which may lead to inverse density-dependence (extinction of the commercial fishery). This approach is considered as highly flexible as it has the capacity to, persistently, evolve and return within a wide range of equilibrium states determined by the external forcing (combined effects from the environment and fishing mortality), allowing for stable, periodic and chaotic dynamics. The framework formalizes concepts such as variable carrying capacity, dynamical continuum, orbits of stability (cycles or pseudo-cycles), linked equilibria, ceilings and floors, density-dependent and density-independent compensation/s and depensation/s, interdependencies and lags with system wide external variables and -among other factors- the combined effects from the environment and (differential effects of) fishing mortality at the population, cluster and community levels.

A Bayesian/Monte Carlo Markov Chain test run is carried out with the logistic equation modified with an EF (SST variation around the mean) term: results showed a convergence with estimations from the MOSA framework.

An explanation on why classical models (logistic equation and derivatives) were a key reason for the inability to detect lags and dependencies is given. Also, the following concepts were discussed (in the paper): general issues; environmental forcing; population speed changes (as function of the EF); signal, noise, variability and residuals; the MOSA; variable carrying capacity (ceilings, Ki); minimum populations (floors, K0i); dynamical continuum; differential effects of fishing mortality; multiple (stable) equilibria and pseudo-equilibria; fishing in multiple-equilibrium systems; extinction of the commercial fishery; case studies to support the MOSA; the Bayesian framework.

Finally, issues concerning future work are proposed concerning the fusion of the MOSA-Bayesian/MCMC in order to improve our knowledge of the WGH and sustainability of the stocks.

6.4 Short-term and medium-term forecasts

The DLS framework developed by ICES is a potential approach to provide advice in this case of stock with only a qualitative assessment. The approach is based on the trend in the stock response (survey biomass estimates) to the fishing pressure. The empirical basis is given a generic expression $C_{y+1}=Catch_{recent}*b*r*f*\Theta$, where $Catch_{recent}$ is the average catch over some period, b an evaluation of whether the stock is at risk of productivity impairment given by $\min[1,b_{current}/MSYB_{trigger}proxy]$, r is the trend in development of the stock (normally SSB), f is the ratio of $F_{msy}proxy/F_{current}$ and Θ is an expression of the uncertainty of the information (also referred to as a precautionary factor) where Θ=1when b, r and f are computed, otherwise Θ=0.9 (Treble and Jørgensen, WD 6).

6.5 Biological reference points

A Master thesis on reference points for the NAFO 0+1 stock was presented for the benchmark workshop (Chrysafi, 2013). No reference points have yet been set for the stock due to difficulties associated with establishing an analytical assessment. The lack of reference points excludes Greenland halibut from being a part of MSY management schemes or being eco-labelled. The main problems associated with the Greenland halibut assessment are: the biased age reading, the lack of spawningstock biomass (SSB)–Recruitment relationship and the unknown absolute biomass of the stock. The methods used so far for the assessment of the stock, fail to provide any reference points and the obtained results are considered highly biased. Therefore, in this work, alternative assessment methods, developed for data poor cases, are applied to Greenland halibut, utilizing all the available information on the species, in order to produce reference points for the stock. The data limited methods used are: the catch-MSY tool utilizing catch data developed by Martel and Froese (2012), the Yield-per-recruit analysis utilizing life-history traits developed by Le Quesne and Jennings (2012) and the DCAC method utilizing catch data developed by MacCall (2009). Furthermore, the age-based SAM model was also used in order to evaluate the limitations of the available data on Greenland halibut used for the current assessment. The models yielded similar results with a precautionary proxy of F_{MSY}= 0.8–0.15 year-1, B_{MSY}= 160 000 t and MSY= 19 000 t.

Since assumptions for these approaches were deliberately set conservative, further work with same model approaches could be improved by having expert opinions on the different options. This work is therefore encouraged by the benchmark to continue and reported to NAFO Scientific Council at their June meeting 2014.

6.6 Conclusions

The benchmark concluded that available data do not currently allow an analytical assessment and that any advice must therefore be based on a qualitative assessment based on survey indices and cpues from the commercial fishery. The newly developed DLS approach by ICES could be a candidate approach for a qualitative assessment of the stock and an advice rule. However, WKBUT felt that the approach was promising but that it needed further exploration especially a justification for which surveys to use to estimate r and the precautionary factor. In addition, attempts to estimate MSY reference points (Section 6.5) should be developed further and possibly implemented into advisory procedures. Finally the benchmark encouraged the studies on environmental drivers to be continued ultimately to implement the dynamics in a future analytical assessment.

6.7 References

Chrysafi, A. 2013. Reference points for the Greenland halibut stock component in NAFO Subarea 0 + Division 1A offshore + Divisions 1B–1F. Master Thesis, DTU Aqua, Nov. 2013.

Jørgensen, O.A. and M. Treble. 2013. Input to and assessment of the Greenland halibut stock component in NAFO Subarea 0 + Division 1A offshore + Divisions 1B–1F. WKBUT 2013 WD 5.

Solari, A, Jørgensen, O and H. Siegstad. 2013. On halibut dynamics. WKBUT 2013 WD 8.

Treble, M.A. and O.A. Jørgensen. 2013. Survey approach to assessment of Greenland halibut in SA 0+1. WKBUT 2013 WD 6.

Annex 1: Terms of Reference

WKBUT Benchmark Workshop on Greenland Halibut Stocks

2012/2/ACOM44 A **Benchmark Workshop on Greenland Halibut Stocks** (WKBUT), chaired by External Chair Joanne Morgan, Canada and ICES Chair Jesper Boje, Denmark, and attended by two invited external experts David Miller (Netherland) and Hans Lassen (Denmark) will be established and work by correspondence and during WebEx meeting Tuesday 29 October 2013 on data compilation and at ICES Headquarters for a four day Benchmark meeting 26–29 November 2013 to:

a) Evaluate the appropriateness of data and methods to determine stock status and investigate methods for short-term outlook taking agreed or proposed management plans into account for the stocks listed in the text table below. The evaluation shall include consideration of:

   i) Stock identity and migration issues;

   ii) Life-history data;

   iii) Fishery-dependent and fishery-independent data;

   iv) Further inclusion of environmental drivers, multispecies information, and ecosystem impacts for stock dynamics in the assessments and outlook.

b) Agree and document the preferred method for evaluating stock status and (where applicable) short-term forecast and update the stock annex as appropriate. Knowledge of environmental drivers, including multispecies interactions, and ecosystem impacts should be integrated in the methodology.

   If no analytical assessment method can be agreed, then an alternative method (the former method, or following the ICES data-limited stock approach) should be put forward;

c) Evaluate the possible implications for biological reference points, when new standard analyses methods are proposed. Propose new MSY reference points taking into account the WKFRAME results and the introduction to the ICES advice (section 1.2).

d) Develop recommendations for future improving of the assessment methodology and data collection;

e) As part of the evaluation:

   i) Conduct correspondence work on data compilation and hold a WebEx meeting on 29 October. Stakeholders are invited to contribute data (including data from non-traditional sources) and to contribute to data preparation and evaluation of data quality. As part of the data compilation work consider the quality of data including discard and estimates of misreporting of landings;

   ii) Following the DC correspondence work, produce working documents to be reviewed during the Benchmark meeting at least seven days prior to the meeting.

Stock	Assessment Lead	WG
Greenland halibut in Subareas I and II	Oleg Smirnov	AFWG
Greenland halibut in Subareas V, VI, XII and XIV	Jesper Boje	NWWG
Greenland halibut in NAFO Area 0 and 1	Ole Jørgensen	NAFO stock - Greenland

The Benchmark Workshop will report by 1 February 2014 for the attention of ACOM.

Annex 2: List of participants

NAME	ADDRESS	PHONE/FAX	E-MAIL
Bjarte Bogstad	Institute of Marine Research PO Box 1870 Nordnes 5817 Bergen Norway	Phone +47 92422352 Fax +47 55 23 86 87	bjarte.bogstad@imr.no
Jesper Boje ICES Chair	DTU Aqua - National Institute of Aquatic Resources Section for Fisheries Advice Charlottenlund Slot Jægersborg Alle 1 2920 Charlottenlund Denmark	Phone +45 358834 64 Fax +45 339 63333	jbo@aqua.dtu.dk
Anatolii Chetyrkin	Knipovich Polar Research Institute of Marine Fisheries and Oceanography(PINRO) 6 Knipovitch Street 183038 Murmansk Russian Federation	Phone +7 Fax +7	chaa@pinro.ru
Anna Crysafi	DTU Aqua - National Institute of Aquatic Resources Section for Fisheries Advice Charlottenlund Slot Jægersborg Alle 1 2920 Charlottenlund Denmark		annchr@aqua.dtu.dk
Bjarki Elvarsson	Marine Research Institute PO Box 1390 121 Reykjavík Iceland	Phone +354 Fax +354	bthe@hafro.is
Inge Fossen	Møreforsking AS Industriveien 18 Kristiansund Norway	Phone +47 9963 9431 Fax +47	inge@mfaa.no
Agnes C. Gundersen	Møreforsking AS PO Box 5 NO-6021 Aalesund Norway	Phone +47 70111621 Fax +47 70111601	agnes@mfaa.no

Name	Address	Phone/Fax	E-mail
Elvar Halldor Hallfredsson	Institute of Marine Research Tromsø PO Box 6404 9294 Tromsø Norway	Phone +47 77609756 Cell: +47 92609745	elvarh@imr.no
Rasmus Hedeholm	Greenland Institute for Natural Resources PO Box 570 3900 Nuuk Greenland	Phone +299 361291 Fax +299 36 1212	rahe@natur.gl
Daniel Howell	Institute of Marine Research PO Box 1870 Nordnes 5817 Bergen Norway	Phone +47 55 23 86 79 Fax +47 55 23 8531	daniel.howell@imr.no
Carsten Hvingel	Institute of Marine Research PO Box 1870 Nordnes 5817 Bergen Norway	Phone +47 77609750 Fax +47 77609701	carsten.hvingel@imr.no
Ole Jørgensen	DTU Aqua - National Institute of Aquatic Resources Section for Fisheries Advice Charlottenlund Slot Jægersborg Alle 1 2920 Charlottenlund Denmark		olj@aqua.dtu.dk
Yuri Kovalev	Knipovich Polar Research Institute of Marine Fisheries and Oceanography(PINRO) 6 Knipovitch Street 183038 Murmansk Russian Federation	Phone +7 8152 472 469 Fax +7 8152 473 331	kovalev@pinro.ru
Hans Lassen Invited Expert	Møllevænget 7 3000 Helsingør Denmark	Phone +45 49218016 / +45 21483799	Hans.Lassen.NMTT@GMAIL.COM
David Miller Invited Expert	Wageningen IMARES PO Box 68 1970 AB Netherlands	Phone +31 3174 853 69 Fax +31	david.miller@wur.nl
Joanne Morgan External Chair	Fisheries and Oceans Canada Science Branch PO Box 5667 St John's NL A1C 5X1 Canada	Phone +1 (709) 772-2261 Fax +1	Joanne.Morgan@dfo-mpo.gc.ca

NAME	ADDRESS	PHONE/FAX	E-MAIL
Oleg Smirnov	Knipovich Polar Research Institute of Marine Fisheries and Oceanography(PINRO) 6 Knipovitch Street 183038 Murmansk Russian Federation	Phone +7 815 247 2231 Fax +7 815 247 3331	smirnov@pinro.ru
Aldo P. Solari	Greenland Institute for Natural Resources PO Box 570 3900Nuuk Greenland	Phone +299 361 296 Fax +299	apso@natur.gl
Petur Steingrund	Faroe Marine Research Institute PO Box 3051 110 Tórshavn Faroe Islands	Phone +298 353 900 Fax +298 353 901	peturs@hav.fo
Gudmundur Thordarson	Marine Research Institute PO Box 1390 121 Reykjavík Iceland	Phone +354 5752000 Fax +354 5752001	gudthor@hafro.is
Tone Vollen	Institute of Marine Research PO Box 1870 Nordnes 5817 Bergen Norway	Phone +47 Fax +47	tone.vollen@imr.no

Annex 3: Stock Annex

Greenland halibut in V, VI XII and XIV

Stock specific documentation of standard assessment procedures used by ICES.

Stock	Greenland halibut in V, VI XII and XIV
Working Group	North Western Working Group
Date	1 December 2013
Comments	updated after WKBUT 25–29/11-2013, in Section B3 and B4 on surveys and cpues from fishery, in Section C assessment methods, and in Section G Biological reference points. Only these sections are included in this annex.

B.3. Surveys

Three surveys are being conducted, separately in Va, Vb and XIV.

Icelandic survey in Va

An October groundfish survey in Icelandic waters, covering the distributional area of Greenland halibut within the Icelandic EEZ, was started in 1996. The survey is a fixed station stratified random survey consisting of approximately 300 stations on the continental shelf and slope down to a depth of 1300 m. 176 stations of the stations in the survey are on depths between 400 and 1500 meters. Since 2001 the fishable biomass of Greenland halibut (fish of length equal to or greater than 50 cm) has decreased significantly, but stabilized at a low level since 2004.

Faroese survey in Vb

Since 1995, a Faroese Greenland halibut survey has been carried out on the southern and eastern slope on the Faroe Plateau at depths of 400–600 m. The survey is designed as an exploratory fishery where the skipper decides haul location; due to the design of the survey with a mix of fixed stations in combination with an exploratory part, and in addition to a shift on area coverage over time, it has been considered inappropriate as a biomass indicator at present time.

WD 20 in 2011 provides a description of the Faroese Greenland halibut survey. A brief summary is provided here. The survey was initiated in 1995. The survey vessel "Magnus Heinason" is used to the purpose; i.e. the same vessel, which conducts the groundfish surveys in Faroese waters. The trawl is a star trawl with a mesh size of 135 mm in the codend, a rock-hopper gear, and doors of the Thyborøn type. The bridles are 120 m long. A few hauls have been taken with codends having 40 mm mesh size (as in the standardized surveys). The towing speed is approximately 3 nautical miles per hour. The tow duration has normally ranged between three and six hours, most commonly three or four hours; i.e. a covered distance of 9 to 12 nautical miles. In 1995, there was a one-week trip at the beginning of July (19 hauls) whereas the other years a two-week trip (around 42 hauls) has been conducted in late May to early June (except for 24 hauls in 2003 when there was a strike and in 2010 when technical problems with the survey vessel only allowed one haul to be taken). There has been no major change in the gear or the rigging of the gear during the period.

Hauls are taken continuously both day and night, and there is normally little sailing between hauls. Since the major distribution of Greenland halibut occurs along a rather narrow strip of water, which could be expected to vary slightly in depth and probably thickness from year to year, it was decided not to use fixed stations but rather to follow the distribution of Greenland halibut each year. In such a rather one-dimensional distributional area, it was decided to use long tows (several hours) so that the fishing time could be maximized. An increase in the towing duration along this relatively homogeneous area (in terms of fish density and fishing depth) meant that the exact towing and hauling positions became less important, compared with short hauls in a heterogeneous environment (as in the groundfish surveys). A drawback of this design was that the distributional area of Greenland halibut was rather poorly covered the first four years, from 1995 to 1998. From 1999 and onwards, the trawlable area was better covered, although technical difficulties prevented stations to be taken in certain areas certain years (the trawl was stuck each time). On some occasions, additional hauls were taken outside the Greenland halibut area. This was partly done to allow at least some comparison with the standardized groundfish surveys (which covers shallower waters), but mainly to sample cod stomachs (in 1997).

Greenlandic halibut survey in XIVb

Since 1998, a Greenland survey for Greenland halibut has been carried out in East Greenland waters from 60°N to 67°N at the main commercial fishing grounds at depths of 400–1500 m in late June/early July (Figure 15.5.4.). No survey took place in 2001. Total biomass in 2008 was estimated at 11 000 tons which is a 50% reduction from 2006 (Figure 15.5.5). Compared to the period 1999–2001, total biomass estimates for the period 2002–2006 is somewhat lower, and were followed by a period of even lower biomasses from 2007 to 2010. In September 2006 an extension of the Greenland survey was conducted north (67°N–72°N) of the area annually surveyed in East Greenland waters. The survey found poor concentrations of Greenland halibut; of 44 hauls Greenland halibut were only found in 18 hauls and only with one haul having a catch higher than 50 kg (30 min hauls).

The survey is documented in an annual WD at the WG.

Calibration of surveys in Va and XIVb

As a part of the 2006 surveys the Icelandic and the Greenlandic research vessels "Arni Fridriksson" and "Paamiut", respectively, met in Icelandic waters in October to conduct parallel trawling experiments. A total of eleven parallel hauls were made. The original plan called for more hauls but due to problems on board Paamiut, the experiment had to be halted. Because of the small number of hauls it was impossible to get good estimates of the relative trawling efficiency of the two vessels. However the average catch of Greenland halibut standardized to number or weight per km^2 was highest for Paamiut but there was no statistical difference (95% level) in the catches between the two vessels.

Combination of survey indices for use as single index in assessment

Greenland halibut in Subareas V, VI, XII, and XIV is surveyed by three surveys aimed at this stock: The Icelandic Autumn survey (IAGS), the Greenlandic Greenland halibut survey (EG) and the Faroe Greenland halibut survey. In many aspects the Icelandic and Greenland Survey are similar and combined they cover most of the known distribution of Greenland halibut in that management area. Apart from the northern most fishing area in the Greenland EEZ the Faroe survey covers the rest of the area. However the Faroe survey design is very different as it is not standardized.

In order to construct a combined index from the Greenland and the Iceland survey (EG and IAGS) a single stratification scheme was constructed that covers both survey areas. The main objectives in the scheme were to have a fairly large number of stations in each strata (>6) and to have the stratas small so that biomass is not being extrapolated over large unsurveyed areas. The first objective was not reached in all stratas for the EG as it has fairly few stations (40–55) whereas the IAGS has around 177 stations at depths greater than 400 m.

The combined index will be used as input data in the assessment from the 2014 assessment.

B.4. Commercial cpue

Haul by haul logbooks are available from Va, Vb and XIV.

Indices of cpue for the Icelandic trawl fleet directed at Greenland halibut for the period 1985–2008 were estimated from a GLM multiplicative model, taking into account changes in the Icelandic trawl catch due to vessel, statistical square, month, and year effects. All hauls with Greenland halibut exceeding 50% of the total catch were included in the cpue estimation. The cpue indices from the trawling fleets in Divisions Va, as well as in Vb and XIVb were used to estimate the total effort for each year (y) for each of the divisions according to:

$$E_{y,div} = Y_{y,div} / CPUE_{y,div}$$

where E is the total effort and Y is the total reported landings.

Information from logbooks from the Faroese otterboard trawl fleet (>1000 hp) are available. Only hauls where Greenland halibut consisted of more than 50% of the catches and conducted on depths more than 450 meters were selected for the analyses. The standardization procedure for the logbooks was similar to that of the Va fleet.

For Division XIVb, logbook data were available from both Greenland and foreign fleets. In the time-series a variable proportion of all logbooks have been available for analysis (on average 40%, since 2006 more than 90%). Hauls where targeted species was Greenland halibut and where catch weight exceeds 100 kg were selected, as no information on other species caught was available. Cpue from logbooks in the years 1991–2008 were standardized in the same way as described for fleets in Va and so was effort.

At WKBUT in 2013 analyses of the cpue series (Thordarson WD 20, WKBUT), showed that the high cpue in the early part of the time-series was mainly due to high cpues in 2nd quarter, while this pattern is not distinct in the remaining part of the series, e.g. from mid-1990s and onwards. The reason for these seasonal spikes according to Dr Einar Hjörleifsson (IMR, Iceland) is what fisherman claimed to be fishing on spawning aggregations in spring at fishing grounds known in Iceland as 'Hampiðjutorgið'. The trawlers would search for the boundary of the Greenland current where the fish would aggregate, and consequently trawlers concentrated their effort in those spots. In reality the trawlers cued in line and did go over the spot one after another. A similar phenomenon has been seen in the redfish fishery in the Irminger Sea with were very high catch rates. WKBUT agreed that work should be accomplished to consider this phenomenon in standardization of the index for use in the assessment model at the NWWG 2014.

C. Assessment methods

C.1 Stock production model

Since 2008 assessment and management advice was derived using a stochastic version of the logistic production model and Bayesian inference (Hvingel *et al.*, 2008 WD #4).

Modelling framework

The model was built in a state–space framework (Hvingel and Kingsley, 2006; Schnute, 1994) with a set of parameters (θ) defining the dynamics of the stock. The posterior distribution for the parameters of the model, $p(\theta | data)$, given a joint prior distribution, $p(\theta)$, and the likelihood of the data, $p(data | \theta)$, was determined using Bayes' (1763) theorem:

(1) $$p(\theta \mid data) \propto p(data \mid \theta)\, p(\theta)$$

The posterior was derived by Monte-Carlo-Markov-Chain (MCMC) sampling methods using WinBUGS v.1.4.3 (Spiegelhalter *et al.*, 2004).

State equations

The equation describing the state transition from time t to t+1 was a discrete form of the logistic model of population growth including fishing mortality (e.g. Schaefer, 1954), and parameterized in terms of *MSY* (Maximum Sustainable Yield) rather than *r* (intrinsic growth rate) (cf. Fletcher, 1978):

(2) $$B_{t+1} = B_t - C_t + 4MSY\frac{B_t}{K}\left(1 - \frac{B_t}{K}\right)$$

K is the carrying capacity, or the equilibrium stock size in the absence of fishing; B_t is the stock biomass; C_t is the catch taken by the fishery.

To reduce the uncertainty introduced by the "catchabilities" (the parameters that scales biomass indices to real biomass) equation (2) was divided throughout by B_{MSY} (Hvingel and Kingsley, 2006). Finally a term for the process error was applied and the state equation took the form:

(3) $$P_{t+1} = \left(P_t - \frac{C_t}{B_{MSY}} + \frac{2\,MSY\,P_t}{B_{MSY}}\left(1 - \frac{P_t}{2}\right)\right) \cdot \exp(\nu_t)$$

where P_t is the stock biomass relative to biomass at MSY ($P_t = B_t / B_{MSY}$) in year t. This frames the range of stock biomass (*P*) on a relative scale where $P_{MSY}=1$ and $K=2$. The 'process errors', v, are normally, independently and identically distributed with mean 0 and variance σ_v^2 .

Observation equations

Five candidate biomass indices were available: The Icelandic survey and cpue series and the Greenland survey series are reasonably well correlated. However, for unknown reasons the Greenland cpue series showed trends conflicting with those of the other biomass indices; even if restricted to data just opposite the midline next to the Icelandic fishery and were therefore not included. The Faroese survey was due to design not considered to reflect stock dynamics. Further, as this survey only covers areas contributing less than 4% of the catches it was not included either.

The model thus synthesized information from input priors and three independent index series of GHL biomasses and one series of catches by the fishery (Table 1). The three series of GHL biomass indices were: a standardized series of annual commercial-vessel catch rates for 1985–2007, cpuet, and two trawl-survey biomass indices for 1996–2007, Icet, and 1998–2007, Greent. These indices were scaled to true biomass by catchability parameters, qcpue, qIce and qGreen. Lognormal observation errors, ω, κ

$$
\begin{aligned}
CPUE_t &= q_{cpue} B_{MSY} P_t \exp(\omega_t) \\
Ice_t &= q_{Ice} B_{MSY} P_t \exp(\kappa_t) \\
Green_t &= q_{Green} B_{MSY} P_t \exp(\varepsilon_t)
\end{aligned}
\tag{4}
$$

The error terms, ω, κ

with mean 0 and variance σ^2_{cpue}, σ^2_{Ice} and σ^2_{Green}.

Total reported catch in ICES Subareas V, VI, XII and XIV 1960–2007 was used as yield data (Table 1). The fishery being without major discarding problems or variable misreporting, reported catches were entered into the model as error-free.

Priors

Bayesian philosophy considers that an observer maintains a model-perhaps mental or conceptual-of reality that is subject to being modified, updated, by observations (Hvingel and Kingsley, 2006). As a quantitative version of this, Bayesian statistics considers that quantitative observations, data, can be used to update pre-existing probability distributions of the values of parameters defining a quantitative model. In such a discrete updating process, the prior distributions pre-date and are therefore independent of the study that furnishes the data on which the updating is based. The prior distribution for a parameter should incorporate all the information that is already available, but if none can be identified a low-information or "reference" prior (Kass and Wasserman, 1996) is used.

Initial stock size: We did not have any information on the size of the stock in 1985 when the stock index series start and an informative prior could not be constructed. However, we did know that the fishery din not start until 1961 (Table 1) and it was therefore likely that the stock was close to *K* in 1960. To provide this information to the model we made it simulate stock development from 1960 and on giving P_{1960} a normal prior with a mean of 2 (K=2) and a standard error of 0.071 (Figure 4). As we had no observations on stock size until 1985 we ran the model for the 1960–1984 period without the process error in order not to blow up the uncertainty and avoid unrealistically large values of the P_{1985}-estimate due to the long period of 'prediction' (1960 to 1985 = 25 years). The resulting effective prior for P_{1985} had a median of 1.58 and an inter-quartile range of 1.43 to 1.74 (Table 5, Figure 4)

The prior distributions for the error terms associated with the biomass indices (the observation errors) were assigned inverse gamma distributions (the gamma distribution, G(r,μ), is defined by: $\mu^r x^{r-1} e^{-\mu x}/\Gamma(r)$; x>0) as error standard deviations typically follow this kind of distribution. Their standard deviations were given inverse gamma distributions with 95% of their values between 0.06 and 0.26 (Table 2) corresponding to CVs ranging from 7 to 26%; considered to represent a typical range for such data.

The catchabilities q_{Ice} , q_{Green} and q_{cpue} are confounded with the carrying capacity K. A uniform distribution was therefore not non-informative, and a prior distributions uniform on a log scale was preferred as a reference prior (cf. Gelman *et al.*, 1995; Punt and Hilborn, 1997; McAllister and Kirkwood, 1998; Hvingel and Kingsley, 2006). For all these catchabilities the distributions were truncated at -10 and 1 (log scale), the range chosen large enough as not to interfere with the posteriors.

To provide the model with information on the order of magnitude of K, its prior was constructed as follows: Mean biomass densities recorded by the two surveys (Table 1) are some 0.5 tons/km^2. If we assume that the surveys 'sees' around $^1/_3$ of the biomass and that K is in the area of 3–4 times larger than this 1996–2007 level we end up around 5 tons/km^2 corresponding to 750 ktons in the total area. The prior for K was therefore given a normal prior with a mean of 750 ktons and standard error of 300 supposed to account for our prior uncertainty and provide a reasonable range of what K might be (Table 6). The sensitivity of model results to changes in this prior was investigated (see later text and Table 6).

Low information or reference priors were given to MSY, and σ_v as we had little or no information on what their probability distributions might look like. MSY was given a uniform prior between 0 and 300 ktons. The upper limit was chosen high enough not to truncate the posterior distribution (Figure 4).

Convergence diagnostics

In order to check whether the sampler had converged to the target distribution a number of parallel chains with different starting points and random number seeds were analysed by the Brooks, Gelman and Rubin convergence diagnostic (Gelman and Rubin, 1992; Brooks and Gelman, 1998) A stationarity test (Heidelberger and Welch, 1983) was applied to individual chains. If evidence of non-stationarity is found iterations were discarded from the beginning of the chain until the remaining chain passed the test. Raftery and Lewis's (1992) tests for convergence to the stationary distribution and estimation of the run-lengths needed to accurately estimate quantiles were used, and finally the Geweke convergence diagnostic was applied (Geweke, 1992). This ensured that only samples from the target posterior were used for inference.

Model check

In order to check whether the model was a 'good' fit to the data, different goodness-of-fit statistics were computed. First, we calculated the simple difference between each observed data point and its trial value in each MCMC sampling step. The summary statistics of the distributions of these residuals indicated by their central tendency whether the modelled values were biased with respect to the observations.

Secondly, the overall posterior distribution was investigated for potential effects of model deficiencies by comparing each data point with its posterior predictive distribution (Posterior Predictive Checks; Gelman *et al.*, 1995; 1996). If the model fitted the observed data well, the observed data and the replicate data should look alike. The degree of similarity between the original and the replicate data points was summarized in a vector of p-values, calculated as the proportion of n simulations in which a sampling of the posterior distribution for an observed parameter exceeded its input value:

$$p.value = \frac{1}{n}\sum_{j=1}^{N} I((data_j^{rep}, \theta_j) - (data^{obs}, \theta_j)) \quad (5)$$

where $I(x)$ is 1 if x is true, 0 if x is false. Values close to 0 or 1 in the vector *p-value* would indicate that the observed datapoint was an unlikely drawing from its posterior distribution.

Derived parameters and risk calculations

The mortality caused by fishery, *F*, is scaled to F_{MSY} (fishing mortality that yields MSY) for the same reasons as relative biomass was used instead of absolute. The equations added for generating posterior distributions of the *F* ratio were:

$$Fratio_t = \frac{F_t}{F_{MSY}} = \frac{-\ln\left(\frac{B_t - C_t}{B_t}\right)}{\frac{MSY}{B_{MSY}}} \quad (6)$$

The risk of a parameter transgressing a reference point is the relative frequency of the MCMC sampled values (after convergence has occurred) that are smaller (or larger, depending on type) than the reference points.

C.2 Gadget model

A Gadget model approach to assess the stock was considered at WKBUT in 2013 as an alternative to the stock production model. Gadget should continue to be developed and be reviewed at an inter-benchmark. This work will likely take one to two years and the date of the inter-benchmark should be set two to three months after the work is complete in order to give participants time to review the analyses. The Gadget model should include the anticipated revised cpue, length frequencies representative of all the catch, the new combined survey index, a growth function based on Icelandic tagging data, length selectivities by sex, iterative reweighting as in the assessment of tusk in Va. Uncertainties on the estimates, tests of sensitivity to the natural mortality assumption, and analyses of possible reference points should be presented.

G. Biological Reference Points

WKBUT in 2013 proposed a set of reference points as derived from this model as B_{lim}=0.3B_{MSY} , F_{lim}=1.7F_{MSY} and MSY$B_{trigger}$ as 0.5B_{MSY} based on the following considerations:

B_{lim}

The Schaefer production curve fitted by the assessment model is the estimated stock–recruitment relation of the stock. The slope of this curve is decreasing linearly (Figure. G.1) i.e. there is not a distinct "change-point" where recruitment starts to decline rapidly as the stock is reduced, which could provide a candidate for a B_{lim} reference.

A B_{lim} could instead be set in relation to the time it takes for the stock to recover from this point (cf. Cadrin, 1999). The time needed to rebuild an overfished stock from B_{lim} back to B_{MSY} depends on the stock size at B_{lim}, the rate of growth and fishing mortality.

At 30%B_{MSY} production is reduced to 50% of its maximum (Figure G.1). This is equivalent to the SSB at 50% R_{MAX} (maximum recruitment). Greenland halibut is believed to be a slow growing species i.e. with relative low r (intrinsic rate of increase) (Figure G.2 left). This means that even without fishery it would take some ten years to rebuild the stock from 30%B_{MSY} to B_{MSY} (calculated by setting r=0.21, the 75th percentile), but likely longer (Figure G.2 right).

Once fished down to low levels the stock will, due to the predicted slow recovery potential, spend proportionally longer time at low levels once a recovery plan is implemented and fishing pressure is relaxed. Longer time at low levels means higher risk of "bad things" happening which could destabilize the stock. B_{lim} therefore be set no lower than 30% B_{MSY}.

F_{lim}

An F-ratio (F/F_{MSY}) corresponding to a yield of 50%MSY (50%R_{MAX}) at a stock biomass of 30%B_{MSY} (suggested B_{lim}) may be derived from equation 3 as follows:

$$\frac{production}{B_{MSY}} = \frac{2\,MSY\,P_t}{B_{MSY}}\left(1-\frac{P_t}{2}\right),$$

$$\text{at equilibrium: } C = production \text{ and}$$

$$F = \frac{C}{B} = \frac{C}{B_{MSY}}\frac{B_{MSY}}{B} \Rightarrow$$

$$F = \frac{2\,MSY\,P_t}{B_{MSY}}\left(1-\frac{P_t}{2}\right)\frac{1}{P}, \quad \text{as } F_{MSY} = \frac{MSY}{B_{MSY}} \Rightarrow$$

$$\frac{F}{F_{MSY}} = Fratio = 2 - P$$

if B_{lim} is 30%B_{MSY} (P=0.3) then the corresponding F_{ratio} is 1.7 (Figure G.1). The proposed F_{lim} at 1.7F_{MSY} is the fishing mortality that will drive the stock biomass to B_{lim}.

MSY$B_{trigger}$

In order to have a safety margin between the defined B_{lim} and a MSY $B_{trigger}$, taking account of the precision of the assessment, ICES have previously used a factor of 1.4 or if error is known in assessment, then B_{lim}e [6]

is assumed at 0.3 then MSY $B_{trigger}$ will be estimated at approx. 0.5B_{MSY}, which is proposed as MSY $B_{trigger}$ reference point for this stock. Similar MSY $B_{trigger}$ values in this order of magnitude have been adopted for several ICES and NAFO stocks.

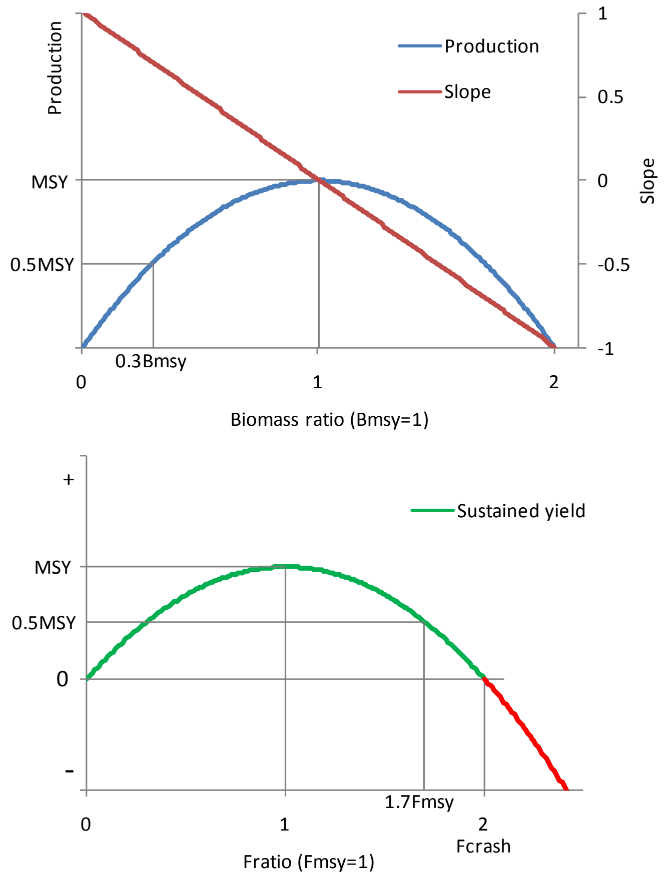


Figure G.1. The logistic production curve in relation to stock biomass (B/B_{MSY}) (*upper*) and fishing mortality (F/F_{MSY}) (*lower*). *Upper*: points of maximum sustainable yield (MSY) and corresponding stock size are shown as well as the slope (red line) of the production curve (blue line); *lower*: points of MSY and corresponding fishing mortality and F_{crash} ($F \geq F_{crash}$ do not have stable equilibriums and will drive the stock to zero).

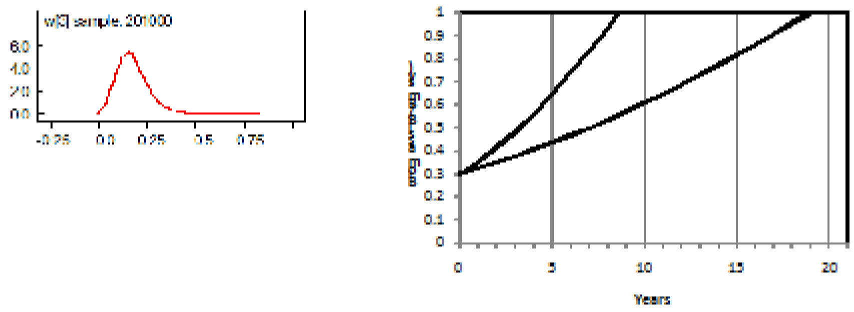


Figure G.2 ***Left*****: The posterior probability density distribution of *r*, the intrinsic rate of growth. Right: estimated recovery time from B_{lim} ($0.3B_{MSY}$) to B_{MSY} (relative biomass = 1) given *r*-values ranging within the 95% conf. lim. of the posterior (left figure) and no fishing mortality.**

Annex 4: Draft ToR for workshop on NEA Greenland halibut, WKNGHD

The **Workshop on Northeast Arctic Greenland Halibut Data and Assessment Methods** (WKNGHD) chaired by Elvar Halldor Hallfredsson, Norway, will meet at Svanhovd, Norway, 14–16 October 2014 to:

1) For the commercial fleet data:

- 1.1) Russian and Norwegian cpue indices exhibit different trends over time that need to be examined if cpue series are used as population indices input to the assessment.
- 1.2) Sex composition of catches at each fishery should be considered used.
- 1.3) Analyses should consider whether adjustments for a 'technology creep' have occurred.

2) For the survey series, identification of what part of the NEA Greenland halibut population each survey covers and to the surveys ability to reflect the dynamics of the assessed population.

3) Regarding analytical assessment, review the two models presented to WKBUT 2013 (production model and a GADGET) in relation to new information on input data, and in relation to recommendation in the WKBUT report (ref).

WKNGHD will report by 3 November 2014 for the attention of ACOM.

Supporting information

Priority	The current activities of this Group will lead ICES to a final benchmark assessment of this stock. Consequently, these activities are considered to have a high priority.
Scientific justification	The Russian fishing vessel index in 1964–2012 shows a weak reaction to large changes in catch while both this series and the Norwegian low-tonnage trawl vessels show abrupt changes in the level of cpue. These aspects need to be examined, in particular to determine if the time-series need to be split. The trawl fleet catches contain more males than the gillnet/longline fleet which catch females primarily. So they may not reflect total-stock biomass dynamics properly if male and female stocks have a different dynamics. The gear and fishing efficiency have clearly increased over the period the time-series cover for these fisheries. Any attempts to quantify this parameter will improve the quality of the cpue series. The current surveys likely cover different portions of the population both spatially but also different length/ages. A comparion of surveys and their expected coverage of life stages of Greenland halibut will require detailed examination and comparison of the data (total number and weight, length–frequencies by sex) for all series at the most disaggregated level possibly (preferably on a haul by haul basis).
Resource requirements	The research programmes which provide the main input to this group are already underway, and resources are already committed. The additional resource required to undertake additional activities in the framework of this group is negligible.
Participants	The Group is expected to be attended by some 5–8 experts.
Secretariat facilities	None.
Financial	No financial implications.
Linkages to advisory committees	Direct linkages with ACOM.
Linkages to other committees or groups	AFWG
Linkages to other organizations	None

Annex 5: Working documents

List of working documents submitted to WKBUT 26–29 November 2013

WD 1 Thordarson, G. Surveys on Greenland halibut (*Reinhardtius hippoglossoides*) in Va.

WD 2 Thordarson, G. A note on growth assumptions used in the Gadget model for Greenland halibut (*Reinhardtius hippoglossoides*) in Subareas V, VI, XII, and XIV.

WD 3 Steingrund, P. Growth of Greenland halibut (*Reinhardtius hippoglossoides*) in Faroese waters based on mark–recapture experiments.

WD 4 Thordarson, G. and B. Elvarsson. Exploratory gadget stock assessment of Greenland halibut (*Reinhardtius hippoglossoides*) in Subareas V, VI, XII, and XIV.

WD 5 Jørgensen, O.A. and M. Treble. Input to and assessment of the Greenland halibut stock component in NAFO Subarea 0 + Division 1A offshore + Divisions 1B–1F.

WD 6 Treble, M.A. and O.A. Jørgensen. Survey approach to assessment of Greenland halibut in SA 0+1.

WD 7 Boje, J. MSY approximations for Greenland halibut in V+XIV.

WD 8 Solari, A, Jørgensen, O and H. Siegstad. On halibut dynamics.

WD 9 Hedeholm, R., Post, S.L. and J. Boje. A new look at the Greenland halibut survey on the East Greenland shelf 1998–2012.

WD 10 Thordarson, G. Constructing a combined index for Greenland halibut (*Reinhardtius hippoglossoides*) in Subareas V, VI, XII, and XIV from the Icelandic autumn survey and the Greenland deep-water survey.

WD 11 Hvingel, C. Some investigations on the Bayesian assessment model for GHL in ICES Division V+XIV.

WD 12 Elvarsson, B. A study on the possible scenarios for the exploratory gadget stock assessment model for Greenland halibut (*Reinhardtius hippoglossoides*) in Subareas V, VI, XII, and XIV.

WD 13 Steingrund, P. A production model of Greenland halibut (*Reinhardtius hippoglossoides*) in Faroese waters.

WD 14 Bakanev, S. Assessment of the Barents Sea Greenland halibut stock using the stochastic version of the production model.

WD 15 Howell, D., Hallfredsson, E.H., Vollen, T., and Å. Fotland. Exploratory GADGET stock assessment of NEA Greenland halibut (*Reinhardtius hippoglossoides*).

WD 16 Hallfredsson, E.H. A note on growth of Greenland halibut, and status of age readings by new age reading method in Norway.

WD 18 Elvarsson, B. A note on the growth based on tag–recapture experiments on Greenland halibut (*Reinhardtius hippoglossoides*) in Subarea Va.

WD 19 Steingrund, P. Biomass indices of Greenland halibut (*Reinhardtius hippoglossoides*) in Faroese waters.

WD 20 Thordarson, G. A note on the Greenland halibut (*Reinhardtius hippoglossoides*) cpue estimates from Va.

Surveys on Greenland halibut (*Reinhardtius hippoglossoides*) in Va

Gudmundur Thordarson

Fisheries Advisory Section
Marine Research Institute, Reykjavík, Iceland
(gudthor@hafro.is)

Do not cite without authors permission

November 8, 2013

1 Surveys on Greenland halibut in Va

The Marine Research Institute conducts annually many survey cruises which are aimed at various species. The main two surveys that provide fisheries indiependent measures on Greenland halibut in Va are the Spring survey (March Survey) and the Autumn or October Survey. Both being bottom-trawl surveys. The Spring Survey is focused on depths shallower than 500m and has a relatively dense station-net on the shelf (approx 530 stations). As the Spring Survey does not cover the full depth range of Greenland halibut it is not considered fully representative for the species in Va.

On the other hand the Autumn Survey has around 380 stations but also covers much larger area to depths below 1000m and is aimed at Greenland halibut and *S. mentella* so the distance between the stations is much greater. This survey has been conducted since 1996 and is the main source of fisheries independent data on Greenland halibut in Va.

The text in the following sections up to and including section 5 is mostly a translation from **?**. Where applicable the emphasis has been put on Greenland halibut.

2 Spring Survey

From the commencing of the Spring Survey the stated aim has been to estimate abundance of demersal fish stocks, particularly the cod stock with increased accuracy and thereby strengthening the scientific basis of fisheries management. That is to get fisheries independent estimates of abundance that would result in increased accuracy in stock assessment relative to the period before the Spring Survey. Another aim was to start and maintain dialogue with fishers and other stakeholders.

2.1 Preparation

Planing of the Spring Survey started in 1984 and the emphasis was mainly on two things. First that the survey was extensive enough so there would be little doubt of its usefulness as method for estimating abundance of demersal species. Second the Survey should be planned in close cooperation with fishers and other stakeholders in the fishing industry. That is to utilise the experience of stakeholders in choosing the time of the survey, area surveyed, where to place tow-stations and which fishing gear to base the design of the survey gear on.

To help in the planning, experienced captains were asked to map out and describe the various fishing grounds around Iceland and then they were asked to choose half of the tow-stations taken in the survey. The other half was chosen randomly.

2.2 Timing, area covered and tow location

It was decided that the optimal time of the year to conduct the survey would be in March, or 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 in March (**?**). Also previous survey attempts had taken place in March and for possible data comparison it made sense to have the Survey in March.

The total number of stations was decided as 600 and the aim of having so many stations was to decrease variance in indices but was also inside the constraints of what was feasible in terms of survey vessels and workforce available. With 500-600 tow-stations the expected CV of the survey would be around 13% for cod.

The survey area was the Icelandic shelf down to 500m and at the EEZ-line between Iceland and Faroe Islands. Stations were placed so that the highest station density were in the areas of highest concentrations of cod. The survey area was divided into two main areas i.e. North and South. It was assumed that 25-30% of the cod stock (in abundance) would be in the southern area at survey time but 70-75% in the north. 425 tow-stations were therefore placed in the cooler northern area which is also the main nursery area for cod. A total of 175 tow stations were placed in the warmer southern area which also is the main spawning area for cod. The two areas were then divided into several sub-areas, four in the south and six in the north (Figure 1). Stations were allocated to the subareas based on perceived densities of cod (**?**).

The base unit in allocating tow-stations on a finer area scale are the statistical-squares. Up to 16 stations are in each statistical-square in the northern region and up to 7 in the southern region. Experienced captains were asked to name the position of half the tows in each statistical-square and the other half was placed randomly. The captains were asked to decide the tow direction for all the stations.

2.3 Vessels, fishing gear and fishing method

From the early stages of planing 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 1972-1973 to conduct the survey. Each year 5 trawlers have participated in the survey each in a dedicated area (NW,N, E, S, SW). The 10 Japan-built trawlers were all build 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 had some modifications since the start of the survey, most of them in 1986-1988.

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

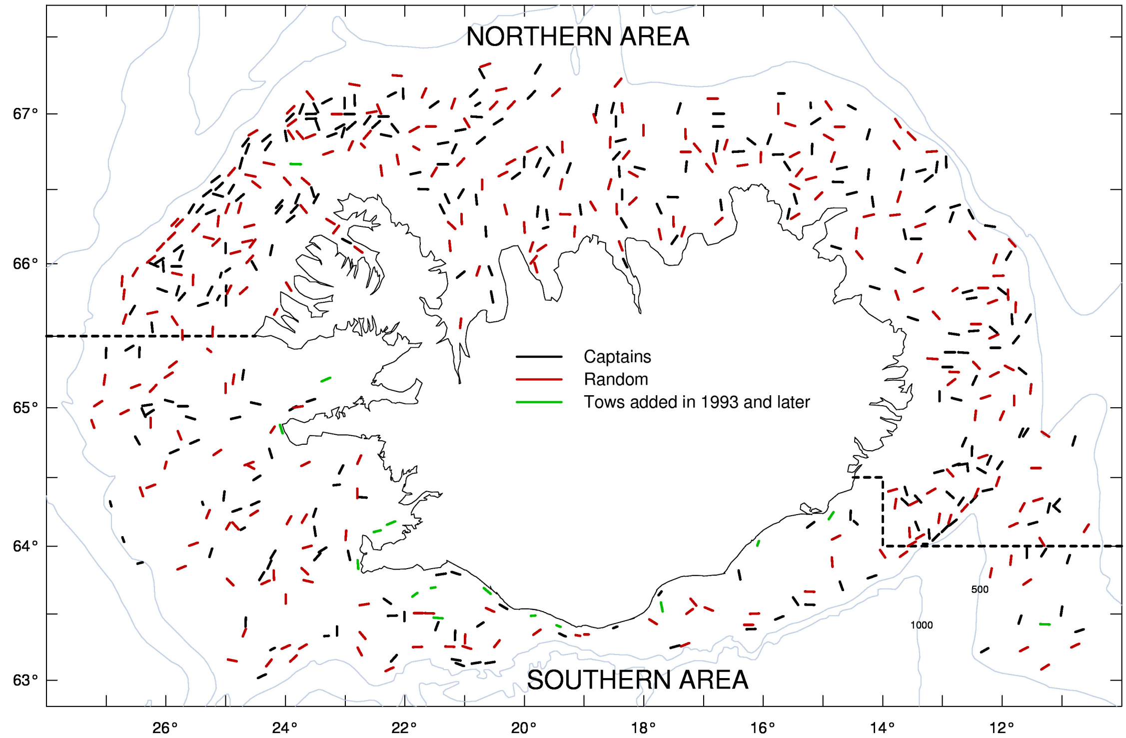


Figure 1: Tow-stations in the Spring Survey (March). Black lines indicate tow-stations selected by captains of commercial trawlers, red lines tow-stations selected randomly and green lines stations that were added in 1993 or later. The broken black lines indicate the original division of the study area into Northern and Southern area. The 500 and 1000 m depth contours are shown.

Length of each tow was set 4 nautical miles and towing speed at approx. 3.8 nautical miles per hour. Minimum towing distance so that the tow is considered valid for index calculation is 2 nautical miles. Towing shall stop if wind is more than 17-21 m/sec, (8 Beaufort).

2.4 Later changes and alterations to the survey

2.4.1 Vessels and fishing gear

The trawlers used in the survey have been changed somewhat in later years. The changes include alteration of hull shape (bulbous bow), hull extended by several meters, larger engines and some other minor alterations. These alterations have most likely 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. In recent years research vessels have taken part in the Spring Survey after elaborate comparison studies. The r/v Bjarni Sæmundsson has surveyed the NW-region since 2007 and r/v Árni Friðriksson has surveyed the Faroe-Iceland ridge in recent years and from 2010 also the SW-area.

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. The increase in the weight of the otter-boards 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.

2.4.2 Trawl-stations

Initially the numbers of trawl-stations surveyed was expected to be 600. However this number was not covered until 1995. The first year 593 tow-stations were surveyed but in 1988 the tow-stations had been decreased down to 545 mainly due to bottom topography but also due to drift ice that year. In 1989 - 1992 between 567 and 574 tow-stations were surveyed annually. In 1993, 30 tow-stations were added in shallower waters as an answer to stakeholders critique. Until 1995 between 596 to 600 tow-stations were surveyed annually but in 1996 14 stations that were added in 1993 were omitted. Since 1991 additional tows have been taken at the edge of the survey area if the amount of cod has been high at the outermost stations.

In 1996 the whole survey design was evaluated with the aim of reduce cost. The number of stations was decreased to 532 stations. The main change was to omit all of the 24 tow-stations from the Faroe-Iceland ridge. This was the state of affairs until 2004 when in response to increased abundance of cod on the Faroe-Iceland ridge 9 tow-stations were surveyed. Since 2005 all of the 24 stations omitted in 1996 have been surveyed each year.

In the early nineties there was a change from Loran C positioning system to GPS. This may have slightly changed the positioning of the to tow-stations as the Loran C system was not as accurate as the GPS.

3 Autumn Survey

The Icelandic Autumn Ground-fish Survey (AGS) has been conducted annually since 1996 by the Marine Research Institute (MRI). 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 Icelandic Ground-fish Survey (IGS) conducted annually in March 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.

3.1 Timing, area covered and tow location

The Autumn Survey is conducted in October as it is considered the most a suitable month in relation to diurnal vertical migration, distribution and availability of Greenland halibut and deep-sea 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 as covered by IGS. 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.

3.2 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 log-books 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 were unchanged.

The number of stations in the deep-water area was therefore 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 log-book database of the bottom trawl fleet fishing for Greenland halibut 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 log-books of the bottom trawl fleet 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 have been 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 since 2000 has been around 381 (Table 1).

The R/V "Bjarni Sæmundsson" has been used in the shallow-water area from the beginning of the survey. For the deep-water area MRI rented one commercial trawler 1996-1999, but in 2000 the commercial trawler was replaced by the R/V "Árni Friðriksson" (Table 1).

In 2011, due to industrial actions by the crews on the research vessels the Autumn survey was not completed. Therefore indices are not calculated for that year.

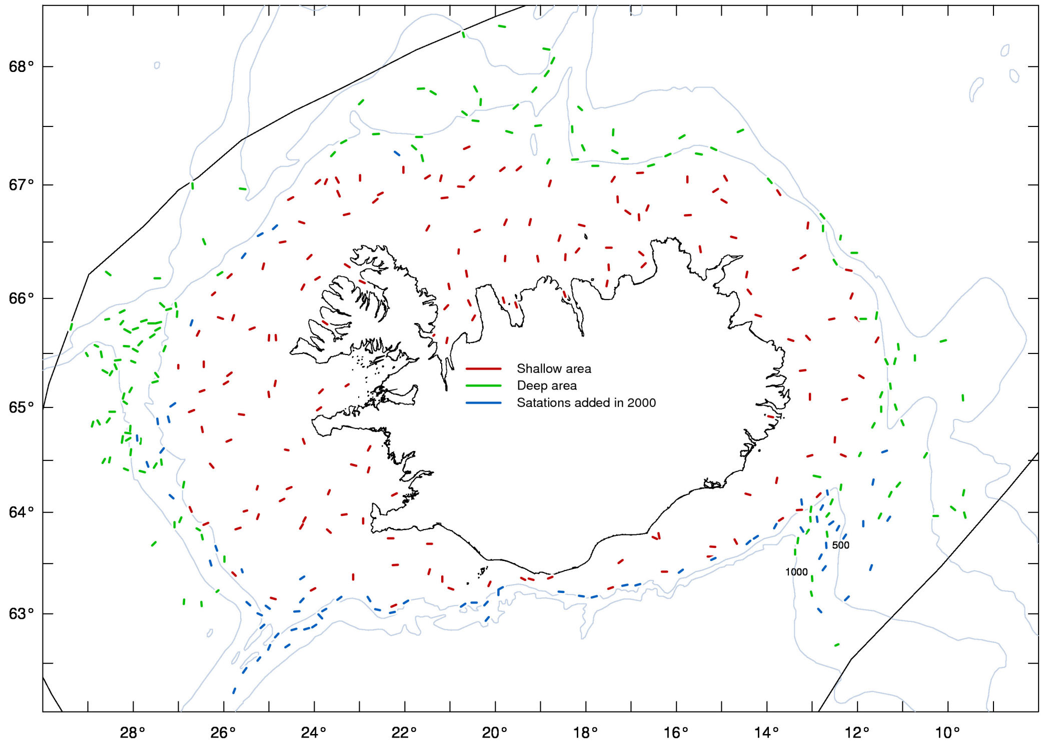


Figure 2: Stations in the Autumn Ground-fish Survey (AGS). R/v "Bjarni Sæmundsson" takes stations in the shallow-water area (red lines) and r/v 'Árni Friðriksson' takes stations in the deep-water areas (green lines), the blue lines are stations added in 2000.

Table 1: Vessels used in the Autumn Ground-fish Survey 1996-2009, their survey areas, and the number of station taken.

Year	Shallow waters Vessel name	No.Stations	Deep waters Vessel name	No.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	163	r/v Árni Friðriksson	219	382
2001	r/v Bjarni Sæmundsson	161	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	182	r/v Árni Friðriksson	219	401
2009	r/v Bjarni Sæmundsson	178	r/v Árni Friðriksson	219	397
2010	r/v Bjarni Sæmundsson	179	r/v Árni Friðriksson	209	388
2011	r/v Bjarni Sæmundsson	50	r/v Árni Friðriksson	87	137
2012	r/v Bjarni Sæmundsson	179	r/v Árni Friðriksson	208	387

3.3 Fishing gear

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

The bottom trawl used in the shallow water is called 'Gulltoppur'. The headline is 31.0 m, and the fishing line is 19.6 m. The trawl used in the deep-water area is 'Gulltoppur 66.6m'. The headline is 35.6 m and the fishing line is 22.6 m.

Towing speed and distance: 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).

4 Data sampling

The data sampling in the Spring and Autumn survey are quite similar. In short there is more emphasis on stomach content analysis in the Autumn Survey than the Spring Survey. However this does not apply to Greenland halibut as no stomach content analysis is done on the species in the surveys.

4.1 Length measurement, counting (sub-sampling)

All fish species are measured for length. For the majority of species including Greenland halibut, 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 4 times the length interval of a given species. Example: If the continuous length distribution of a species at a given station is between 35 and 65 cm, the length interval is 30 cm and the number of measurements needed is 120. If the catch of the species at this station exceeds 120 individuals, the rest is counted. For Greenland halibut in the Autumn survey 5 times the length interval is measured.

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.

4.2 Recording of weight, sex and maturity stages

Weight, sex and maturity data is collected from Greenland halibut sampled in the autumn survey.

4.3 Otolith sampling and weighing

Otoliths are randomly sampled from the following species: cod, haddock, saithe, golden redfish, ling, blueling, tusk, Atlantic wolffish, spotted wolffish, greater argentine, Atlantic halibut, Greenland halibut, plaice, lemon sole, witch, megrim, dab, long-rough dab, lumpsucker and deep-sea redfish.

For Greenland halibut a minimum of 10 and a maximum of 50 otoliths are collected from each haul. Otoliths are sampled at a 3 fish interval so that if in total 100 Greenland halibuts are caught in a single haul, 33 otoliths are sampled.

4.4 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 co-operation with the cruise leader.

Tow information:

General: Year Station Vessel registry no. Cruise ID, Day./month, Statist. Square, Sub-square, Tow number., Gear type no. , Mesh size, Briddles length (m).

Start of haul: Pos. N, Pos. W, Time (hour:min), Tow direction in degrees, Bottom depth (m), Towing depth (m), Vert. opening (m), Horiz. opening (m).

End of haul: Pos. N, Pos. W, Time (hour:min), Warp length (fm), Bottom depth (m), Tow length (naut. miles), Tow time (min) , Tow speed (knots).

Environmental factors:

Wind direction, Air temp ℃, Wind speed, Bottom temp ℃, Sea surface, Surface temp ℃, Tow.d. temp ℃, Cloud cover, Air pressure, Drift ice.

5 Data processing

5.1 Abundance and biomass estimates at a given station

As described above (4.1) the normal procedure is to measure at least 4 times the length interval of a given species. The number of fish caught of the length interval L_1 toL_2 is given by:

$$P = \frac{n_{measured}}{n_{counted} + n_{measured}} \tag{1}$$

$$n_{L_1-L_2} = \sum_{i=L_1}^{i=L_2} \frac{n_i}{P} \tag{2}$$

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:

$$B_{L_1-L_2} = \sum_{i=L_1}^{i=L_2} \frac{n_i \alpha L_i^{\beta}}{P} \tag{3}$$

Where L_i is length and α and β are coefficients of the length-weight relationship.

5.2 Index calculation

For calculation of indices the Cochran method is used (Cochran 1977). The survey area is split into sub-areas or stratas and an index for each subarea is calculated as the mean number in a standardized tow, divided by the area covered multiplied with the size of the sub-area. The total index is then a summed up estimates from the sub-areas or stratas.

In the Autumn Survey there are two different types of Trawls in use, one for depths greater than 400m and one for depths less than 400m. The shallower trawl is slightly smaller than the trawl used at depths greater than 400m. The diameter of the smaller trawl is 54m but 63.45m in the deep-trawl. Therfore the catches from the smaller trawl are multiplied by 1.175 (63.45/54).

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

$$\bar{Z}_i = \frac{\sum_i Z_i}{N_i} \tag{4}$$

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

$$I_i = \bar{Z}_i \left(\frac{A_i}{A_{tow}} \right) \tag{5}$$

and the sample variance in the i-th stratum:

$$\sigma_i^2 = \left(\frac{\sum_i (Z_i - \bar{Z}_i)^2}{N_i - 1} \right) \left(\frac{A_i}{A_{tow}} \right) \tag{6}$$

where A_i is the size of the i-th stratum in square nautical miles (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:

$$I_{region} = \sum_{region} I_i \tag{7}$$

The variance is:

$$\sigma_i^2 = \sum_{region} \sigma_i^2 \tag{8}$$

and the coefficient of variation is

$$CV_{region} = \frac{\sigma_{region}^2}{I_{region}} \tag{9}$$

The sub-areas or stratas used in the Icelandic groundfish surveys are shown in figure 3. The division into stratas is based on the so-called BORMICON areas and the 100, 200, 400, 500, 600, 800 and 1000 m depth contours.

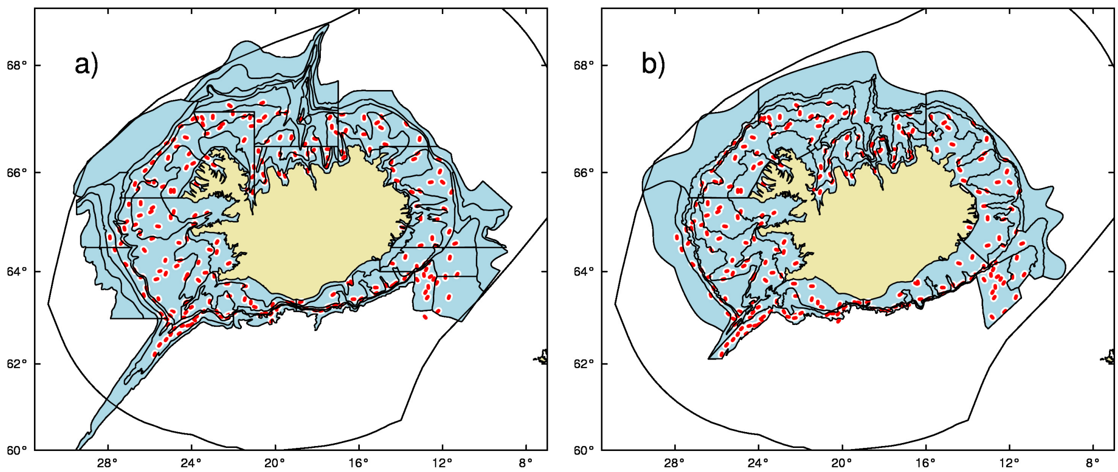


Figure 3: Comparison of the spring survey (a) and autumn survey (b) stratification scheme (black lines). The red dots represents stations occupied in the 2005 autumn survey.

6 Surveys in Va relative to Greater Silver Smelt distribution as observed from logbooks

6.1 Spring survey

The Spring Survey is not thought to cover the distributional area of Greenland halibut in Va well (Figure 4).

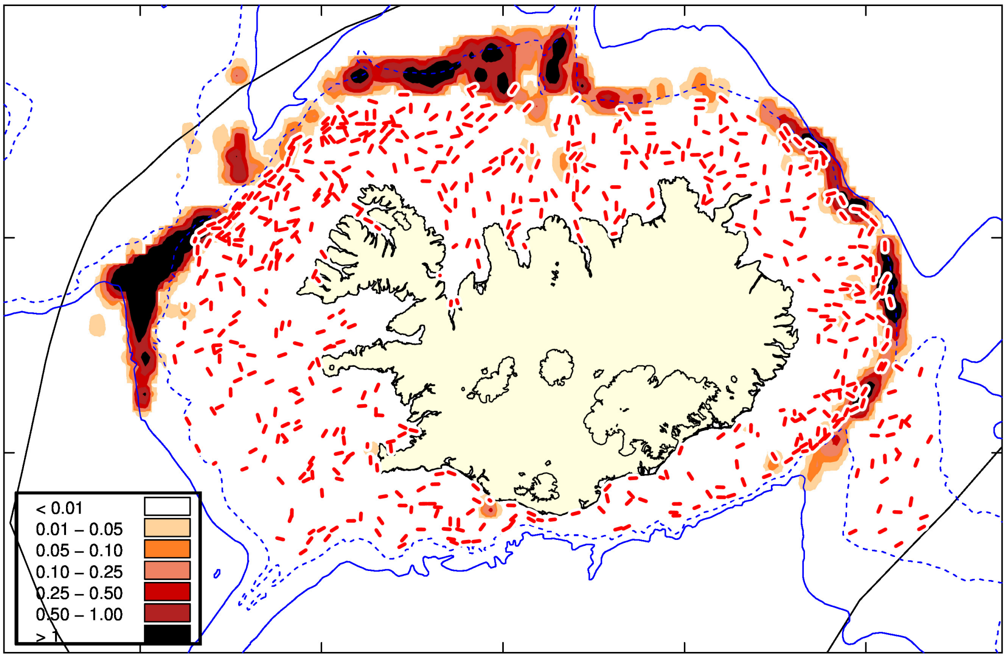


Figure 4: Contour-plot of the distribution of commercial catches of Greenland halibut in Va (tonnes/square mile) in 2012, red lines are tow-stations in the Spring Survey (March). The 500 and 1000 m depth contours are shown.

6.2 Autumn survey

The Autumn survey covers the main fishing area of Greenland halibut in Va reasonably well (Figure 5).

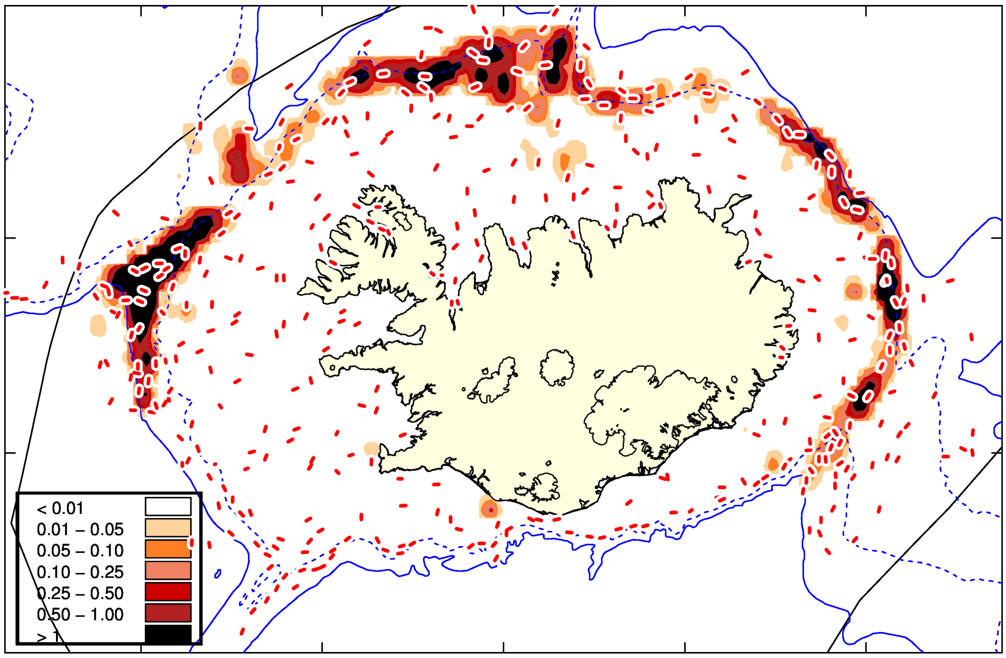


Figure 5: Contour-plot of the distribution of commercial catches of Greenland halibut in Va (tonnes/square mile) in 2008, red lines are tow-stations in the Autumn Survey (October). The 500 and 1000 m depth contours are shown.

7 Data collected in surveys on Greenland halibut in Va

The sampling proceadure used in both the Spring and Autumn Surveys was explained in section 4 on page 7. This section gives an overview of the data on Greenland halibut in Va available from the surveys.

7.1 Spring Survey

Otoliths have only been collected sporadically in the Spring survey (Table 2). Only otoliths collected in 1985 were aged.

Annully between 200 and 2000 Greenland halibut have been measured for length and between 0 and 1300 have been caught on top of those measured.

Table 2: Sampling of Greenland halibut in Va from the Spring Survey in 1985 to 2012. The otolith sampled column contains all otoliths sampled including those that have been aged. Similarly the Number measured column includes all the the Greenland halibut that otoliths were sampled from.

Year	Otoliths sampled	Otoliths aged	Number measured	Number counted
1985	674	657	1967	284
1986	0	0	1536	315
1987	0	0	824	204
1988	0	0	1518	461
1989	0	0	1555	733
1990	11	0	1199	0
1991	0	0	678	0
1992	0	0	1219	480
1993	0	0	1132	1319
1994	0	0	800	472
1995	0	0	660	21
1996	0	0	666	0
1997	0	0	275	0
1998	7	0	329	715
1999	1	0	319	0
2000	2	0	310	0
2001	0	0	365	5
2002	3	3	230	105
2003	4	0	383	0
2004	3	0	167	0
2005	1	0	165	0
2006	0	0	422	42
2007	2	0	379	0
2008	0	0	600	0
2009	0	0	804	230
2010	0	0	819	773
2011	1	0	670	225
2012	0	0	1041	520

7.2 Autumn Survey

In table 3 an overview of the sampling from the Autumn Survey is given. Since 1996 between 400 and 1400 otoliths have been sampled but none of them aged.

Between 700 and 4000 Greenland halibut have been measured annually since 1996 and between 0 and 800 have been counted on top of the ones measured.

Table 3: Sampling of Greenland halibut in Va from the Autumn Survey in 1996 to 2009. The otolith sampled column contains all otoliths sampled including those that have been aged. Similarly the Number measured column includes all the the Greenland halibut that otoliths were sampled from.

Year	Otoliths sampled	Otoliths aged	Number measured	Number counted
1996	1121	0	2507	4
1997	1482	0	3687	177
1998	1359	0	3285	424
1999	1460	0	3966	180
2000	1476	0	3850	80
2001	1505	0	4035	466
2002	1228	0	3181	715
2003	894	0	1743	2
2004	706	0	1266	6
2005	819	0	1871	85
2006	841	0	1586	0
2007	914	0	1991	41
2008	1227	0	2856	21
2009	1479	0	3825	803
2010	1144	0	3168	145
2011	355	0	737	0
2012	1395	0	3773	522

8 Total indices of biomass and abundance

In figure 6 the normal presentation of survey indices in Va is shown. It can be seen that there does not appear to be any trend in the Spring Survey whereas in the Autumn Survey indices have been increased in the beginning then decreased after 2000 but have an increasing trend since 2007.

As noted earlier the Spring Survey does not cover the main fishing grounds of Greenland halibut in Va it is not considered fully reprasentitive of trends in abundance or biomass in Va.

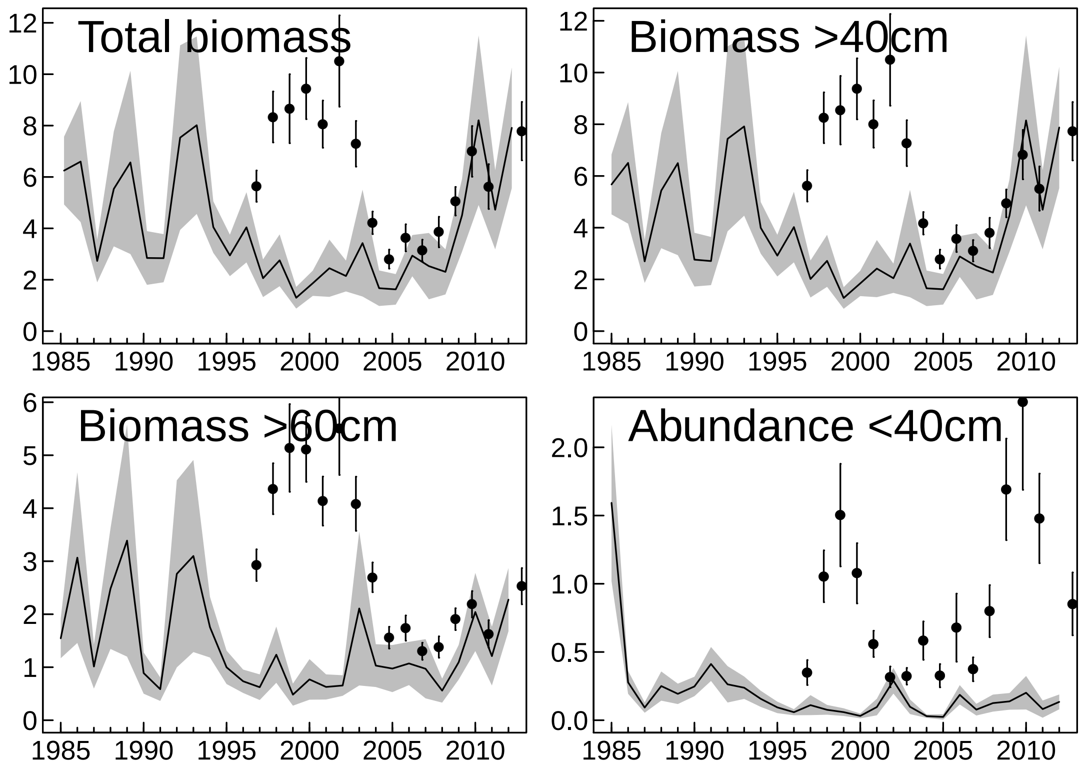


Figure 6: Greenland halibut in division Va. Shown are a) total biomass indices, b) biomass indices larger than 40cm, c) biomass indices larger than 60cm and d) abundance indices smaller than 40cm. the lines with shades show the Spring Survey indices from 1985 (SMB) and the points with the vertical line show the Autumn Survey (SMH) from 1997. The shades and vertical line indicate +/- 1 standard error.

8.1 Autumn survey indices divided by sex

As there is considerable difference in growth between the sexes for Greenland halibut it is of interest to calculate indices for the sexes separately. In general the trend for the sexes is the same, but the index has been increasing slightly faster for females than for males (Figure 7).

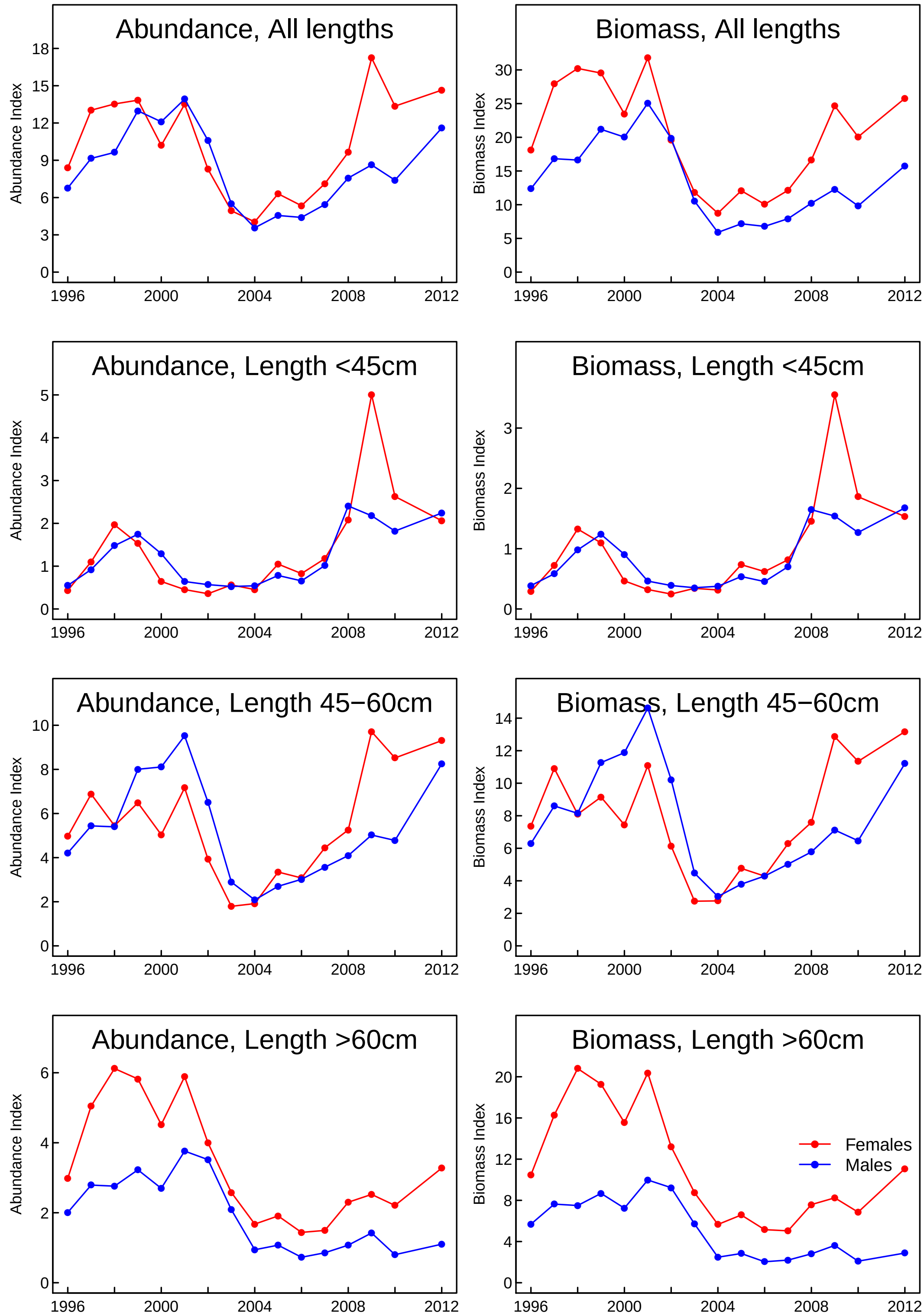


Figure 7: Greenland halibut in division Va. Abundance and biomass indices from the Autumn survey divided by sex for various length groups.

8.2 Length distributions from the Autumn survey

In figure 8 the stratified length distributions from the autumn survey are shown. No obvious cohorts or tops can be observed from the length distributions.

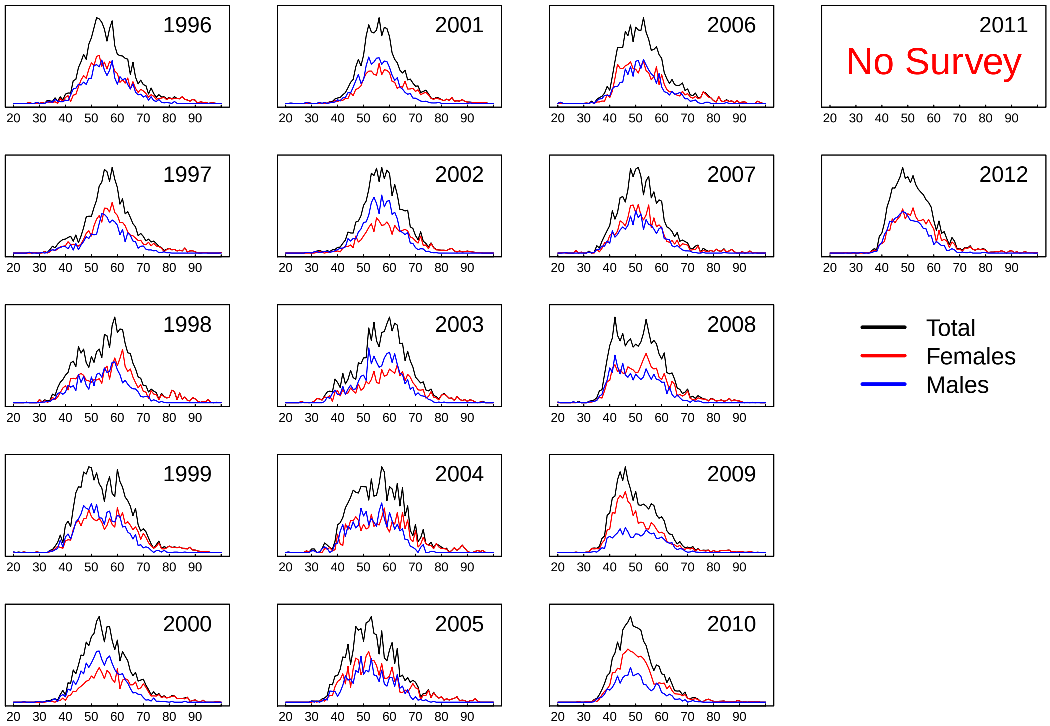


Figure 8: Greenland halibut in division Va. Stratified length distributions from the Autumn survey, divided by sex and combined (Total).

A note on growth assumptions used in the Gadget model for Greenland halibut (*Reinhardtius hippoglossoides*) in Subareas V, VI, XII, and XIV

Gudmundur Thordarson

Fisheries Advisory Section
Marine Research Institute, Reykjavík, Iceland
(gudthor@hafro.is)

November 12, 2013

Abstract

Greenland halibut has not been aged for many years in Subareas V, VI, XII, and XIV (NWWG) as ageing has been considered un-reliable. Recent studies from Norway indicate that Greenland halibut grows considerably slower than previously thought. The limited growth data from Norway does not cover the observed length distributions for the NWWG-ghl. In this document four growth scenarios used in the Gadget model variants are presented.

1 Introduction

The four different growth scenarios or variants used in the Gadget model for Greenland halibut in Subareas V, VI, XII, and XIV are:

Growth Scenario 1: Using Norwegian estimates of mean length, assuming that the standard deviation is 15% of a given mean length at age.

Growth Scenario 2: Same as one except that the growth curve for females is changed *ad hoc* so that it covers length of females observed in data from Va. These growth assumptions are the one used in the base run of the model (See WKBUT2013:WD-03).

Growth Scenario 3: Using old age estimates from Va from 1969 to 2002.

Growth Scenario 4: Same as 3 except the ageing is scaled to the Norwegian age estimates.

Growth scenarios 1 and 2 are put in the model as `catchstatistics: lengthgivenstddev` for each sex and linked to the survey data. Growth scenarios 3 and 4 are however implemented as `catchdistribution`.

2 Available data on growth of Greenland halibut

Ageing of Greenland halibut has not been conducted for many years as the ageing of the species was not considered reliable. In recent years Norwegian studies based on recapture experiments have shown that Greenland halibut grows much slower than previously thought. In Figure 1 a comparison of the estimated mean length at age from old Icelandic age data from bottom trawls and Norwegian data kindly provided by Dr. E. Hallfredsson is shown. The Icelandic estimates indicate an almost linear growth for both sexes. According to this female Greenland halibut reaches around 80 cm at the age of 14 but according to the Norwegian estimates around 68 cm. Similar holds true for the males. Considerable effort was however put into ageing Greenland halibut in Va in the years between 1997 and 2002 (Figure 2).

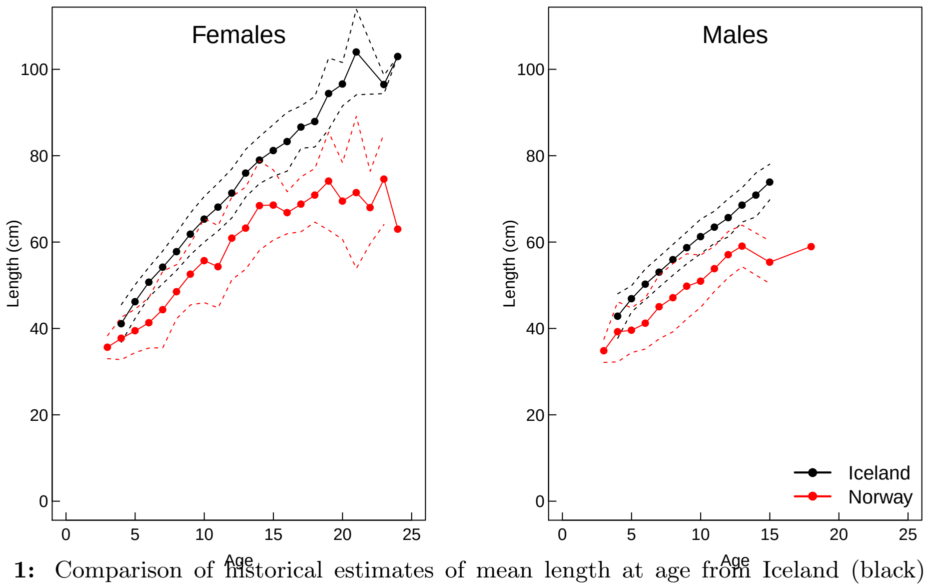


Figure 1: Comparison of historical estimates of mean length at age from Iceland (black) and a new method for ageing from Norway (red). Broken lines show ± one standard deviation of the mean.

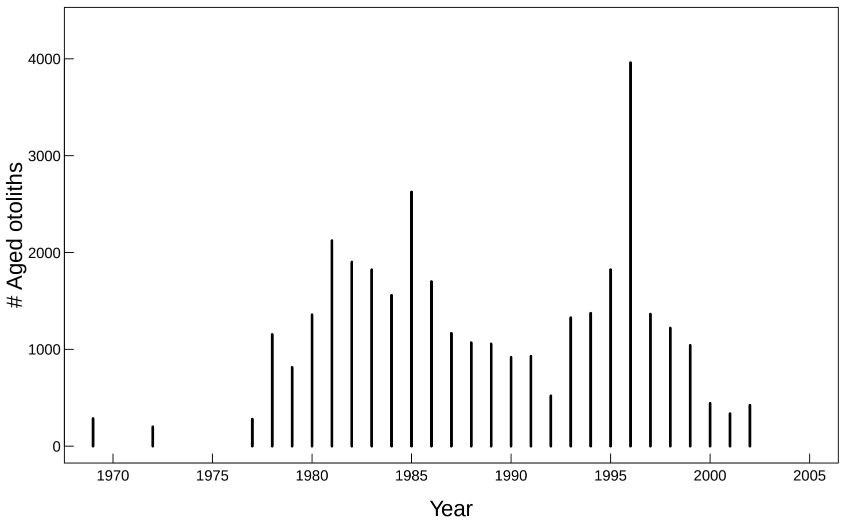


Figure 2: Number of aged Greenland halibut otoliths from commercial trawls in Va.

2 Available data on growth of Greenland halibut

3 Growth scenario 1: Using the Norwegian data

Growth scenario 1 uses the Norwegian data but makes a few assumptions, mainly a von Bertalanffy growth curve is fitted through the data and then it is assumed that the standard deviation is 15% of the mean length for a given age group. For females this makes little difference but for males as the data is scarce for the oldest age groups this assumption changes the assumed standard deviation considerably for those age groups, i.e. older than age 10 (Figure 3).

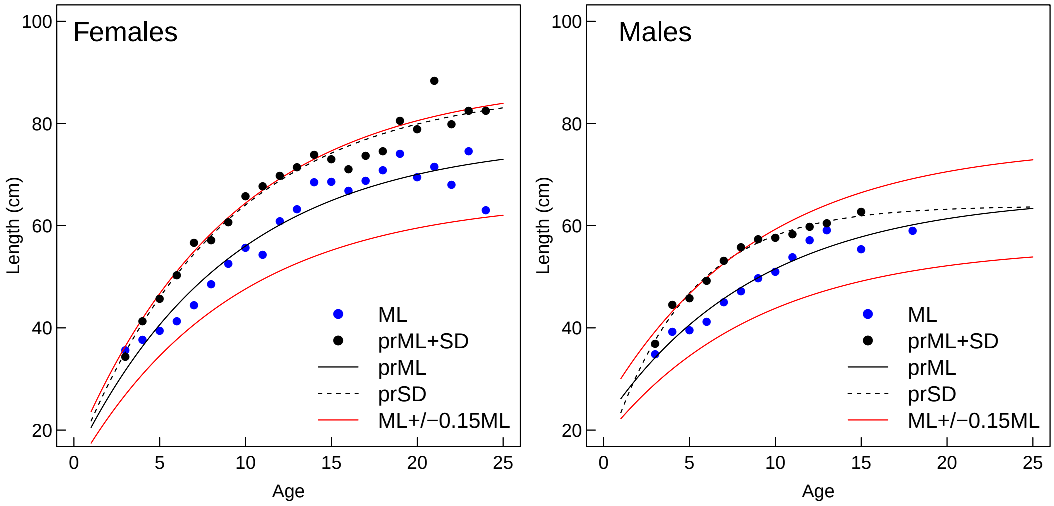


Figure 3: Growth scenario 1 used in the Gadget model, Norwegian data. Blue points: Mean length at age (ML), black points: Standard deviation of mean length added to predicted values from a von Bertalanffy growth curve (black line). Broken black line: von Bertalanffy growth curve fitted to predicted length plus the standard deviation. Red line: Assuming standard deviation to be 15% of the mean length for a given age group.

4 Growth scenario 2: Using the Norwegian data, adjusting growth of females

The main problem with growth scenario one is that according to the estimated growth curves, no Greenland halibut can reach more than 80 to 90 cm. This halibut would then be over 20 years of age. As the data used in the gadget model includes a considerable amount of measurements of 80 to 110 cm Greenland halibut it is necessary to address this somehow (Figure 4a). If not then this causes considerable conflict in the model.

The approach taken in this scenario is simply to assume more rapid growth of females. The parameters of the von Bertalanffy growth curve are simply set at: $L_\infty = 105$, $K = 0.726$ and $t_0 = 2.26$. This assumption is entirely *ad hoc*.

5 Growth scenario 3: Using the Icelandic data

As seen in figure 1 on page 2 there is considerable difference in the estimated mean length at age (Table 1). As a large number of aged otoliths is available from 1969 to 2002 it is of interest to test this data in the Gadget model. The raw age distribution do not show many strong cohorts that can be tracked through the years (Figure 5).

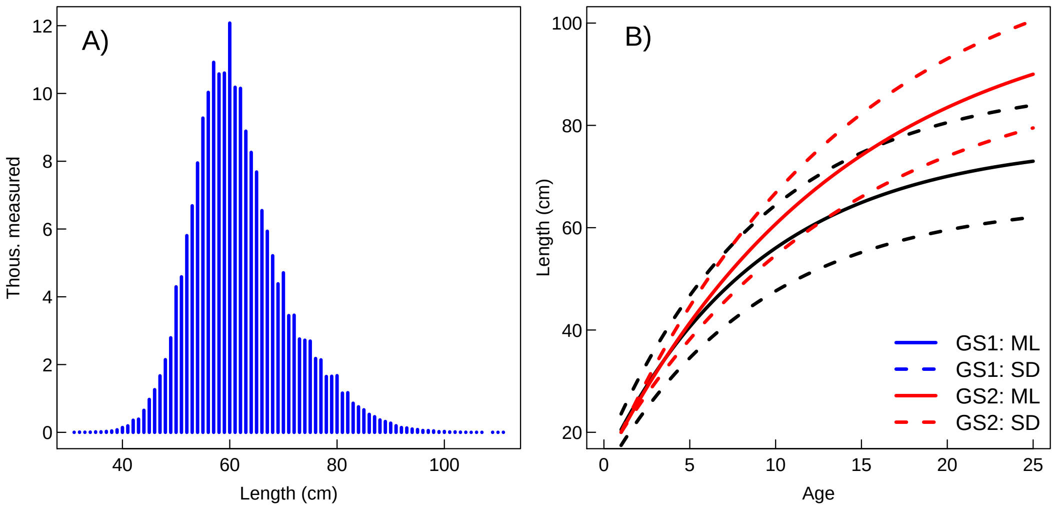


Figure 4: Growth scenario 2 used in the Gadget model. A) Histogram of length measurements from commercial catches in Va. B) Revised growth curve for female Greenland halibut (red line) and the assumed standard deviation (broken red line). For comparison growth scenario 1 is plotted (black lines).

Table 1: Aged otoliths of Greenland halibut in Va, by sex and time step (3 month)

Year	Females Step 1	Step 2	Step 3	Step 4	Sum Females	Males Step 1	Step 2	Step 3	Step 4	Sum Males	Sum all
1969	0	0	112	0	112	0	0	174	0	174	286
1972	0	0	173	0	173	0	0	27	0	27	200
1977	0	150	0	0	150	0	129	0	0	129	279
1978	0	655	0	0	655	0	499	0	0	499	1154
1979	149	221	82	0	452	47	182	133	0	362	814
1980	0	460	0	221	681	0	516	0	160	676	1357
1981	0	840	169	44	1053	0	688	227	154	1069	2122
1982	278	870	0	0	1148	100	653	0	0	753	1901
1983	133	543	114	138	928	61	490	283	60	894	1822
1984	169	435	103	68	775	29	550	96	125	800	1575
1985	884	880	20	216	2000	186	348	0	90	624	2624
1986	0	907	0	78	985	0	555	0	160	715	1700
1987	0	613	0	35	648	0	454	0	66	520	1168
1988	111	461	0	0	572	84	413	0	0	497	1069
1989	0	262	146	0	408	0	523	122	0	645	1053
1990	0	468	0	0	468	0	450	0	0	450	918
1991	0	552	0	0	552	0	377	0	0	377	929
1992	22	198	0	46	266	8	194	0	52	254	520
1993	68	418	0	141	627	30	522	0	148	700	1327
1994	134	295	0	50	479	125	650	0	117	892	1371
1995	62	412	252	128	854	49	434	158	156	797	1651
1996	725	628	347	324	2024	534	793	356	251	1934	3958
1997	322	271	53	54	700	273	211	70	110	664	1364
1998	432	82	177	0	691	280	92	80	0	452	1143
1999	135	209	132	98	574	120	179	79	77	455	1029
2000	22	12	71	79	184	14	1	133	111	259	443
2001	51	79	0	13	143	40	125	0	16	181	324
2002	44	107	0	0	151	52	177	0	0	229	380

5 Growth scenario 3: Using the Icelandic data

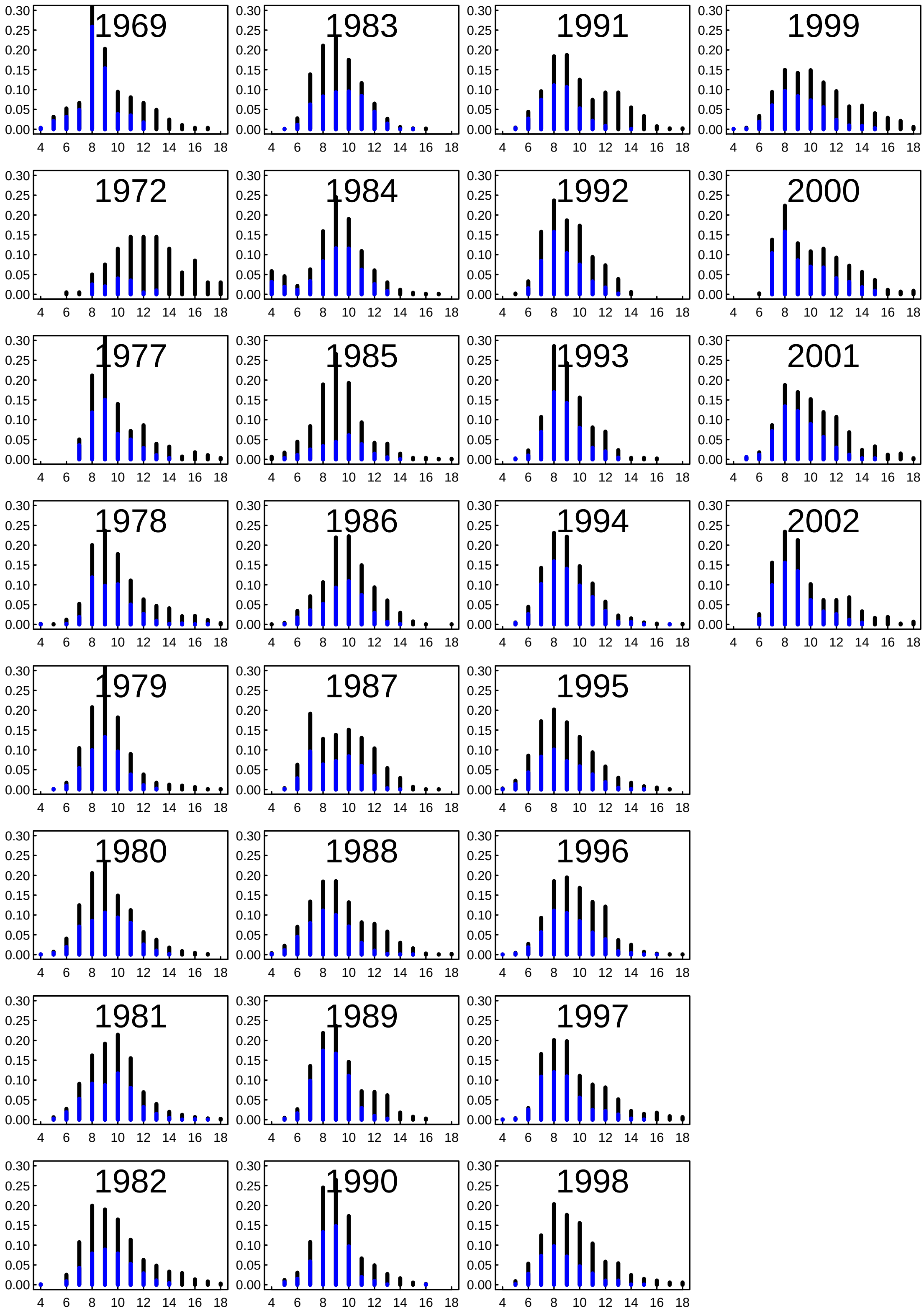


Figure 5: Growth scenario 3 used in the Gadget model. Raw age distributions from commercial trawls in Va..

5 Growth scenario 3: Using the Icelandic data

6 Growth scenario 4: Using the Icelandic data, scaled to the Norwegian growth data

As seen in figure 1 there is a difference in both growth rate and and the shape of the growth curve. Growth according to the Icelandic data is more or less linear whereas in the Norwegian data a more typical slowing of growth in the older age groups can be observed.

For the younger age groups the differences between the ageing appears fairly consistent (Figure 6). Therefore scaling the Icelandic ageing to the Norwegian may seem like a sensible thing to do. The approach taken here is simply to use the lengths from the aged Icelandic material and use the Von Bertalanffy parameter estimates from the Norwegian data to come up with an 'adjusted age-estimate'. The Von Bertalanffy growth curve is simply rearranged from:

$$L_i = L_\infty(1 - e^{-K(a_i - t_0)}) \tag{1}$$

to

$$a_i = t_0 - \frac{ln(1 - \frac{L_i}{L_\infty})}{K} \tag{2}$$

This results in a considerable shift in the age distributions as can be seen in figure 7 and in some years age 25 is a large proportion of the age distribution.

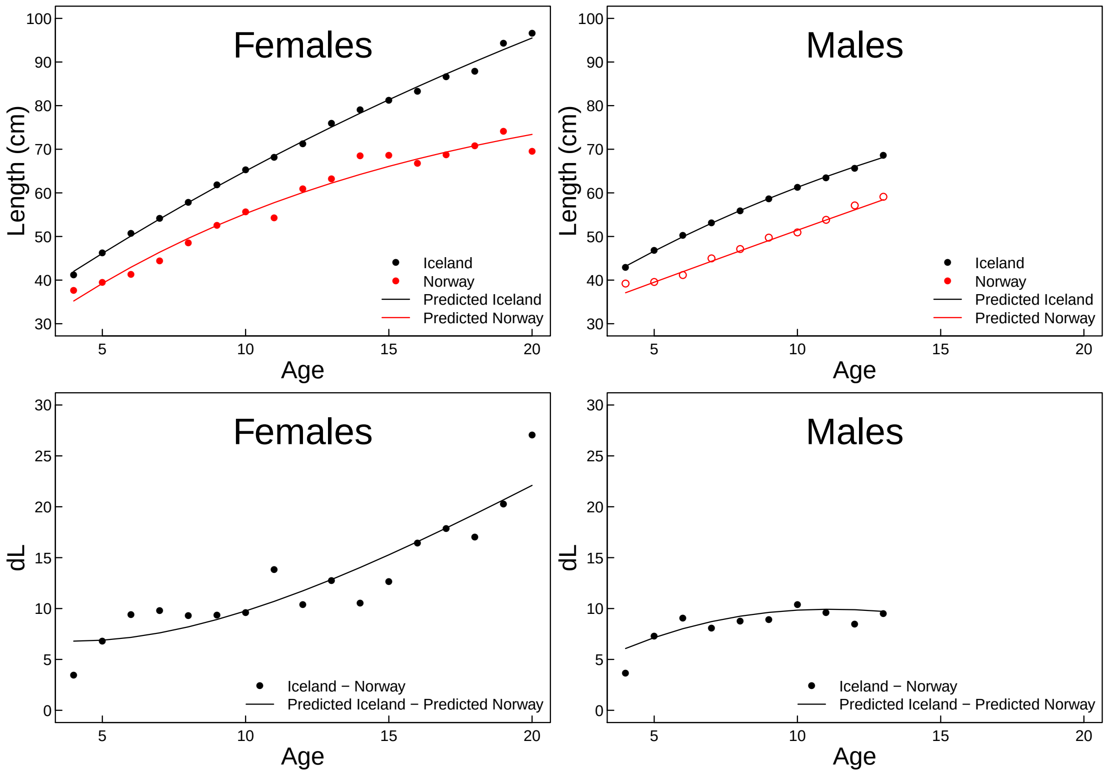


Figure 6: Mean length at age by sex (Upper) as estimated from Icelandic (black points) and Norwegian age (red points) estimations and a fit from a von Bertalanffy growth curve (black and red lines). Differences between mean length at age for females and males (Lower)

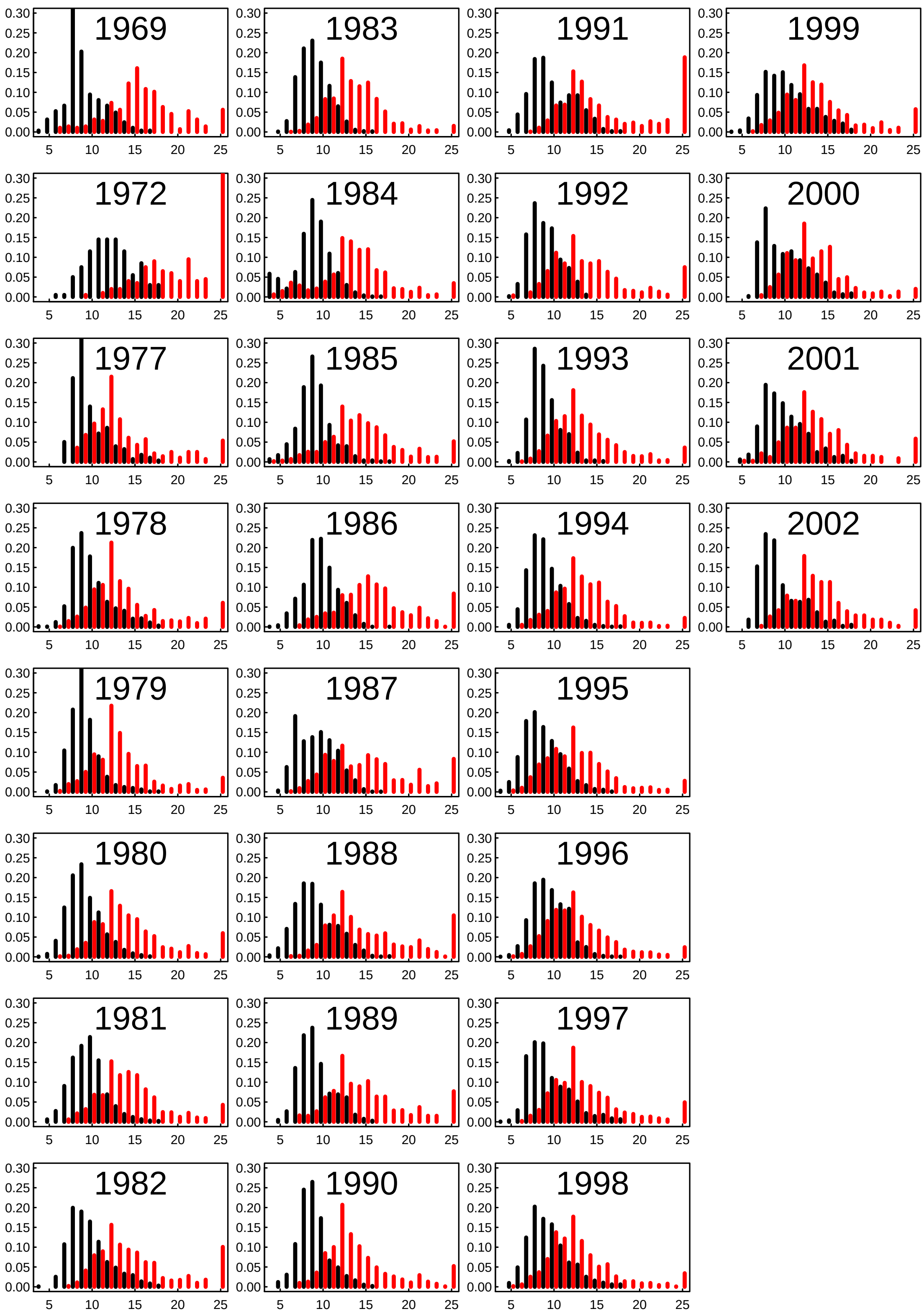


Figure 7: Growth scenario 4 used in the Gadget model. Age distributions from commercial trawls in Va. Red bars are the adjusted ageing wheras the black are the original ageing

6 Growth scenario 4: Using the Icelandic data, scaled to the Norwegian growth data

Growth of Greenland halibut (*Reinhardtius hippoglossoides*) in Faroese waters based on mark-recapture experiments

Petur Steingrund, Faroe Marine Research Institute

Abstract

In July 2002 at total of 223 Greenland halibut were tagged with conventional and data-storage-tags southeast of Faroe Islands, and 29 of them (13 %) were recaptured during the following two years. In February 2004 a total of 105 Greenland halibut were tagged on the Faroe-Iceland Ridge, and 4 recaptured (3.8 %). In August 2011 a total of 84 Greenland halibut were tagged northeast of the Faroes with data-storage-tags, and 10 are recaptured so far (11.9 %). A total of 35 of the recaptured specimens had information about the length at recapture. The annual growth rate (+- 95% confidence interval) of these specimens was 3.3 (2.6 to 4.1) cm per year. The ambient temperature of 11 specimens with data-storage-tags was on average 2.05 ^{o}C. The growth rate of Greenland halibut may, therefore, not be significantly different from Atlantic cod at the same temperature.

Introduction

In this working document I describe the three tagging experiments with Greenland halibut that have been performed by gillnetting in Faroese waters and where there have been recaptures. I do not include the two other tagging experiments (2002-2003) by trawling where there have been no recaptures.

Material and methods

During 22-25 July 2002, a total of 223 Greenland halibut were tagged with conventional (208) and data-storage-tags (15) southwest of Faroe Islands. The commercial gillnetter “Thor” was used. The conventional tags were of the Lea type whereas the data-storage-tags were of the Star-Oddi DST-milli type (measuring temperature and depth).

During 4-11 February 2004, a total of 105 Greenland halibut were tagged with conventional (55) and data-storage-tags (50) on the Faroe-Iceland Ridge. The commercial gillnetter “Thor” was also used this time. The conventional tags were of the spaghetti type (Floy tag) whereas the data-storage-tags were of the Star-Oddi DST-milli type.

During 22-25 August 2011, a total of 84 Greenland halibut were tagged with data-storage-tags northeast of Faroe Islands. The commercial gillnetter “Oknin” was used. The data-storage-tags were of the Star-Oddi DST magnetic type, see NORA (2011).

At once the gillnets entered the deck the most lively individuals were selected for tagging. Great care was taken to minimize handling and abrasion of skin mucus. The conventional tags were attached to the right dorsal side of the fish, a few centimetres behind the head. A needle was used to pierce a hole in the fish so that the nylon thread of the Lea tag could be attached. A pistol provided by Floy inc. was used to attach the spaghetti tags. The data-storage-tags were attached by two methods. Most of them were implanted into the buccal cavity. A slit was cut on the left side allowing the tag to be inserted into the buccal cavity. A conspicuous rubber thread (yellow or red), already attached to the tag, went out to the exterior, and thereafter, the hole was sewed with an absorbable surgical thread. Some of the fish got the DST attached externally to the right dorsal side just below the dorsal fin. A plastic housing surrounded the tag. The plastic housing was attached to the fish by using wires of titanium, which were pressed through the fish and bent in such a way on the other side of the fish that the tag was firmly attached to the fish. It was not possible to keep the fish in seawater during the tagging process, which took a few seconds for conventional tags and 1-2 minutes for data-storage-tags. Most of the DST-tagged fish were doubled tagged with conventional tags also. The total length (rounded down to the nearest cm) was recorded.

When the fish were recaptured, we normally got information about recapture date and position. In many cases we also got information about the length of the individual. Most of the fish were delivered to the institute, allowing the measurement of the length to be done in the same way as when the fish was tagged.

A regression analysis (MS Excel) was used to estimate the annual (365-day) growth rate. The regression analysis also provided the 95 % confidence interval.

Results

A total of 43 specimens are recaptured so far, and 35 of them had information about the length (Table 1). Two of the 35 specimens had migrated out of Faroese waters, one to Iceland and one to Shetland (Figure 1).

The recaptured specimens were often shorter after recapture than before, a seemingly perplexing observation. However, the specimens were measured alive at tagging and had in most instances been frozen after recapture. Recaptured fish, e.g. cod, often shrink by one centimetre if they are not instantly measured, and they shrink even more after freezing and subsequent thawing. Most of the recaptured specimens were delivered to the institute where the length could be measured accurately. In the analysis of growth, I have also included those specimens, which were length-measured by the fishermen.

Relating the length increments with the time a liberty, an annual growth rate of 3.3 cm was obtained (Table 2), the 95 % confidence interval ranging between 2.6 and 4.1 cm per year. The ambient temperature of the specimens fitted with data-storage-tags was 2.05 ^{o}C (Table 1).

Discussion

Even though there might be uncertainties associated with the length measurements of the tagged and recaptured specimens, there was, nevertheless a rather close relationship between length increase (growth) and time at liberty.

There is much controversy about the age reading of Greenland halibut (ICES, 2011). Two groups of methods suggested quite different growth rates, either being 10-12 years for a 70 cm long fish or around 20 years. If the growth rate (in length) of Greenland halibut is roughly constant at lengths of 40 to 70 cm, then the tagging results presented in this working document (3.3 cm per year) suggests that these 30 cm are grown over a period of 9 years. The total age of a 70 cm long fish would then be 9 + 6 = 15 years, if we assume that a 40 cm long fish is 6 years old. Hence, the growth rate indicated by the tagging studies is intermediate between the two groups of methods described in ICES (2011).

The ambient temperature of data-storage-tagged Greenland halibut was on average 2.05 ^{o}C (Table 1). Comparing the growth rate of Greenland halibut with cod at the same temperature indicates that there is no difference between cod and Greenland halibut (Table 3), since a change in length of 2.7 cm is within the confidence interval presented in Table 2.

A potential way to model the growth of Greenland halibut in the various areas in the North Atlantic could be to use the growth rates of cod at the temperatures found in the areas where Greenland halibut are distributed.

Acknowledgements

I thank the crew, who tagged and worked up the Greenland halibut specimens at Faroe Marine Research Institute. I also thank the Nordic project (NORA, 2011) for the financial support of a part of the tagging material presented in this working document – especially the Norwegian team, which allowed that all their share of the Nordic project (50 DST tags) were deployed in Faroese waters.

References

Brander, K.M. 1995. The effect of temperature on growth of Atlantic cod (*Gadus morhua* L.). ICES Journal of Marine Science, 52: 1-10.

ICES 2011. Report of the workshop on age reading of Greenland halibut (WKARGH). ICES CM 2011/ACOM:41.

NORA 2011. NORA project: Hellefisk vandringsmønster. Final report to NORA (in Scandinavian languages and in English). 65 pp.

Tables and Figures

Table 1. Information about Greenland halibut tagging experiments in Faroese waters with special reference to growth estimates where the recapture length is known.

Tagging Tag ID	Tag type	PositionN	PositionW	Depth fathoms	Recapture PositionN Dec.deg.	PositionW Dec.deg.	Distance naut.miles	Tagging Date	Recapture Date	Time days	Tagging Length cm	Recapture Length cm	Measured	Growth cm	Time years	Temperature Degree C	N
FO29259	Lea	60.91	-5.43	284	60.97	-2.70	82.1	25/07/2002	25/09/2002	62	57	54	Self	-3	0.1699		
2421	DST	60.83	-5.62	282	61.22	-4.95	30.6	22/07/2002	31/07/2002	9	55	55	Lab	0	0.0247	2.46	765
FO29131	Lea	60.91	-5.43	284	60.83	-5.62	7.1	22/07/2002	02/08/2002	11	57	56	Lab	-1	0.0301		
FO29162	Lea	60.83	-5.62	282	60.80	-5.75	4.3	22/07/2002	31/07/2002	9	59	57	Lab	-2	0.0247		
FO29198	Lea	60.54	-5.93	280	60.43	-6.00	7.0	23/07/2002	28/07/2002	5	60	58	Lab	-2	0.0137		
FO29174	Lea	60.82	-5.69	281	60.79	-5.87	5.5	22/07/2002	31/07/2002	9	60	59	Lab	-1	0.0247		
FO29193	Lea	60.54	-5.93	280	60.43	-6.00	7.0	23/07/2002	28/07/2002	5	60	59	Lab	-1	0.0137		
FO29252	Lea	60.91	-5.43	284	60.80	-5.75	11.5	25/07/2002	31/07/2002	6	61	59	Lab	-2	0.0164		
FO29253	Lea	60.91	-5.43	284	61.20	-5.03	21.3	25/07/2002	15/09/2002	52	59	59	Lab	0	0.1425		
FO29303	Lea	60.85	-5.52	293.5	60.80	-5.75	7.6	25/07/2002	02/08/2002	8	62	59	Lab	-3	0.0219		
FO29309	Lea	60.85	-5.52	293.5	60.80	-5.75	7.6	25/07/2002	02/08/2002	8	61	59	Lab	-2	0.0219		
FO29179	Lea	60.82	-5.69	281	60.75	-6.17	14.8	22/07/2002	27/10/2004	828	58	60	Self	2	2.2685		
FO29155	Lea	60.85	-5.52	293.5	61.83	-5.50	58.8	22/07/2002	15/10/2002	85	62	61	Lab	-1	0.2329		
FO29325	Lea	60.83	-5.62	282	60.80	-5.75	4.3	25/07/2002	02/08/2002	8	63	62	Lab	-1	0.0219		
FO29294	Lea	60.85	-5.52	293.5	61.22	-4.95	27.7	25/07/2002	31/07/2002	6	64	63	Lab	-1	0.0164		
FO29272	Lea	60.88	-5.47	289	60.65	-7.05	49.4	25/07/2002	29/02/2004	584	55	64	Lab	9	1.6000		
FO29284	Lea	60.88	-5.47	289	60.75	-6.17	22.3	25/07/2002	27/10/2004	825	60	64	Self	4	2.2603		
FO29288	Lea	60.85	-5.52	293.5	61.23	-5.03	26.7	25/07/2002	19/08/2002	25	60	65	Self	5	0.0685		
FO29211	Lea	60.56	-5.85	303	60.73	-5.92	10.5	23/07/2002	03/10/2004	803	60	66	Lab	6	2.2000		
FO29237	Lea	60.58	-5.90	292	60.65	-7.05	34.7	23/07/2002	29/02/2004	586	61	67	Lab	6	1.6055		
FO29267	Lea	60.88	-5.47	289	61.20	-5.05	22.9	25/07/2002	11/09/2002	48	67	67	Lab	0	0.1315		
FO29255	Lea	60.91	-5.43	284	60.63	-7.20	55.6	25/07/2002	31/01/2004	555	64	68	Lab	4	1.5205		
FO29154	Lea	60.85	-5.52	293.5	61.22	-4.95	27.7	22/07/2002	31/07/2002	9	71	72	Lab	1	0.0247		
FO29169	Lea	60.83	-5.62	282	66.37	-12.55	391.7	22/07/2002	24/03/2004	611	65	72	Self	7	1.6740		
FO29240	Lea	60.60	-6.96	342	60.65	-7.05	4.2	24/07/2002	29/02/2004	585	59	62	Lab	3	1.6027		
FLF105285	Spaghetti	63.01	-8.21	559	63.28	-10.36	66.6	10/02/2004	03/12/2005	662	60	64	Lab	4	1.8137		
5730	DST	63.01	-8.21	560	60.92	-7.17	129.7	10/02/2004	04/07/2004	145	66	65	Lab	-1	0.3973	1.10	3108
FLF116586	DST	62.80	-5.77		62.45	-4.37	47.0	24/08/2011	31/12/2011	129	56	54	Self	-2	0.3534	1.94	3503
FLF116622	DST	62.58	-5.05		62.62	-5.37	9.7	23/08/2011	15/10/2011	53	55	54	Lab	-1	0.1452	2.57	1007
FLF116592	DST	62.62	-5.28		62.25	-4.50	32.2	25/08/2011	02/10/2011	38	59	57	Self	-2	0.1041	1.80	966
201	DST	62.72	-5.45		62.50	-5.00	18.7	22/08/2011	01/09/2011	10	61	60	Lab	-1	0.0274	0.32	198
209	DST	62.70	-5.47		62.48	-4.60	29.1	23/08/2011	20/01/2012	150	61	60	Lab	-1	0.4110	2.08	3583
FLF116590	DST	62.73	-5.58		60.95	-5.33	107.3	24/08/2011	07/11/2011	75	62.5	61	Lab	-1.5	0.2055	1.75	1799
FLF116601	DST	62.67	-5.33		62.57	-5.42	6.5	22/08/2011	09/09/2011	18	65	62	Lab	-3	0.0493	3.99	428
FLF116584	DST	62.80	-5.78		62.57	-5.50	16.4	24/08/2011	01/09/2011	8	64	63	Lab	-1	0.0219	3.06	220
FLF116591	DST	62.73	-5.57		62.64	-5.33	9.0	24/08/2011	17/03/2012	206	65	64	Lab	-1	0.5644	1.45	4943
Average		61.40	-5.75	309.4	61.47	-5.90	39.3	30/11/2004	19/06/2005	201	61.0	61.4		0.46	0.5507	2.05	1865

Table 2. Regression statistics when relating the growth increment (dependent variable) to the elapsed time (in years, one year = 365 days) since tagging. The output is from MS Excel.

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.849
R Square	0.720
Adjusted R Square	0.712
Standard Error	1.662
Observations	35

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	234.362	234.362	84.887	1.20865E-10
Residual	33	91.109	2.761		
Total	34	325.471			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-1.556	0.347	-4.478	0.000085	-2.263	-0.849
Years	3.338	0.362	9.213	1.20865E-10	2.601	4.076

Table 3. Expected growth of cod at a temperature of 2.05 ^oC (Brander, 1995).

Growth rate of cod (Brander, 1995):

Weight at age in kg = 10.28/(1+exp(0.082(41.27 - temperature x age)))

Temperature:	2.05	Deg. C
Fulton K	0.97	

Age years	Weight kg	Length cm	Change cm
1	0.40	34.4	
2	0.47	36.3	1.9
3	0.55	38.3	2.0
4	0.64	40.4	2.1
5	0.75	42.6	2.2
6	0.87	44.8	2.3
7	1.02	47.2	2.3
8	1.18	49.6	2.4
9	1.37	52.1	2.5
10	1.58	54.7	2.6
11	1.82	57.3	2.6
12	2.09	59.9	2.7
13	2.38	62.6	2.7
14	2.70	65.3	2.7
15	3.05	68.0	2.7
16	3.42	70.7	2.7
17	3.82	73.3	2.6
18	4.23	75.8	2.5
19	4.65	78.3	2.5
20	5.08	80.6	2.3

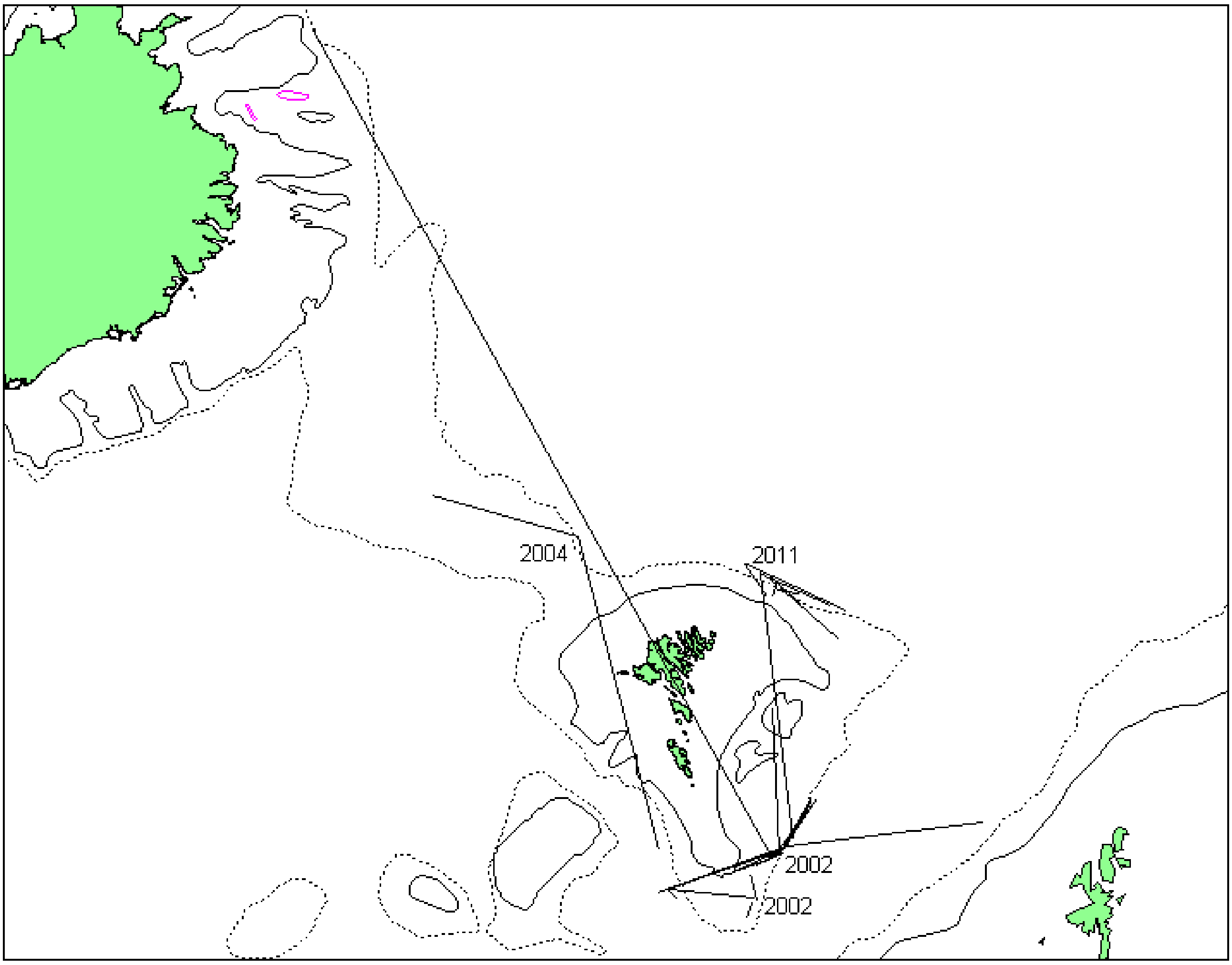


Figure 1. Tagging experiments with Greenland halibut in Faroese waters (62^{o} N, 7^{o} W) with special reference to growth estimates. In August 2002 the taggings were performed southeast of the Faroes, in February 2004 on the Faroe-Iceland Ridge, and in August 2011 northeast of the Faroes. Only specimens with known length at recapture are shown. The 200 and 500 m depth contours are shown.

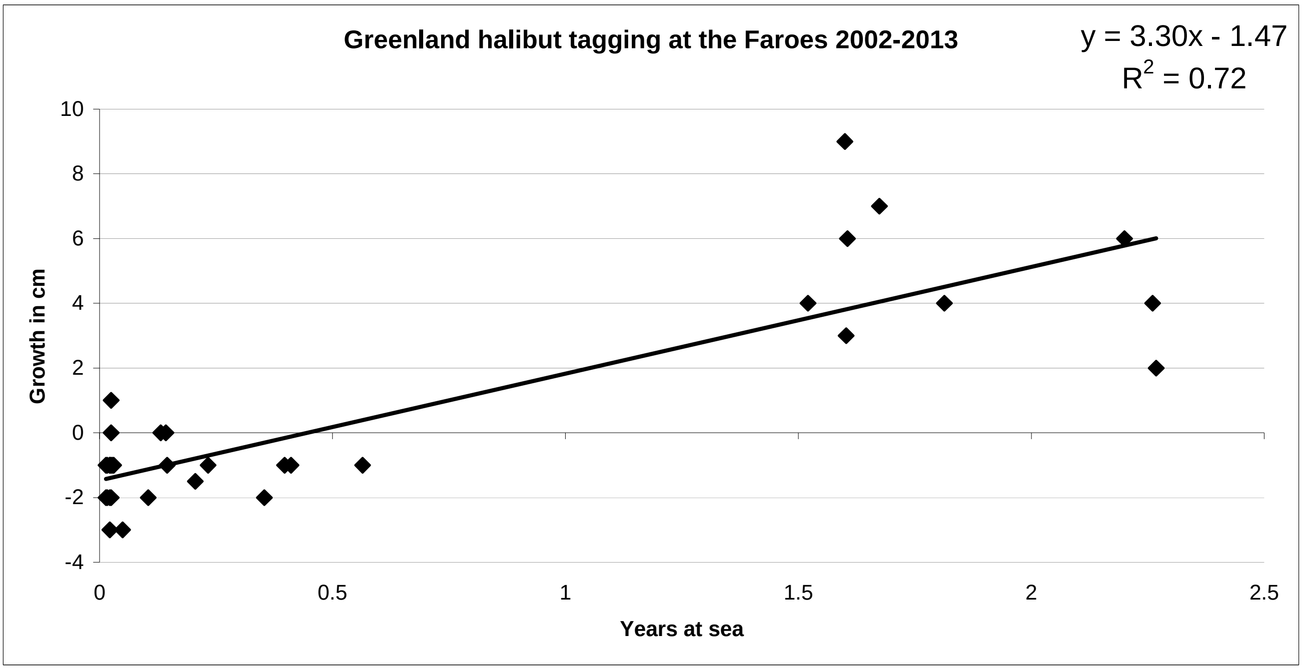


Figure 2. Tagging experiments with Greenland halibut in Faroese waters with special reference to growth estimates. Results from a regression analysis with growth as the dependent variable and time at liberty (in years, one year = 365 days) as the independent variable.

Exploratory gadget stock assessment of Greenland halibut (*Reinhardtius hippoglossoides*) in Subareas V, VI, XII, and XIV

Gudmundur Thordarson & Bjarki Þór Elvarsson

Fisheries Advisory Section
Marine Research Institute, Reykjavík, Iceland
(gudthor@hafro.is)

Do not cite without authors permission

November 21, 2013

Abstract

This document describes an exploratory stock assessment of Greenland halibut in in Subareas V, VI, XII, and XIV using the Gadget model. The model is able to follow trends in the tuning data and the fit to other data-sets is good. The main challenge in terms of the model is growth assumptions. The model estimates that SSB was around 62 Kt in 2012 and F_{15-20} at 0.19. Fishing at $F_{0.1}$ would result in catches of around 19 kt in 2013.

1 Description of gadget

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

Gadget is distinguished from many stock assessment models used within ICES (such as XSA) in that Gadget is a forward simulation model, and is structured around both age and length. It therefore requires direct modeling of growth within the model. An important consequence of using a forward simulation model is that the plus groups (in both age and length) should be chosen to be large enough that they contain few fish, and the exact choice of plus group does not have a significant impact on the model.

1.1 Setup of a gadget run

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

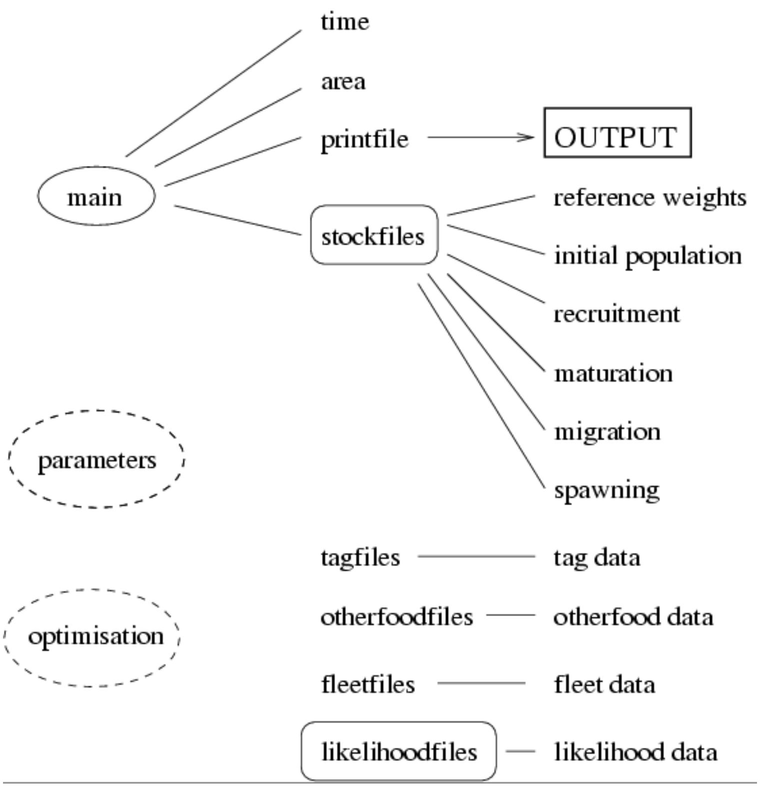


Figure 1: Schematic description of a Gadget model

1.2 Simulation model

In a typical Gadget model the simulated quantity is the number of individuals, N_{alsyt}, at age $a = 3 \dots 25$, in a length-group l, representing lengths ranging between 20 and 120 cm in 1 cm length-groups, stock component s where $s = 0, 1$ denotes the males and female stock component respectively, at year y which is divided into quarters $t = 1 \dots 4$. The length of the time-step is denoted Δt. The population is governed by the following equations:

$$
\begin{aligned}
N_{alsy,t+1} &= \sum_{l'} G_l^{l'} \left[(N_{al'syt} - C_{fal'st})e^{-M_a \Delta t}\right] && \text{if } t < 4 \\
N_{a+1,ls,y+1,1} &= \sum_{l'} G_l^{l'} \left[(N_{al'sy,4} - C_{fal's,4})e^{-M_a \Delta t}\right] && \text{if } t = 4 \text{ and } a < 25 \\
N_{a,ls,y+1,1} &= \sum_{l'} G_l^{l'} (N_{al'sy,4} - C_{fal'sy,4} + N_{a-1,l'sy,4} - C_{f,a-1,l'sy,4})e^{-M_a \Delta t} && \text{if } t = 4 \text{ and } a = 25
\end{aligned}
\tag{1}
$$

where $G_l^{l'}$ is the proportion in length-group l that has grown $l' - l$ length-groups in Δt, C_{falsyt} denotes the catches by fleet $f \in \{A, C\}$, A and C denote the survey and commercial fleets respectively[1], M_a the natural mortality at age a[2].

1.2.1 Growth

Growth in length is modeled as a two–stage process, an average length update in Δt and a growth dispersion around the mean update (as described in ?). Average length update is modeled by calculating the mean growth for each length group for each time step, using a parametric growth function. In the Greenland halibut model a simplified form of the Von Bertanlanffy function has been employed to calculate this mean length update.

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

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

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

$$\sum_i p_{il} = 1$$

and

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

Here Δl is the calculated mean growth and p_{il} is the proportion of fish in length group l growing i length groups. Here the growth is dispersed according to a beta–binomial distribution parametrised by the following equation:

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

where α is subject to

$$\alpha = \frac{\beta \Delta l}{n - \Delta l} \tag{4}$$

where n denotes the maximum length group growth and $(l' - l)$ the number of length-groups grown.

[1] The survey fleet catches are given a nominal catch to allow for survey age and length distribution predictions.

[2] A short note on notation, here l is used interchangeably as either the length-group or the midpoint of the length interval for that particular length-group, depending on the context.

1.2.2 Recruitment and initial abundance

Gadget allows for a number of relationships between stock recruitment and the size of the spawning stock to be defined. Here two methods are used, in the period when little data is available a Ricker recruitment function is used:

$$R_y = \mu S_y e^{-\lambda S_y} \tag{5}$$

where R_y is the number of yearly recruits, S_y is the spawning stock size (in numbers) and λ and μ are parameters to be estimated. Recruitment enters to the population according to:

$$N_{1l0yt'} = R_y p_l \tag{6}$$

where t' denotes the recruitment time-step, p_l is the proportion in length-group l that is recruited which is determined by a normal density with mean according to the growth model and variance σ_y^2. When more data is available the number of recruits, R_y is estimated directly.

A simple formulation of initial abundance in numbers is used for each age group in length-group l:

$$N_{als11} = \nu_a q_l \tag{7}$$

where ν_a is the initial number at age a in the initial year and q_l the proportion at length-group l which is determined by a normal density with a mean according to the growth model in equation 2 and variance σ_a^2.

1.2.3 Fleet operations

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

$$C_{flsyt} = E_{ft} \frac{S_f(l) N_{lsyt} W_{ls}}{\sum_{s'} \sum_{l'} S_f(l') N_{l's'yt} W_{l's'}} \tag{8}$$

where E_{ft} is the landed biomass at time t and $S_f(l)$ is the suitability of length-group l by fleet f defined as:

$$S_f(l) = \frac{1}{1 + e^{(-b_f(l - l_{50,f})}} \tag{9}$$

The weight, W_{sl}, at length-group l is calculated according to the following stock component specific length – weight relationship:

$$W_{sl} = \mu_s e^{\omega_s l} \tag{10}$$

1.3 Observation model

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

Importantly this ability to handle length data directly means that the model can be used for stocks such as Greenland halibut where age data is very sparse and considered unreliable. Length data can be used directly for model comparison. The model is able to combine a wide selection of the available data by using a maximum likelihood approach to find the best fit to a weighted sum of the data-sets.

In Gadget data are assimilated using a weighted log–likelihood function. Here four types of data enter the likelihood, length based survey indices, length distributions from survey and commercial fleets, age – length distribution from from the survey and commercial fleets and sex ratio at length.

1.3.1 Survey indices

The survey indices are defined as the total number of fish caught in a survey within a certain length interval. The intervals used here are 19.5 – 44.5 cm, 44.5 – 64.5 cm and larger than 64.5 cm. In addition an index of biomass, the CPUE from the Icelandic Trawl fishery, is fitted. The length distributions are illustrated in figures 2 and 3 on page 14.

For each length range g the survey index is compared to the modeled abundance at year y and time-step t using:

$$l_{gf}^{\mathrm{SI}} = \sum_y \sum_t (\log I_{gfy} - (\log q_f + \log \widehat{N_{gyt}}))^2 \tag{11}$$

where

$$\widehat{N_{gyt}} = \sum_{l \in g} \sum_a \sum_s N_{alsyt}$$

1.3.2 Sex ratio at length

The observed proportions are compared to the modeled proportion using sum of squares:

$$l^{\mathrm{M}} = \sum_y \sum_t \sum_l (\mathfrak{p}_{lyt} - \hat{\mathfrak{p}}_{lyt})^2 \tag{12}$$

where

$$\mathfrak{p}_{lyt} = \frac{\sum_a O_{al1yt}}{\sum_a \sum_{l'} \sum_s O_{alsyt}}$$

and

$$\hat{\mathfrak{p}}_{lyt} = \frac{\sum_a N_{al1yt}}{\sum_a \sum_{l'} \sum_s N_{alsyt}}$$

i.e the observed and modeled sex proportions respectively in length group l, year y and time-step t.

1.3.3 Fleet data

Length distributions are compared using 2 cm length-groups for both commercial and survey fleets using

$$l_f^{\mathrm{LD}} = \sum_y \sum_t \sum_l ({}^L\pi_{lyt} - {}^L\hat{\pi}_{lyt})^2 \tag{13}$$

where f denotes the fleet where data was sampled from and

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

and

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

i.e the observed and modeled proportions in length-group l respectively at year y and time-step t. Similarly age – length data are compared using 4 cm length groups:

$$l_f^{\text{AL}} = \sum_y \sum_t \sum_a \sum_l \sum_s (\pi_{falsyt} - \hat{\pi}_{falsyt})^2 \tag{14}$$

where

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

and

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

1.3.4 Iterative re–weighting

The total objective function used the modeling process combines equations 11 to 14 using the following formula:

$$l^{\text{T}} = \sum_g \sum_{f\in\{S,A\}} w_{gf}^{\text{SI}} l_{gf}^{\text{SI}} + \sum_{f\in\{S,A,C\}} \left(w_f^{\text{LD}} l_f^{\text{LD}} + w_f^{\text{AL}} l_f^{\text{AL}}\right) + w^{\text{M}} l^{\text{M}} \tag{15}$$

where $f = S, A$ or C denotes the spring survey, autumn survey and commercial fleets respectively and w's are the weights assigned to each likelihood components.

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

Assigning likelihood weights is not a trivial matter, has in the past been the most time consuming part of a Gadget model. Commonly this has been done using some form of 'expert judgement'. General heuristics have recently been developed to estimated these weights objectively. Here the iterative re–weighting heuristic introduced by **?**, and subsequently implemented in **?**, is used.

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

1. Calculate the initial sums of squares (SS) given the initial parametrization for all likelihood components. Assign the inverse SS as the initial weight for all likelihood components.

2. For each likelihood component, do an optimization run with the initial SS for that component set to 10000. Then estimate the residual variance using the resulting SS of that component divided by the degrees of freedom (df^*), i.e. $\hat{\sigma}^2 = \frac{SS}{df^*}$.

3. After the optimization set the final weight for that all components as the inverse of the estimated variance from the step above (weight $= 1/\hat{\sigma}^2$).

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

1.4 Optimisation

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

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

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

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

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

2 Model settings

Greenland halibut is assumed to be a rather long lived, slow growing deep-water species so it would take a cohort a long time to pass through the fishery. The simulation therefor goes back to 1961. Since data on recruitment is limited in the early years a ricker stock recruitment function, described in equation 5, is used for the first 20 years of the simulation. An overview of the data-sets and model parameters used in this case study is shown in Tables 1 and 2 respectively.

Table 1: Overview of the likelihood data used in the model. Survey indices are calculated from the length distributions and are dis-aggregated ("sliced") into three groups illustrated in figures 2 and 3. Number of data-points refer to aggregated data used as inputs in the Gadget model and represent the original data-set. All data can obtained from the Marine Research Institute, Iceland.

Origin	Time-span	Length group size	Num. data-points	Likelihood function
	Length distributions:			
October Survey	3^{th} quarter, 1996 – 2012	2 cm	545 (females) and 406 (males)	See eq. 13
Commercial catches	All quarters, 1969 – 2013	2 cm	3970 (both)	See eq. 13
	Survey indices			
October Survey	3^{th} quarter, 1996 – 2012	–		See eq. 11
	Sex ratio by length group			
Commercial catches	1^{st} quarter, 1969 – 2013	2 cm	4204	See eq. 12
	Age data			
Commercial catches	1^{st} quarter, 1969 – 2013	2 cm	*	

2.1 Growth

Ageing of Greenland halibut is difficult but advances have been made in recent years by IMR in Tromso, Norway. The main result is that Greenland halibut does seem to grow at a much slower rate than previously thought (Dr. Elvar Hallfredsson pers. comm.). Considerable amount of age data is available for Greenland halibut in Subareas V, VI, XII and XIV but the estimation of age is according to the old ageing method. Therefore data from area I and II collected from the Norwegian Greenland halibut survey are used (Table 3). A detailed description of the problems regarding growth are given in WKBUT:WD-02. Suffice to say growth in the base model presented here assumes growth scenario 2 (in WD-02). The Norewegian data is limited as can be seen by the low sample size in the older age groups, specially in the case of males (Table 3, on page 9).

Table 2: An overview of the estimated parameters in the model. For those parameter with fixed values a description of how these values were derived can be found in **?** and references therein.

Description	Notation	Comments	Formula
Natural mortality	M_a	Fixed at 0.1 for ages 3 to 25	See eq. 1
Growth function	K, L_∞, t_0	Estimated from growth data for each sex	See eq. 2
Growth implementation	β	n is fixed at 15 length-groups	See eq. 3
Fleet selection	b_f, $l_{50,f}$		See eq. 9
Number of recruits by year	R_y	$y \in [1984, 2003]$. σ_y^2, i.e. variance in recruitment length, based on length distributions obtained in the autumn survey.	See eq. 6
Initial abundance at ages 3 – 25 in 1961	η_a	$a \in [3, 25]$. σ_a^2, i.e. variance in initial length at age a, based on length distributions obtained in the spring survey.	See eq. 7
Survey catch-ability	q_f	Intercept term in a log–linear relationship with abundance. The slope term is assumed to be 1 for all indices.	See eq. 11
Length–weight relationship	μ_s, ω_s	Different values by stock component, estimated outside of the model	See eq. 10

Table 3: Greenland halibut: Mean length at age from the Norwegian Greenland halibut survey. Data from Dr. E. Hallfredsson IMR.

Age	Females Length	Sd	N	Males Length	Sd	N
3	35.67	2.66	6	34.82	2.68	11
4	37.68	4.91	19	39.21	6.96	28
5	39.43	5.02	30	39.58	5.16	26
6	41.33	5.86	40	41.16	5.92	43
7	44.39	8.86	44	44.98	7.40	58
8	48.51	6.26	45	47.12	7.89	49
9	52.56	7.12	27	49.74	7.54	31
10	55.70	9.71	40	50.94	6.05	31
11	54.29	9.52	17	53.82	5.24	28
12	60.89	9.60	37	57.12	5.34	16
13	63.24	9.51	21	59.11	4.81	9
14	68.46	10.34	13			
15	68.59	8.11	17	55.33	4.93	3
16	66.80	4.87	10			
17	68.75	6.36	12			
18	70.83	6.21	6	59.00	NA	1
19	74.11	11.35	9			
20	69.50	8.87	6			
21	71.50	17.62	4			
22	68.00	8.39	6			
23	74.60	10.53	5			
24	63.00	NA	1			

2 Model settings

2.1 Growth

2.2 Natural mortality

Choice of natural mortality (M) is problematic as is normally the case in stock assessments. Here M is assumed to be constant with age at 0.1.

2.3 Fleets and selection

In the model there are three commercial fleets and two survey fleets. The commercial fleets are the Icelandic (IceTrawl), Greenlandic (GreTrawl) and Faroese (FarTrawl). As there is only length measurements from the Icelandic fleet it is assumed that the other two fleets have the same selection as the Icelandic fleet. The selection is described by a logistic function and total catch in tonnes is specified for each time-step.

CPUE data from Icelandic trawlers is used as a tuning series in the model. The Icelandic autumn survey and the Greenlandic Greenland halibut survey are on the other hand modelled as fleets with constant effort and a non parametric selection pattern that is estimated for each length group.

3 Input data

3.1 Commercial catches

3.1.1 Landings

In the model there are three fleets, namely Iceland, Greenland and the Faroe Islands. It is assumed that all catches are caught with bottom trawl in the model. As there is no information on the split of catches between time steps from the Faroe and Greenland the catches are just split evenly (Table 4).

Table 4: Greenland halibut:. Commercial catches in tonnes by fleets, steps (3 month) and years.

Year	Faroe				Greenland				Iceland			
	1	2	3	4	1	2	3	4	1	2	3	4
1961	0	0	0	0	0	0	0	0	19	5	12	26
1962	0	0	0	0	0	0	0	0	21	5	13	28
1963	0	0	0	0	0	0	0	0	29	7	18	41
1964	0	0	0	0	0	0	0	0	36	9	22	49
1965	0	0	0	0	0	0	0	0	51	12	31	70
1966	0	0	0	0	0	0	0	0	61	15	37	84
1967	0	0	0	0	0	0	0	0	231	55	141	319
1968	0	0	0	0	0	0	0	0	165	40	100	227
1969	0	0	0	0	0	0	0	0	183	44	112	253
1970	0	0	0	0	0	0	0	0	255	61	155	351
1971	0	0	0	0	0	0	0	0	218	52	133	301
1972	0	0	0	0	0	0	0	0	199	48	122	275
1973	0	0	0	0	0	0	0	0	154	37	94	213
1974	0	0	0	0	0	0	0	0	273	66	167	377
1975	0	0	0	0	0	0	0	0	177	42	108	244
1976	81	81	81	81	1008	1008	1008	1008	13	3	8	18
1977	164	164	164	164	1474	1474	1474	1474	76	18	46	105
1978	149	149	149	149	611	611	611	611	85	20	52	118
1979	102	102	102	102	1568	1568	1568	1568	128	31	78	176
1980	294	294	294	294	560	560	560	560	210	50	128	289
1981	142	142	142	142	804	804	804	804	116	28	71	161
1982	258	258	258	258	777	777	777	777	1410	21618	4901	394
1983	359	359	359	359	273	273	273	273	4874	11519	10745	1231
1984	766	766	766	766	220	220	220	220	3349	16601	5661	4456
1985	532	532	532	532	189	189	189	189	5781	14355	3831	5242
1986	235	235	235	235	254	254	254	254	2572	19347	4423	4722
1987	261	261	261	261	209	209	209	209	1941	33516	4747	4572
1988	242	242	242	242	287	287	287	287	1373	42832	3490	935
1989	402	402	402	402	365	365	365	365	2048	50566	4305	1414
1990	320	320	320	320	372	372	372	372	2316	30025	2533	1700
1991	416	416	416	416	287	287	287	287	3058	25636	2901	3220
1992	567	567	567	567	316	316	316	316	4262	18671	4214	4857
1993	1118	1118	1118	1118	610	610	610	610	5196	15066	9548	3274
1994	1306	1306	1306	1306	1023	1023	1023	1023	4286	11961	7176	3613
1995	958	958	958	958	1273	1273	1273	1273	3753	11695	7685	4369
1996	1617	1617	1617	1617	1825	1825	1825	1825	3902	8165	5517	4384
1997	1229	1229	1229	1229	2146	2146	2146	2146	2987	7293	4757	3259
1998	956	956	956	956	1489	1489	1489	1489	1744	3351	1776	2731
1999	1066	1066	1066	1066	1255	1255	1255	1255	2249	3059	3028	2866
2000	1273	1273	1273	1273	1696	1696	1696	1696	1650	4079	4859	4549
2001	988	988	988	988	1676	1676	1676	1676	4078	6748	2812	3011
2002	674	674	674	674	1830	1830	1830	1830	2931	9786	3811	2737
2003	548	548	548	548	2015	2015	2015	2015	3121	9391	5024	2829
2004	429	429	429	429	2403	2403	2403	2403	2958	6232	3606	2690
2005	223	223	223	223	2601	2601	2601	2601	2212	5167	3298	2345
2006	218	218	218	218	2198	2198	2198	2198	3282	4643	2160	1721
2007	265	265	265	265	2808	2808	2808	2808	2099	3965	1984	1546
2008	440	440	440	440	2621	2621	2621	2621	1246	4830	2613	3009
2009	435	435	435	435	2628	2628	2628	2628	2762	5635	4532	2861
2010	353	353	353	353	2822	2822	2822	2822	2915	4841	3133	2421
2011	372	372	372	372	2935	2935	2935	2935	4384	3700	1894	3237
2012	372	372	372	372	2935	2935	2935	2935	3454	4456	2934	2921
2013	NA	NA	NA	NA	NA	NA	NA	NA	2985	317	NA	NA

3.1.2 Length distributions

The data available for Greenland halibut can be seen in table 5 which lists the number of available length measurements from Icelandic trawls by years and time steps. Also length distributions from the Autumn survey are included in the model (Figure 2 and 3).

Table 5: Greenland halibut:. Number of available length measurements from Icelandic bottom trawls used as input data into the Gadget model by years and steps (3 month).

Year	Trawl			
	1	2	3	4
1969	*NA*	*NA*	348	*NA*
1972	*NA*	*NA*	200	*NA*
1973	*NA*	*NA*	873	*NA*
1976	*NA*	*NA*	226	*NA*
1977	925	1465	1960	*NA*
1978	*NA*	3114	561	390
1979	2443	3143	616	833
1980	1872	12783	824	2900
1981	178	7003	2182	1653
1982	1229	6031	2897	*NA*
1983	2366	5865	2398	815
1984	1197	6073	1282	1245
1985	3382	5331	1674	913
1986	245	5724	1725	1085
1987	924	3808	213	1096
1988	1578	11334	706	*NA*
1989	268	2082	2087	490
1990	715	9970	216	155
1991	1715	8096	50	1415
1992	2429	5967	100	907
1993	978	5892	*NA*	1395
1994	4374	3959	191	400
1995	396	3164	1724	2388
1996	5130	9348	5164	5003
1997	5703	7310	1607	2250
1998	166	297	4449	2619
1999	1720	5016	7206	3002
2000	4458	13921	4664	4140
2001	6087	1893	2037	1051
2002	5220	9705	1516	1283
2003	4812	11596	5371	7971
2004	7258	9764	*NA*	4555
2005	9579	10814	564	242
2006	7974	8087	451	355
2007	5033	3017	413	181
2008	2363	22142	1111	1841
2009	11251	8788	3626	534
2010	4619	7151	219	371
2011	12562	6735	*NA*	3410
2012	12383	4007	1344	6204
2013	2170	*NA*	*NA*	*NA*

3.1.3 Data on sex by length

In table 6 is an overview of the available data on sex by length from commercial catches.

Table 6: Greenland halibut:. Number of available length measurements by females and males from Icelandic bottom trawls used as input data into the Gadget model by years and steps (3 month).

Year	Females				Males			
	1	2	3	4	1	2	3	4
1969	NA	NA	151	NA	NA	NA	197	NA
1972	NA	NA	173	NA	NA	NA	27	NA
1973	NA	NA	157	NA	NA	NA	43	NA
1977	NA	161	NA	NA	NA	139	NA	NA
1978	NA	685	NA	NA	NA	521	NA	NA
1979	288	409	82	NA	151	406	134	NA
1980	NA	469	NA	233	NA	530	NA	163
1981	NA	851	195	44	NA	697	253	156
1982	292	751	NA	NA	106	619	NA	NA
1983	137	554	115	140	63	495	284	60
1984	171	443	NA	69	29	556	NA	130
1985	908	898	20	220	186	349	NA	90
1986	NA	916	NA	80	NA	568	NA	161
1987	NA	629	NA	35	NA	459	NA	69
1988	112	475	NA	NA	85	420	NA	NA
1989	NA	272	153	NA	NA	536	128	NA
1990	NA	494	NA	NA	NA	464	NA	NA
1991	NA	560	NA	NA	NA	381	NA	NA
1992	22	203	NA	47	8	195	NA	53
1993	68	438	NA	148	30	547	NA	152
1994	138	314	NA	61	128	672	NA	139
1995	64	434	267	142	60	448	170	164
1996	2816	4194	2210	2103	1967	4118	2163	1532
1997	3173	3737	280	529	2467	2949	300	712
1998	1896	749	1107	555	1361	630	584	375
1999	170	306	260	471	130	223	150	376
2000	212	242	247	464	147	283	303	639
2001	420	277	64	56	306	237	26	54
2002	390	535	NA	157	304	762	NA	104
2003	364	445	412	209	258	743	244	222
2004	373	936	NA	189	375	705	NA	260
2005	390	397	NA	NA	240	522	NA	NA
2006	413	500	36	21	309	575	14	14
2007	130	42	14	NA	140	64	21	NA
2008	181	824	NA	145	119	907	NA	105
2009	544	272	309	38	456	428	151	32
2010	342	344	NA	NA	158	456	NA	NA
2011	655	314	NA	91	375	386	NA	59
2012	565	233	30	187	234	137	19	88
2013	193	NA	NA	NA	57	NA	NA	NA

3.2 Tuning data

The tuning data used in the base model is a CPUE from commercial trawlers in Icelandic waters and the Icelandic Autumn survey. The Autumn survey abundance indices are aggregated into three length intervals for each sex (Figures 2 and 3).

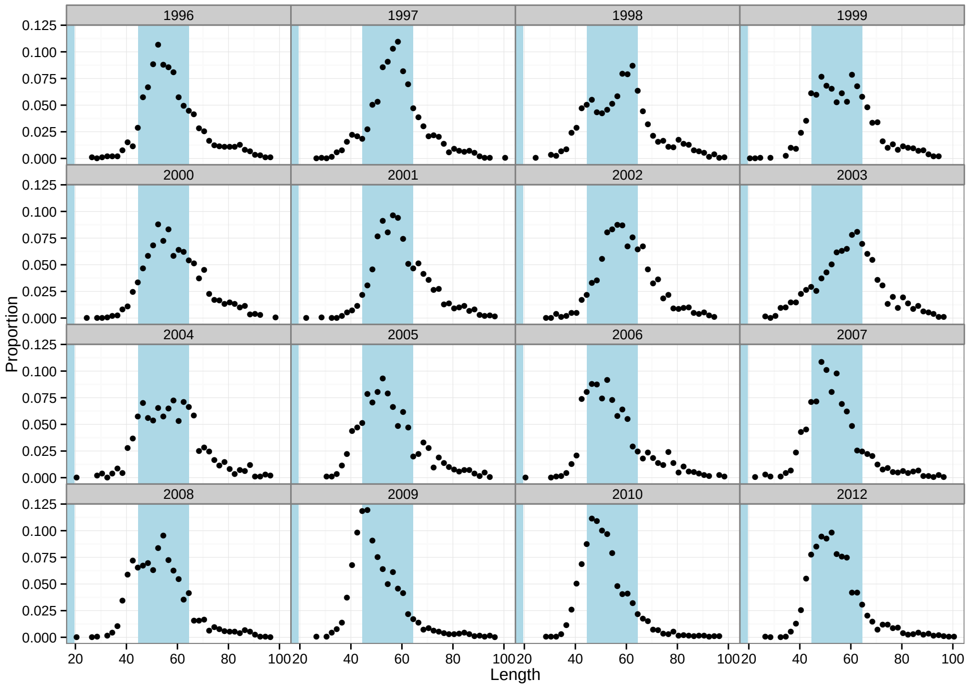


Figure 2: Female length distributions from the autumn survey by year. Length intervals used for survey indices are shown as solid colors.

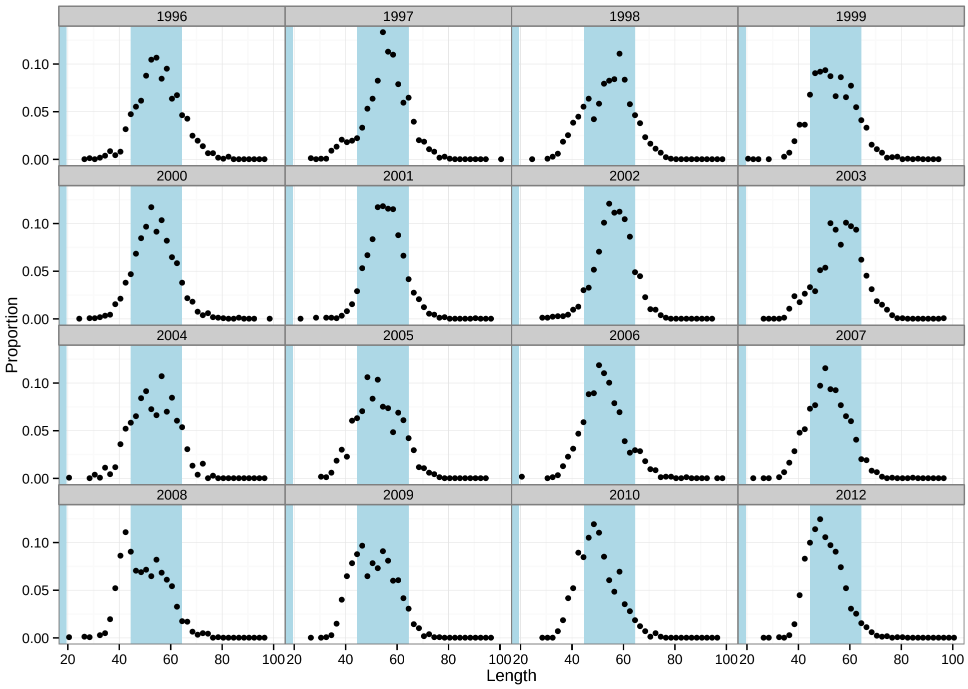


Figure 3: Male length distributions from the autumn survey by year. Length intervals used for survey indices are shown as solid colors.

4 Results

4.1 Iterative re-weighting

Gadget allows for an extensive comparison to the fitted data-set. An overall picture of the model fit is provided in table 7. Overall the model is seen to fit the data relatively well, compared to the best possible fit. The age data (Growth scenario 2, WD-02), not surprisingly, appears to be contradicted in all other data-sets while in the final run the squared residuals are only by an order of 2 larger than the optimal fit. In the final run the predicted survey indices for the smallest length-groups appear to have the poorest fit to the data.

4.2 Fit to individual data sets

4.2.1 Abundance indices

The fit to the abundance indices is shown in figure 4. In general the model captures the main trends in the Autumn survey index (GHLFem and GHLmale). However there is a considerable more smoothing in the final run than when the indices are over-weighed (broken line in figure 4). The same applies for the more longer CPUE-series.

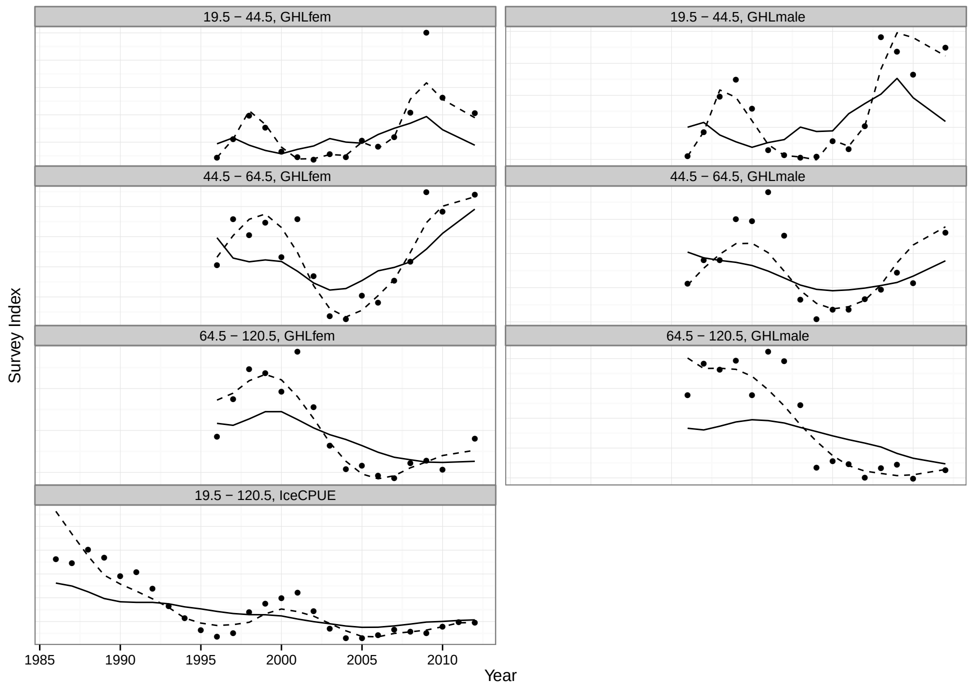


Figure 4: Abundance indices from the survey (length aggregated and divided by sex) and CPUE from the commercial catches. Points denote the observed values, solid lines final fit and broken lines fit from the best fit from the iterative reweighing (explained in the text).

Table 7: Diagnostic from the iterative reweighing procedure. The lines denotes the likelihood component that was heavily weighted while the rows denote the ratio of that component score to the best score.

	SexRatio IceTrawl.lik	FemSmh ML.lik	MaleSmh ML.lik	Female SmhLD.lik	IceTrawl LD.lik	MaleSmh LD.lik	FemSmh 2045.si	FemSmh 4565.si	FemSmh 65120.si	MaleSmh 2045.si	MaleSmh 4565.si	MaleSmh 65120.si	VaCPUE .lik	under-stocking	bounds bounds
ind2045	1.78	697.39	532.09	15.28	7.67	14.53	1.00	4.85	6.49	1.00	3.00	5.66	2.17		
ind4565	1.66	128.41	440.35	10.11	7.90	14.54	16.12	1.00	7.80	25.88	1.00	8.00	2.38		
ind65120	1.50	248.93	120.85	11.47	8.17	14.24	18.20	15.27	1.00	14.18	3.53	1.00	4.03		
VaCPUE.lik	1.66	149.12	212.69	11.77	12.17	35.50	19.82	23.49	17.26	12.75	10.51	93.33	1.00		
MaleSmhLD.lik	2.41	537.29	82.73	5.93	5.47	1.00	18.01	7.03	14.67	19.03	2.47	4.67	2.39		
IceTrawlLD.lik	1.39	858.91	254.49	4.53	1.00	7.65	26.91	13.30	5.81	26.19	4.16	2.70	3.55		
FemaleSmhLD.lik	1.45	475.01	88.81	1.00	4.05	7.92	29.25	5.18	9.89	49.48	2.64	3.89	3.13		
MaleSmhML.lik	2.21	584.80	1.00	9.69	3.01	6.36	10.60	7.37	3.46	9.73	3.06	4.09	3.54		
FemSmhML.lik	1.50	1.00	134.57	2.85	6.45	9.61	12.78	3.13	6.57	11.14	3.16	2.29	3.04		
SexRatioIceTrawl.lik	1.00	445.89	51.70	8.96	5.02	7.08	11.17	11.85	4.38	8.53	3.67	1.88	2.63		
final	1.39	2.65	2.45	1.88	1.09	2.83	15.74	4.45	3.66	16.11	2.38	4.71	3.14		

4.2.2 Length distributions

Length distributions by sex from survey and commercial catches and their respective fits are illustrated in figures 5 to 7. The fit is seen to improve in the terminal years.

Sex ratio by length is shown in figure 8.

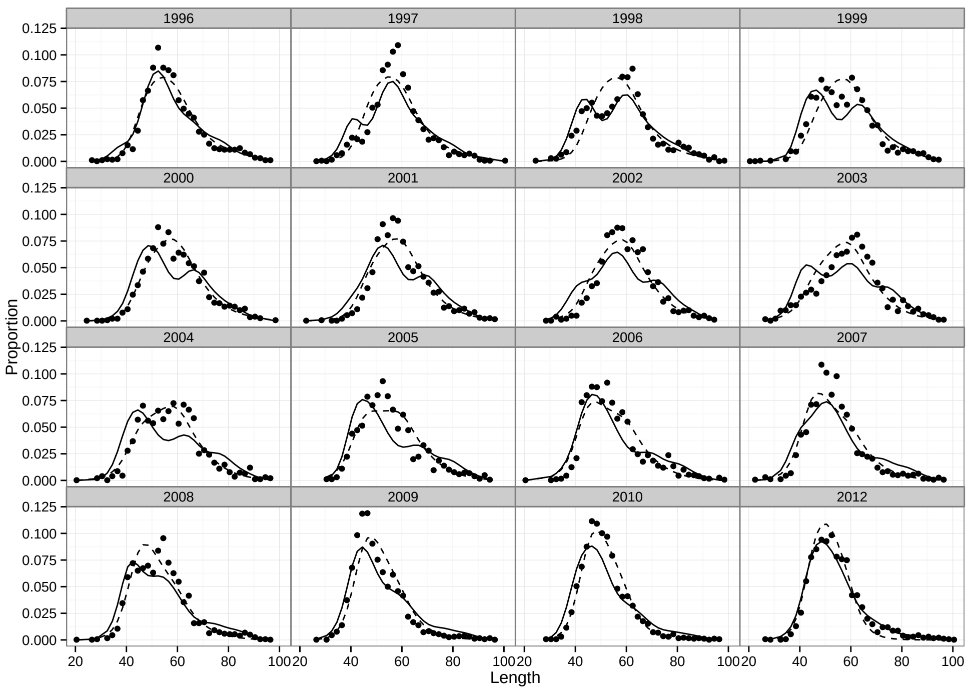


Figure 5: Female length distribution from survey. Points denote the observed values, solid lines final fit and broken lines fit from the best fit from the iterative reweighing (explained in the text).

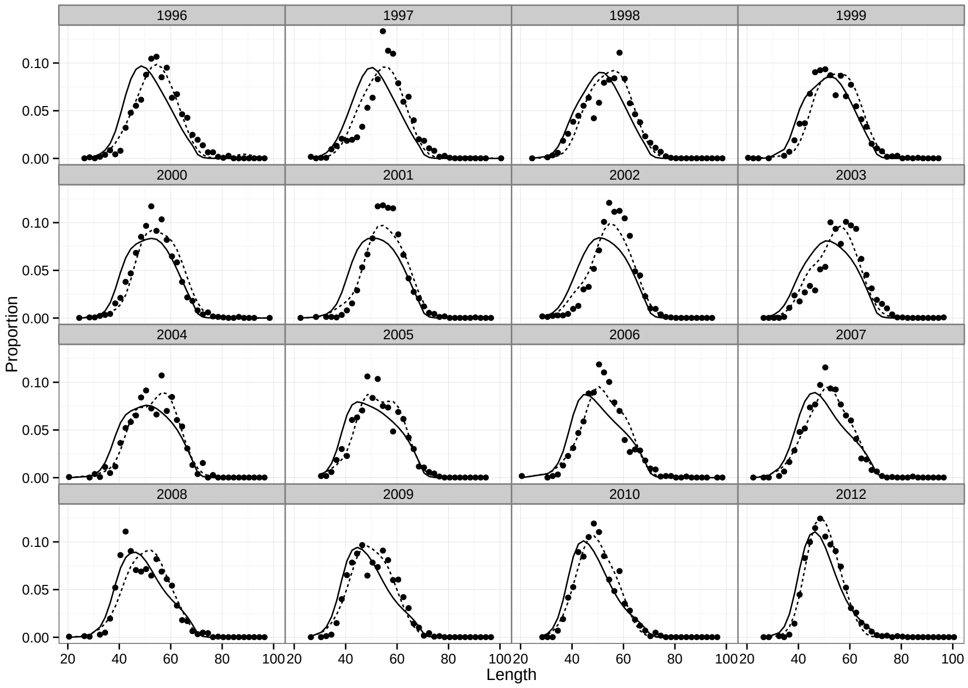


Figure 6: Male length distribution from survey. Points denote the observed values, solid lines final fit and broken lines fit from the best fit from the iterative reweighing (explained in the text).

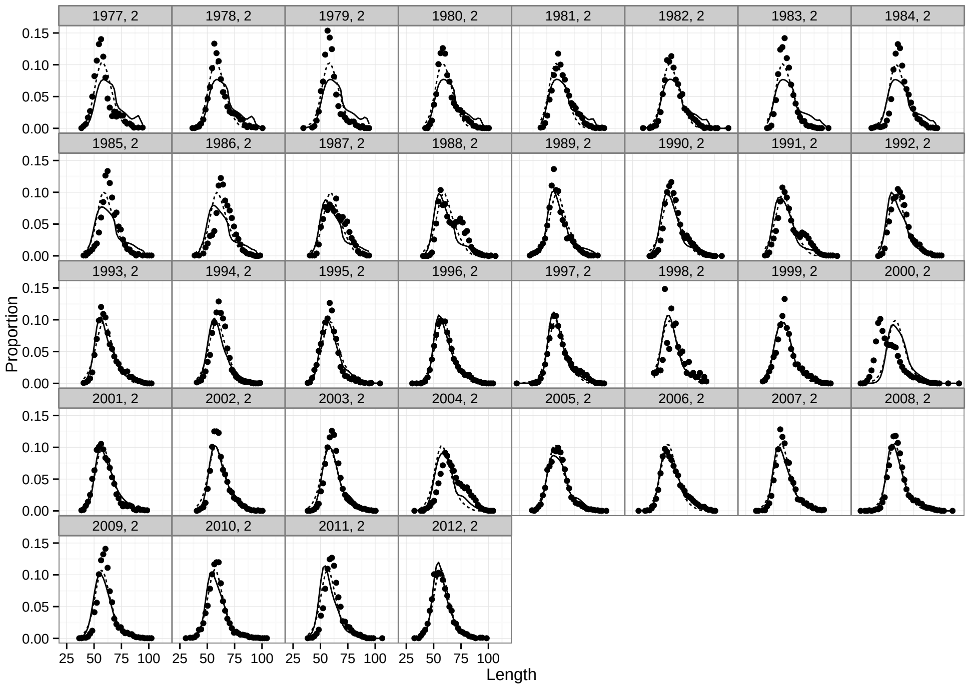


Figure 7: Length distribution from commercial catches. Points denote the observed values, solid lines final fit and broken lines fit from the best fit from the iterative reweighing (explained in the text).

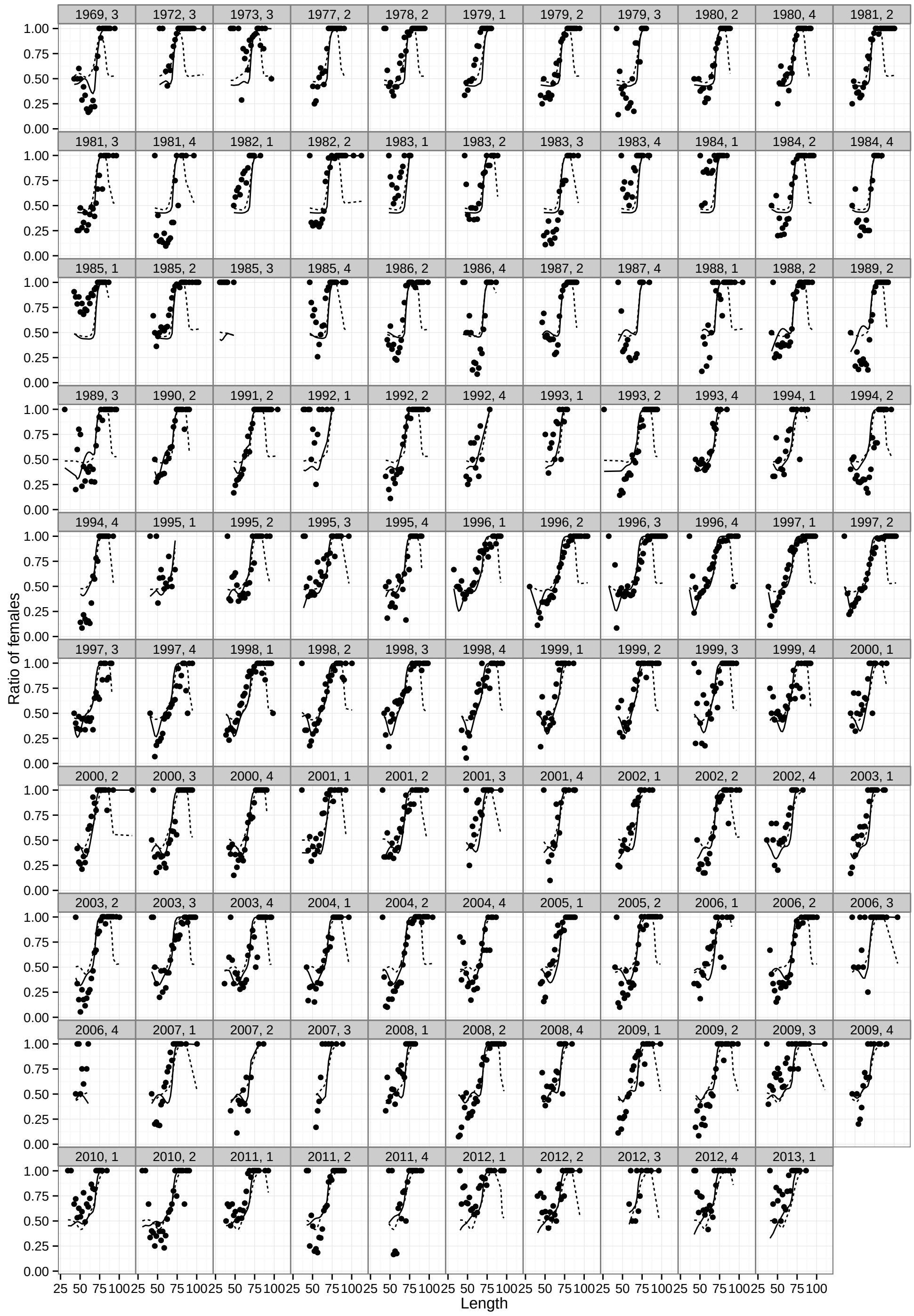


Figure 8: Ratio of females in commercial catches by length. Points denote the observed values, solid lines final fit and broken lines fit from the best fit from the iterative reweighing (explained in the text).

4.2.3 Growth data

The two components that contain the only information on growth in the model are `FemSmhML.lik` and `MaleSmhML.lik`. These components are a 'pseudo data' as the growth data is set as being mean length at age in the Autumn survey (SMH). As can be seen in figure 9 the fit is good. In the future the growth parameters would be fixed and these two likelihood components would be omitted.

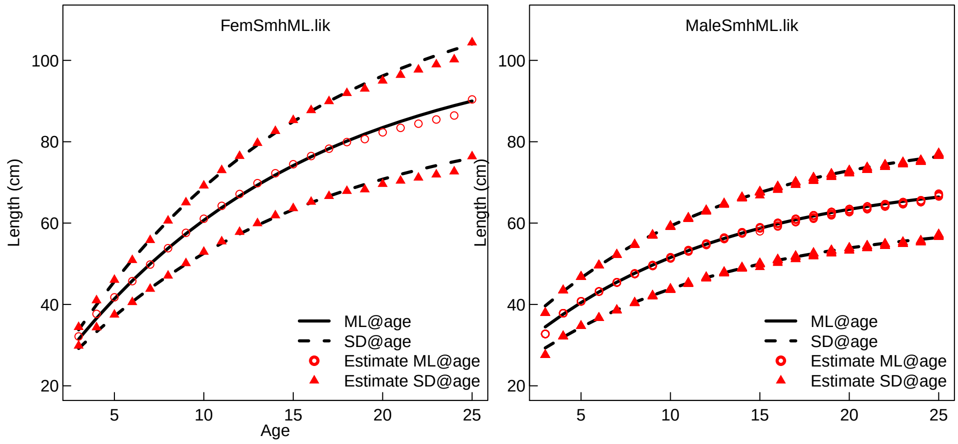


Figure 9: Fit to 'pseudo-data' on mean length at age and given standard deviation for females and males in the Gadget model.

4.3 Estimates

4.3.1 Selectivity

The estimated selection curve for Greenland halibut is rather steep and the inflection point (L_{50}) is at 51 cm, a rather low value. This means that a large proportion of females is caught immature, this is not as apparent for males. The estimated selection curve from the survey on the other hand does not have a steep slope and L_{50} is estimated at 39 cm (Figure 10).

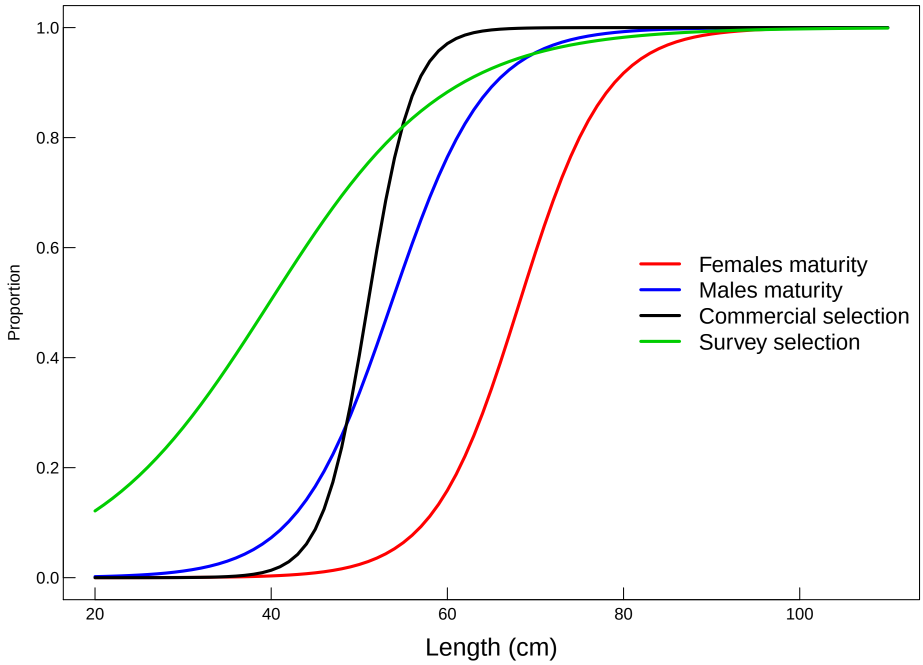


Figure 10: Estimated selection curves for Greenland halibut in the Gadget model for commercial catches (black line) and from the Icelandic Autumn Survey (green line). For comparison the maturity ogives for males (blue line) and females (red line) used for estimating SSB are shown.

4.3.2 Biomass and recruitment

The model starts in 1961, but the period between 1961 and 1982 can be viewed as a burn in period where the sock is 'growing' until the fishery starts in earnest. Therefore estimates are only presented from 1982 and on-wards.

According to the model all measures of biomass, (total biomass, spawning stock biomass (SSB) and harvestable biomass) have declined since 1982 (Figure 11). Total biomass and harvestable biomass show some indication of increase since 2005 - 2010. Terminal estimate of SSB is around 71 thous tonnes but harvestable biomass is estimated at around 130 thous tonnes. The difference can be explained by the difference between the selection curve in the fishery and the maturity ogives.

Estimates of recruitment show large fluctuations between years. This is most likely a model artifact as there is no age structured data to anchor annual recruitment estimates.

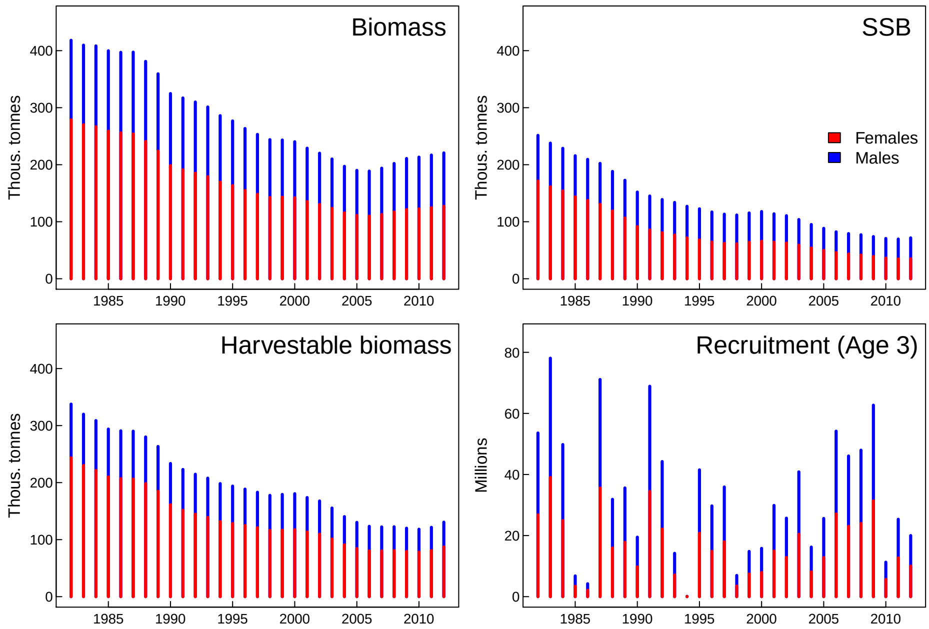


Figure 11: Estimates of total biomass, spawning stock biomass (SSB) and harvestable biomass along with recruitment for Greenland halibut in the Gadget model.

4.3.3 Fishing mortality

For convenience the age interval used for calculating $\bar{F}$ is set at fully selected age groups. In this case ages 15 to 20. The reason for this is that in forward projections the model uses fully selective lengths when using fishing mortality (as opposed to assume fixed catch levels in prognosis). This also has the added benefit of eliminating the difference in $\bar{F}$ between the sexes, which is the result of different growth rates. As an example the difference between the combined fishing mortality (both sexes) and the female fishing mortality for ages 10 to 15 is 19% but for the ages 15 to 20 the difference drops to 2%.

Trends in fishing mortality as estimated in the model are shown in figure 12. It can be seen that for most of the period fishing mortality has been above $F_{0.1}$ (For definition see 4.4).

4.3.4 Estimated age structure

The estimated age structure in the stock is shown for selected years in figure 13. It can be seen in 1985 the model is predicting more or less un-exploited stock and the cohort structure is a function of the stock-recruitment relationship used in the period between 1961 and 1981. Age 25, which is a plus group, is quite significant in 1985 but diminishes and is almost non-existant in 2000 and 2012.

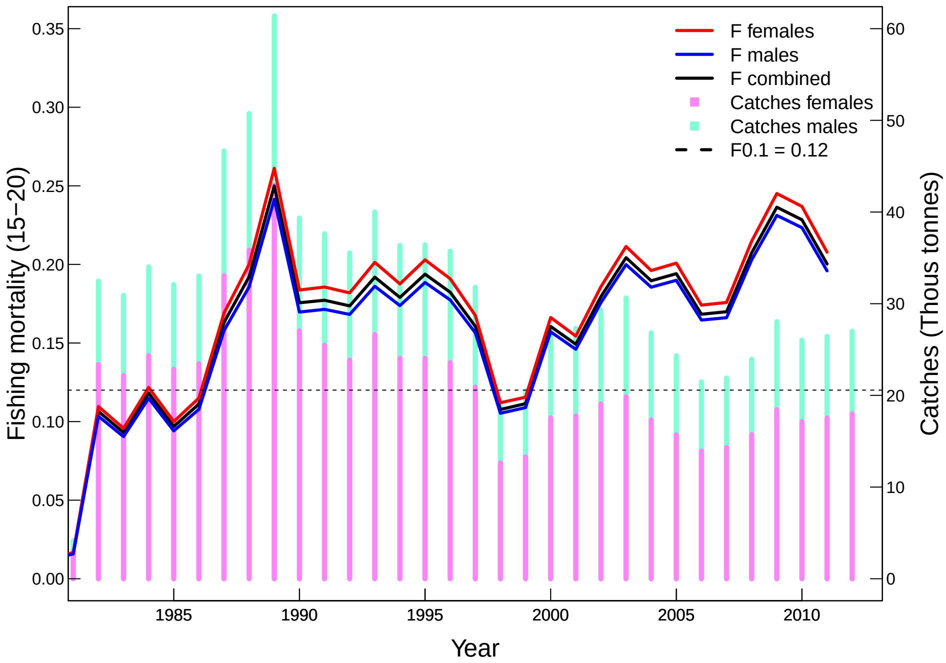


Figure 12: Estimates of fishing mortality (F_{5-20}) and catches divided by sex.

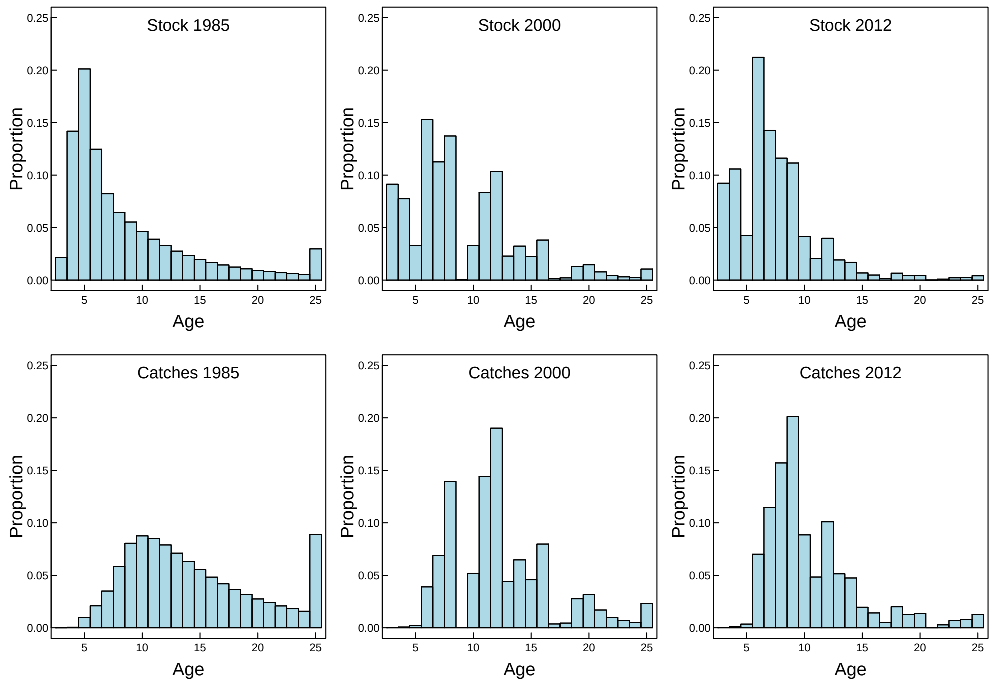


Figure 13: Estimated age structure in stock and in catches in the Gadget model

4.4 Yield per recruit

Yield-per-recruit is calculated by following one year class of million fishes for 24 years through the fisheries calculating total yield from the year class as function of fishing mortality of fully recruited fish. In the model, the selection of the fisheries is length based so only the largest individuals of recruiting year classes are caught reducing mean weight of the survivors, more as fishing mortality is increased. This is to be contrasted with age based yield-per-recruit where the same weights-at-age are assumed in the landings independent of the fishing mortality even when the catch weights are much higher than the mean weight in the stock. In general YPR-curvers estimated as in Gadget give a more conservative estimates (lower) of $F_{0.1}$ and F_{max}.

In the base Gadget model F_{max} is not well defined at 0.25. Therefore $F_{0.1}$ at 0.12 might be a better reference point for target fishing mortality (Figure 14). It should be noted that $F_{0.1}$ is very close to the assumed natural mortality in the model ($M = 0.1$).

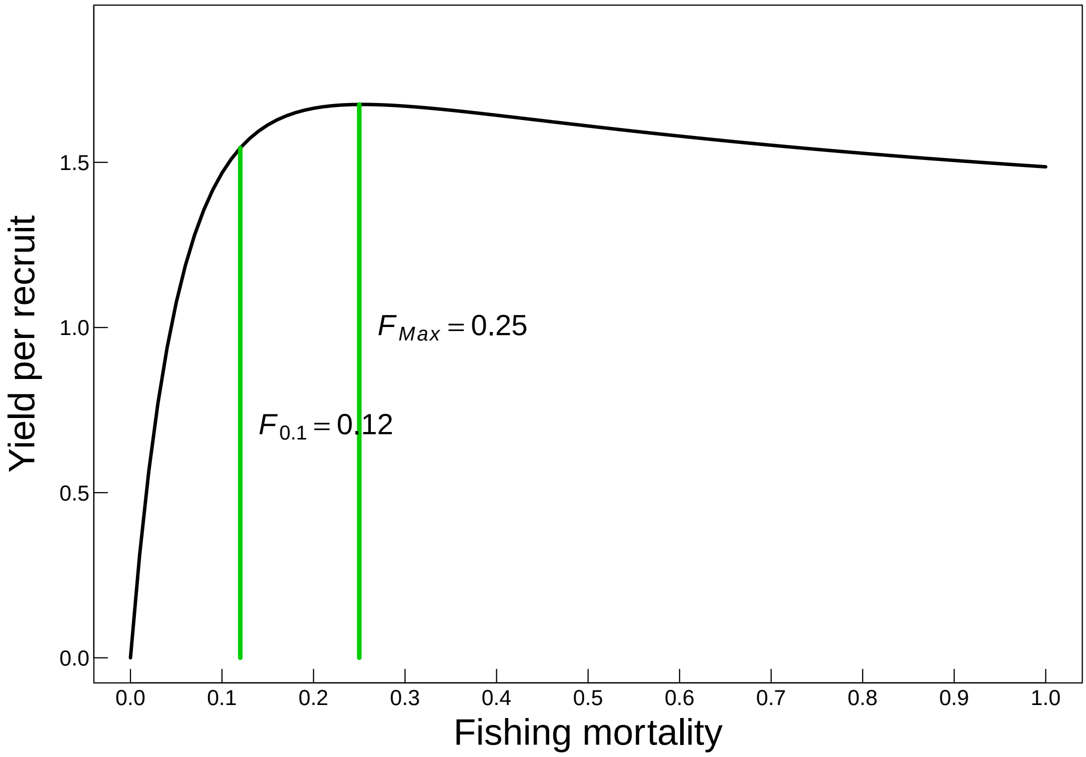


Figure 14: Yield per recruit as estimted in the Gadget model.

4.5 Prognosis

For prognosis three scenarios are tested (Table 8). Fishing at $F_{0.1}$, F_{max} and the same fishing mortality as in 2012 (F_{2012}). The assumptions used for the prognosis is that catch in the first quarter of 2013 is equal to the catches in quarter 1 in 2012. Recruitment in 2012 and onwards is set as the average of the estimated recruitment in 2009 to 2011. As growth is fixed in the model, there is no need for any assumptions on weight.

When fishing at $F_{0.1}$, the scenario with the lowest F catches in 2014 would be 19 thous. tonnes, rising slowly to 22.7 thous. tonnes in 2018. At the same time SSB would increase from 62 thous. tonnes in 2012 to 106 thous. tonnes in 2018.

Fishing at F_{max} would result in catches increasing to 35 thous tonnes in 2014 but then decrease to around 30 thous tonnes in 2018. SSB would remain at similar level from 2012 to 2018.

The intermediate scenario, fishing at the same level as in 2012 would result in catches around 26-28 thous tonnes in 2012 to 2018 and SSB would increase to 80 thous. tonnes in 2018, from around 27 thous. tonnes in 2012.

Table 8: Greenland halibut: Prognosis from the Gadget model, assuming recruitment in 2012 and onwards to be equal to average recruitment in 2009 to 2011 i.e. 33.1 million.

Year	Biomass	Harvestable biomass	SSB	Catch	F_{15-20}
$F_{0.1}$					
2012	222.643	130.629	71.7421	26.995	0.19
2013	226.439	140.459	75.0846	19.442	0.12
2014	238.312	156.642	84.0691	19.125	0.12
2015	247.866	168.133	93.2251	20.438	0.12
2016	255.676	176.129	101.8615	21.365	0.12
2017	262.168	182.365	109.3934	22.098	0.12
2018	267.597	187.599	115.5329	22.714	NA
F_{max}					
2012	222.643	130.629	71.7421	26.995	0.19
2013	226.439	140.459	75.0846	32.912	0.25
2014	220.151	140.163	75.1047	35.208	0.25
2015	213.327	136.013	74.9091	34.085	0.25
2016	207.135	130.328	74.1138	32.667	0.25
2017	202.068	125.168	72.6456	31.410	0.25
2018	198.123	121.109	70.7110	30.426	NA
F_{2012}					
2012	222.643	130.629	71.7421	26.995	0.19
2013	226.439	140.459	75.0846	26.793	0.19
2014	228.336	147.582	79.1374	28.334	0.19
2015	228.405	150.007	82.8715	28.703	0.19
2016	227.670	149.648	85.7716	28.608	0.19
2017	226.729	148.554	87.5717	28.399	0.19
2018	225.820	147.504	88.3255	28.203	NA

References

Begley, J. & Howell, D. (2004). An overview of Gadget, the globally applicable area-disaggregated general ecosystem toolbox. ICES CM, 1–15.

Bertsekas, D. (1999). Nonlinear programming. Athena Scientific, 2nd edn.

Corana, A., Marchesi, M., Martini, C. & Ridella, S. (1987). Minimizing multimodal functions of continuous variables with the ”simulated annealing” algorithm corrigenda for this article is available here. ACM Transactions on Mathematical Software (TOMS), **13**, 262–280.

Frøysa, K., Bogstad, B. & W Skagen, D. (2002). Fleksibest–an age-length structured fish stock assessment model. Fisheries Research, **55**, 87–101.

Hooke, R. & Jeeves, T. (1961). Direct Search Soulution of Numerical and Statistical Problems. ACM Journal, **8**, 212–229.

WD 5

WKBUT 2013

Input to and Assessment of the Greenland Halibut Stock Component in NAFO Subarea 0 + Division 1A Offshore + Divisions 1B-1F

O.A. Jørgensen
DTU-Aqua, Technical University of Denmark,
Charlottenlund Slot, DK 2920 Charlottenlund, Denmark
and
M. A. Treble
Fisheries and Oceans Canada, Freshwater Institute,
501 University Cres., Winnipeg, Manitoa, Canada R3T 2N6

Introduction

Distribution
Greenland halibut **(***Reinhardtius hippoglossoides* (Walbaum)) is distributed throughout the entire rim of the North Atlantic (Bowering and Nederaas, 2000) at depths down to at least 2 200 m (Boje and Hareide, MS 1993).

Studies have indicated that Greenland halibut in the North Atlantic is genetically homogeneous (Vis *et al.*, 1997 and recent Roy. *et al* in press). Tagging studies (Bowering, 1984; Boje, 2002 and recent unpublished studies (Greenland Institute of Natural resources) have shown that the Greenland halibut population in the Baffin Bay, Davis Strait and Labrador Sea must be considered as a single stock unit, probably closely connected to the "stock" at East Greenland, Iceland and Faroe Islands.

Spawning
The most important spawning area in the Northwest Atlantic is probably located in the Davis Strait in deep relatively warm water south of the sill between Greenland and Baffin Island (67°N) (Templeman, 1973). This is supported by maturity and migration studies by Jørgensen (1997) and Gundersen *et al.* (2010) although no females in spawning condition have been observed. The Greenland halibut populations in the Davis Strait, Baffin Bay, inshore areas in Northwest Greenland and to a large extend the east coast of Canada area believed to be recruited from this spawning stock. Spawning has also been observed in the Flemish Pass (off Newfoundland), although only 20% of the mature females had hydrated eggs in the peak spawning period in August (Junquera and Zamarro, 1994). Further, spawning has been observed in the resident stock in Gulf of St. Lawrence and to a minor degree along the slope off Labrador (Bowering and Brodie, 1995).

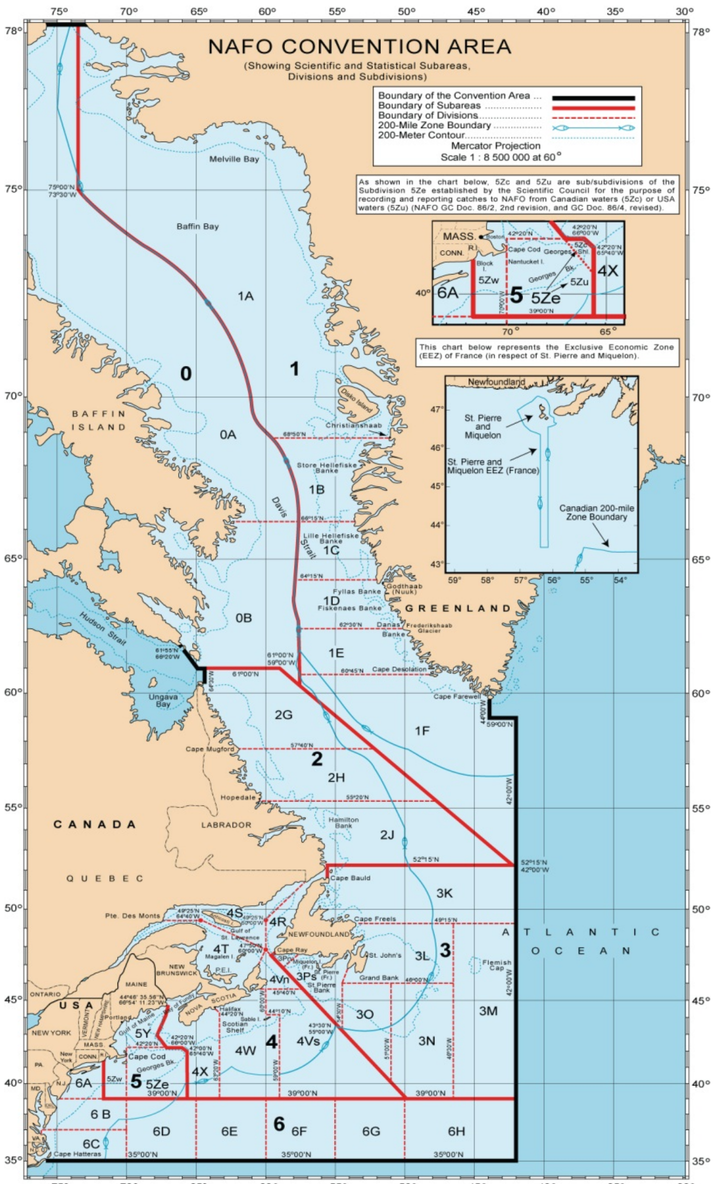


Fig 1. NAFO convention area with Sub Areas 0-6 and NAFO Divisions.

Maturity information for Greenland halibut from NAFO Subarea 0, collected during surveys between 1999 and 2008 indicate L_{50} for females was generally higher in Div. 0A (67 cm to 84 cm from 5 surveys) than in Div. 0B (62 cm and 67 cm from 2 surveys) (Harris et al. 2002). There was also a significant decline in the Div. 0A L_{50} between surveys conducted in 1999 and 2004 and those conducted in 2006 and 2008. Males mature at a smaller size, with the L_{50} for Div. 0A of 54 cm to 66 cm and for Div. 0B it was 39 cm and 43 cm.

There has been a fairly recent discovery concerning Greenland halibut productivity. Research by Kennedy *et a*l. 2011 and Rideout *et al.* 2012 demonstrated that female Greenland halibut take more than one year to develop eggs for spawning and that they carry eggs at two different stages of development. This finding has implications on the assessment of maturity and overall productivity of Greenland halibut.

Age Determination
A Greenland halibut age determination workshop in 2011 concluded that there is considerable uncertainty about accuracy in the current age reading methods (see section in STACREC 2011 report) and the age reading procedure is currently under revision hence no ages are available and aged based analysis have not been up dated.

Management.
Greenland halibut in the inshore areas in Div. 1A are recruited from the off shore spawning area. Tagging experiments have shown that when the have reached the fjords the stay there and don't return back to the spawning area. Very little spawning has been observed in the inshore areas and the "populations" are hence totally dependent on recruitment from off shore areas. Since 1994 the "populations" in the inshore area in Div. 1A have been assessed as separate stocks (Fig. 1).

The Greenland halibut stock in Subarea 0 + Div. 1A offshore and Div. 1B-1F is part of a common stock distributed in Baffin Bay and Davis Strait and southward to Subarea 3. Since 2001 advice has been given separately for the northern area (Div. 0A and Div. 1AB) and the southern area (Div. 0B and 1C-F) in order to spread out the fishing effort. The advice TAC has been increased stepwise mainly in Div. 0A+d Div. 1AB but also in Div. 0B + Div. 1C-F

TAC and nominal catches.

A TAC was first established for SA 0+1, including Div. 1A inshore, in 1976 and set at 20 000 t. It increased to 25 000 in 1979 and remained at this level until 1994. In 1994 NAFO Scientific Council decided to make separate assessments and advice for the inshore area in Div. 1A and for SA 0 + Div. 1A offshore + Div.1B-1F. As a result the TAC for SA 0 + Div. 1A offshore + Div.1B-1F decreased to 11 000 t and remained at this level until 2001 with almost all the catch coming from Div. 0B and Div. 1CD. Between 2001 and 2010 the TAC increased to 27 000 t following a series of new surveys in previously unassessed areas of Div. 0A and 1AB and improving stock status in Div. 0B and 1CD. Since 2001 the TAC has been divided between Div. 0A+1AB and Div. 0B+1C-F with current levels of 13 000 t for Div. 0A+1AB and 14 000 t for Div. 0B+1CD, respectively (Fig. 2).

Catches have been reported to NAFO STATLANT 21 since 1965. Catches in 0 + Div. 1A offshore + Div.1B-1F were at very low levels from 1965-1972, then fluctuated between approximately 4 500 t and 20 000 t from 1973 - 1980. Catches during the period from 1981 to 1989 varied around 3 000 t, increased to 18 500 t in 1992 then declined to 11 800 t in 1994. Catches were relatively stable at approximately 8 500 t from 1995 to 2000. Since then catches have increased to current levels of 27 300 t following increases in the TACs, with the TAC achieved in most years (Fig. 2).

Almost all catches are taken offshore (inshore catches in Div.1C-1F < 500 tons). All offshore catches in Div. 1C-1F are taken in Div. 1CD. The reported discard is usually < 1% of the catches.

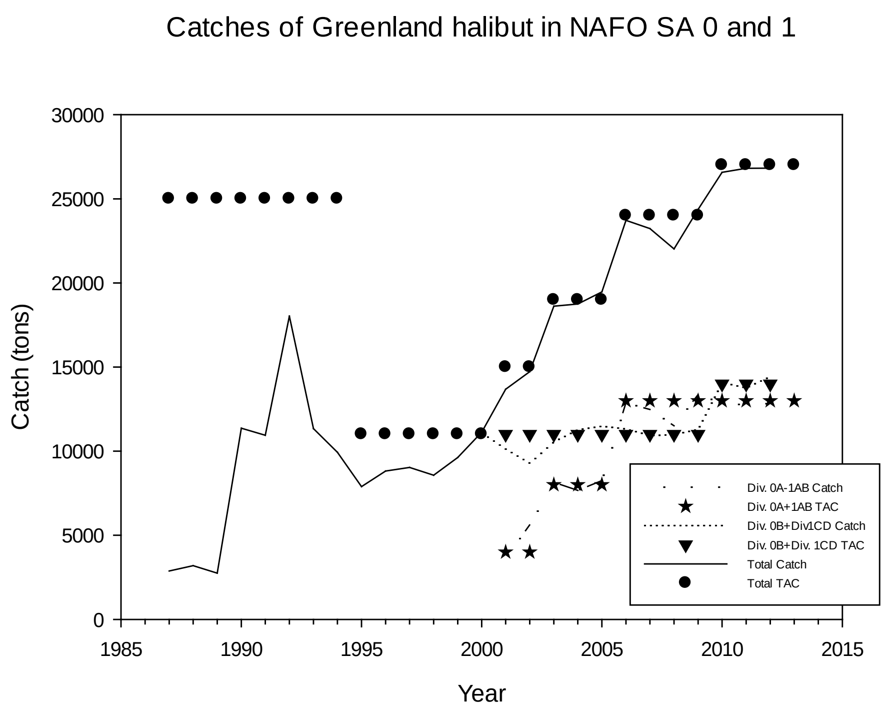


Fig. 2. Catches and TAC for Greenland halibut in Div. 0A+1AB, Div.0B+1CD and total from 1987-2012.

Input to assessment

Fishery

Catches distributed on NAFO divisions and gear (mainly trawl but also gill net in Div. 0A and 0B) are available from 1965, but catches are minor until 1972 (Fig 2.)

Length frequencies have been available from the trawl fishery since 1987, and more irregularly from gill net and long line fishery (Fig 3).

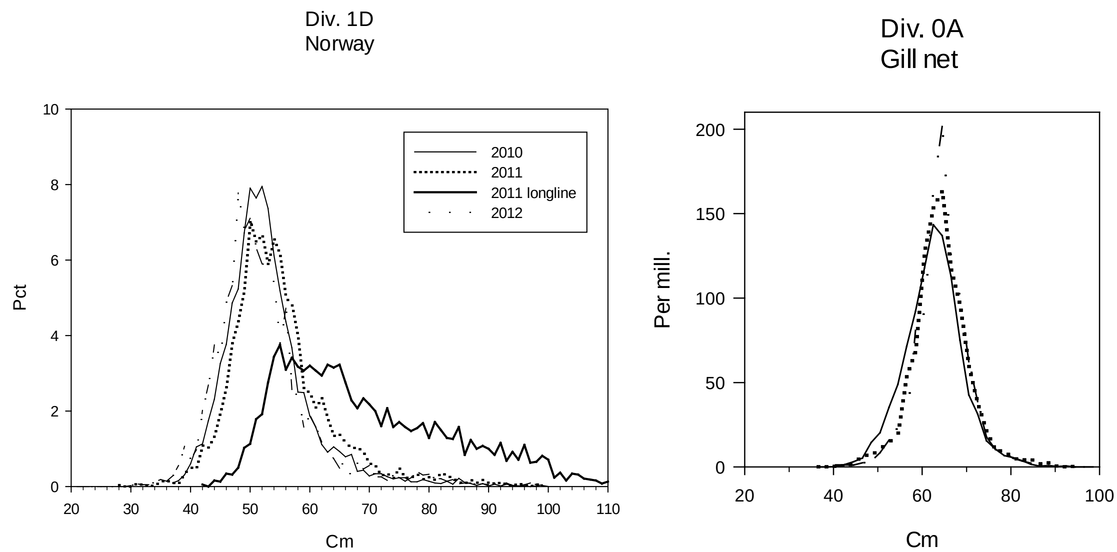


Fig.3. Left: Typical length distribution in the trawl fishery in Div. 1CD with a mode around 50 cm as seen in all years. Right: Typical length distribution in the gill net fishery with a mode around 65 cm. The length distributions indicate that the trawl fishery is very selective taking few fish above 55 cm.

<u>Standardized CPUE series</u> based on log books (trawl haul by trawl haul and by gill net are available from all divisions from1988 in Div. 0B and 1CD and onwards and from 1996 in Div. 0A and Div. 1AB and onwards (Fig. 4 + Fig. 5).

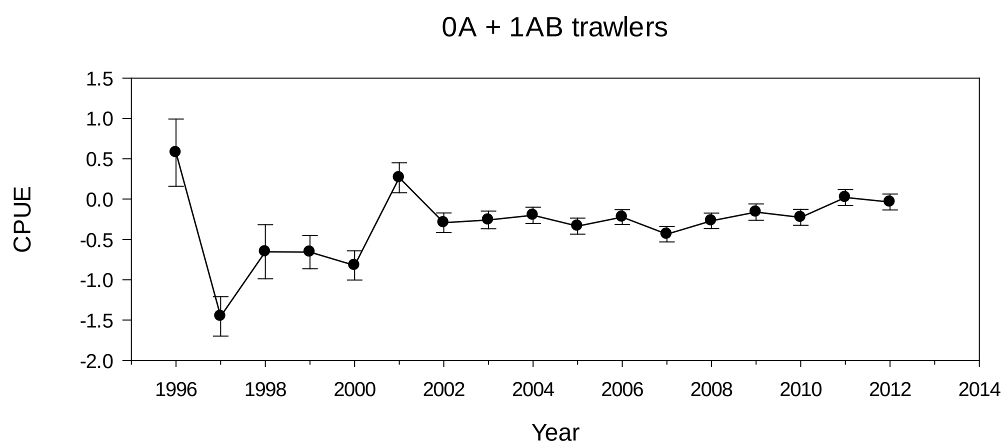


Fig 4. Standardized trawl CPUE from Div. 0A and Div. 1AB. Data from before 2001 are based on trial fisheries conducted by one-few vessels.

<u>Catch in numbers by age</u> in the commercial fishery are available from 1987-2002.

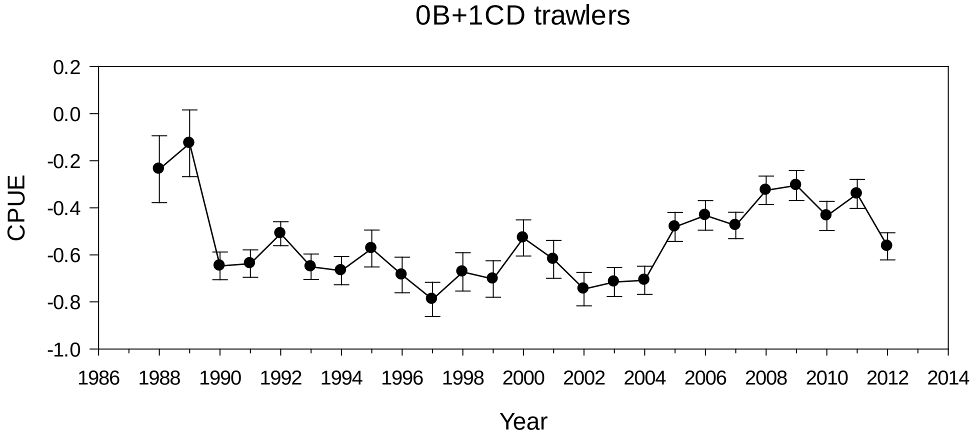


Fig. 5. Standardized trawl CPUE from Div. 0B and Div. 1CD. Data from 1988 and 1989 are based on one large vessel.

Survey

Swept area biomass and abundance estimates from surveys conducted annually in Div. 1CD (1987) 1988-1995 and 1997-2013 and biannually in Div. 0A-south. since 1999 (see WP this meeting) (Fig. 6). Further, there have been irregular surveys in Div. 0B and Div. 1A. The survey biomass is distributed approximately 50:50 between Div. 0A and Div.1AB and Div. 0B and Div. 1CD and the survey in Div. 0A-south is considered as a proxy for the biomass in the northern area and the survey in Div. 1CD is considered as a proxy in the southern area. Further, biomass and abundance (recruitment age one) estimates are available from a survey covering depths down to 600 m in Div.1A-1F.

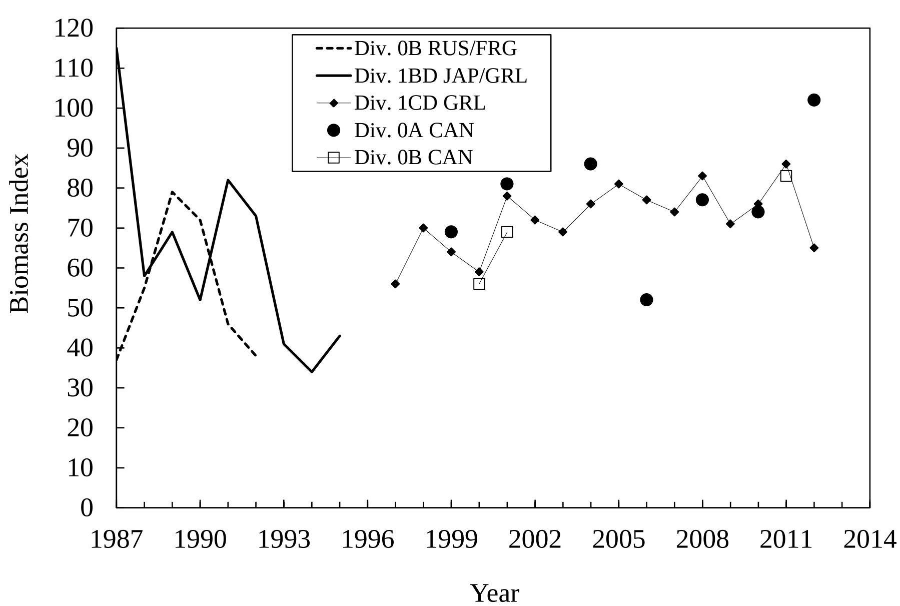


Fig 6. Swept area biomass from various surveys. The survey in Div. 0A in 2006 was incomplete.

Length distributions by depth and sex are available from all surveys.

Age distribution is available from the survey in 1CD from 1997-2009.

Recruitment index, age one, is available from bottom trawl surveys from 1992 to 2013.

Assessment

Yield per Recruit Analysis.

The level of total mortality has in 1994-1996 been estimated by means of catch-curves using data from the offshore longline fishery in Div. 1D. Z was estimated from regression on ages 15-21. A relative F-at-age was derived from the catch curve analysis, where the trawl, longline and gillnet catches were weighed and scaled to the estimated stock composition. In all three years NAFO Standing Committee on Fisheries (NAFO STACFIS) considered that the estimation of Z was based on too limited samples and represented too small a part of the fishery and that the outcome of the catch curve analysis was too uncertain to be used in the yield per recruit analysis. No update of the Yield per Recruit Analysis has been made in recent years due to lack of age data.

XSA.

Extended Survivors Analysis
An XSA has been run unsuccessfully several times during the 1990'ies, using a survey series covering 1987-1995 as tuning. STAFIS considered the XSA's unsuitable for an analytic assessment due to high log-catchability residuals and S.E.'s and systematic shift in the residuals by year. Further, a retrospective plot of F_{bar} showed poor convergence. In 1999 the XSA analyses was rerun including the latest two years surveys (1997-1998, new vessel and gear) but the outcome of the analysis did not improve.

In 2002 an XSA analysis was run using the catch data for SA 0+1, calibrated with trawl survey data (age 5-15) from the Greenland deep sea surveys (1997-2001) in Div. 1CD. The assessment results were considered to be provisional due to problems with the catch-at-age data and the short time series, the assessment is, however, considered to reflect the dynamics in the stock. The rate of exploitation had been relatively stable in recent years between 0.2-0.3 (F_{bar} 7-13). The input parameters to the analysis and the outcome of the analysis is given in SCR 02/68.

The XSA was run again in 2003 with the 2002 survey and catch data and updated catch data from 2001 (very small changes). The assessment results were considered to be provisional due to problems with the catch-at-age data and the short time series. The assessment was, however, considered to some extent to reflect the dynamics in the stock. The rate of exploitation had been relatively stable in recent years between 0.2-0.3 (F_{bar} 7-13). The summary of the XSA is given in SCR (03/54).

The XSA has not been run since 2003 as no catch-at-age data are available for 2003-2012.

Spawning stock/recruitment relations.

A spawning stock/recruitment plot based on the available observations from the joint Japan/Greenland survey and the Greenland survey has been attempted but no further analysis of spawning stock recruitment relationships have been made due to few observations distributed on two different surveys, poor estimate of spawning stock biomass (survey trawls only take a very small proportion of the mature fish), poor estimates of ages of old fish, the survey covers only a restricted part of the area covered by the assessment, and knife edge maturity ogive was applied. Further, the age of the recruits is poorly estimated (the Petersen method). The plot has not been updated because of the lack of age data.

Relative F

A relative F index has been estimated from the catches and the swept area biomass estimates from Div. 1CD (catch/biomass). This index has fluctuated between 0.02 and 0.17 but was relatively stable around 0.08 during 1997 to 2011, then increased to 0.11 in 2012 due to a decline in the estimated biomass.

This Relative F index has not yet been used in the assessment as a proxy for F. There are questions about its validity or usefulness because of the catchability of the survey trawl (few mature fish) and it covers only a small portion of the stock area. **Comments on the use of this approach to develop a proxy for F in case of this stock are welcome.**

ASPIC

ASPIC was run in 1999 with standardized CPUE data and a biomass index as inputs. Three CPUE series were available, one series covering Div. 0B during the period 1990-1998, one covering Div. 1CD during the period 1987-1998 and a series combining the two data sets. The biomass index was from 1CD and covered the period 1987-1995 and 1997-1998. Several runs showed that the combined CPUE series from Div. 0B+1CD fitted the total catch data best in terms of r^2 and “total objective function”. Runs with biomass alone gave relatively bad fits in terms of “total objective function” and r^2 and the modeled population trajectory declined drastically over the period. Runs with the CPUE series from 0B gave unrealisticly high B_{msy} and negative r^2. The run with the combined CPUE series showed, however, that sensitivity analysis should be run, because “the B1-ratio constraint term contributed to loss”. Several runs with different realistic values for the constraint did not solve the problem. Further, the coverage index and nearness index was equal in all runs. Several runs with different constraints on r and MSY were tried but it did not change the outcome of the analysis. Removing the three first years from the input data gave negative r^2. To get measures of variance the run with the combined CPUE series was bootstrapped (500 re-samplings).

The results showed that estimated fishing mortalities for 1987-1998 were less than the (bias-reduced) estimate of F_{msy} (0.22) except for one year (1992). A number of essential parameters are quite imprecisely estimated (r, q, F_{msy}), and it is considered that the estimates of MSY and F_{msy} were not precise enough to be used.

An ASPIC was run in 2009, but the outcome of the analysis did not change significantly from the analysis in 1999, mainly because there is very little contrast in the input data and the data series was relatively short.

The ASPIC Fox model was tested again during the 2012 assessment. Three different formulations were run: 1) one was with the 0B + 1CD trawl CPUE series and the 0B +1CD catch for 1988-2011; 2) with two 1CD survey series (1988-1995 and 1997-2011) and 1CD catch (1988-2011); and 3) the most recent 1CD survey series (1997-2011) and 1CD catch (1988-2011). The first formulation using CPUE resulted in a poor fit of observed and estimated values, with low r-square (.319) and low nearness index (.369). The logistic fit failed in the second formulation. The third formulation resulted in an unbelievably high MSY with F of 0. The estimate of catchability (q) was also extremely low. The model fit was not robust to changes in model parameters. Given that there is little variation in this time series and it is still relatively short (1997-2011) for a long lived species like Greenland halibut this model was not accepted.

Biological reference points

Yield per recruit analysis or other age-based methods are not available, for estimating biological reference points and there is no accepted analytical model,therefore quantitative estimation of reference points is not possible.

NAFO SC has recommeded that for data limited stocks a proxy of B_{lim} could be estimated based on the survey indexes that are used as the primary basis for advice for this stock (SCS 04/12). If the highest value of the index is consistent with when the stock is thought to have been fully exploited, i.e. at Bmsy, then a 70% decline would be appropriate (SCS 04/12). The NAFO Study Group did not consider this expert system approach to developing a Precautionary Approach model to be a final product, they found that it provided a structure that NAFO SC could consider using to capture the knowledge base constituting best scientific practice with respect to Limit Reference Points (LRPs) within NAFO. The expert system can be updated on an ongoing basis as methodology and thinking with respect to LRPs advance,

In 2013 this expert system was used and proxies for B_{lim} were set as 30% of the mean of the survey biomass for 1997-2012 in Div. 1CD and the mean of 7 surveys in Div. 0A-south conducted during 1999-2012, respectively.

However, B_{msy} is not known for this stock and it may be that the stock is currently below $B_{msy,}$ so NAFO SC advised that if the stock indexes increase B_{lim} should be increased accordingly.

Questions Concerning the Assessment

1) We currently use two survey indeces to inform our advice on TAC for two portions of the stock area: 0A-1A(offshore)+1B and Div. 0B-1C-F. So we are essentially treating these areas as two sub-stocks. We are concerned that this may not be the best way to assess this stock given the highly migratory nature of fish in the offshore, lack of genetic structure, differences in maturity status between north and south, etc. The north-south division was made as the fishery expanded north in the early 2000's and there was a desire to see the effort distributed throughout the stock area. However, since it is a single stock we are wondering if we should consider combining the two surveys to create a single stock index to assess status. This could be possible since the surveys are made with the same vessel and gear and have a similar design. We could still provide advice on separate TAC's for the northern and southern divisions based on the current TAC proportions or stock distribution**. If Canada moved to an annual assessment of Div. 0A this idea of a single index made up of survey biomass/abundance from 0A and 1CD combined might be something to consider? Advice from the experts on how best to structure our surveys and the stock indexes would be welcome.**

2) If the Relative F Index described above were considered an acceptable proxy for F how should it be calculated? Would we calculate separate indexes for 1CD and 0A? Or could we create a single index by combining catches and surveys from these two areas?

3) The survey trawl catchability is such that we do not get an estimate of the population or SSB so it is a relative index of biomass comprised primarily of fish <55cm . However, 30% (0B) - 50% (0A) of the fishery in Canada is gill net that catches mature fish >55 cm. So we have no way of assessing this catch against the corresponding portion of the mature population. We use the recruitment index to gauge status of spawners. This seems to be the best we can do but **advice or comments from the experts on our approach and the sustainability of a mixed gear fishery that is targeting both ends of the population (immature and large mature females) would be welcome.**

More information

More detailed information about background and input to the assessment can be found in NAFO SCR Doc. 13/035: Assessment of the Greenland Halibut Stock Component in NAFO Subarea 0 + Division 1A Offshore + Divisions 1B-1F, and Scientific Council Report 2013, Section on GHL in the folder with background material.

WD-6

WKBUT 2013

Survey approach to assessment of Greenland halibut in SA 0+1

M. A. Treble
Fisheries and Oceans Canada, Freshwater Institute,
501 University Cres., Winnipeg, Manitoa, Canada R3T 2N6
and
O.A. Jørgensen
DTU-Aqua, Technical University of Denmark,
Charlottenlund Slot, DK 2920 Charlottenlund, Denmark

Introduction

ICES has developed an empirical approach to providing advice in the case of data limited stocks based on the trend in the stock response to the fishing pressure (ICES CM 2012/ACOM:39). The empirical basis is given a generic expression $C_{y+1}=Catch_{recent}*b*r*f*\Theta$, where $Catch_{recent}$ is the average catch over some period, b an evaluation of whether the stock is at risk of productivity impairment given by $min[1,b_{current}/MSYB_{triggerproxy}]$, r is the trend in development of the stock (normally SSB), f is the ratio of $F_{msyproxy}/F_{current}$ and Θ is an expression of the uncertainty of the information (also referred to as a precautionary factor) where Θ=1when b, r and f are computed, otherwise Θ=0.9 (where 0.9 is an arbitrary number requiring input from managers).

The generic expression is presented in tabular form, which facilitates determination of the model parameters. The table categorises different conditions of productivity status, trend in stock development and exploitation status. Two tables are provided, one for situations where it is possible to produce numerical estimation of b, or r, or f and a second one for situations where more than one of these is parameters is unknown or not enumerated.

The use of the precautionary factor (Θ) allows for the inclusion of the Precautionary Approach (PA) in a quantitative way in the advice framework for “data poor” stocks. In the model formulations in the tables Θ is represented by pb and/or pr and/or pf to link it directly to the stock pressure or state indices in the formulation. It is recognized that Θ represents an element of risk evaluation, and whilst an arbitrary figure of 0.9 is proposed (ICES 2012) ICES CM 2012/ACOM:39) this value needs to be established by fishery managers.

The report of ICES WKFRAME III goes on to say that this empirical approach is an option that could be considered for use beginning in 2012. However, there are shortcomings that imply the tables should be used with care and for example the frequency of the management action needs to be considered. The report concludes by suggesting that this framework be considered a work in progress, while work continues to develop species specific harvest control rules that may provide a more appropriate longer term solution.

<u>Application of the ICES Framework for data poor stocks for Greenland Halibut in Subarea 0 and 1</u>

We would suggest using the second table (3.5.2 in ICES 2012) because we are not able to estimate SSB (b) or $F_{msyproxy}$ (f). We have stock abundance indexes based on surveys that are used to assess the status of two portions of the stock area, 0A1AB and 0B1C-F. There is a slight increasing trend in the 0A1AB area and the 0B1C-F index is stable.

For 0B1C-F the stock trend is not changing, biomass index is above the trigger ($B_{lim)}$ but the exploitation rate is unknown so the recommended formulae would be C_{y+1}=$Catch_{recent}$*1*1*pf.

The calculation of r should in principle represent the spawning stock biomass (SSB index). However, if such an index is not available any other measure which is a proxy for the SSB could be used, although they note that an abundance index which is dominated by recruitment would not have desirable properties in this respect. The trawl surveys used to determine biomass and abundance of Greenland Halibut tend to be dominated by immature fish so they may not be ideal for use in estimating stock response but they are currently the only source of fishery independent data to determine stock status. So it is proposed that total survey biomass be used as a proxy for SSB and to estimate r. Standardized catch per km^2 could also be used but the trends are the same.

The number of years used in the calculation of r should be large enough to be able to reflect the consequences of management actions (e.g. an increasing stock trend after some years of low fishing mortality and therefore it should be related to the species longevity and productivity. Larger values of n should be used for longer lived, less productive species. The ICES report suggested an arbitrary figure of n=5. We could use this value unless we feel a larger value would be warranted. Greenland Halibut are relatively long lived (max age of 30+ years) so a value greater than 5 might be considered. For illustrative purposes n=5 will be used here.

The calculation depends on how the time series looks. The report offers several possibilities. They suggest the index could be plotted on a log scale and if it is linear then a simple linear regression could be applied to estimate the slope, calculated over the last 5 points. More sophisticated methods could be used if the relationship is not linear. Finally, the calculation of an index average in the 2 final years divided by the index average in the 3 immediately preceding years could also be used (given n=5).

To avoid large changes in catch that may not reflect population changes it is advised to define an interval within which r is restricted, and the example of 0.5 to 1.5 is given. So the maximum change permitted does not exceed 50%.

We have not had any discussions on the level of risk that managers would prefer so in this case will use the precautionary factor of 0.9 given in by ICES (ICES 2012).

The term $Catch_{recent}$ can mean the most recent year but may mean a longer period of years for long lived species. For Greenland Halibut in SA0+1 catches have tended to be fairly stable at the recommended TAC (Fig. 1) and so for illustrative purposes the most recent TAC advice is used for $Catch_{recent}$ value.

An overall cap on the percent the TAC can change from one year to the next may also be considered (e.g. 20%) and this would be developed in discussion with managers.

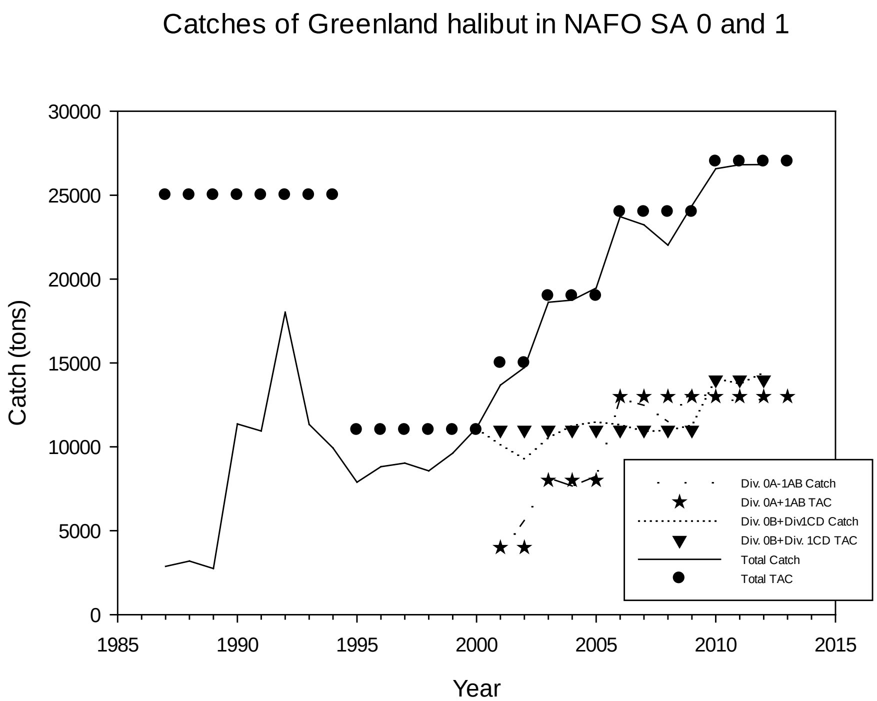


Fig. 1. Catches and TAC' for Div. 0+1, Div 0A-1AB and Div. 0B-1C-D, respectively.

Calculation for Div. 0A1AB

Calculation of r

Div. 0A-south has been surveyed biannually since 1999 and as a result advice is provided every two years for catch in Div. 0A1AB. A number of important strata were not covered in 2006 and the survey coverage was hence incomplete.

The average estimated biomass was 88379 tons in the two recent surveys (2010-2012), while the average biomass in the three preceding surveys was 71877 tons (2004, 2006 and 2008) (Fig. 1) resulting in r=1.23. However, the 2006 survey is known to be an under-estimate so if it was excluded and the average biomass calculated across the three preceding valid surveys (2001, 2004 and 2008) biomass would be 81453 tons resulting in r=1.09.

For 0A1AB the stock trend is increasing (Fig. 2), biomass index is above the trigger ($B_{lim)}$ but the exploitation rate is unknown, so the recommended formulae from the second table would be C_{y+1}=$Catch_{recent}$*r*1*pf.

Catch in 2014=13,000 t*1.23*1*.9=14,391 t or Catch in 2014=13,000 t*1.09*1*.9=12,753 t.

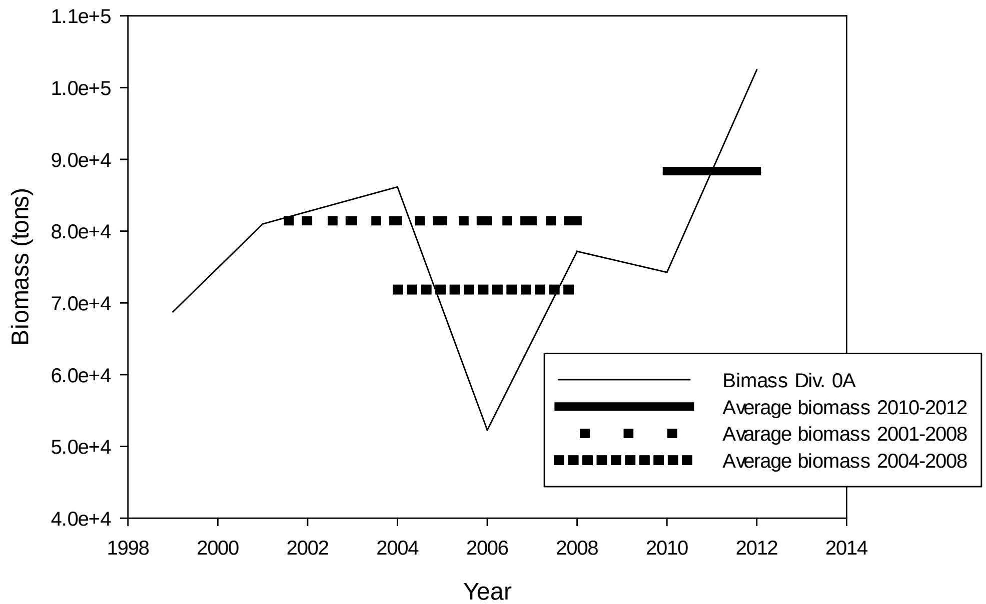


Fig. 2. Swept area biomass in Div.0A-south, average biomass in the latest two surveys and the preceding three surveys with or without 2006, that had an incomplete coverage.

Calculations for 0B1C-F

Div. 1CD has been surveyed annually since 1997 so advice on TAC is given on an annual basis. An earlier index is available for 1987-1995 using a different vessel and gear but it has not been standardized to the new survey series so these data are not included here.

For 0B1C-F the stock trend is not changing (Fig. 3), biomass index is above the trigger ($B_{lim)}$ but the exploitation rate is unknown so the recommended formulae from the second table would be C_{y+1}=$Catch_{recent}$*1*1*pf. Note this formulae does not include a calculation of r because the determination was that the trend is stable so the formulae is simply the current catch times the precautionary factor for f.

Catch in 2014=14,000 t *1*1*0.9=12,600 t

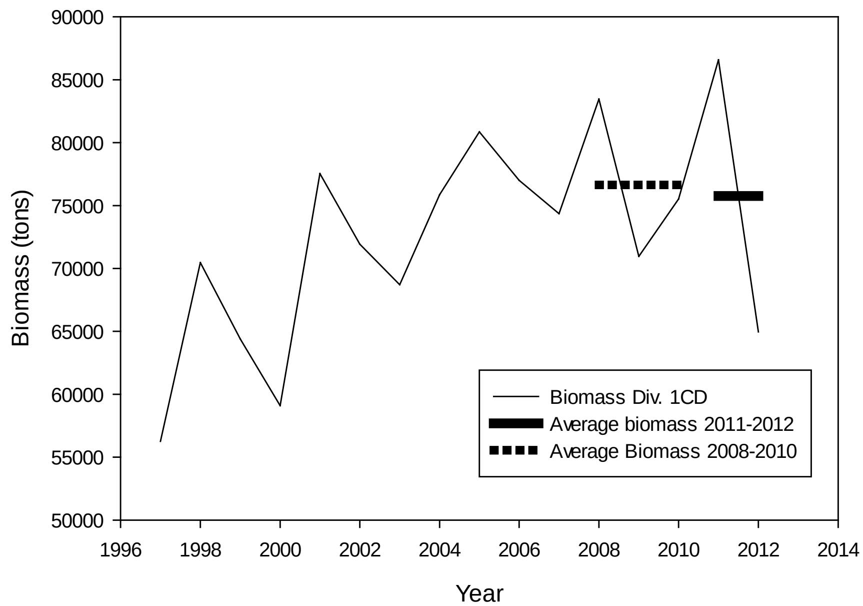


Fig. 3. Swept area biomass in Div. 1CD, average biomass in the latest two surveys and the preceding three surveys, respectively.

Discussion/Questions

Is this approach appropriate and something we should seriously consider developing for SA0+1 Greenland halibut?

We do have a proxy for B_{lim} recently defined by NAFO STACFIS based on the two survey indexes and so would it be acceptable to use $B_{current}/MSYB_{trigger}$ as the proxy for b? In the current situation this ratio would exceed 1 so it would not be a factor but this formula, coming from the first table (3.5.1 in ICES 2012) might be more informative than if we assume we have no estimates for b or f and apply the formula from the second table (3.5.2).

The ICES report notes that because of the delay between action (change in catch) and response (state of the stock (b), trend in stock development (r), and pressure from the fishery (f), the advice from these tables should not be assumed to be applicable as annual advice. The period chosen will depend on the particular species dynamics and stock in question.

It is also mentioned that this approach may not be applicable in all cases and they give some examples (section 3.2.2 in ICES 2012) and they go on to suggest the proposed HCRs be evaluated using both stock specific implementations and by simulation. They acknowledge this simulation testing could take a lot of effort and suggest it might be more effectively deployed in developing fishery specific HCRs. Our question is that in the case of this Greenland Halibut stock is it possible to develop fishery specific HCRs with the data available and if so how would we do so?

On page 21 of the ICES report they mention that if indices are going to be used directly to give advice, a GLM model, winsorisation or other stabilizing mechanisms should be used when the indices are compiled. Should we be doing this for SA0+1 Greenland Halibut. What method is relevant for this stock?

The report also notes in the discussion that “a different catch advice can be derived by making expert judgement for proxies for $MSYB_{trigger}$ and $F_{msyproxy}$, and making expert judgements on the exploitation pressure and stock state relative to these. This implies that the advice will depend on the scientific argumentation put forward to support an expert judgment”. This is the approach we presently rely on to give advice for SA0+1 Greenland Halibut and at least in Canada we are finding it harder and harder to explain exactly what the basis for the advice is. Industry is calling for us to move forward with implementing a Precautionary Approach and develop Harvest Control Rules that will help them achieve Marine Stewardship Council or other eco-label designations. Having a framework such as this one developed by ICES for data poor stocks to guide our advice for Greenland Halibut in SA0+1 could be very helpful.

ICES recommends to calculate the “stock response rate” based on 5 years (surveys?). Is that sufficient for a long lived species as Greenland halibut? It may not be and the framework actually recommends that r be calculated over a time frame that is considered appropriate for Greenland Halibut. We could look at different time frames, maybe 7 years?

There are a number of irregular surveys in the assessment area *eg* in Div. 0B, Div. 1A and the northern part of Div. 0A. The information from these surveys could not directly be included in the method. How could this information be dealt with?

The survey in Div. 1CD is incomplete in 2013 as was the survey in Div. 0A in 2006, how is this probably recurrent problem dealt with? One of the options for calculating r was to use a simple linear regression through the time series chosen, this may be an option to consider in the situation where the index is fluctuating but the general trend is linear. If we had a longer time period (e.g. n=7-8 years) then this problem would not be that critical. You could drop the bad years and still have sufficient data to calculate r.

Survey biomass estimates are subject to quite some variation which will lead to a “bumpy” advise even though TAC only is allowed to change with 20% from year to year. This is why they recommend this approach is best suited for for multi-year advice, not annual, which is essentially what we have done in the past with our adhoc expert opinion. We advise on an increase and then watch to see how the stock responds over 3-5 years or more.

References

ICES 2012. Report of the Workshop 3 on Implementing the ICES F_{msy} Framework. ICES Advisory Committee. ICES CM 2012/ACOM:39

WD07 ICES WKBUT 23.-26.11.2013

MSY approximations for Greenland halibut in V+XIV

J Boje
DTU Aqua
Denmark

'Catch-MSY' approach

MSY for Greenland halibut in V+XIV was estimated using the approach by Martell and Froese (2013). The approach is based on a production model where abundance indices and catches are used to estimate the population parameters r and K. Martell and Froese used this concept without any abundance estimates and thereby estimates a range of likely pairs of r and K and associated approximation of MSY. In this context, the approach is used to illustrate a possible range of MSY for the stock given likely r and K values.

The analyses were conducted with r code available at fishbase.de/rfroese.

Reliable catch data is available back to the start of the fishery in 1961 (NWWG 2013) and the stock is therefore assumed to be close to virgin state (at or near K) at this entry of fishery. Biomass was therefore assumed being 70-100% of k at beginning of time series and 20-50% of k at present level (end of series). Process error was set to 0.02.

Qualified guesses of r were in the range found in the literature (Fishbase: 0.04-0.15) and in previous ASPIC and biomass models run (NWWG) in the range 0.10-0.56.

The approach was initially run with different broad initial guesses on r and K and assumptions on size biomass at start of fishery. Within all combinations of r ranges (0.02-0.4) and upper boundaries of k (6 mill t), MSY was estimated between approx. 20kt and 28kt.Based on the lowest viable k (900 kt) associated with lowest r (0.05), this k was defined as upper limit of k. The result of this run is provided in Fig. 1. Given the ranges assumed for r and k, a MSY proxy is distributed between 20 and 30 kt with a mean around 25 kt (Fig 1F).

Fig 2 provides the sensitivity of MSY estimation for various combinations of k and r ranges. At low r values (0.05-0.3) assumptions on the upper k limit will affect MSY estimates , while at higher ranges of r the upper k limit assumption will not affect MSY estimates due to the narrow distribution of viable combinations (Fig 1B).

Conclusion: without qualified prior assumptions MSY estimates from this approach is always estimated higher than 20 kt, but considering estimates of population growth (r) from other studies, a likely MSY is about 25 kt. which equals mean catches in the last two decades.

Depletion Corrected Average Catch (DCAC)

The DCAC approach is based on the potential-yield formula (Alverson and Pereyra, 1969; Gulland, 1970), where Bmsy is assumed 50% biomass at origin and Fmsy is assumed eq to natural mortality, M. Taking account of the removals from the stock over a number of years and assumptions on M, Fmsy in relation to M, Bmsy in relation to biomass at origin, the sustainable yield (DCAC) component is approximated.

Assuming a windfall ratio of 0.75, i.e. that B0 is reduced by 75% since the beginning of the time series, a DCAC is estimated to approx. 21 kt. (Table 1, blue field). For a number of alternative windfall ratios (0.4-0.6) the estimated DCAC only varied insignificant (21-23 kt, Table 1). Also alterations in Bmsy/B0, Fmsy/M distribution, M and windfall distributions did not change the estimated DCAC significantly (lower part of Table 1).

Within the assumed settings of model parameters the DCAC estimate therefore seem robust.

Table 1. Input settings and estimated DCAC, sd of estimate and CI range.

	Estimate	SD	DCAC (median) kt	CI (5-95%) kt
M	0.15	0.5		
Fmsy/M	1	0.2		
Bmsy/Bo	0.5	0.1		
Windfall ratio Δ	0.75	0.15	21.253	16.2-23.9
Windfall ratio Δ	0.60	0.15	22.048	17.2-24.4
Windfall ratio Δ	0.50	0.15	22.642	18.1-24.8
Windfall ratio Δ	0.40	0.15	23.251	19.1-25.1
Bmsy/Bo	0.4	0.1	20.283	14.3-23.6
Lognormal Fmsy/M	1	0.2	21.819	17.6-24.4
M	0.2	0.5	22.819	17.6-24.4
Bounded beta distrib Δ	0.75	0.15	21.257	16.1-24.0
Lognormal Δ	0.75	0.15	21.221	16.1-23.8
100000 iterations (default 10000)			21.265	16.1-24.0

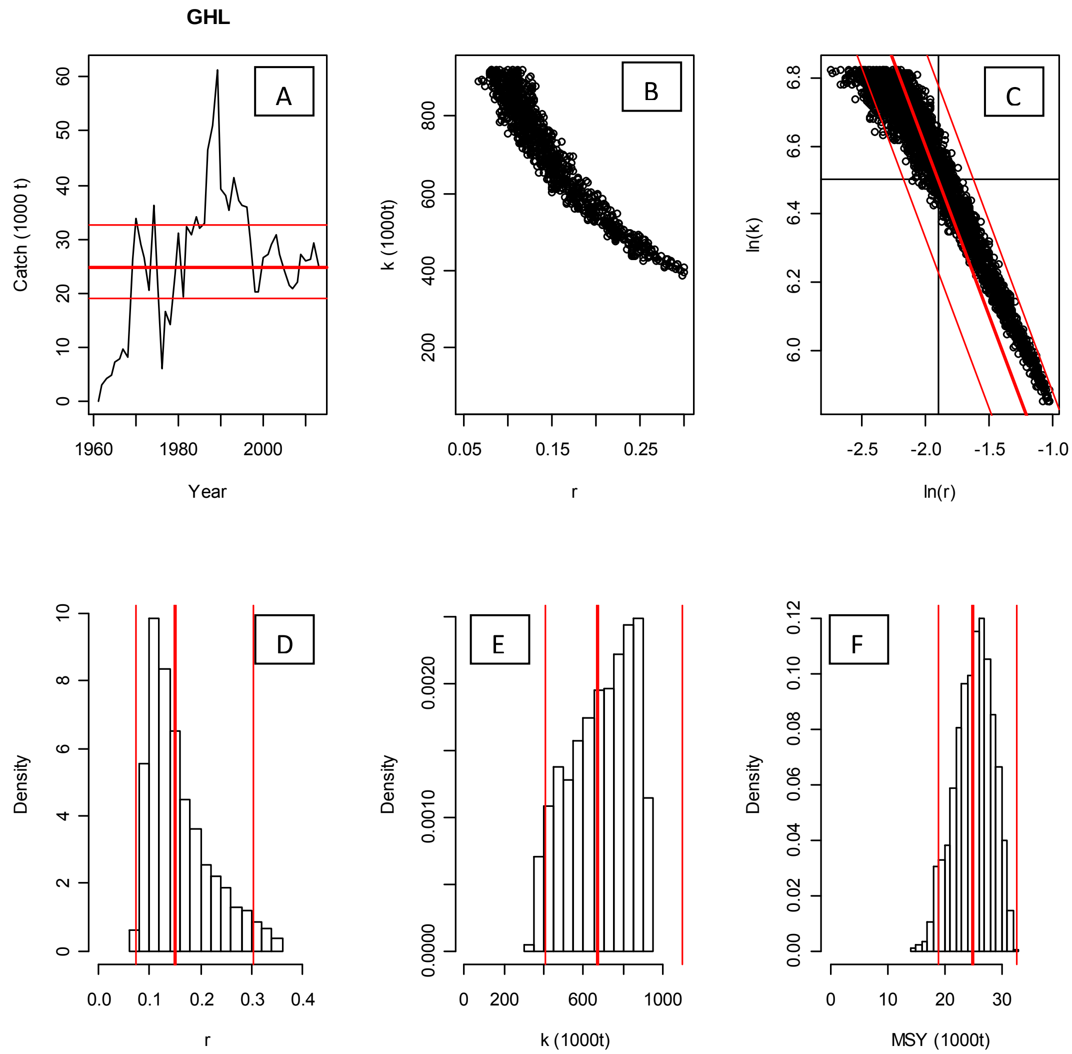


Fig 1. Output from MSY-catch analysis. A: catch series with indication of MSY and 95% conf. limits. B: viable combinations of r and k, C: r and k in log space, D: distribution of r with mean and 95% conf limits, E: distribution of k with mean and 95% conf limits , F: distribution of MSY proxy with mean and 95% conf limits.

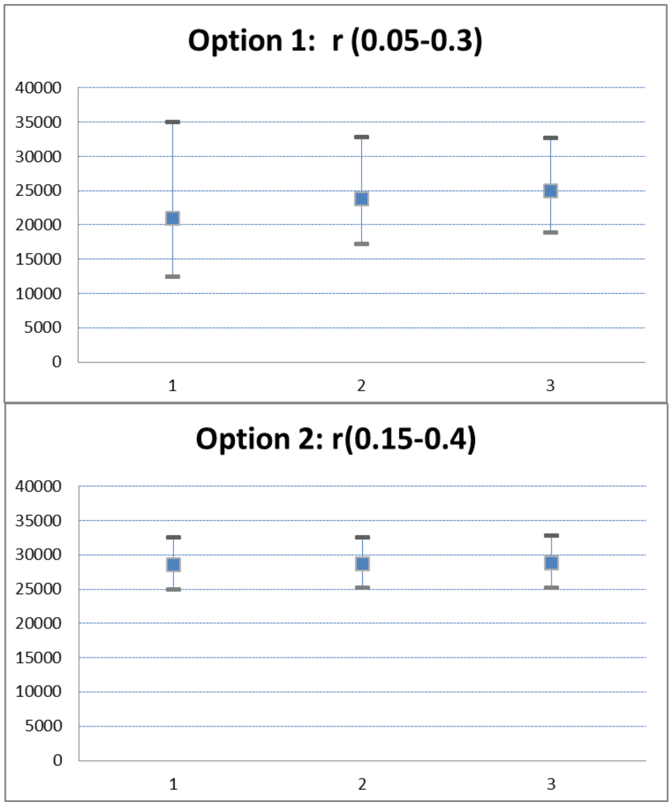


Fig. 2. Scenarios of MSY proxy estimates for 1: k eq 100*maxCatch, 2: k eq 50*maxCatch and 3: k eq 15*maxCatch for upper scenario with low r range and lower with higher r range.

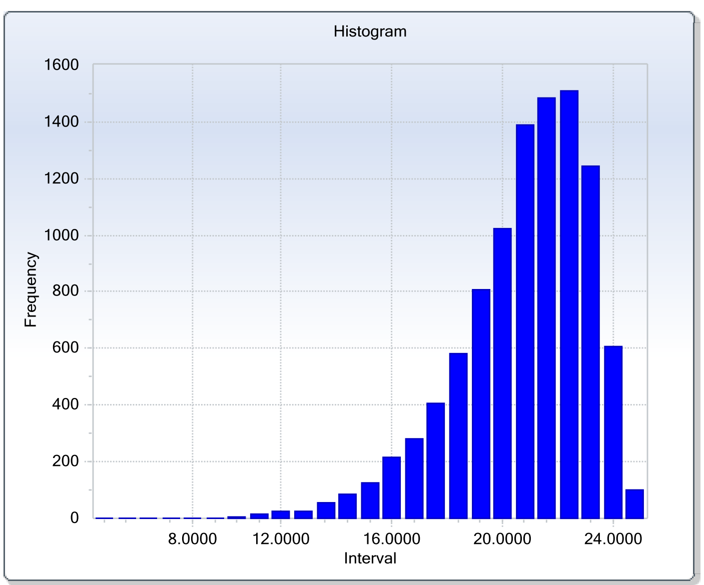


Figure 3. DCAC distribution at parameter settings: M=0.15, Fmsy/M=1, Bmsy/B0=0.5, Δ=0.75; median DCAC=21.253 kt

ON HALIBUT DYNAMICS

¤ ***E***nvironmental ***f***orcing.

¤ ***M***ulti ***O***scillatory ***S***ystem ***A***pproach.

¤ ***A MOSA-B***ayesian fusion.

Aldo Solari, Ole Jørgensen *and* Helle Siegstad
Fish and Shrimp Division
Greenland ***I***nstitute *of* ***N***atural ***R***esources

Benchmark Workshop on Greenland Halibut Stocks.

Copenhagen, 26-29th November, 2013.

¤ *N* o t e s.

¤ (i). *N* o t e s.

On the authors.

Aldo P. Solari (Ph.D., Senior research scientist[1]). Email: <apso@natur.gl> works on the analysis and mathematical modelling of stock dynamics in fish, cephalopods and shellfish. Corresponding author for this report.

Ole Jørgensen (Ph.D., Senior research scientist[2]). Email: <olj@aqua.dtu.dk> has been the Academic Manager of the "Cooperative agreement between Greenland Institute of Natural Resources and DTU Aqua", aimed to support the GINR within general fisheries biology, assessment, survey planning and evaluation and education and support of young scientists. West Greenland Halibut survey Leader since the mid 80´s.

Helle Siegstad (Head of Dept.[1]). Email: <hesi@natur.gl> has been the Director of the Fish and Shrimp Division -since 1995- with overall responsibilities on Research and Development, data, publications (scientific and popular) and communications of research results and fishery management issues.

(1). Fish and Shrimp Dept., Greenland Institute of Natural Resources (GINR). Kivioq 2, 3900 Nuuk, Greenland.

(2). National Institute of Aquatic Resources (DTU AQUA), Section for Ecosystem based Marine Management. Technical University of Denmark, Charlottenlund Slot, Jægersborg Allé 1, 2920 Charlottenlund.

Programming. The ***R*** (and ***S+***) analysis and programming were carried out by (Computer scientist) S. Rodríguez <silvia.rguez@gmail.com>.

Data sources. West Greenland Halibut surveys and population series: Greenland Institute of Natural Resources (**GINR**). Environmental and satellite: **PODAAC, NOAA, US NAVY, GEBCO. Google** and **USGS** (Landsat image). Data belongs to their respective owners and the terms and conditions of use are set forth by the original sources.

On the present report. The material presented herein is part of on-going work for which it is *not to be cited* without prior authorization from the authors. The ground material presented under the section "Multi-Oscillatory System Approach" was put forward -as per request of the EU, Goverment of Mauritania and European stakeholders- at the Long Distance Fleet Regional Advisory Council (LDRAC; October, 2011 and January, 2012), the Scientific, Technical and Economic Committee for Fisheries (STECF; April, 2012) and European-Mauritanian Scientific Committee for Fisheries (November, 2011 and April 2013) meetings. Part of this approach was developed within the frameworks of the EU (ISTAM, EUROCEANS), FAO/Fisheries and international/national projects and concerted actions at the University of Las Palmas, Spanish Oceanography Institute (IEO) and the Greenland Institute of Natural Resources (GINR).

Some of the text for the captions described under the Environmental Forcing section may be, in part, repetitive in order to facilitate the reading.

☐ END OF SECTION ■

R/V Paamiut, Trip 2, 2013. Davis Strait.

¤ *L*ist of *C*ontents. [pp]

¤ 1. ***S***ummary *and* ***K***ey words.

Summary.

The dynamics of the West Greenland Halibut (WGH, *Reinhardtius hippoglossoides*) is studied. Abundance, Biomass and Mean Catch Per Tow, MCPT (years 1997-2011) and Age class 1 (years 1991-2011) are analysed in relation to the winter (December-March) North Atlantic Oscillation (NAO) and monthly Optimum Interpolated Sea Surface Temperature (SST, years 1982-2013) sampled for the area (Lat. 62.5-64.5º N and Long. 55.5-57.5 º W) of the Age class-0 pelagic drift. Environmental variables (External Forcing) were aggregated to a temporal resolution of a yearly mean, maximum, minimum and Standard Deviation, SD. All data was log transformed and standardized.

It is both observed and suggested that:

Environmental forcing (EF): (i) The population variables were significantly correlated ($p<0.05$); MCPT was selected for further analysis as it may be regarded as a proxy for both abundance and catch/effort/area; (ii) NAO and SST means and minima (N=33) were inversely correlated ($p<.05$) indicating that positive and negative winter NAO values may imply colder and warmer surface/mixing layer (winter) conditions, respectively: it is considered that this mesoscalar mechanism may have an impact on the juvenile halibut pelagic drift area implying a relatively higher survival rate of Age class 1 during negative NAO (milder winters) and (iii) Correlation between SST_{SD} and MCPT lagged 6 years was significant ($p<0.05$), being the inverse of one another from which it is suggested that (c1) the SST oscillations around the mean may be a key factor affecting Age class 1 strength (lagged 1 year) and subsequently overall Abundance six years after (biased by recruitment at Age 6); (iv) we may expect floor and ceiling values in abundance in 2014/2018 and 2017, respectively and (v) the positive and negative trends and amplitudes determined by the peak values may be useful to propose a range of sustainable catches adapted to the variable carrying capacity of the environment (as reflected by the SST variation and other system wide external variables contributing to the forcing such as upwelling strength and overlapping between primary production and halibut Age class 1 drift); (vi) A multi resolution decomposition (MRD) wavelet analysis on the SST minima and Age class 1 series showed the signals are the inverse of one another as a one year lag is considered and periodicities of approximately 10 years cycles (5 in each compensatory or depensatory phase) were detected.

Multi-oscillatory System Approach (MOSA): (i) Correlations were significant ($p<0.05$) between both Age class 1, Abundance and Mean Catch Per Tow (MCPT). It is assumed that Abundance can be biased by Age class 6 (recruits); (ii) The phase plane between age class 1 and Abundance (lagged 5 years, $p<0.05$) showed two orbits of stability for which two singular points on equilibrium values were detected by non-linear (locally weighted) fitting. Although Age class 1 series can be relatively noisy, Abundance can be estimated assuming the appropriate lags; (iii) A Multi-oscillatory System Approach (MOSA) is proposed for the halibut dynamics: in this framework, recruitment (*R*) to the population, area and fishery, production per Spawning Stock Biomass (*R/SSB*) and Abundance are considered as a system or summation of non-linear functions with dynamic features ranging from chaos (the ceiling, when external conditions are extremely benign), going through a range of relatively stable, converging cycles (as external stress increases), to a quasi-standstill state with no clear oscillations (when the minimum viable population is being approached) which may lead to inverse density-dependence (extinction of the commercial fishery). This approach is considered as highly flexible as it has the capacity to, persistently, evolve and return within a wide range of equilibrium states determined by the external forcing (combined effects from the environment and fishing mortality), allowing for stable, periodic and chaotic dynamics. The framework formalises concepts such as variable carrying capacity, dynamical continuum, orbits of stability (cycles or pseudo-cycles), linked equilibria, ceilings and floors, density dependent and density-independent compensation/s and depensation/s, interdependencies and lags with system wide external variables and -among other factors- the combined effects from the environment and (differential effects of) fishing mortality at the population, cluster and community levels.

A Bayesian/Monte Carlo Markov Chain test run is carried out with the logistic equation modified with an EF (SST variation around the mean) term: results showed a convergence with estimations from the MOSA framework.

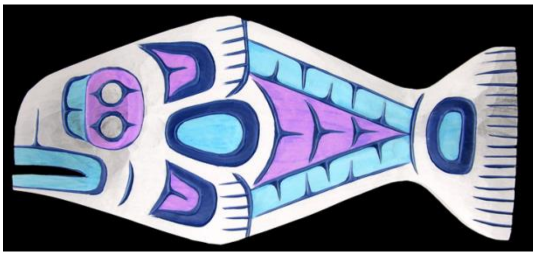
An explanation on why classical models (logistic equation and derivatives) were a key reason for the inability to detect lags and dependencies is given.

Also, the following concepts are discussed: general issues; environmental forcing; population speed changes (as function of the EF); signal, noise, variability and residuals; the MOSA; variable carrying capacity (ceilings, K_i); minimum populations (floors, $K0_i$); dynamical continuum; differential effects of fishing mortality; multiple (stable) equilibria and pseudo-equilibria; fishing in multiple-equilibrium systems; extinction of the commercial fishery; case studies to support the MOSA; the Bayesian framework.

Finally, issues concerning future work are proposed concerning the fusion of the MOSA-Bayesian/MCMC in order to improve our knowledge on the WGH and sustaiability of the stocks.

Key words. *West Greenland, halibut, dynamics, multi-oscillatory, system, orbits, environmental forcing, variable carrying capacity,* $MSY_{K/2}$*, bayesian.*

□ END OF SECTION ■



¤ *I*ntroduction.

¤ 2. *I*ntroduction.

There is an incresing body of evidence suggesting that population dynamics are complex processes characterised by dependencies and strong correlations, lags, feed-back mechanisms, and -among other factors- speed changes in population growth due to the combied effects from the variable carrying capacity of the environment (environmental forcing) and differential responses to fishing mortality regimes.

In Solari et al. (2010), we observed that the study of fish population dynamics for fisheries management advice began at the end of the 19th century (Petersen, 1896). The increasing body of observational evidence led several of the pioneers in fishery science (Petersen, 1896; Hjort, 1913; Hjort, 1926; Graham, 1935; Russel, 1939; Iselin, 1938; Iselin, 1940; Rollefsen, 1948, among others) to propose the linkages (of cause and effect) between the physical world and ecological responses (in small pelagic and demersal fish, birds and marine mammal species) such as fecundity, rates of growth, size/age-at-maturity, recruitment, abundance and catches as multi-oscillatory/multi-periodic (density-independent and density-dependent) processes which occur at different spatio-temporal scales. During the first half of the century, under the auspices of the International Council for the Exploration of the Sea (ICES), there were intense debates on the ecological theory of fish population regulation and recruitment was identified as a key factor controlling fishery yield fluctuations (Hjort, 1914; Hjort, 1926; Russel, 1939; Graham, 1935). Also, several of the recent authors (to name a few: Barange et al., 2009; Chavez et al., 2003; Schwartzlose et al., 1999; Hsieh et al., 2009; Machu et al., 2009; Relvas et al., 2009; Borges et al., 2003) have suggested possible links between stocks/populations and the environmental forcing (for instance, upwelling intensity and climatic variability) and, also, the difficulty to apply traditional ("classical") population approaches (logistic equation and derivatives) which are based on both a single equilibrium and an invariant carrying capacity.

The classical approaches excluded dynamical features critical to understand the mechanics behind the data (linking and transition mechanisms between steady states, system behaviour, extinction of the commercial fishery, environmental interactions, among other factors) and were highly restrictive as they assumed that (i) populations under exploitation would respond in a compensatory way to fishing under all conditions, numbers, fishing mortality and environmental perturbations; (ii) during the temporal evolution of the SR system (over forty years for many of the available population series), a single equilibrium was assumed; (iii) an invariant carrying capacity although the environment generally follows an ever changing transition scheme; (iv) the weight of all of the data points would be the same (temporal evolution and dependencies within and between variables were ignored) and (v) residuals were assumed to be the result of a random process. It is clear that, a best statistical fit under those assumptions will both perform poorly and be unable to explain a major part of the variability in the data and mechanics from a complex, multivariate, dynamical system (Solari, 2008).

Furthermore, McAllister and G. P. Kirkwood (1998) reviewed the conceptual basis for Bayesian statistical estimation in the context of both fisheries stock assessment and management: one of the advantages of the Bayesian approach (using random sampling to iterate and converge numerical results) is that it permits the consideration of structurally different models as alternative hypotheses and account for uncertainties.

2.1. Aims of the present study.

The fundamental aims of the present study were to (i) determine whether we may find indications of an environmental forcing on West Greenland halibut dynamics; (ii) analyse the results in light of classical and alternative population models; (iii) develop a Bayesian approach which may take into consideration memories (>1 year), appropriate lags and responses to a set of system wide independent variables and (iv) propose further improvements on both the deterministic and probabilistic frameworks. The ulterior aims of this line of work are to improve our knowledge on halibut dynamics in order to contribute to advances both in the fields of sustainability/biological conservation and fisheries management. Finally, is is intended that argumentation, results, inference and modelling approaches should be expressed in terms that comply with the requirements of the scientific and civil (non-mathematically oriented) communities.

2.2. Data.

The following data was used in the present study, namely: (a) Landsat image (after Google and US Geological Survey, 2013); (b) Monthly winter (December-March) means of the North Atlantic Oscillation (NAO) index (N=64 years*4 months= 256), after NOAA (2013); (c) Monthly mean (Optimum Interpolated) SST (^{o}C, N=381 months, November 1981-August 2013), after IGOSS (2013) on part of the halibut juvenile mixing layer drift area within Lat. 62.5-64.5º N and Long. 55.5-57.5 º W; (d) Biomass (10^3 Tn), Abundance ($N=10^6$) and Mean Catch Per Tow (MCPT, Tn/Km^2), years , 1997-2011 (N=15), after Jørgensen (2012) and (e) age class 1 (M, N=21), years 1991-2011 (totals from both Disko bay and West Greenland off-shore substocks), GINR (2013). In several of the analysis throughout the study, we chose to use MCPT as it is a proxy both for Abundance with a spatio-temporal component (i.e. time series with a quantitative measure of catch per unit area) and Catch Per Effort (CPE), as well.

2.3. Methods.

We log transformed the data (Log) to meet conditions for statistical normality. Furthermore, we worked on standardized data (Z; with mean = zero) as we were interested in maxima and minima, variations or dispersion around the means (SD), as well as general (linear and non-linear) and local trends (slopes, steepness, amplitudes and time length of the local trends), and to facilitate visual comparison.

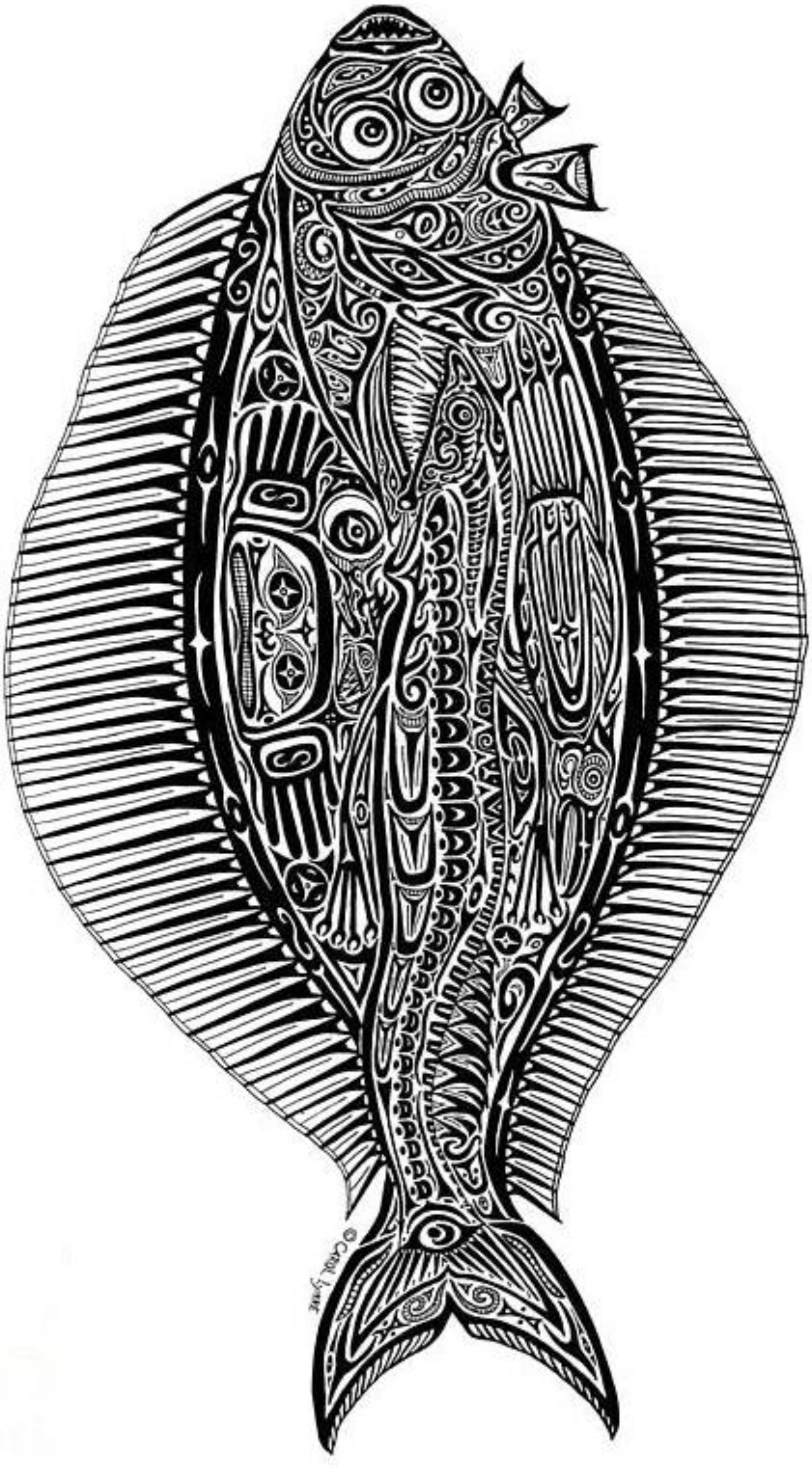
We used statistical tests which may give us indications on whether there are periodicities, lags, dependencies and persistency or memory effect in the series (auto- and cross correlations, the Hurst exponent and Multi-Resolution Decomposition (MRD) wavelet analysis - which splits up the signals in different frequencies, identifies cyclic patterns in different frequencies and has a higher resolution than Spectral analysis).

Also, we used the Hurst (H) exponent (after Hurst, 1951; Auto Signal, 2002) to determine whether the series differed from a random walk and as a quantitative measure of the underlying trends (persistence or memory): while values of H = 0.5 correspond to Gaussian or true white noise (i.e. the observations are independent from preceding values), those approaching (or higher than) 0.75 will reflect a persistency or memory effect (each data value is related to some number of preceding values) in the time series.

Moreover, while we are interested in both outliers and the conditions which may cause both ceilings and floors in the temporal evolution of numbers, noise reduction may be a key factor for both curve fitting and modelling population processes: to both smooth (de-noise) and determine whether trends remain in the series, we used (i) simple regressions, either as an indicator of general equilibrium values (in which the fitted system or relationship does neither grow nor decrease) or to determine the "replacement line" (i.e. the abundance or recruitment needed to replace the stock); (ii) cubic splines (for interpolation) and Locally Weighted Scatterplot Smoothing (LOWESS) and (iii) Distance-Weighted Least Squares (DWLS) to determine the equilibrium (singular) cut points which show the boundaries of the periodic oscillations and continuous fitting of different orbits of stability (i.e. cycles) and (iv) second degree fittings are used for approximating models which are derived from the logistic equation. Furthermore, we used to plot the phase planes and trajectories (determined by a cublic spline) in order further analyse and fit orbits of stability (cycles) with their singular points, ceilings (variable carrying capacities), floors (minimum viable population values), K/2 and $MSY_{K/2}$.

☐ END OF SECTION ■

¤ *E*nvironmental *f*orcing.



¤ 3. *E*nvironmental *f*orcing.

The availability of in-situ environmental time series for the WGH is limited due to habitat, depth ranges and technical factors. However, it was assumed that the environmental forcing may affect Age class 1 within the pelagic drift area, a process which will bias Abundance (lagged 6 years, which is the expected time for recruitment to the population). Besides the population series, we chose to work on environmental proxies which are known as meso-scalar, system wide variables which may affect dynamics in the mixing layer, that is: the NAO and SST. A summary of results follow below[1]:

In Fig. 3.1, we show a representation of the sub-area of juvenile halibut pelagic drift (N1-N2 is Lat. 64.5-62.5º N, W1-W2 is Long. 55.5-57.5º W) selected for sampling monthly mean SST.

In Fig. 3.2, we show the standardized (Z), log transformed (Log) monthly means (aggregated per year) of the (i) winter (December-March) North Atlantic Oscillation (NAO) index (N=128) and (ii) (Optimum Interpolated) Sea Surface Temperature (SST, ^{o}C, N=384) series between years 1982-2013, sampled from part (Lat. 62.5-64.5º N, Long. 55.5-57.5 º W) of the halibut juvenile pelagic drift area. Series were smoothed by cubic splines and Locally Weighted Scatterplot *S*moothing *(*LOWESS) and correlation was highly significant ($p<.05$). Even correlations between Log NAO means and minima were (negatively) correlated to SST minima at the same significance level. It is suggested that the series may be the inverse of one another. Also, positive and negative winter NAO values may imply colder and warmer surface/mixing layer (winter) conditions, respectively: it is considered that this mesoscalar mechanism may have an impact on the juvenile halibut pelagic drift area implying a relatively higher survival rate of Age class 1 during negative NAO periods (milder winters).

[1] Some of the text in the descriptios of the captions is repetitive in order to facilitate the reading.

In Fig. 3.3, we show the log transformed (Log) Sea Surface Temperature (SST, ^oC) variation (Standard Deviation, SD, dashed line) and mean (continuous line) series between years 1982-2013 for the halibut juvenile pelagic drift area within (Lat. 62.5-64.5º N, Long. 55.5-57.5 º W). Series were smoothed by cubic splines (dashed lines) and Locally Weighted Scatterplot *S*moothing *(*LOWESS, dotted lines). Means and variations around the mean may show different (opposite) general and local trends. Such variations can be the signal to which the WGH population (through Age class 1) may respond to. Even correlations between SST means and maxima and minima were significant ($p<0.05$).

In Fig. 3.4, the log transformed (Log) pupulation series are depicted: Biomass (10^3 Tn), Abundance ($N=10^6$) and Mean Catch Per Tow (MCPT, Tn/Km^2) for years 1997-2011 (N=15, interpolated by a cubic spline). Correlations were significant ($p<0.05$) and we chose MCPT for further work as it is an abundance proxy which incorporates both catch per effort and spatial components.

In Fig. 3.5, the log transformed (Log) Age class 1 ($N*10^6$) series are depicted for years 1991-2011: totals (continuous line) from both Disko bay (pointed line) and West Greenland off-shore (dashed line) substocks, N=21). Series were smoothed by cubic splines and a Locally Weighted Scatterplot *S*moothing *(*LOWESS).

In Fig. 3.6, we show the standardized (Z) log transformed (Log) Sea Surface Temperature (SST, ^oC) variation (Standard Deviation, SD, dashed line) for a sub-area (Lat. 62.5-64.5º N, Long. 55.5-57.5º W) of the halibut juvenile pelagic drift and the Mean Catch Per Tow (MCPT, Tn/Km^2) series (lag=6) for years 1997-2011 (N=15), interpolated by cubic splines and smoothed by Locally Weighted Scatterplot *S*moothing *(*LOWESS, dotted lines). It is suggested that recruitment (at age class 6) and abundance in WGH respond as the inverse to SST variations around the mean ($p< 0.05$) within the pelagic drift area: if this inference is correct, we may expect floor and ceiling values in abundance in 2014/2018 and 2017, respectively (indicated by the arrows). The general (linear) and local (non-linear) positive and negative trends and amplitudes determined by the peak values may be useful to propose a range of sustainable catches adapted to the variable carrying capacity of the environment.

In Fig. 3.7, we show the standardized (Z) and log transformed (Log) Age class 1 (lagged 1 year) from the West Greenland halibut stock (years 1991-2011; totals from both Disko bay and off-shore substocks, after GINR, 2013) and Sea Surface Temperature (SST_{SD}) dispersion around the mean (after IGOSS, 2013) series, interpolated and smoothed by cubic splines (thiner lines) and Locally Weighted Scatterplot *S*moothing *(*LOWESS; thicker lines), respectively. In order to determine the relatively noise Age class 1 series could be correlated to SST, the series were processed by the T4253H Smoothing Function (thicker dotted line) showing correlations ($p<0.05$) to both the SST variation around the mean and minima. While the smoothing can be understood as a way to force the significance of the correlation (inflation of the memory effect onto the series), it may also give us an indication of a negative correlation or sensibility for both of the external variables.

In Fig. 3.8, we depict the Multi Resolution Decomposition (MRD, S-8) wavelet analysis on the standardized, log transformed Sea Surface Temperature (SST) minima (upper caption) and Age class 1 from the West Greenland halibut stock (years 1991-2011, totals from both the Disko bay and off-shore substocks. The continuous and dashed lines indicate the peaks for both the sum of signals, 8-years process (D1, D2) and smoothed low frequency (S2) process. The signals appear to be the inverse of one another as a one year lag is considered and periodicities of approximately 10 years cycles (5 in each compensatory and depensatory phase).

The Hurst (H) exponent (value between parenthesis) showed the following results: NAO maxima (0.75) and minima (0.89); SST SD (0.7), maxima (0.87) and minima (0.9); Age class 1 offshore (0.93) and Disko Bay (0.88). All of these H values ($H \geq 0.75$, $H_{max}=1$) showed clearly that (i) the variables differed signficantly from a random walk (for which $H \leq 0.5$) and (ii) there is a relatively strong memory or persistence in the series implying that none of these variables can be considered as random. Furthermore, while there were not sufficient degrees of freedom for the H test in the population series (Biomass, abundance and MCPT, N=15), the Age class 1 (N=21) series -which are often noisy- showed a high value of H. Similar results are expected for the population variables in as the degrees of freedom of the series increase. The persistence in the series validates further the assumption that processes such as recruitment strongly depend on environmental pulses/oscillations which drive changes in population growth.

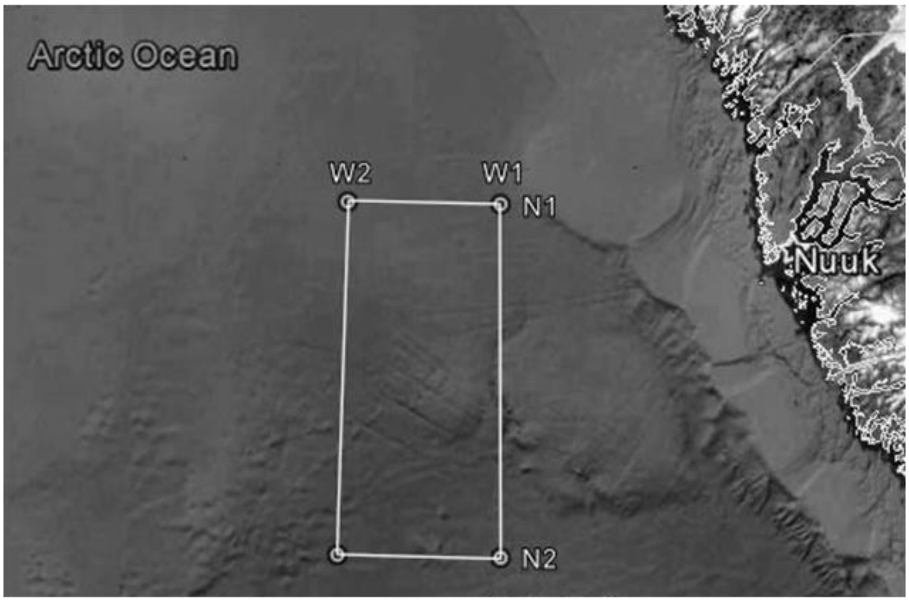


Figure 3.1. Sub-area of juvenile halibut pelagic drift (N1-N2 is Lat. 64.5-62.5º N, W1-W2 is Long. 55.5-57.5º W) selected for sampling monthly mean (Optimum Interpolated) Sea Surface Temperature (SST, ^{o}C, N=384) between years 1982-2013. Landsat image after Google and US Geological Survey (2013).

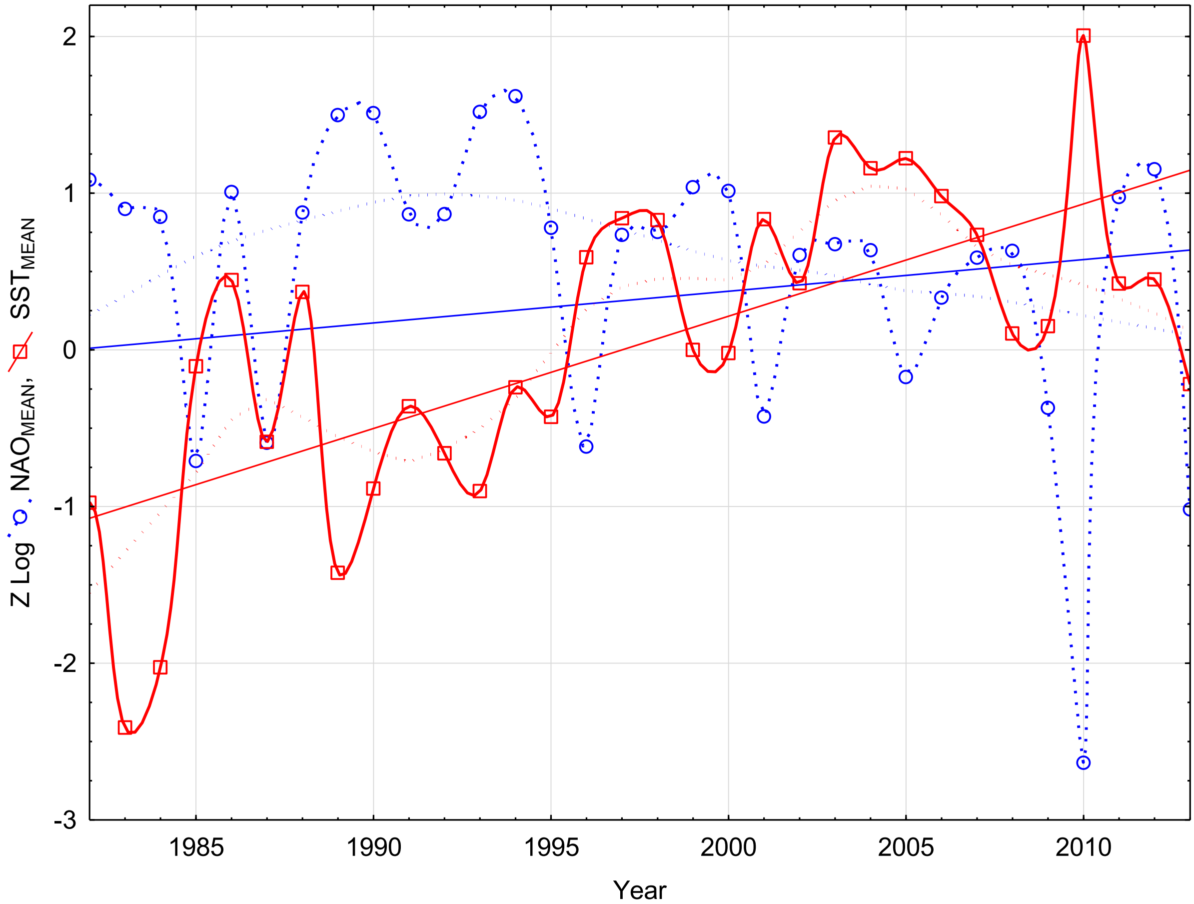


Figure 3.2. Standardized (Z), log transformed (Log) monthly means (aggregated per year) of (a) winter (December-March) North Atlantic Oscillation (NAO) index (N=128), after NOAA (2013) and (b) Optimum Interpolated Sea Surface Temperature (SST, ^{o}C, N=384), after IGOSS (2013) between years 1982-2013 from part of the halibut juvenile pelagic drift area within Lat. 62.5-64.5º N and Long. 55.5-57.5 º W. Series were smoothed by cubic splines and Locally Weighted Scatterplot Smoothing (LOWESS) and correlation was highly significant ($p<.05$). Even correlations between Log NAO means and minima were (negatively) correlated to SST minima at the same significance level. It is suggested that the series may be the inverse of one another.

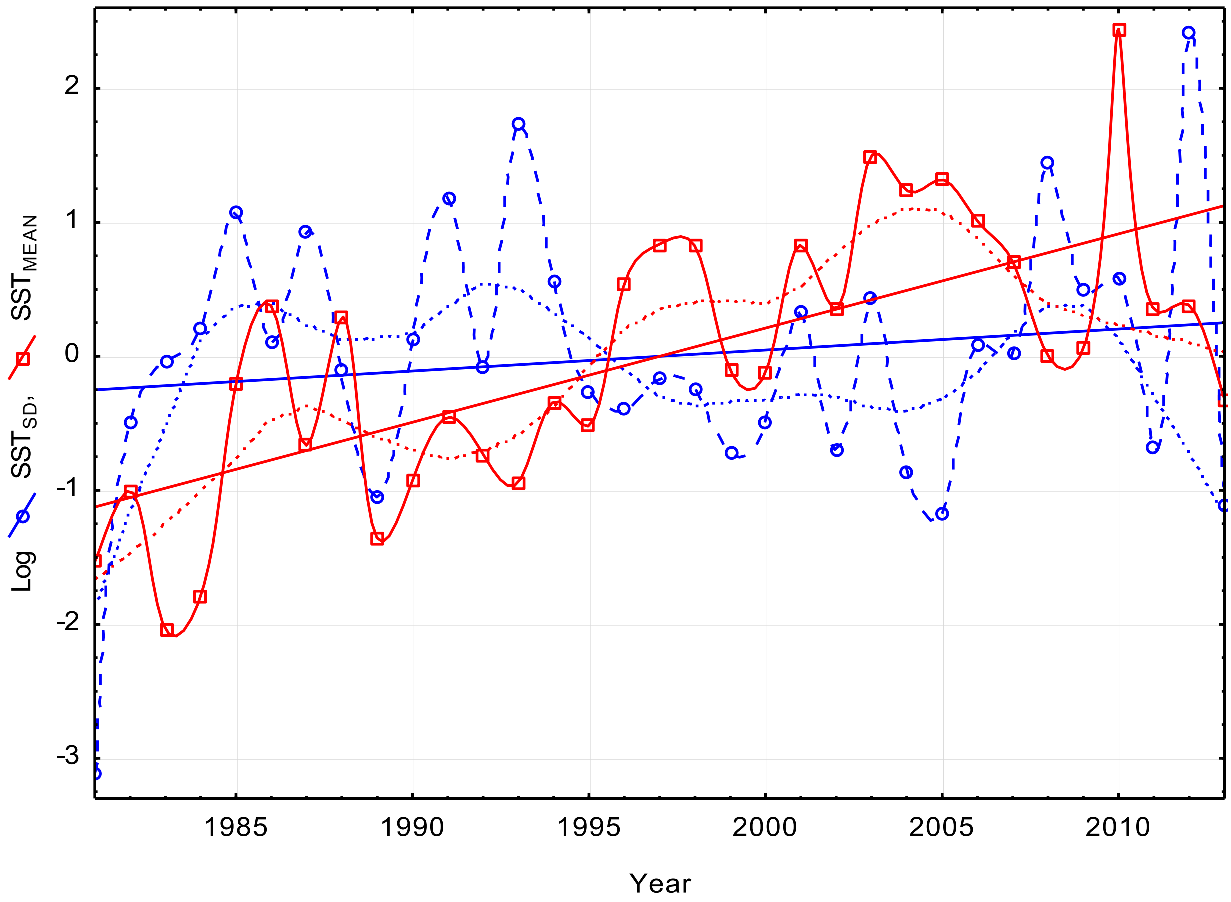


Figure 3.3. The log transformed (Log) Sea Surface Temperature (SST, ^{o}C) variation (Standard Deviation, SD, dashed line) and mean (continuous line) series between years 1982-2013 (after IGOSS, 2013) for the halibut juvenile pelagic drift area within Lat. 62.5-64.5^{o} N and Long. 55.5-57.5^{o} W. Considering a lag = 6, it is suggested that recruitment in West Greenland halibut (at age class 6) responds to SST variations around the mean within the pelagic drift area ($p < 0.05$). Series were smoothed by cubic splines and Locally Weighted Scatterplot Smoothing (LOWESS).

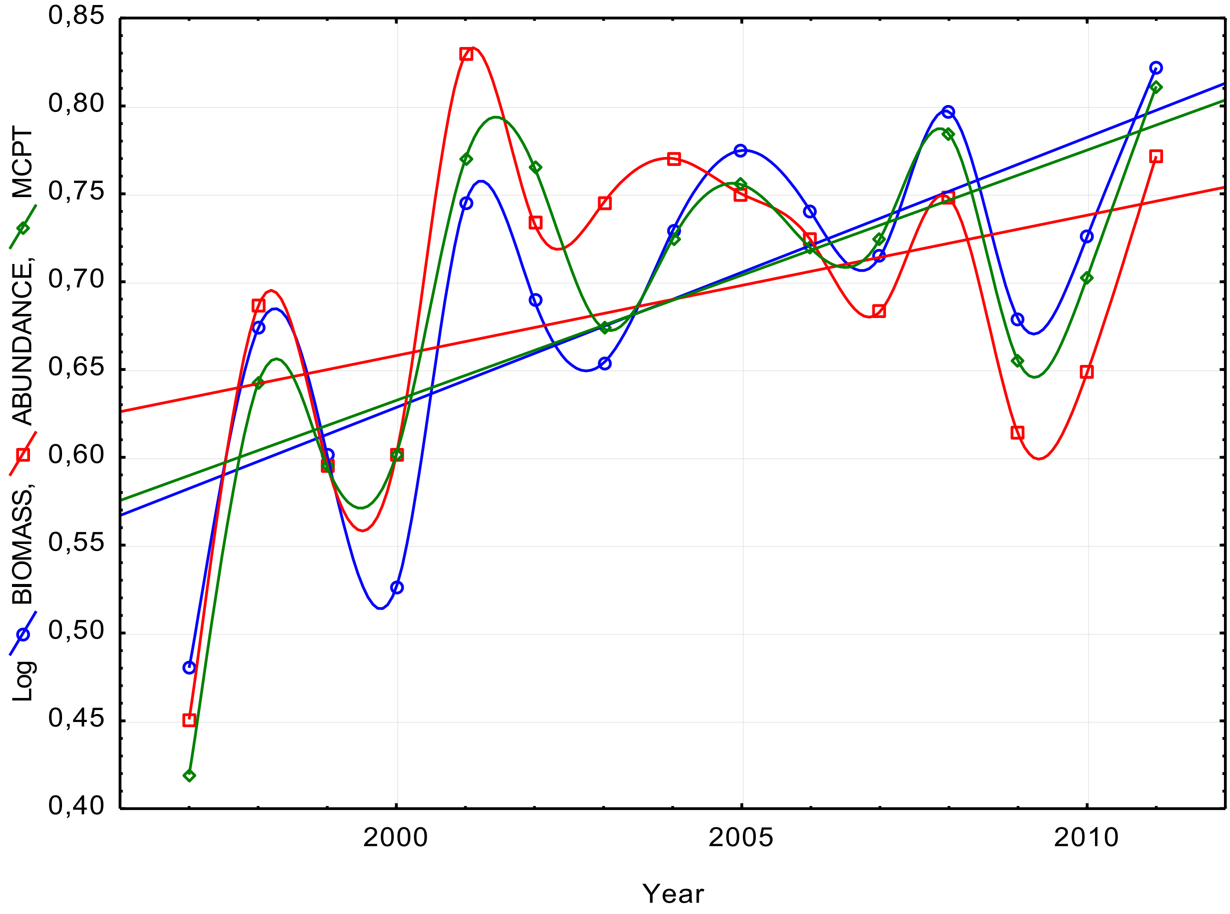


Figure 3.4. The log transformed (Log) Biomass (10^3 Tn), Abundance ($N=10^6$) and Mean Catch Per Tow (MCPT, Tn/Km^2) series for years 1997-2011 ($N=15$, interpolated by a cubic spline), after Jørgensen (2012) and GINR (2013). Series were correlated ($p<0.05$).

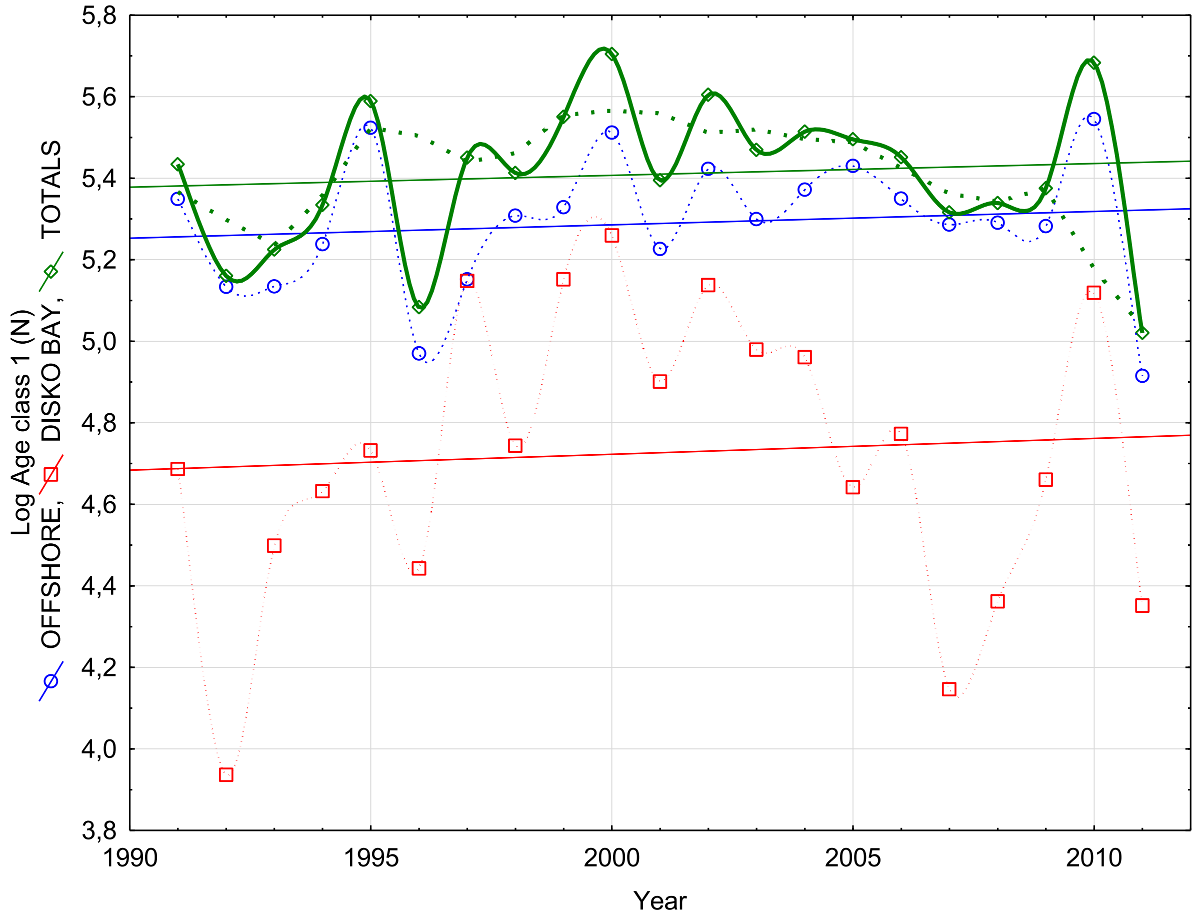


Figure 3.5. The log transformed (Log) Age class 1 ($N*10^6$), years 1991-2011, totals (continuous line) from both Disko bay (pointed line) and West Greenland off-shore (dashed line) substocks, N_{years}=21), after GINR (2013). Series were smoothed by cubic splines and a Locally Weighted Scatterplot Smoothing (LOWESS).

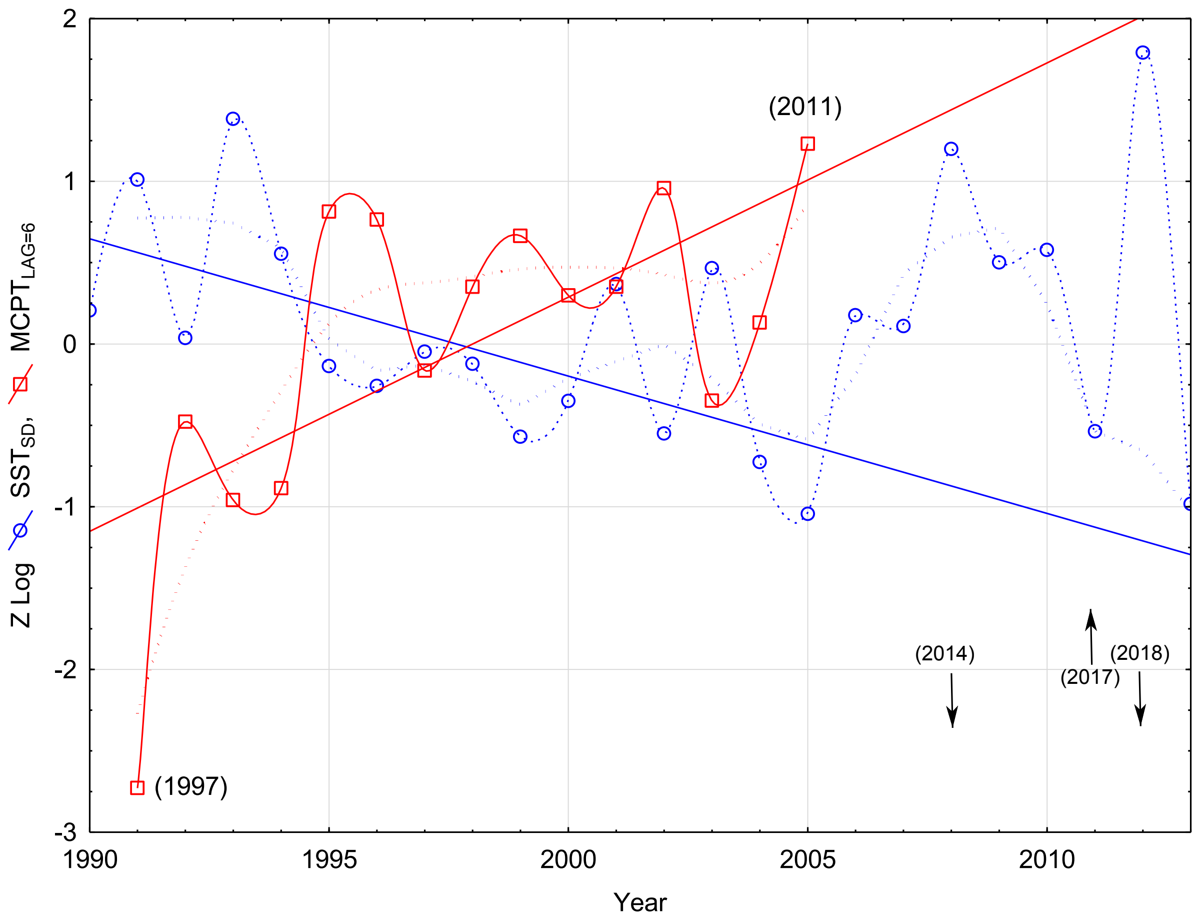


Figure 3.6. The standardized (Z) log transformed (Log) Sea Surface Temperature (SST, °C) variation (Standard Deviation, SD, dashed line), after IGOSS (2013) for the halibut juvenile pelagic drift area within Lat. 62.5-64.5° N and Long. 55.5-57.5 ° W and Mean Catch Per Tow (MCPT, Tn/Km^2) series, after Jørgensen (2012) and GINR (2013), with lag = 6 for years 1997-2011 (N=15), interpolated by cubic splines and smoothed by Locally Weighted Scatterplot *S*moothing *(*LOWESS, dotted lines). It is suggested that recruitment (at age class 6) and abundance in West Greenland halibut respond as the inverse to SST variations around the mean ($p < 0.05$) within the pelagic drift area. If the above assumption (i.e. "SST_{SD} is a the inverse of recruitment with lag=6") is correct, we may expect floor and ceiling values in abundance in 2014/2018 and 2017, respectively (indicated by the arrows). The positive and negative trends and amplitudes determined by the peak values may be useful to propose a range of sustainable catches adapted to the variable carrying capacity of the environment.

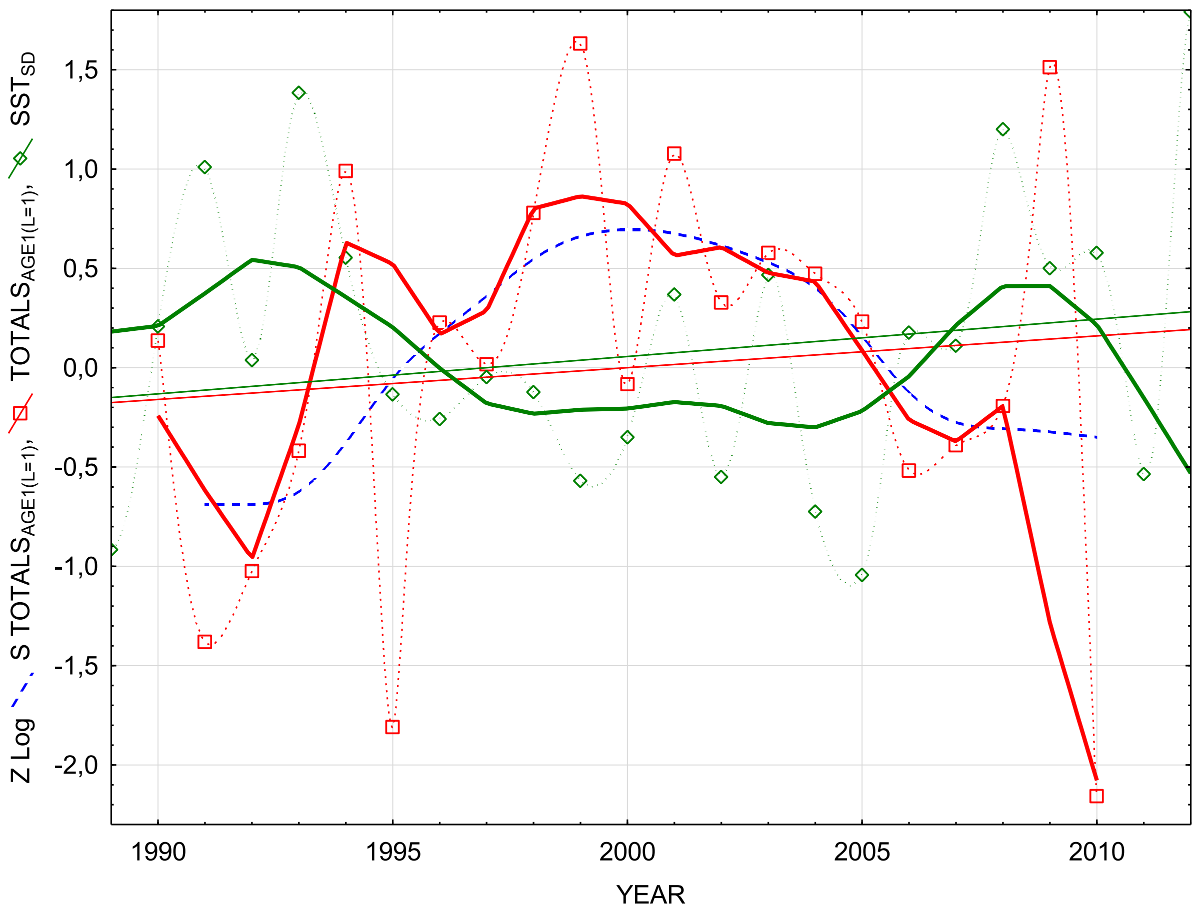


Figure 3.7. The standardized (Z) and log transformed (Log) Age class 1 (lagged (L) 1 year) from the West Greenland halibut stock (years 1991-2011; totals from both Disko bay and off-shore substocks, after GINR, 2013) and Sea Surface Temperature (SST_{SD}) dispersion around the mean (after IGOSS, 2013) series, interpolated and smoothed by cubic splines (thiner lines) and Locally Weighted Scatterplot Smoothing *(*LOWESS; thicker lines), respectively. In order to determine the relatively noise Age class 1 series could be correlated to SST, the series were processed by the T4253H Smoothing Function (thicker dotted line) showing correlations ($p<0.05$) to both the SST variation around the mean and minima. While the smoothing can be understood as a way to force the significance of the correlation (inflation of the memory effect in the series), it may also give us an indication of a negative correlation or sensibility for the external variables.

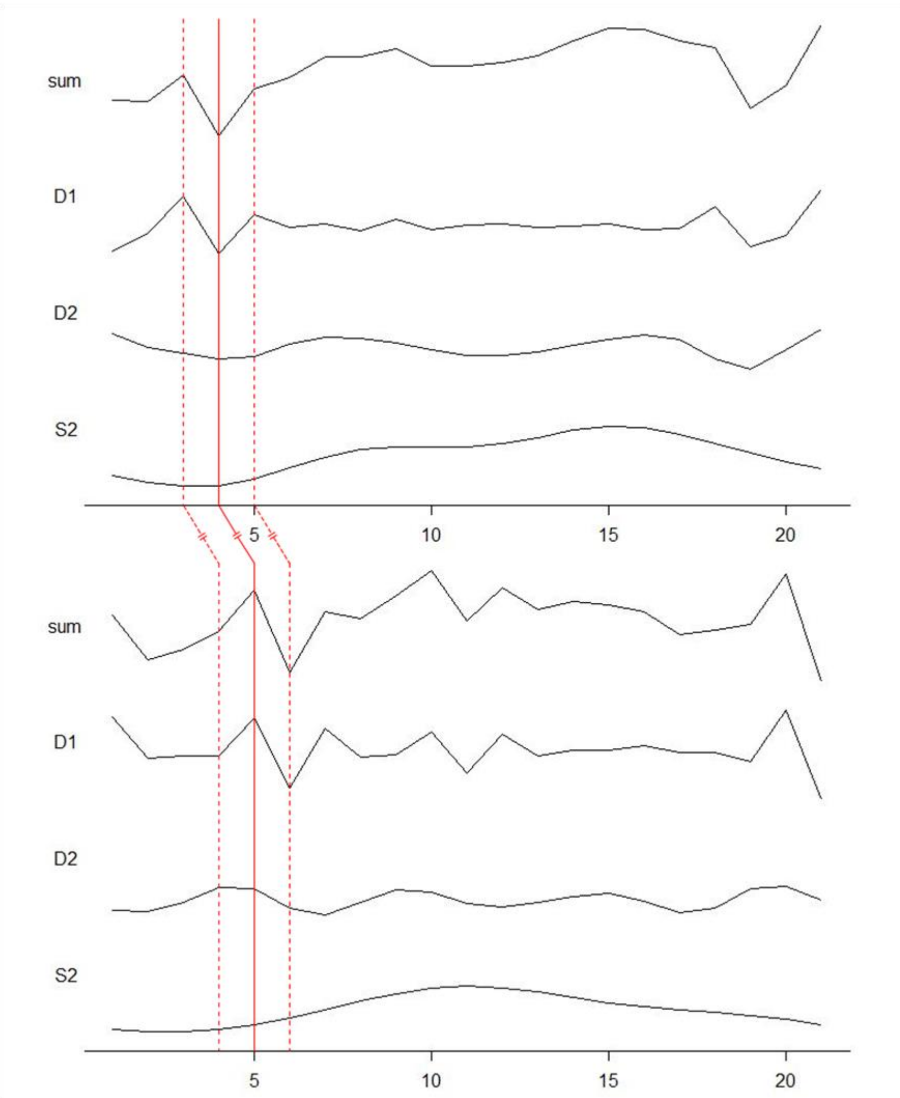
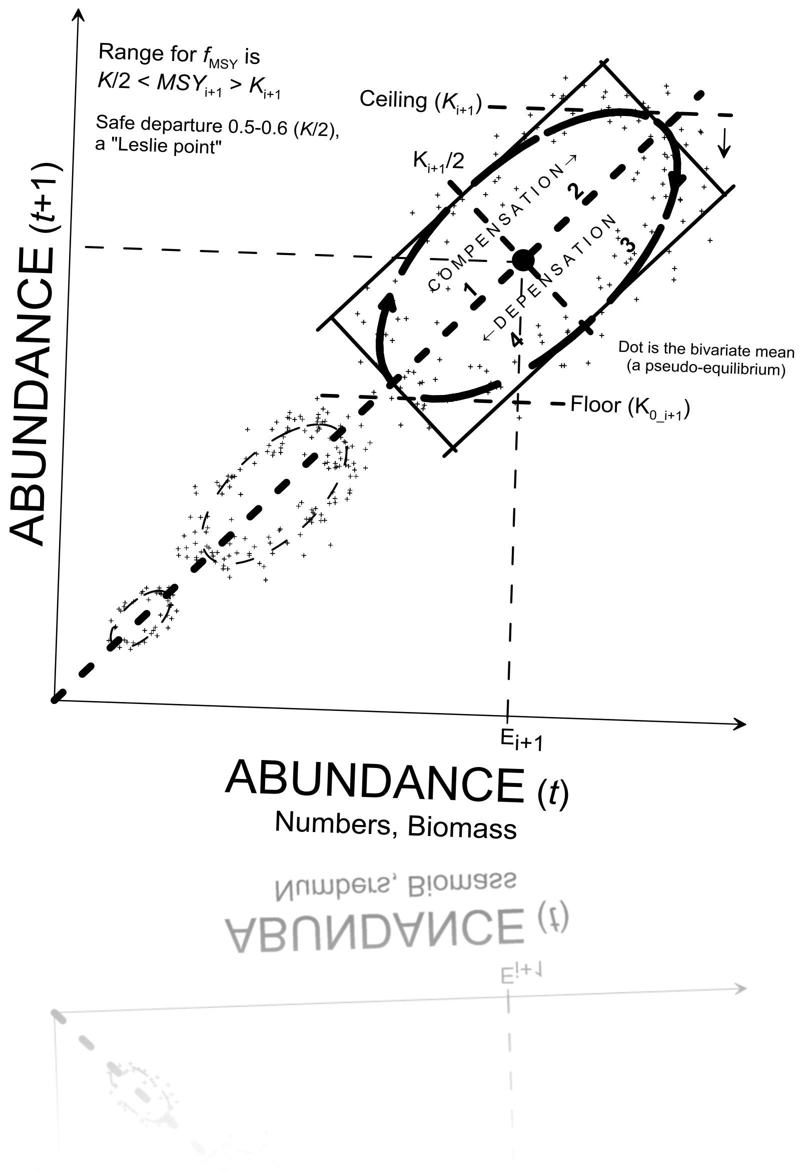


Figure 3.8. Multi resolution decomposition (MRD) S-8 wavelet analysis (S+, 2006) on the standardized, log transformed Sea Surface Temperature (SST) minima (upper caption) and Age class 1 from the West Greenland halibut stock (years 1991-2011, totals from both the Disko bay and off-shore substocks; after GINR, 2013). The continuous and dashed lines indicate the peaks for both the sum of signals, 8-years process (D1, D2) and smoothed low frequency (S2) process. The signals appear to be the inverse of one another as a one year lag is considered and periodicities of approximately 10 years cycles (5 in each compensatory or depensatory phase).

☐ END OF SECTION ■

¤ ***M***ulti ***O***scillatory ***S***ystem ***A***pproach.



¤ 4. ***M***ulti ***O***scillatory ***S***ystem ***A***pproach.

In previous papers by Solari et al. (1997), Bas et al. (1999), Martin et al. (1998) and Solari et al. (2003, 2008 a-c, 2010, 2011, 2012 a-b, 2013), we proposed recruitment both to the population (influx of juveniles to the adult population), area (migration of cohorts/individuals into fishery areas) and fishery (dynamics of the fishery) as a system or summation of non-linear functions (multiple orbits of stability or equilibrium states) with dynamic features ranging from chaos (when external conditions are extremely benign), going through a range of relatively stable, converging cycles (as external stress increases) to a standstill state with no clear oscillations (when the minimum viable population is being approached): the system was suggested to have the capacity to, persistently, evolve and return within a wide range of equilibrium states allowing for multiple carrying capacities as well as density-dependent (compensation and depensation due to population numbers), density-independent (compensation and depensation due to environmental fluctuations and fisheries) and inverse-density-dependent (per capita reproductive success and recruitment declines at low population levels) coupled mechanics. A graphical representation of the model is shown in Fig. 4.1. In general terms, the MOSA is a framework based on a General Additive Model (GAM) and a difference delayed (non-linear) equation, it is open for incorporation of new terms and assumes the following: (i) discrete orbits of stability which are linked by a dynamical continuum (linear and non-linear fittings), (ii) a variable carrying capacity (K_i) or ceiling (a critical threshold between different equilibrium states) and a minimum viable population ($K0_i$) or floor, both of which are particular for each orbit; (iii) compensatory (positive growth) and depensatory (negative growth) phases both density-dependent and density-independent; (iv) differential intrinsic rates of increase ($a_{1\ \dots\ 4}$) within (and between) orbits, each of which starts operating at slope = 0 (as the trajectory approaches K_i and $K0_i$) and inflection points (as the trajectory reaches maximum slopes, K/2 and D/2); (v) differential Catch Per Unit Effort ($CPUE_i$), Maximum Surplus Yield (MSY_i) and effects of fishing mortality (F_i).

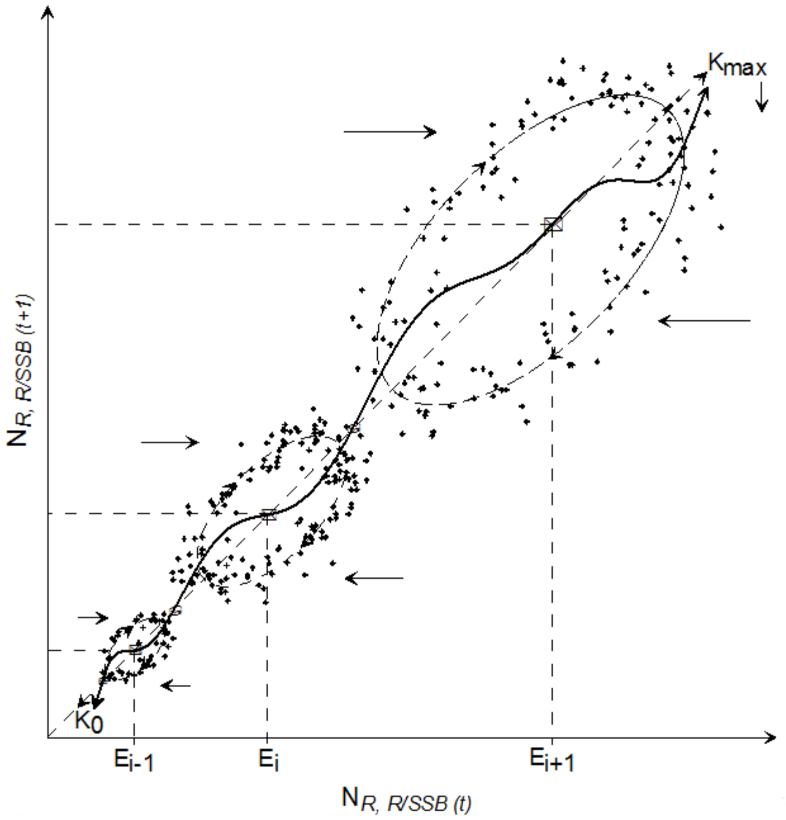


Figure 4.1. A graphical representation of the Multi-Oscillatory System Approach (MOSA), after Solari et al. (1997) and derivative studies propose recruitment (*R*) to the population, area and fishery and production per Spawning Stock Biomass (*R/SSB*) as a system or summation of non-linear functions allowing for stable, periodic and chaotic dynamics. The framework proposes concepts such as variable carrying capacity, ceilings and floors, density dependent and density-independent compensation/s and depensation/s, interdependencies and lags with system wide external variables and -among other factors- the combined effects from both the environmental forcing and differential effects of fishing mortality. The dynamical continuum (represented by the non-linear fit and overall linear equilibrium values) consist of several orbits of stability with corresponding “steady states” (E_i), maximum carrying capacity (K_{max}) and minimum viable population (K_0). Also, every orbit will be limited by a local ceiling (K_i) and floor (K_{0i}). Arrows indicate positive (→) and negative (←) growth. The MOSA framework (validated on small and medium pelagics, demersals, tunas, sharks) is useful to estimate abundance in the short term (4-8 years) and propose sustainable fishing strategies adapted to a changing environment and past exploitation levels.

Our dynamical framework was justifiable on an ad hoc basis because of the flexibility it afforded. Also, it offered some conceptual advantages over classical approaches (logistic equation and derivatives) as it allowed for (i) multiple equilibria or discrete, relatively stable phase states, independent but linked to each other (no mathematical interdependence between the functions due to the additive nature of the approach), (ii) either higher or lower equilibria could be incorporated into the system, (iii) transitions between equilibria due to density-dependent and density-independent oscillations could be linked and, among other features, (iv) several maxima and minima and depensatory dynamics could be described in the same relationship, allowing for simultaneous equilibrium states and dynamical similarity, at different spatio-temporal scales and substocks/local populations. All of these features may vary, depending on the particular case for each stock and, as we see it, it may provide a more realistic perspective of the structure and dynamics of fish populations as presented in the case studie on WGH which follows.

The MOSA has been validated for several stocks such as Baltic and Icelandic cods (Solari et al., 1997; Bas et al., 1998; Solari, 2008), skipjack tuna (Solari et al., 2003), sardine as an example of a small pelagic species (Solari et al., 2011), the common octopus as an example of a cephalopod (Solari, 2008; Solari, 2011) and several coastal fish species (Solari, 2011). Also, there have been further applications such as (i) the framework assumes a spatial factor which has been used to develop a Spatial Exclusion Approach (Balguerías and Solari, 2013) which has been adopted by the EU and Mauritania for management of the octopus stocks in NorthWest Africa - and other species elsewhere (EC-STECF, 2012; RIM-UE, 2013) and (ii) a geometric approach (Solari, 2012 a-b) which is the translation of the framework and validations to the non-mathematically oriented readers. Moreover, the framework can be used at the population, cluster and community (multispecies) levels by describing the processes in a matrix based on the base equation.

There are Spatial Exclusion (SEA) and Geometric approaches which we may put forward in the future.

According to the criteria proposed in the MOSA, we now analyse the Age class 1 and Abundance series and phase plane.

In Fig. 4.2, we show the log transformed (Log) age class 1 (N=21) and Abundance (N=15) series ($N*10^6$) for years 1991-2011, lagged 5 years. Correlations were significant ($p<0.05$) between both Age class 1, Abundance and Mean Catch Per Tow (MCPT). It is assumed that Abundance can be biased by Age class 6 (recruits). Series were interpolated by cubic splines and fitted by Locally Weighted Scatterplot Smoothings *(*LOWESS) and linear regressions.

In Fig., 4.3, Figure 4.3. The phase plane between age class 1 and Abundance (lag = 5, correlation $p<0.05$). The Locally Weighted Scatterplot Smoothing *(*LOWESS) showed two singular points (S_1 and S_2) on equilibrium values for the orbits of stability (O_1 and O_2) shown by the trajectory. Although Age class 1 series can be noisy, the short-term local trend and slope and approximate numbers (abundance biased by recruits at Age class 6) can be estimated (5 years in advance) both numerically and geometrically. Vertical and horizontal marks indicate maximum and zero slopes, respectively. K_i and $K0_i$ are the ceilings (variable carrying capacities) and floors (minimum viable populations) for each orbit and are determined by the combined effects from the environmental forcing and fishing mortality. Start and end of the lagged Abundance series are years 1991 and 2005, respectively. Both O_1 and O_2 were detected by the Multi Resolution Decomposition and linked to cycles in the dispersion of the SST around the mean.

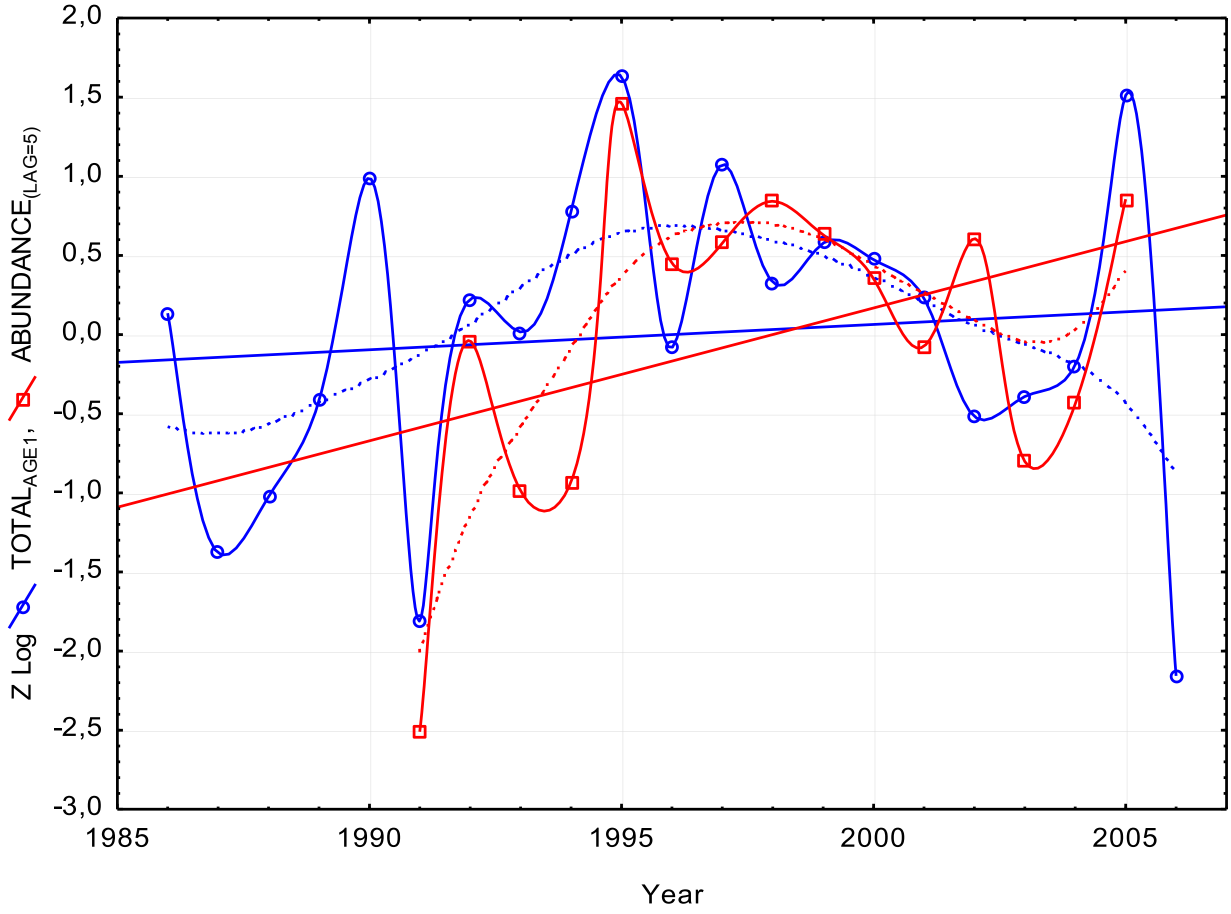


Figure 4.2. The log transformed (Log) age class 1 ($N*10^6$) and Abundance ($N=10^6$), years 1991-2011 (after Jørgensen, 2012 and GINR, 2013), lagged 5 years. Correlations were significant ($p<0.05$) between both Age class 1, Abundance and Mean Catch Per Tow (MCPT). It is assumed that Abundance can be biased by Age class 6 (recruits). Series were interpolated by cubic splines and fitted by Locally Weighted Scatterplot Smoothings *(*LOWESS). Age class 1 is linked to the impact of trends in temperature minima whereas overall abundance (which is biased by recruitment at Age class 6) is linked to variations around the mean in SST.

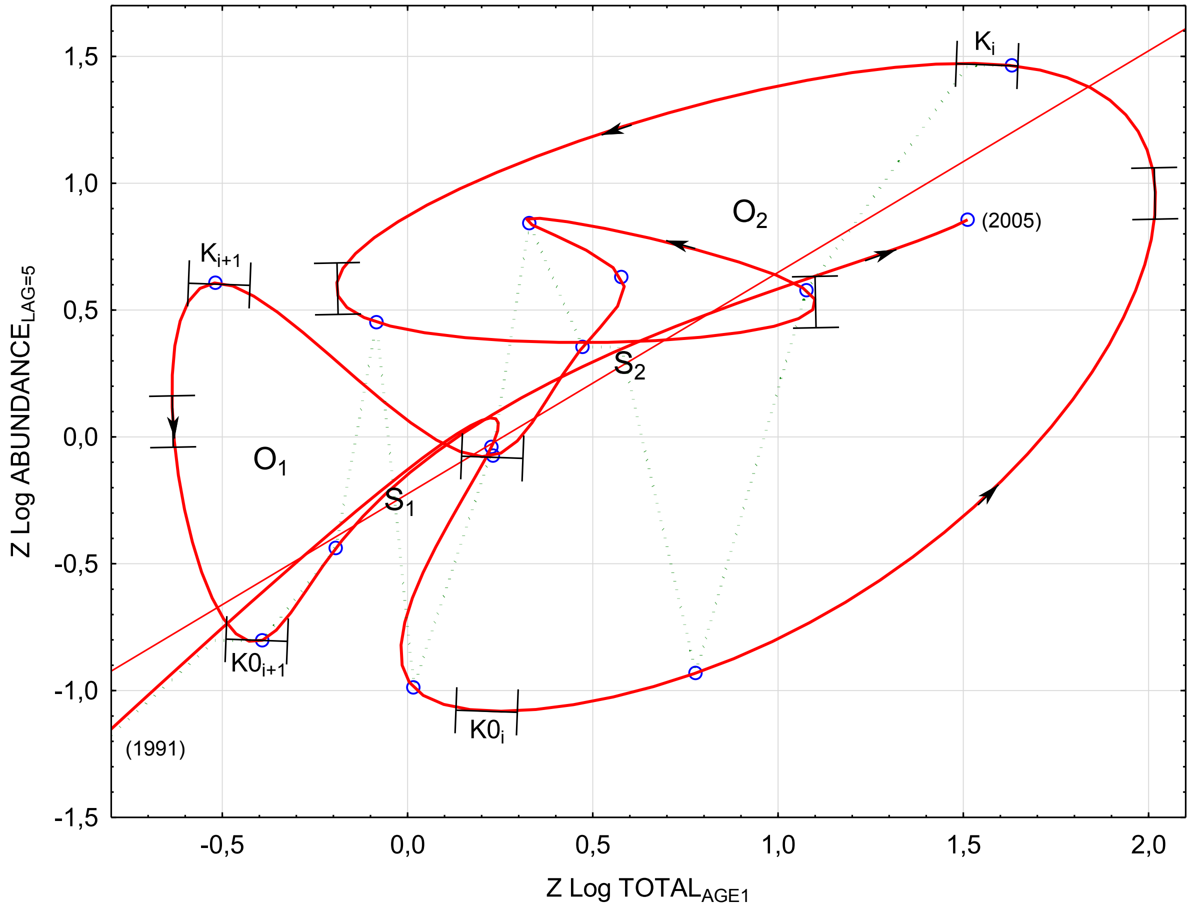


Figure 4.3. The phase plane between Age class 1 and Abundance (lag = 5, correlation $p<0.05$). The Locally Weighted Scatterplot Smoothing (LOWESS) shows two singular points (S_1 and S_2) on equilibrium values for the orbits of stability (O_1 and O_2) shown by the trajectory. Although Age class 1 series can be noisy, Abundance (biased by Age class 6) can be estimated both numerically and geometrically. Vertical and horizontal marks indicate maximum and zero slopes, respectively. K_i and $K0_i$ are the ceilings (variable carrying capacities) and floors (minimum viable populations) for each orbit and are determined by the combined effects from the environmental forcing and fishing mortality which will be differential as population growth becomes either compensatory or depensatory and speed changes will occur after slopes become zero, maximum or inflection points. Start and end of the lagged Abundance series are years 1991 and 2005, respectively.

Also, according to the MOSA, each orbit of stability ($O_{1'}$ and $O_{2'}$) in abundance is expected to result in forward and backwards bending (cyclic) CPUE relationships: to validate the assumption, we show an example based on the CPUE commercial trawl data (N=584; after Jørgensen, 2013; GINR, 2013) for the NAFO Area A0B and years 1990-2012:

Fig. 4.4 shows the log transformed yearly CPUE means, minima and maxima. Correlations are significant ($p<0.05$) and the auto-correlation showed a clear 8 years memory or persistence in the series. The local negative trend (indicated by the dashed lines) was estimated from the Abundance vs SST_{SD} relationship lagged 6 years.

Fig. 4.5-a represents the phase plane (lagged 1 year) of the log transformed and standardized means of the CPUE. The expected cyclic patterns ($O_{1'}$ and $O_{2'}$) are clearly shown.

In Fig. 4.5-b, we show the phase plane (lagged 1 year) of the log transformed and standardized deviations (dispersion of the signal around the mean) of the CPUE. The changes in amplitude (differences between maxima and minima) between both orbits of stability ($O_{1'}$ and $O_{2'}$) reflect the variable carrying capacities (ceilings) and floors (minimum numbers in each orbit), density dependence (which increase with numbers and amplitude) and dynamical similarity (auto-similarity, similar dynamics) at two distinct levels of numbers.

The cyclic patterns in CPUE proposed by the MOSA have been validated for other stocks of demersal and pelagic species (cods, sardines, tunas, mackerel, octopus and sharks among other species) at different spatial scales, oceanographic scenarios and levels of exploitation.

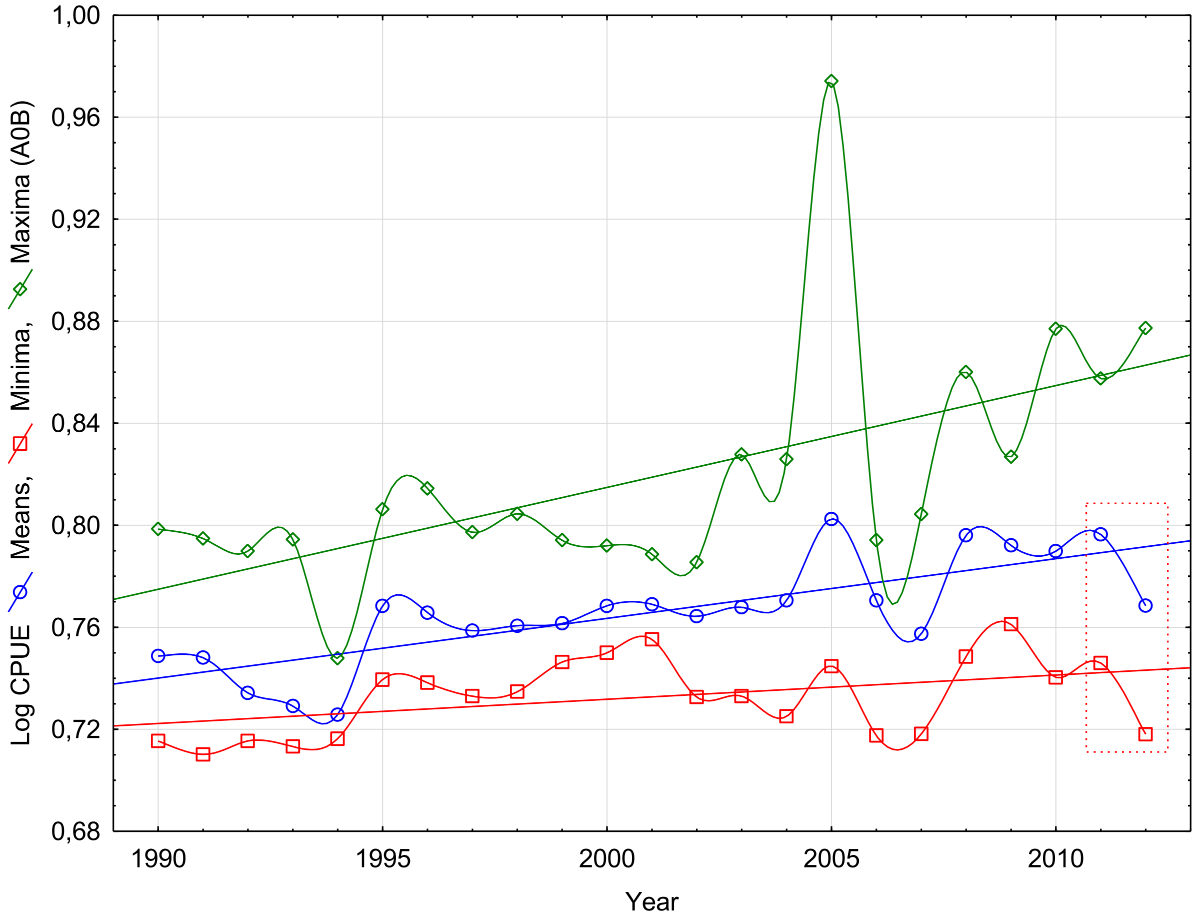


Figure 4.4. The log transformed yearly Catch Per Unit Effort (CPUE, commercial trawlers) means, minima and maxima for the NAFO Area A0B and years 1990-2012. Original data (N=584) after Jørgensen, 2013 and GINR, 2013. Correlations are significant ($p<0.05$) and the auto-correlation showed a clear 8 years memory or persistence in the series. The local negative trend (indicated by the dashed lines) was estimated from the Abundance vs SST_{SD} relationship lagged 6 years.

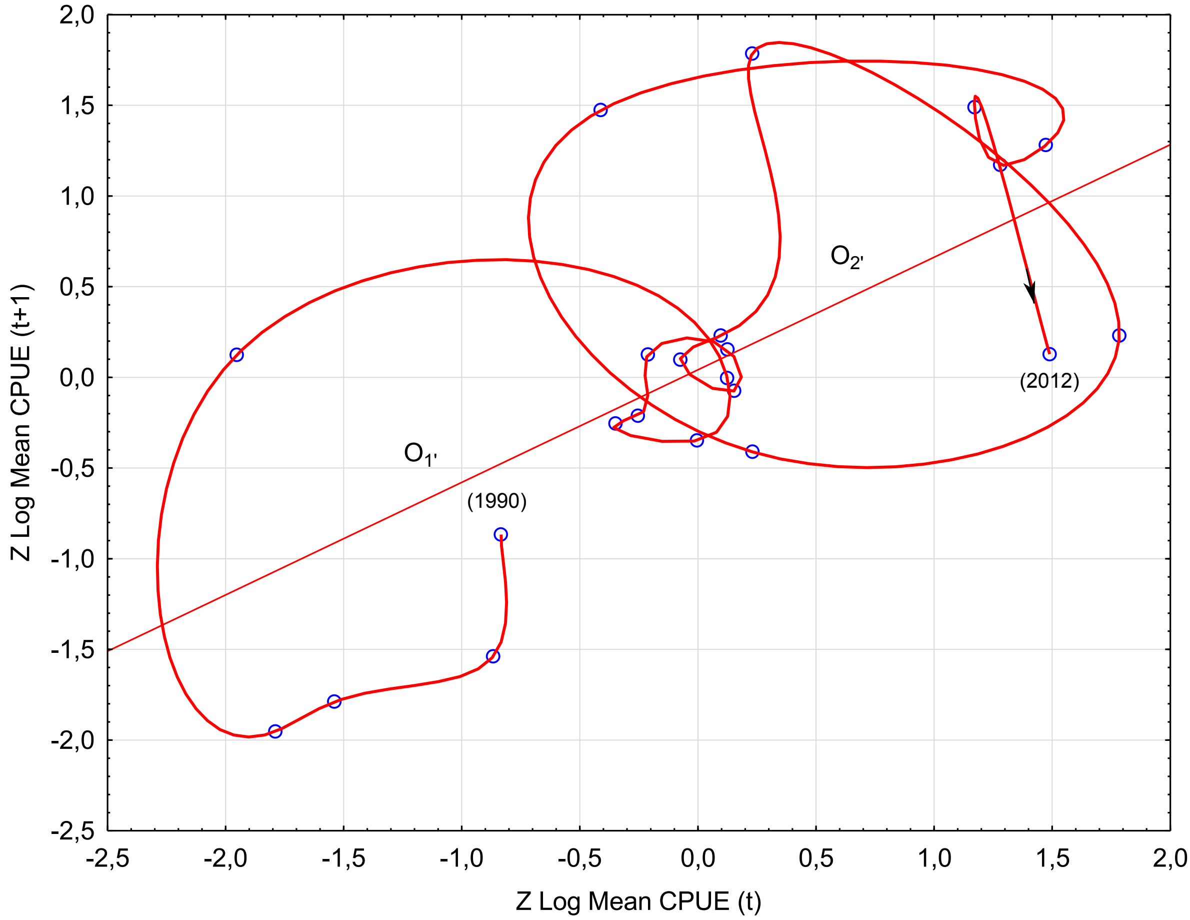


Figure 4.5-a. The phase plane (lagged 1 year) of the log transformed and standardized means of Catch Per Unit Effort (CPUE) for the NAFO Area A0B and years 1990-2012. According to the Multi-Oscillatory System Approach, each orbit of stability ($O_{1'}$ and $O_{2'}$) in both recruitment and abundance will result in forward and backwards bending (cyclic) CPUE relationships. Arrow indicates local (negative growth) trend that started year 2011.

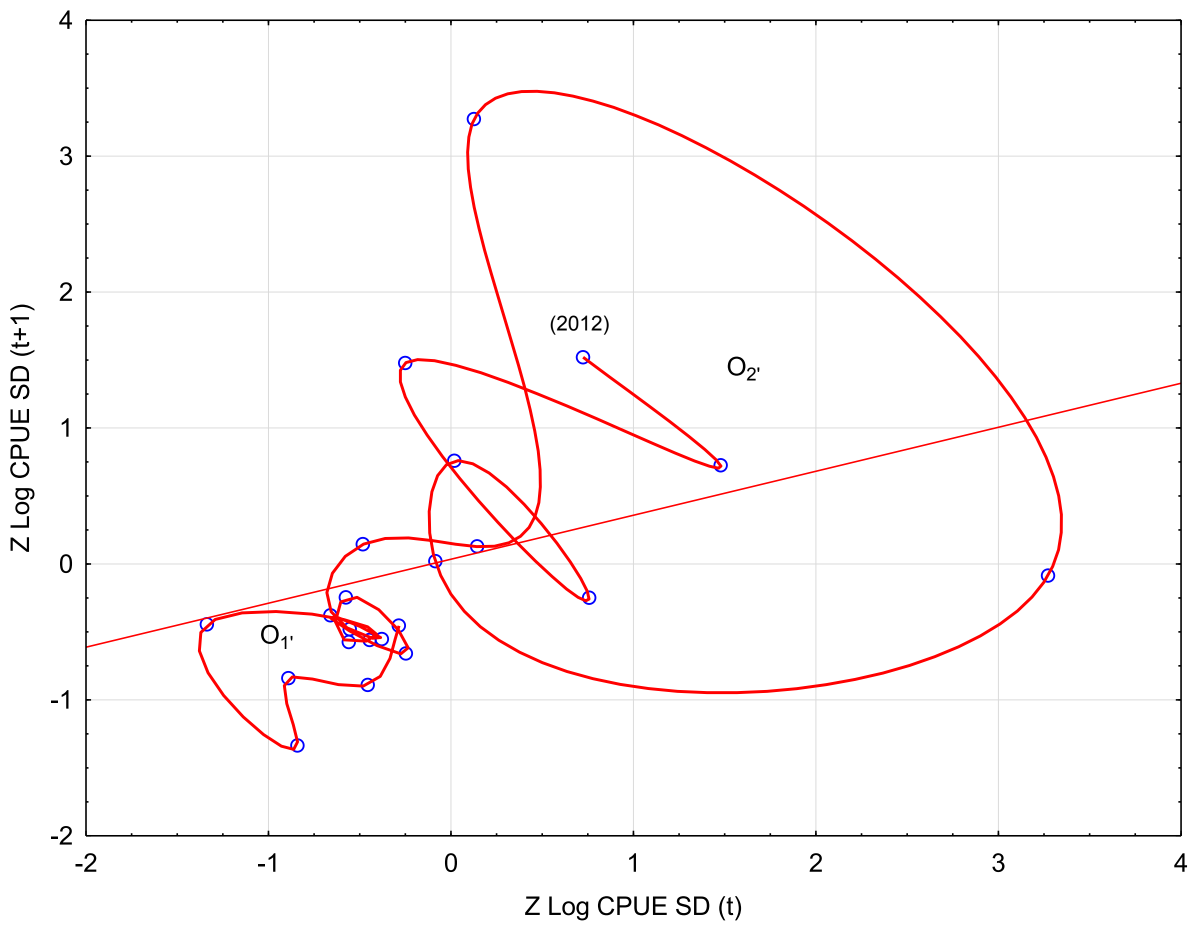


Figure 4.5-b. The phase plane (lagged 1 year) of the log transformed and standardized standard deviations (dispersion of the signal around the mean) of Catch Per Unit Effort (CPUE) for the NAFO Area A0B and years 1990-2012. Amplitude changes between both orbits of stability ($O_{1'}$ and $O_{2'}$) show clearly the variable carrying capacities (ceilings), density dependence and dynamical similarity (auto-similarity) at two distinct levels of numbers.

☐ END OF SECTION ■

And

A Bayesian ***R***un.

(MOSA-Bayesian/MCMC fusion)

¤ 5. *A* *B*ayesian *R*un.

Bayesian approaches to stock assessment provide means to combine information for the stock for which an assessment is needed, in a probabilistic framework. It is even possible to consider uncertainty about which model of the population dynamics is correct (Punt and Hilborn, 2001).

In general, numerical results from Bayesian runs, in the field of fish population dynamics and fisheries assessment, are fitted to the logistic equation or some derivative appraoch such as the Schaefer production model: these classical models –in their original expressions- do not have the resolution to account for neither lags nor persistence or memory in the temporal evolution of the population (which is omitted). However, the Bayesian framework is open to the use of both other models and the modification of the classical population frameworks, as well.

As we showed under the EF and MOSA sections, there is a strong evidence which shows that population processes in WGH are dynamical and respond with delays and feed-back mechanisms to pulses both from the environment and fishing mortality.

For the present Bayesian run, the aims were to (i) incorporate an EF term into the logistic equation, i.e. the variations around the mean in Sea Surface Temperature (SSTsd), in order to find out whether we could estimate the short-term (4-5 years) temporal evolution of the Biomass and (ii) determine whether the results are within the ranges of the orbits of stability we have found through the application of the MOSA (a convergence between both of the frameworks). In this way, we incorporate a system wide, external variable which may change speeds of growth in the population and the 6 years lag found between WGH Abundance and the temperature variation factor, as well.

Testing of different model modifications, parameters and ($1.0*10^5$) iterations were carried out using WinBUGS (Lunn et al., 2000) and complementary *R* scripts. There is a wealth of both papers and books on the subject and further details on the use of WinBUGS and Bayesian/Markov Chain Monte Carlo methods in population dynamics and fisheries assessment can be found elsewhere in the literature.

5.1. Model (Logistic equation modified with an EF term).

In Equation 1, we define the *Biomass (B)* at the year *t*+6 as a function of the *B*, *SSTsd* and *Catch (C)* at year *t* which is expressed as

$$B_{t+6} = B_t + B_t * r * (1 - B_t * SSTsd_t) - \frac{C_t}{K} \qquad \textit{(Eq. 1)}$$

where r and K are the intrinsic rate of increase and (invariant) carrying capacity, respectively.

5.2. Prior distributions, *r* and *K* values and data.

In the process, we sampled *r* and *K* from normal (with arbitrary mean and precision=1/variance, from Gamma distributions) and uniform (with lower and upper limits) distributions, respectively. The selected values were arbitrary (for r) and based on the on peak catch in the series (26.939 Tn, year 2010). This is summarised in Tab. 1.

Data. Population (Biomass*10^3 Tn, Totals, WGH) and environmental (SSTsd) series (years 1997-2011) were log transformed and standardized.

Parameter	Distribution	Initial value
r	~Normal (mean, precision)	0.017 (0.1, 0.1)
	mean~Gamma (5,0.000005)	
	precision~Gamma (6,0.000001)	
K	~Uniform (lower, upper)	50001
	Lower=50000	
	Upper=80000	

Table 5.1. Prior distributions for the parameters *r* (arbitrary intrinsic rate of increase with low variance) and *K* (carrying capacity, based on the possible existence of an upper, third orbit of stability in Abundance), according to the MOSA criteria. Initial values chosen to start the 10^5 iterations.

5.3. Results.

As in the MOSA framework, *r* values are high (due to the near-zero variance we have selected to use). However, the resulting series are analogous as they are log transformed and standarized (to facilitate visual comparision in the graphs). Further values for the carrying capacity (*K*) and the (mean) Biomass, error values and Maximum Surplus Yield (B_{MSY}) were determined to 64 and 32*10^3 Tn, respectively. Resulting values for the posterior distribution are sumarized in Tab. 5.2 a-b.

(*10^3)	**mean**	**sd**	**MC error**
r	5004	2246	6.985
K	64.99	8.673	0.02528
B_{MSY}	32.5	4.336	0.01264

(*10^3)	**2.5%**	**5%**	**10%**	**25%**	**median**	**75%**	**90%**	**95%**	**97.5%**
r	1625	1965	2424	3359	4677	6285	8000	9159	10250
K	50.75	51.51	53	57.48	64.97	72.53	77.01	78.51	79.26
B_{MSY}	25.38	25.76	26.5	28.74	32.49	36.26	38.5	39.25	39.63

Table 5.2. The posterior distribution values from a Bayesian/Monte Carlo Markov Chain run: *r* (instrinsic rate of increase), *K* (carrying capacity) and Biomass of the Maximum Surplus Yield ($B_{MSY}=K/2$) simulated for years 2002-2016 based on WGH Biomass and catch data (N=15, years 1997-2011) and the logistic equation, modified with an environmental forcing term. MC Error is the Markov Chain sampling error.

Quantiles stabilized after 1*10^3 iterations for which we may assume that the incorporation of the EF term into the model may increase the accuracy of the algorithm to estimate abundance in the short term.

In Fig. 5.1, we show the log transformed (Log) and satandardized (Z) observed Biomass (continuous line) and simulated median (dashed line). The oscillation in the simulated data can be linked to SST variations around the mean. The results converge with the short-term estimations from the environmental forcing in light of the MOSA framework.

Figure 5.2. The phase plane on the log transformed (Log), satandardized (Z) observed Biomass (continous line) and Simulated median (dashed line). The oscillation in the simulated data is within the range of the orbits of stability determined both by the environmental forcing and the MOSA framework.

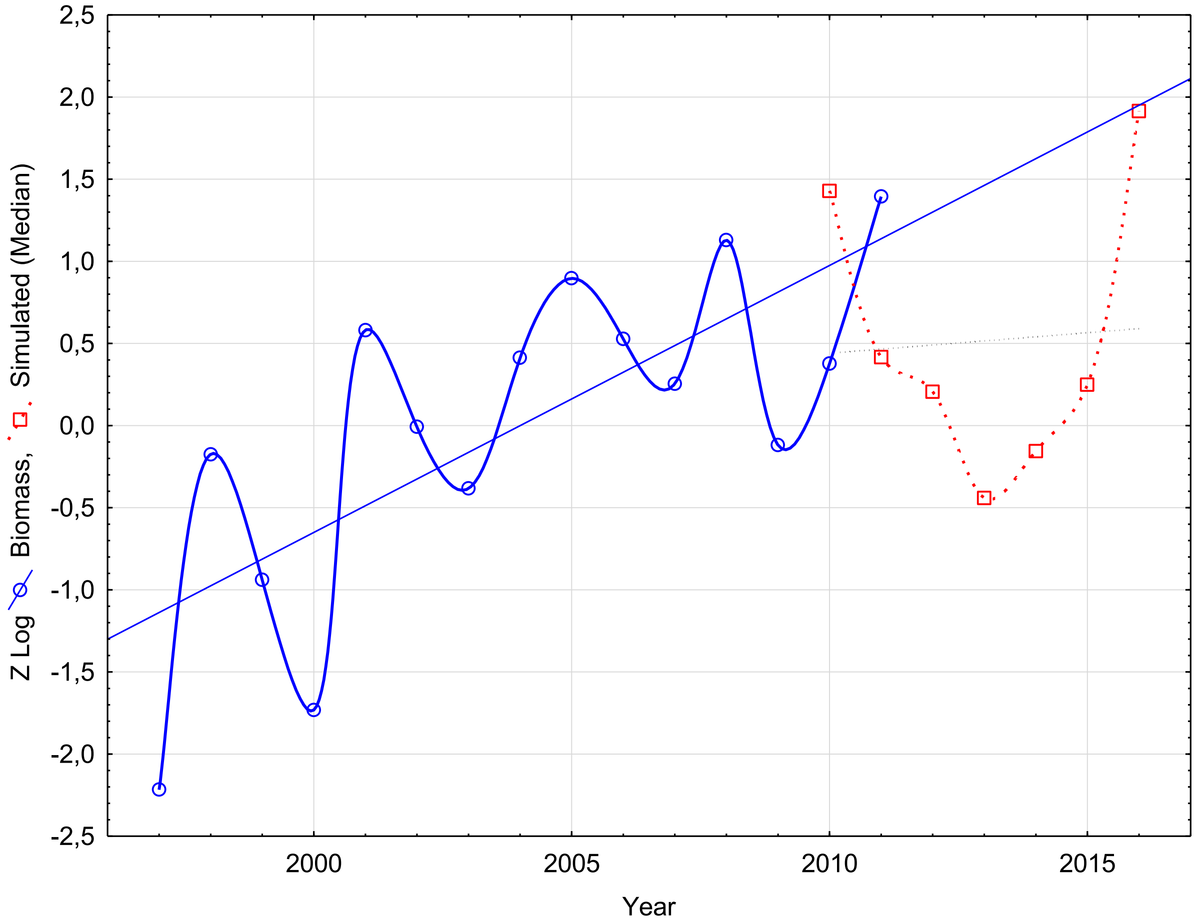


Figure 5.1. The log transformed (Log), satandardized (Z) observed Biomass (continuous line) and Simulated median (dashed line). The blue dashed line is a simple regression for the estimated data. The oscillation in the simulated series can be linked to SST variations around the mean. The results converge with the short-term estimations from the environmental forcing in light of the MOSA framework.

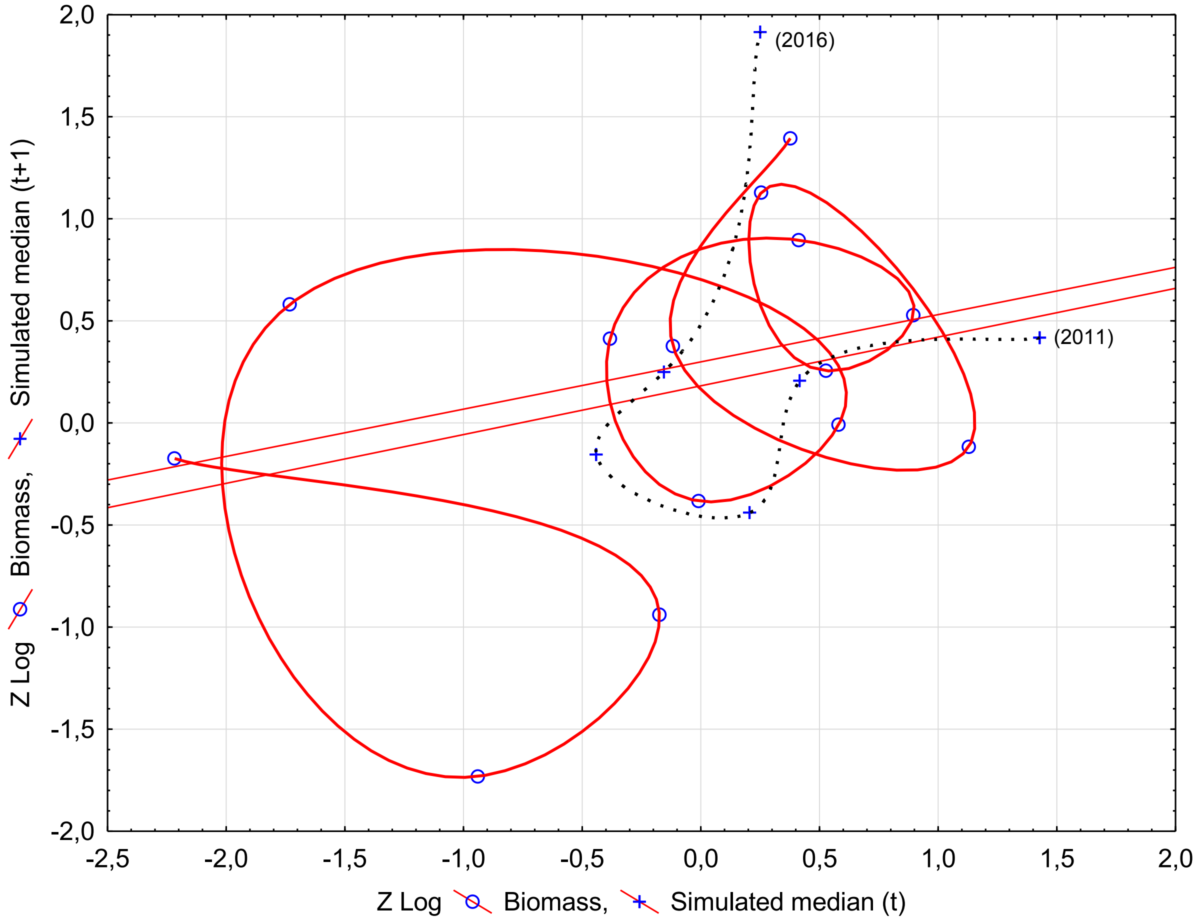


Figure 5.2. The phase plane on the log transformed (Log), satandardized (Z) observed Biomass (continous line) and Simulated median (dashed line). The oscillation in the simulated data is within the range of the orbits of stability determined both by the environmental forcing and proposed by the MOSA framework.

☐ END OF SECTION ■

¤ *D*iscussion.

¤ 6. ***D*** i s c u s s i o n.

For simplicity, the present section will be divided into partial discussions on general issues, the environmental forcing, the alternative Multi-oscillatory and Bayesian frameworks and a final part on future tasks which we can further develop for the study and sustainable fisheries on WGH.

6.1. General issues.

Although we have worked with proxies and the population data had limited degrees of freedom (N=15 and N=21 for Biomass/Abundance/MCPT and Age class 1, respectively), we were able to detect several relationships which may be key factors both in the population dynamics of WGH and for fisheries management issues.

We were able to determine relationships between the population variables, the EF and reference points from both of the frameworks: (i) a NAO-SST inverse relationship; (ii) SST variation and minima with Abundance and Age class 1; (iii) a state-space relationship between Age class 1 and Abundance, as well. Furthermore, we modified the logistic equation with an EF term and through the Bayesian/MCMC, we succeeded to estimate a biomass trajectory which converges with estimations based on the MOSA.

We do not find any antagonism between the MOSA and Bayesian frameworks but a complementarity which may allow us to improve both our knowledge and assessments: in a first step, we found a certain convergence between both of the approaches although they are based on different assumptions and methods. However, we aim to do further sensibility analysis using other, more flexible models within the Bayesian/MCMC approach and incorporate a K(t) or K_i (multi-modal random samplings for certain ranges of the variable carrying capacity) for each discrete situation (orbit) that we may detect and a variable r_i (for the compensatory and depensatory phases within each orbit), lags and local memories as detected in the series. We can use the logistic equation as a “control”. However, the model to which we fit the data in future Bayesian runs will be changed.

6.2. Environmental Forcing.

Both NAO and SST can be regarded as two system wide (meso-scalar operating) variables which we may use to approach the environmental forcing in the dynamics of the WGH: during positive and negative NAO phases, winter temperatures become lower and higher (below and above the linear fit), respectively. The variables appear to be the inverse of one another and may have an impact on the juvenile halibut pelagic drift area off SW Greenland implying a relatively higher survival rate of Age class 1 during negative NAO (milder winters). This mechanism may be a key factor which will affect recruitment and abundance six years later. Furthermore, SST_{SD} showed useful as a proxy for environmental forcing. SST variations around the mean and minima may be regarded as indicators of trends in recruitment and abundance. Also, there will be an optimal range of SST_{SD} values for year class strength.

As for periodic oscillations, the spectral analysis showed 8 years cycles (SST_{SD} and the population variables) and this was confirmed by the Multi-Resolution Decomposition (MRD) wavelet analysis: Age class 1 appears to be sensitive to SST temperature minima while abundance (biased by new recruits at age 6) appears to respond in higher degree to variations or dispersion around the mean. Dynamical (population) systems may be highly sensitive to conditions and changes in speed and slopes in the EF.

The six years lag for the correlations between abundance and SST_{SD} may be related both to the age of recruitment and changes in the speed of growth determined by the fluctuations in the variability of the SST_{SD}. It could be argued that correlations may become significant between two wave-like series as one of the variables is lagged. However, the lag at which the correlations become significant is the expected timing for WGH recruitment. Also, the variables are the inverse of one another and follow local changes in amplitude.

Moreover, Age class 1 showed significant correlations both to SST_{SD} and minima.

The Hust exponent showed that persistence (or memory) in the series is strong and that none of the variables tested for (NAO maxima and minima, SST variation, maxima and minima, as well as Age class 1 offshore and from Disko Bay) can be considered as random variables: although the degree of noise may vary, they all differ significantly from random walks. This validates further the assumption that population processes in WGH depend on environmental oscillations which drive changes in population growth.

Why lag and dependencies were not detected before for the WGH dynamics ? One of the answers can be that classical models (such as the logistic equation and derivatives, in their original expressions) do not have the resolution to incorporate the temporal evolution in the data: neither lags nor memories in the series were taken into consideration. This implies a shortcoming as populations may respond with lags and feed-back mechanisms to a set of system wide, multivariate, external variables which may operate at different (spatio-temporal) scales and frequencies.

6.3 Signal, noise, variability and residuals.

As we see it, one of the questions to pose is not whether WGH population processes are the result of an environmental forcing or stochastic processes but what is the signal-to-noise ratio in the population and environmental series.

While classical models (such as the logistic equation and derivatives) assumed that residuals were fully the result of a random process, we propose in the MOSA framework that these values, to a high degree, comprise signals which incorporate noise due to sampling errors and dispersion/contraction processes (variability) within the marine ecosystem itself, changes in density dependence in different orbits of stability and frequency of operation in the EF variables. This inference is based on results from the correlations and detected memory effects in the series. In general, classical models could explain up to 20-40% of the variability in the data. It is unrealistic to assume that 60-80% of the variability is caused by unidentifiable random processes. The concept of variability which arises from premises such as equal statistical weight for all of the data values and a 2nd order fitting (classical models, “hockey stick” approach and the logistic equation) may are expected to perform poorly.

In Fig. 6.1, we show an example of how we may lose information in a signal, depending on what curve fitting methods we may use according to the assumptions of our models. The logistic model assumes a 2nd order curve fitting with no dependencies or lags to external variables.

Nonlinear data smoothers provide a practical method of finding smooth traces for data confounded with possibly long-tailed or occasionally spikey noise. They are resistant to the effects of extreme observations that are not part of the local pattern, yet they are able to respond rapidly to well-supported patterns (Velleman , 1980). Also, we are interested in outliers and the external conditions (forcing) which causes such peaks: these ceilings and floors where population growth reaches the cero slope (to start either compensatory or depensatory phases) are key situations which will allow us to gain knowledge on possible ranges of the variable carrying capacity, as proposed in the MOSA.

Auto-correlated residuals may be another factor which we should analyse while processing series from systems with strong dependency between the population and environmental or anthropogenic variables.

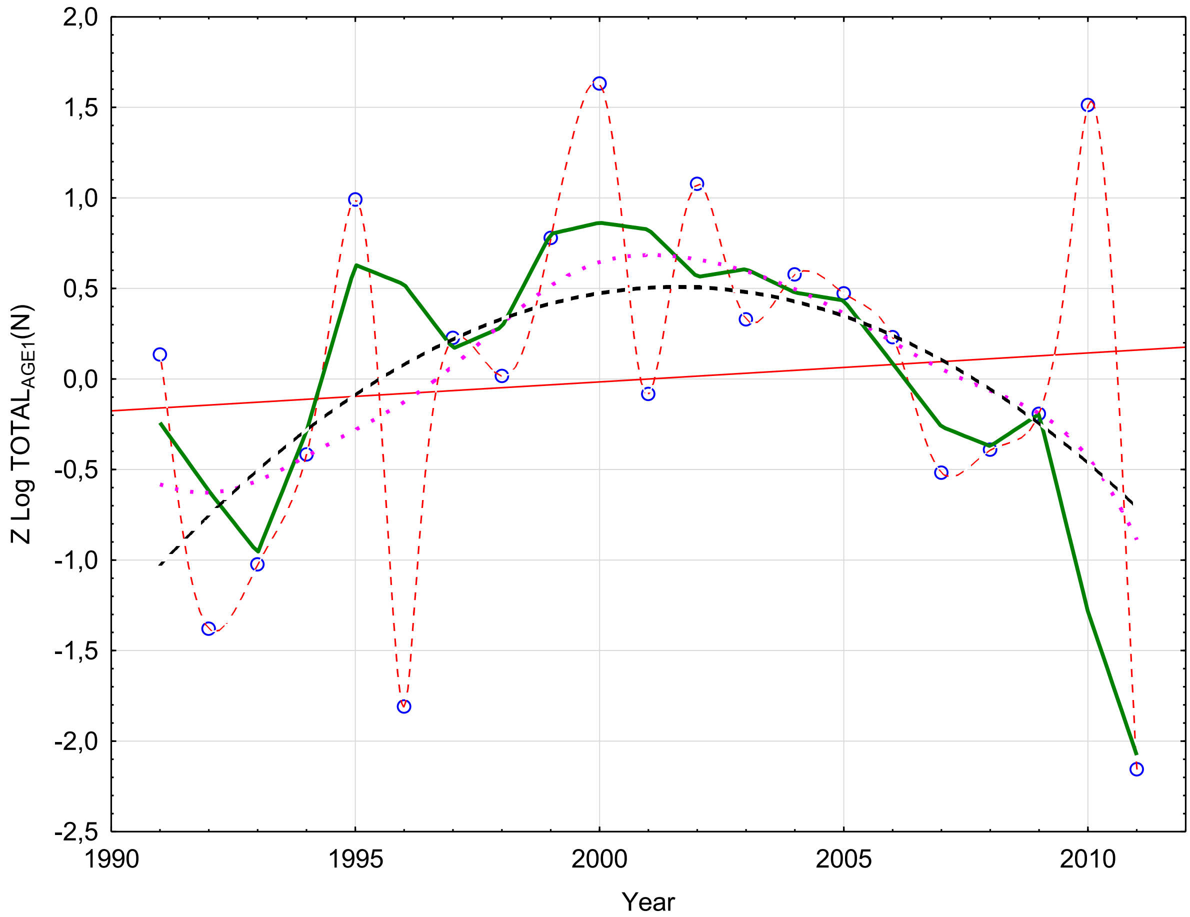


Figure 6.1. The ways we lose the oscillation in a signal: linear regression, cubic spline (dotted), second order fitting (dotted), Locally Weighted Scatterplot Smoothing (LOWESS, continuous) and Distance Weighed Least Squares (DWLS, dashed) fits.

The six year lag detected between the EF and population series may allow us to estimate abundance and do a timely sensitivity analysis for an improved assessment. However, this lag shows the WGH stock may have a slow turnover speed which is critical for the rehabilitation of the stock would overfishing occur.

Lags, variability and dispersion may be considered as fundamental features in the dynamics population systems.

6.4. The MOSA.

The relationship between Age class 1 to recruitment at age 6 follows a pattern (two or several orbits of stability) and we may estimate within certain ranges of certainty the numbers (or biomass) that will enter the adult population.

The fundamental concepts proposed by the MOSA were useful to approach the dynamics of WGH, to find evidence on an EF and to improve our knowledge on this species. Some of the central concepts we would like to discuss (condensed from Solari et al., 2008 and prior and posterior studies) in more detail are as follows:

6.4.1. Variable carrying capacity (ceilings, K_i).

This is a central concept in our criteria. Although oceanographers from the end of the 1800 century observed changes in abundance as function of cyclic patterns in the environment and the early proposal by Hutchinson (1957) of the ecological niche as an n-dimensional hyper-space implied a multiple K_i (or multi-modal K(t) concept), we were first to formalise it in Solari et al. (1997). While carrying capacity is considered as a single value in the classical population approaches, we assumed and validated that (i) it may be both multiple and a threshold between equilibrium states; (ii) it will link different equilibria and each particular steady state will show a particular ceiling and (iii) it may be quantitatively different at different spatial scales while it remains similar from a qualitative point of view. It may be more realistic to consider a population parameter such as K_i as variable: WGH will change habitats and food items, migrate (in Lat./Long. and depth layers) which implies it will encounter a continuous transition scheme with a multiplicity of external pulses which may determine both different density independent inputs and levels of numbers recruited due to a particular K_i for each orbit of stability. All of these factors may suggest that we should approach WGH dynamics with stratified modelling.

6.4.2. Minimum populations (floors, $K0_i$).

As numbers decrease either due fishing mortality, external perturbations or the combined effects from both of these factors, each steady state may, gradually, shift towards a critical value or unstable equilibrium under which stock and recruitment will “jump” onto a lower, relatively stable equilibrium state. Also, the per-capita reproductive success may decline at lower population levels implying that reduced numbers of individuals are recruited to the area of the fishery. Floors may be approached through either density-dependent or density-independent depensation; both of these depensations combined may generate rapid shifts towards lower equilibria. Furthermore, the proposed system may contain an overall minimum viable population under which (a) no oscillations in stock and recruitment will be detected and (b) the commercial fishery may cease.

6.4.3. Dynamical continuum.

Population variables may follow trajectories with transition patterns caused both by intrinsic (due to density-dependent processes) and extrinsic (due to density-independence; environment and fisheries) forcing: all processes can be linked to a dynamical continuum which is the result of (i) a range of orbits of stability which operate between the overall minimum viable population (K_0) and the maximum allowable carrying capacity of the system (K_{max}) and (ii) a constantly changing carrying capacity which will govern system trends and the ranges of the orbits. Transitions towards different orbits of stability may occur as some threshold values ($K0_i$ and K_i) are reached. Garcia (2004, personal communication) suggested both that (i) smooth shifts in stock response may arise due to continuous changes in climate, that is multiple state responses of the spawning stock in the case of multiple states of the environment and (ii) the multiple-oscillatory system could be a “one-state-only” with continuous shifts between levels of numbers and no level being a “stable state” in any way due to the ever changing nature of the carrying capacity. Also, it may induce us to ask better questions on different causal mechanisms. Sharp et al. (1988, 1997, 1998 and 2002) suggested that the present state of world fisheries can be attributed to the denial of the importance of system dynamics.

6.4.4. Differential effects of fishing mortality.

The effects of fishing mortality are differential, according to the MOSA: (i) during density-independent compensation, fishing mortality may not affect the positive trend significantly (unless the orbits of stability are extremely low); this implies that fishing effort may be increased without the risk for depletion; (ii) however, as the trajectory reaches K_i and it turns into density-independent depensation, the effects of fishing mortality may contribute both to speed up the negative trend (the rate of increase becomes lower than otherwise) and shift the trajectory to lower equilibria; (iii) also, during density-dependent compensation, fishing mortality could be maintained relatively constant (unless numbers are extremely low) until a depensatory phase starts operating (after which the fishing pressure should be decreased); (iv) furthermore, during density-dependent depensation, the effects of fishing mortality may be negative if a similar fishing pressure is maintained as during the preceding compensatory trend; in such a case, fishing should be decreased, particularly, as both types of depensation start operating simultaneously. Each orbit of stability may allow a particular level of fishing effort, differentiated due to both the different stages of the oscillation, the level of numbers and the operating K_i.

6.4.5. Multiple (stable) equilibria and pseudo-equilibria (E_i).

There is no evidence in the field data to assume the dynamics of the population systems are governed by a single attractor and a global, invariant carrying capacity and that residuals could solely be a consequence of either random processes or noise. The observed structures and temporal evolution in the data may rather suggest that population systems are governed by multiple attractors (and repellors) which are dynamically linked by multiple carrying capacities and minimum populations through which stock and recruitment may, persistently, evolve and return between a wide range of orbits/pseudo-equilibria allowing for stable, periodic and chaotic dynamics. The trajectories may turn in orbits of stability determined both by density-dependent compensatory and depensatory phases. These pseudo-equilibria may be linked through floors (or minimum threshold values) and ceilings (or maximum threshold values) which appear during transitions determined by the combined effects from fishing mortality and environmental fluctuations: these critical values may be regarded as the minimum population for the higher equilibrium state and the carrying capacity for the lower equilibrium. As the population reaches K_i, the system will "jump" onto the higher equilibrium whereas it will enter the lower equilibrium as $K0_i$ is approached. Also, we may observe that pseudo-equilibria (i) converge as they tend either to zero or to an overall minimum viable population (K_0) and (ii) diverge as they tend to the overall ceiling of the system or maximum carrying capacity (K_{max}). Multiple, linked orbits of stability both within and between relevant spatial scales may describe the dynamics of stock nucleii or local populations, as well. Also, classical approaches may describe different unlinked regimes but will not explain the complex dynamics behind the data. The idea of a dynamic continuum is appealing to describe the phase-space and temporal evolution of a persistent system.

There is a wealth of scientific publications describing population processes which may validate the MOSA: among others, Rothschild (1986) suggested that populations reduced by fishing or anthropogenic substances which compensate for reductions in vital rates may easily transit among stable, periodic and chaotic population dynamics. Garcia (1998) and Sharp et al. (1983) suggested that the Hokkaido sardine series were characterized by loops and proposed an oscillating system consisting two strange attractors, linked by some transitional shifts, operating at two different levels of spawners and recruits. Furthermore, Berg and Getz (1988) suggested that stock and recruitment, in a sardine-like population, moved along a path or attractor in some higher dimension coordinate system. Conan (1994) observed that lobster and snow crab landings in Atlantic Canada may follow two orbits of stability or cycles. Powers (1989) suggested chaotic behaviour for a 2 species system of fish and Tyutyunov et al. (1993) demonstrated cycles of different period and chaos in population dynamics of perch from 10 lakes. Moreover, Caddy (1998) pointed out several other cases, in semi-enclosed areas, where stock and recruitment dynamics could be linked to oscillatory phenomena: (i) an apparent 9-18 year periodicity for the Bay of Fundy scallop stocks (Caddy, 1979); (ii) a 12 year, fishing-effort-independent periodicity in the landings of both hake and red mullet at the island of Mallorca in the Mediterranean Sea (Astudillo and Caddy, 1986) and (iii) a 12-13 year oscillatory pattern in the catches of the Adriatic sardine.

6.4.6. Fishing in multiple-equilibrium systems.

As opposed to single equilibrium systems such as those described by the classical models, systems with multiple orbits of stability may retain their dynamical structure even if fishing effort increases linearly: (i) fishing mortality may increase until an oscillation reaches K_i after which it will drop during depensations and (ii) if fishing effort is further increased, during the depensatory phase of an oscillation, the trajectory may rapidly shift towards lower equilibria and –consequently- fishing mortality will be lower. This stabilizing mechanism with memory effects and time lags may be the cause of the ecological persistency of the system and it is shown by the forward and backwards bending relationships in CPUE.

6.4.7. Extinction of the commercial fishery.

There are several aspects which may be interesting to discuss concerning possible extinctions of the commercial fisheries on the studied populations. Several mechanisms may operate either alone or combined: (i) economical over fishing may imply that fishing mortality becomes asymptotic as the fishery approaches the so called “zero net value” (i.e. economic over fishing resulting in benefits reduced to zero followed by a stabilizing reduction in the fishing effort) as suggested by Clark (1976); (ii) recruitment over fishing may occur due to a backward bending (depensatory) yield against effort relationship due to biological over fishing (as described by Pitcher and Parrish, 1993); (iii) establishment of reduced or extremely low orbits of stability, near K_0, due to either erratic environmental perturbations or the combined effect from the environment and fishing mortality during depensatory trends (as described by Solari et al., 1997) and (iv) inverse-density-dependence (or "Allé effect") which may cause the local extinction of the commercial fishery as recruitment and abundance may tend to zero as the trajectory evolves below K_0.

In Fig. 6.2, we show an schematic overview on the evolution (t ... t_7) of Abundance (A) for a 1 equilibrium (E_i) orbit. This implies that (i) abundance turns in a cyclic pattern or orbit (with positive and negative population growth phases); (ii) there is a dependency on preceding abundances and recruitment; (iii) abundance levels are determined by an environmental forcing with a variable carrying capacity which will affect survival, growth and reproduction and (iv) fishing mortality with differential effects depending on whether it is applied during either positive (compensatory) or negative (depensatory) growth phases. The WGH population series showed changes in the local slopes every 2-3 years as the population trajectory reaches inflection points and zero o maximum slopes. This may induce us to believe that changes are the result of a random process while they may be non-linear oscillations determined by the SST variation around the mean during the juvenile drift phase in the mixing layer.

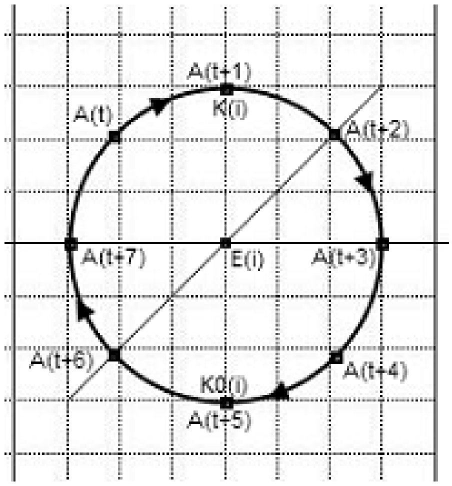


Figure 6.2. Above left: the evolution (*t* ... t_7) of Abundance (*A*) for a 1 equilibrium (E_i) orbit. Abundance turns in an orbit (with positive and negative population growth stages), a ceiling (K_i) or carrying capacity which variates between different orbits and a floor ($K0_i$) which is the minimum viable population value. Effects of fishing mortality are differential during compensation and depensation. In the WGH case, the orbits may be determined by SST variations around the mean (the inverse of abundance with a lag of six years), fishing mortality. Changes in speed of growth occur every 2-3 years as the cycle reaches inflection points, zero and maximum slopes.

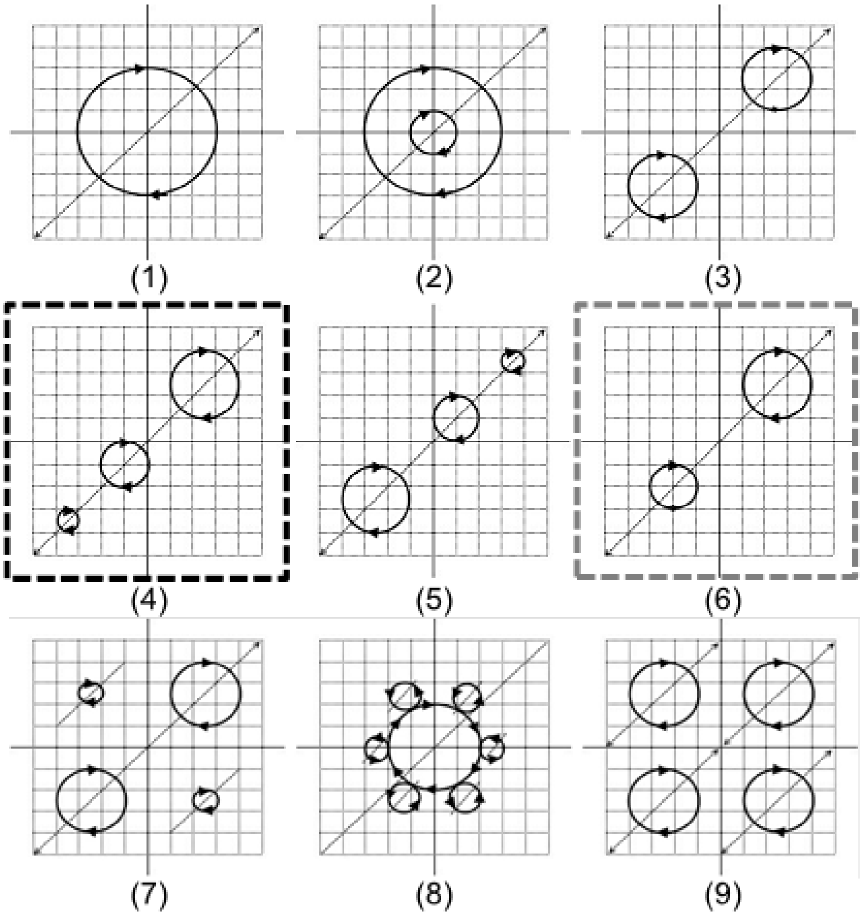


Figure 6.3. Schematic overview for different dynamics detected for several stocks: orbits for a cycle (1), overlapping cycles (2; Icelandic cod), two pseudo-equilbrium system with similar density-dependence (3), a three pseudo-equilibrium system (4; common octopus, European sardine; 5; bluefin tuna under the Maunder Minumum/Min ice age during the 1800's) and a two pseudo-equilibrium system with differential density dependence (6; skipjack tuna, WG halibut, Baltic cod). Relatively rare systems for yellowfin tuna (7), South African anchovy (8) and Naimbian horse mackerel (9).

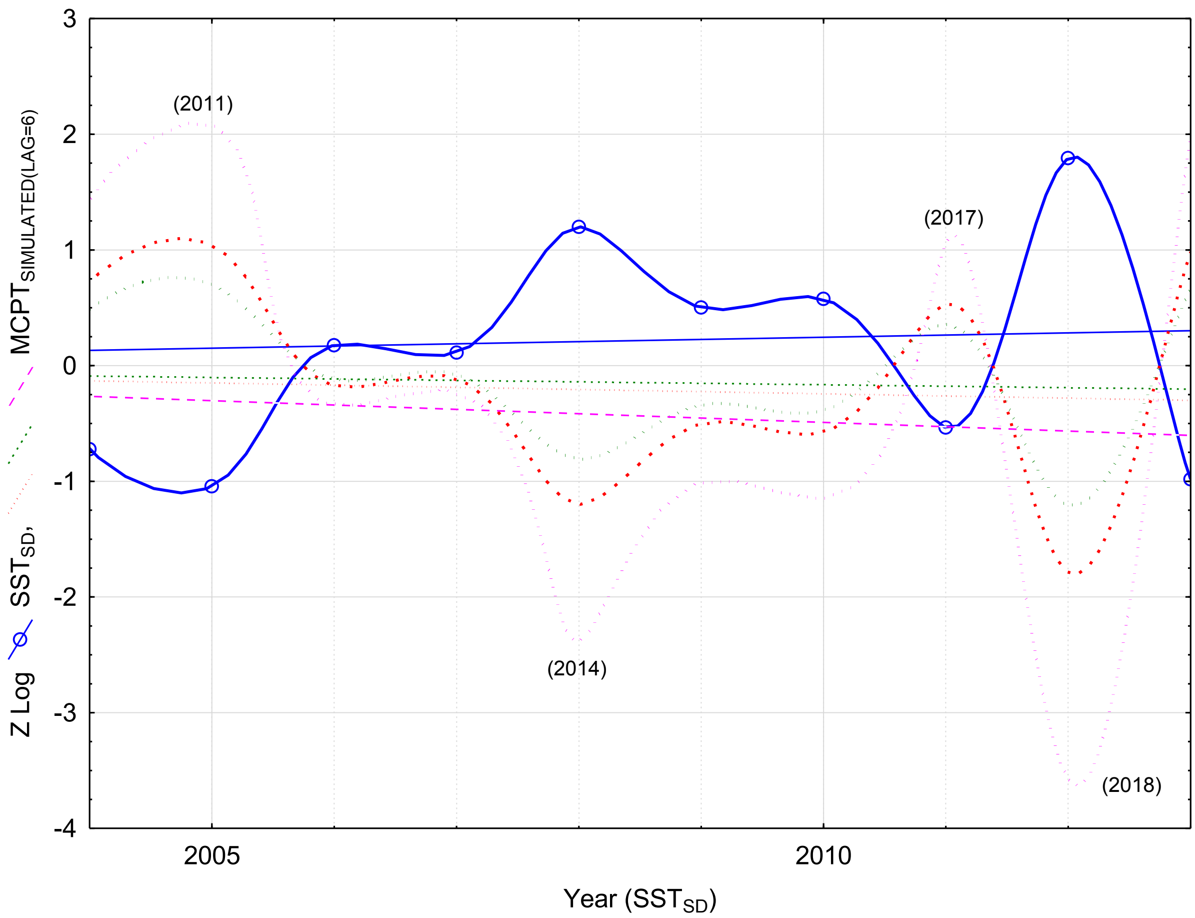
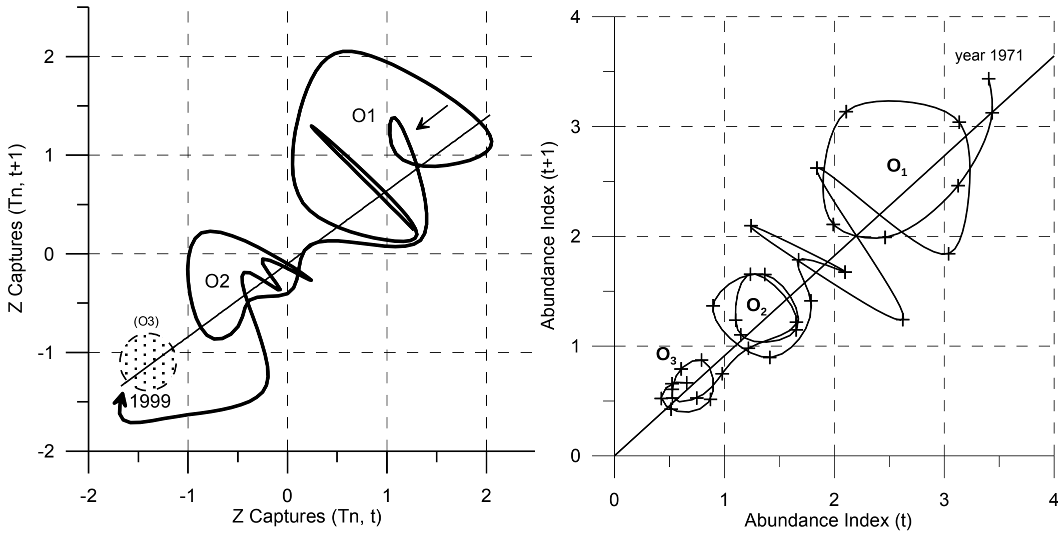
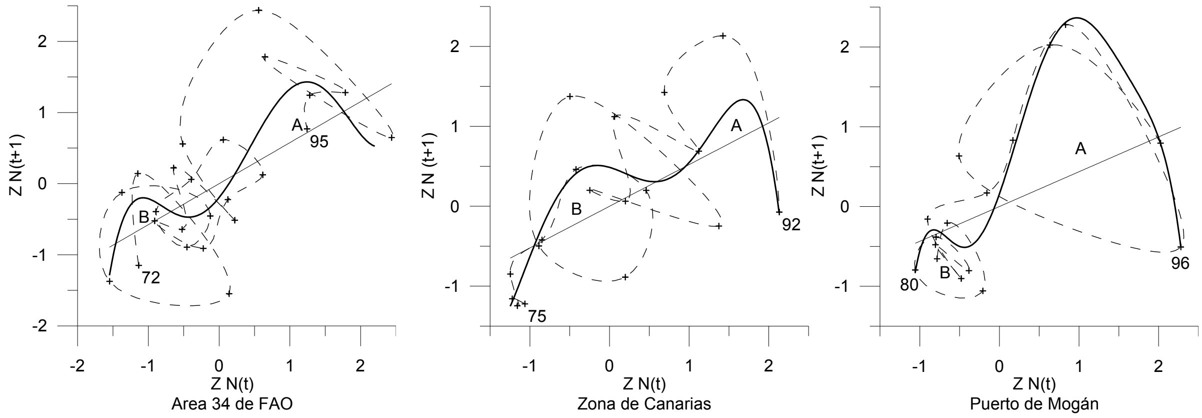


Figure 6.3.4. Estimated/simulated Mean Catch Per Tow (MCPT, an abundance proxy) as the inverse of the Sea Surface Temperature variation (SST_{SD}) within a subarea of the halibut juvenile drift SW off Greenland (Lat. 62.5-64.5º N and Long. 55.5-57.5 º W). Key factors in the analysis, estimation and modelling are outliers, maxima and minima, time length and steepness of the (local) slopes from the positive (compensatory) and negative (depensatory) population growth phases. The speed of change from the external forcing can be one of the fundamental co-factors to drive local changes in population numbers. The proposed values (noiseless inverse) are at equilibrium (the phase plane is a straight line). The estimated abundance should be compensated by an index or k(t) from locally weighted trends (and density dependence at different levels of numbers): in this way, it is possible to estimate abundance more accurately and propose catch ranges adapted to the variable carrying capacity of the environment (future work).

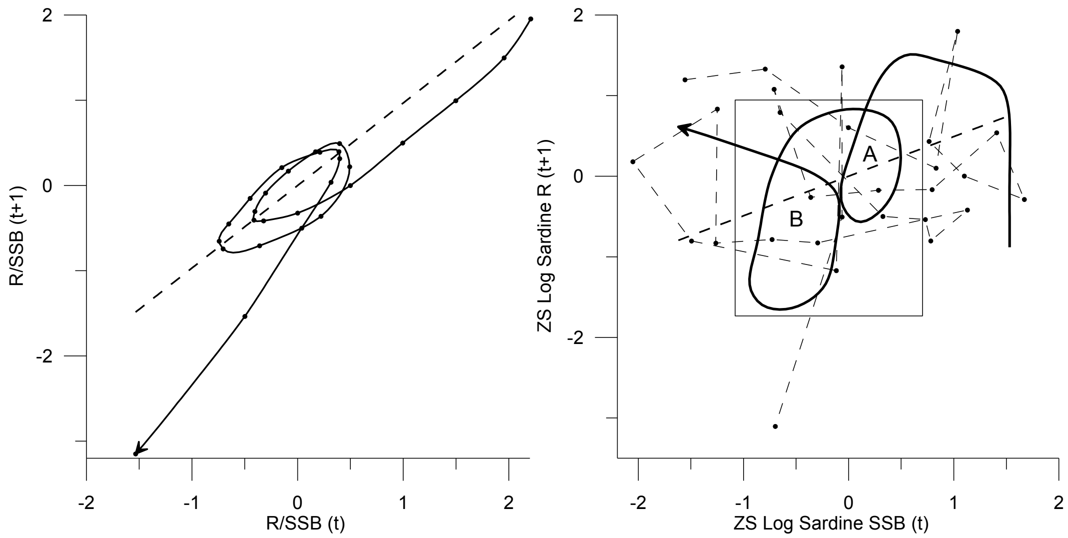
6.4.8. Case studies to support the MOSA.



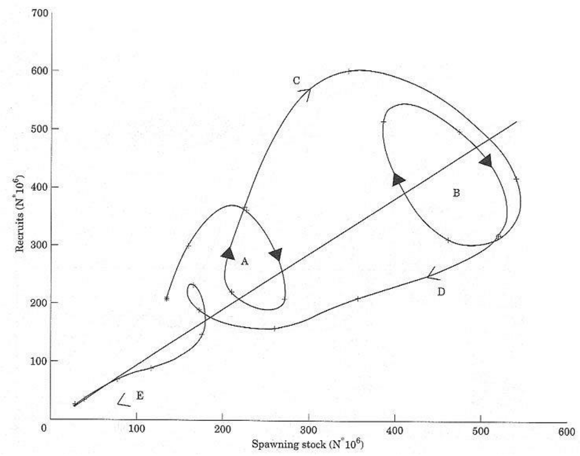
Above left (a), the phase plane of catches (considered to approximate the Stock-Recruitment system). O1 and O2 are orbits of stability. O3 (dotted area) is the future expected range of oscillation from year 2000. Arrow indicates an example of local dynamics. Above right (b), phase plane of the Mauritanian *Octopus* Abundance Index series (1971-2005, after FAO, 2006). O_1-O_3 indicate the orbits of stability as explained in our multi-oscillatory framework. This data clearly validates the dynamical model we have proposed and is similar to the Catch-Effort relationship we have shown for the Spanish *Octopus* fishery in the Saharan upwelling zone (after IEO, 2007). After Solari (2008) and Balguerias and Solari (2012).

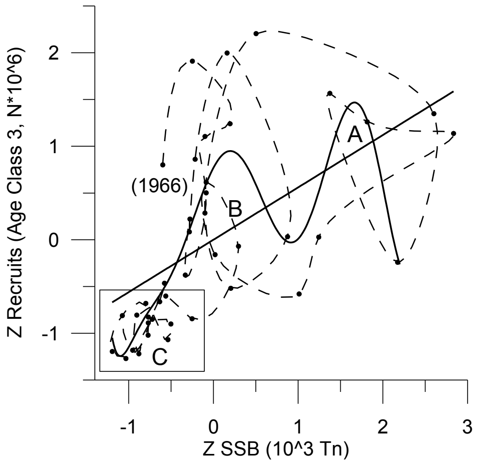


The skipjack case in three different spatial scales (Area 34 de FAO, Canary Islands and the Port of Mogán in Gran Canaria). Catches are assumed to reflect abundance. After Solari et al. (2003) and Solari (2008).



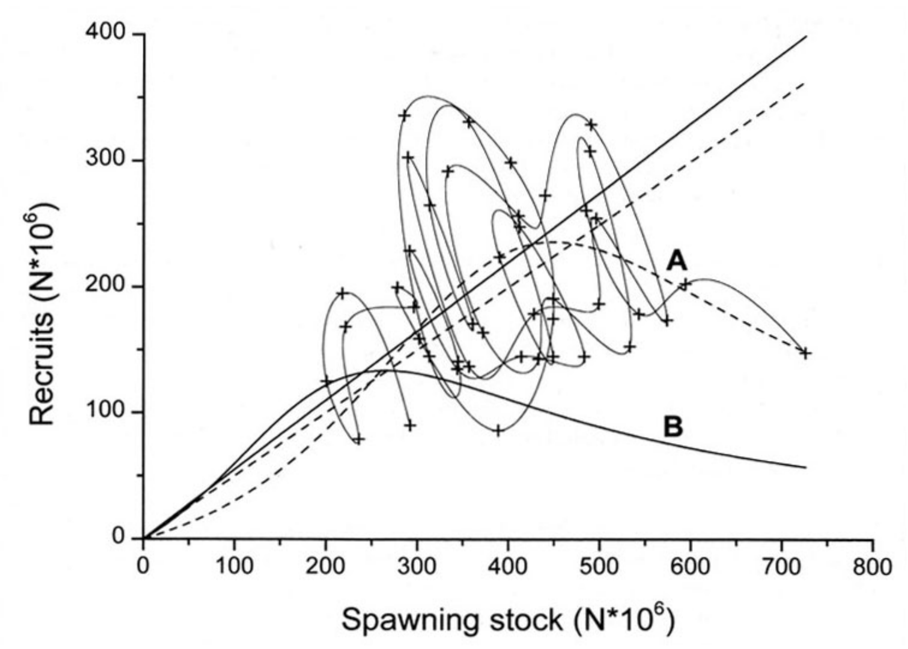
Above left. The phase plane of production (recruitment per spawning stock biomass, *R/SSB*) with lag 1 of the European sardine (*Sardina pilchardus*) in the Iberian upwelling zone for years 1978-2006. The dashed line is a linear regression through the origin. Above right. The stock and recruitment relationship in the European sardine (*Sardina pilchardus*) in the Iberian upwelling zone for years 1978 (start) and 2006 (end, indicated by the arrow). The lag to recruitment is one year. The rectangle indicates the orbits of stability (A, B). The dashed lines are a simple regression through the origin. After Solari et al. (2010).





Above left. Spawning stock and recruitment (+) in Baltic cod as estimated in fishery areas 25-32 for years 1973. A and B describe the low and high equilibrium states (cycles), respectively. Density-dependent compensation and depensation within cycles are indicated by the closed arrows; density-independent compensation (C) and depensation (D) between cycles and inverse density-dependence (E) are indicated by the open arrows. The replacement line is given by a simple regression through the origin. N = number of individuals. After Solari (1997).

Above right. The relationship between Baltic cod Spawning Stock Biomass (SSB) and Recruitment series (after ICES, 2007). A-C indicate the equilibria around which the orbits of stability turn. According to Solari et al. (1997), based on data until 1993, the stock-recruitment system was suggested to rehabilitate (from years 1993 and on) to a low orbit of stability (C, indicated by the rectangle). Both theoretical criteria proposed by the new model and estimations of short to medium term trends were validated by the updated series. The lower caption shows the local dynamics in the low (C) orbits of stability. The straight (replacement) lines are linear regressions through the origin and the non-linear fittings are polynomial (even distance weighted least squares shows similar results) and cubic in the upper and lower plots, respectively. Numerals between parentheses indicate the year of start of the series. After Solari (2008).



An example of a more complex relationship with two orbits of stability. The stock-recruitment relationship in Icelandic cod both interpolated by a cubic spline and smoothed (dotted line). A, B and C represent a high equilibrium, an intermediate and a low equilibrium state. After Bas et al. (1998) and Solari (2008).

6.5. The Bayesian framework.

In Solari et al. (2010), we observed that the logistic equation (and derivatives such as the Schaefer production model) is a tool that dates from Verhulst (1838): technology and frameworks have developed ever since. Although the classical models provided important insights into the population dynamics and resulted in significant advances in fishery science, they are simply tools with limited degrees of resolution (i.e. capacity to incorporate and describe complex dynamics).

The Bayesian/MCMC approach was useful to address WGH dynamics provided that the model to which results are fitted is modified and takes into account a system wide variable which may reflect the EF.

Although the evidence from the EF is strong both in this study and the scientific literature on a multiplicity of cases, we see the probabilistic approach on a deterministic process as a complementary tool to improve our assessments.

We modified the logistic equation and obtained results which converged with estimations from the MOSA framework. However, much work remains to be carried out and discussed on r, K(t), K_i, K/2 and MSY as they may vary depending on the models we use. As we see it, we will be dealing with proxies (not absolute values) and one of the ideas to achieve sustainability (and avoid bio-diversity erosion) is to work with ranges of numbers within a framwork of system dynamics.

Bayesian runs should take into account lags and local memories, a K(t) and be applied to the several discrete dynamical situations (orbits) we may identify. Also, the random sampling for r and K should be adapted to the different population growth phases and density dependent processes such as space, food items and cannibalism among others factors. The fusion between the MOSA and a Bayesian frameworks open new opportunities to improve our work.

6.6. Future work.

We aim to do further work on three main sub-fields, namely: (i) r, K(t), K_i, K/2 and MSY, test for different ad-hoc models for WGH within the MOSA and Bayesian frameworks; (ii) life history determination through the LASER ablation Spectrometry method from which we expect to obtain relatively accurate data to determine timing for recruitment, growth, migration and another quantitative measure of the variable carring capacity of the environment; (iii) acquire in-situ, continous CTD data from survey trawls and (iv) develop further the spatial modelling for this species.

Age class 1 and Spatial Exclusion Area in SW Greenland (during low abundances).

☐ END OF SECTION ■

Suliaq una Kalaallit Nunaata inuinut pigitippara.

(This work is dedicated to the People of Greenland).

¤ 7. Acknowledgements.

All GN personnel (Explorers, R/V Paamiut crew, surveyors, technicians, administrative personnel and scientists) who -through the years- contributed to collect the available data on the West Greenland Halibut (a symbolic species for survival in Greenland). There is much personal and collective efforts into this - not the least from the tax payers and Autonomous Govenrment of Greenland (Sjælvstyret).

Spacial thanks to Research Professor Dr. *Carles Bas*, Honoris Causa (Barcelona), Supervisor without whom the MOSA framework would have taken many more years develop or never had seen the light.

☐ END OF SECTION ■

¤ *R*eferences.

¤ 8. *R* e f e r e n c e s.

Auto Signal (2002). **Auto Signal v1.6.** AISN Software Inc.

Astudillo, A. and J. Caddy (1986). **Periodicidad de los desembarcos de merluza (Merluccius merluccius) y salmonete (Mullus sp. sp.) en la isla de Mallorca**. Int. Symp. Long Term Changes Mar. Fish Pop., Vigo. T. Wyatt and M. G. Larrañeta (editors).

Bas, C, A. P. Solari and J. M. Martín (1999). **Considerations over a new recruitment model for exploited fish populations.** Royal Academy of Sciences, Barcelona. Vol. LVIII, Num. 5:157-183.

Balguerías, E. and A. Solari (2012). **A Non-linear Spatial Exclusion Approach to Fisheries**. Report from the project "Contribution to the Sustainable Management of Cephalopod Resources in the Mauritanian Economic Zone". Spanish Oceanography Institute (IEO).

Barange, M., Coetzee, J., Takasuka, A., Hill, K., Gutierrez, M., Oozeki, Y., van der Lingen, C.,et al.2009. **Habitat expansion and contraction in anchovy and sardine populations**. Progress in Oceanography, 83: 251–260.

Berg, M. and W. Getz (1988). **Stability of discrete age-structured and aggregated delay-difference population models**. J. Math. Biol. 26:551-581.

Borges, M. F., Santos, A. M. P., Crato, N., Mendes, H., and Mota, B. 2003. **Sardine regime shifts off Portugal: a time series analysis of catches and wind conditions**. Scientia Marina, 67(Suppl. 1): 235–244.

Caddy, J. (1979). **Long-term trends and evidence for production cycles in the Bay of Fundy scallop fishery**. Rapp. P.-v. Réun. Cons. int. Explor. Mer, 175:97-108.

Caddy, J. (1998). **Personal communication**. Letter from the Chief, Marine Resource Service, Fishery Resources Division, Food and Agriculture Organization (FAO), Rome, Italy.

Chavez, F. P., Ryan, J., Luch-Cota, S. E., and N˜iquen, M. 2003. **From anchovies to sardines and back: multidecadal change in the Pacific Ocean**. Science, 299: 217–221.

Conan, G. (1994). **Can simple linear correlation satisfactorily detect environmental or interspecific effects on fisheries landings in a chaotic oceanic universe ?**. ICES-Council Meeting, P/8

EC-STECF (2012). European Commission, Joint Research Centre. **Request for advice on the multi- oscillatory model supporting a Spatial Exclusion Approach in Mauritanian Octopus fisheries.** 39th Plenary Meeting Report of the Scientific, Technical and Economica Committee for Fisheries. Plenary Meeting, 16-20 April 2012, Brussels. Edited by John Casey & Hendrik Doerner. Section 5.14, pp. 96-101.

FAO (1983). **Resources**. Fisheries Report series 291(2). San Jose, Costa Rica, April 1983. (G.D. Sharp and J. Csirke, eds.).

Garcia, S. (1998). **Personal communication**. Letter from the Director of the Fishery Resources Division, Fisheries Department, Food and Agriculture Organization (FAO), Rome, Italy.

Graham, M. 1935. **Modern theory of exploiting a fishery application to North Sea trawling**. Journal du Conseil Permanent International pour l'Exploration de la Mer, 10: 264–274.

Hjort, J. 1914. **Fluctuations in the great fisheries of northern Europe, viewed in the light of biologic research**. Rapports et Proce`s-Verbaux des Re´unions du Conseil Permanent International pour l'Exploration de la Mer, 1. 227 pp.

Hjort, J. 1926. **Fluctuations in the year classes of important food fishes**. Journal du Conseil Permanent International pour l'Exploration de la Mer, 1: 5–38.

Hsieh, C. H., Chen, C. S., Chiu, T. S., Lee, K. T., Shieh, F. J., Pan, H. Y., and Lee, M. A. 2009. **Time series analyses reveal transient relationships between abundance of larval anchovy and environmental variables in the coastal waters southwest of Taiwan**. Fisheries Oceanography, 18: 102–117.

Hutchinson, G.E. (1957). **Concluding remarks.** Cold Spring Harbor Symposia on Quantitative Biology 22 (2): 415–427.

Lunn, D.J., Thomas, A., Best, N., and Spiegelhalter, D. (2000) **WinBUGS -- a Bayesian modelling framework: concepts, structure, and extensibility.** *Statistics and Computing*, **10**:325--337.

Machu, E., Ettahiri, O., Kifani, S., Benazzouz, A., Makaoui, A., and Demarcq,H. 2009. **Environmental control of the recruitment of sardines (Sardina pilchardus) over the western Saharan shelf between 1995 and 2002: a coupled physical/biogeochemical modelling experimen**t. Fisheries Oceanography, 18: 287–300.

McAllister M. K. and G. P. Kirkwood (1998). **Bayesian stock assessment: a review and example application using the logistic model.** ICES Journal of Marine Science, 55: 1031-1060. Article No. jm980425.

Martín, J., C. Bas and A. **Solari** (1998). **Report from the workshop 'New, non-linear model for stock-recruitment and management of fish stocks'.** Fisheries Directorate XIV of the EU and Programme FAIR, held in Las Palmas, 31st March-3rd April, 1998.

NOAA (2013). **Climate Prediction Center**, NOAA. http://www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/nao.shtml

Powers, J. E. (1989). **Multispecies models and chaotic dynamics**. ICES-MSM, P/ 21.

Punt, A. E. and R. Hilborn (2001). BAYES-SA: **Bayesian stock assessment methods in fisheries.** User's manual. FAO Computerized Information Series (Fisheries). No. 12. Rome, FAO. 2001.

Relvas, P., Luís, J., and Santos, A. M. P. 2009**. Importance of the mesoscale in the decadal changes observed in the northern Canary upwelling system**. Geophysical Research Letters, 36: L22601.

Russell, E. S. 1939. **An elementary treatment of the overfishing problem**. Rapports et Proce`s-Verbaux des Re´unions du Conseil Permanent International pour l'Exploration de la Mer, 110: 7–14.

Schwartzlose, R. A., Alheit, J., Bakun, A., Baumgartner, T. R., Cloete, R., Crawford, R. J. M., Fletcher, W. J.,et al.1999. **Worldwide large-scale fluctuations of sardine and anchovy populations**. South African Journal of Marine Science, 21: 289–347.

Sharp, G. D. (1988). **Neritic systems and fisheries: their perturbations, natural and man induced**. pp. 155-202 In: Ecosystems of the World: Part 27. Ecosystems of Continental Shelves (H. Postma and J.J. Zijlstra, eds.). Elseviers Scientific Publishing Company, Amsterdam-Oxford-New York.

Sharp, G. D. (1997). **Its About Time: Rethinking fisheries management**. pp. 731-736. In: Developing and Sustaining World Fisheries Resources: The state of science and management. Hancock, Smith, Grant and Beumer, eds. CSIRO, Australia.

Sharp, G. D. (1998). **The Case for Dome-Shaped response Curves by Fish Populations**, pp. 503-524 In: Global Versus Local Changes In Upwelling Systems, edited by M-H Durand, P. Cury, R. Mendelsshon, C. Roy, A. Bakun, and D. Pauly. Report from CEOS Workshop, Monterey, California, September, 1994. ORSTOM Editions, Paris.

Sharp, G. D. (2000). **The Past, Present and Future of Fisheries Oceanography: Refashioning a Responsible Fisheries Science**. pp 207-262 In: Fisheries Oceanography, An Integrative Approach to Fisheries Ecoiogy and Management, P.J. Harrison and T. Parsons, eds. Blackwell Books, London.

Sharp, G. D., L. Klyashtorin, and J. G. Goodridge (2002). **The New Regimes: Fish Stories and Society, Extended abstract/joint poster on long-term consequences of Climate Forcing**. PACLIM, Asilomar, April 2001. In: Proceedings of the Eighteenth Annual Pacific Climate Workshop, G.J. West and L.D. Buffaloe, eds., Tech. Rep. of the Interagency Ecological Program for the San Francisco Estuary.

Solari, A. P., J. M. Martin-Gonzalez and C. Bas (1997). **Stock and recruitment in Baltic cod (Gadus morhua): a new, non-linear approach.** ICES J. of Mar. Sc. 54:427-443.

RIM-UE (2013). **Présentation des résultats du modèle Balgueiras-Solari. Proposition d'un protocole expérimental de mise en œuvre de mesures de gestion spatio-temporelles.** Rapport de la sixième réunion du Comité Scientifique Conjoint RIM-UE. Rennes, 2-5 avril 2013 -

Solari, A. P., J. J. Castro and C. Bas (2003). **On skipjack tuna dynamics: similarity at several scales.** In "Scales in Aquatic Ecology. Measurement, analysis and simulation". Edited by Laurent Seuront (CNRS, France) and Peter G. Strutton (Monterey Bay Aquarium Research Institute, USA). CRC Press.

Solari, A. P. (2008) a. **New non-linear model for the study and exploitation of fishery resources.** Mem. PhD Thesis. University of Las Palmas. President of tribunal: Dr. Serge Garcia (former Director FAO/FIRM).

Solari, A. P., E. Balguerías, C. Bas, E. Beibou, J. J. Castro, A. Faraj, D. Jouffre and M. Taleb (2008) b. **Final Project Report: WP/3 Environmental Models "Multi-oscillatory System Approach".** Improve Scientific and Technical Advices for Fisheries Management (ISTAM).

Solari, A. P., Mª T. G. Santamaría, Mª F. Borges, M. Santos, H. Mendes, E. Balguerías, J. J. Castro and C. Bas (2008) c. **On the dynamics of Sardina pilchardus: orbits of stability and environmental forcing.** (EUROCEANS Concerted Action, 2008).

Solari, A. P. (2009 and 2013 a). **Exito y fracaso de los modelos matemáticos ... (Success and failure of mathematical models ...)** - en "La pesca, entre sus circunstancias y consecuencias". Castro-Hernández, J. J. (ed). 368 pp. ISBN-13: 978-84-92887-27-5. First printing (2009) by the U. of Las Palmas. Second printing (2013) by Textos Universitarios 42. Anroart Ediciones.

Solari, A. P., Mª T. G. Santamaría, Mª F. Borges, A. M. P. Santos, H. Mendes, E. Balguerías, J. A. Díaz Cordero, J. J. Castro and C. Bas (2010) a. **On the dynamics of Sardina pilchardus: orbits of stability and environmental forcing.**ICES J. of Mar. Sc. 67(8).

Solari, A. P. (2010) b. **Report on the mission for a workshop on General Linear (GLM's) and Additive (GAM's) Models and Mixed Approaches (MA's) for the Estimation of Abundance and Management in Artisanal Fisheries in the Islamic Republic of Mauritania.** Project GCP/MAU/032/SPA. Food and Agriculture Organization (FAO), United Nations.

Solari, A. P. (2011). **Report on the mission for the Estimation of Abundance and Management Recommendations for the Artisanal Fisheries in the Islamic Republic of Mauritania**. Project GCP/MAU/032/SPA. Food and Agriculture Organization (FAO), United Nations.

Solari, A. P. (2012) a. Report on the mission "**Sustainable Strategies for the Study and Exploitation of *Octopus* stocks in the Islamic Republic of Mauritania: Geometric Approach and Sustainable Total Allowed Catches (S-TAC's)**". Project GCP/MAU/032/SPA. Food and Agriculture Organization (FAO), United Nations.

Solari, A. P. (2013) b. **Report on the mission for a seminar on the Dynamics, Spatial Exclusion Model and Geometric Approach for the study and management of the *Octopus* stocks in the upwelling areas of the Islamic Republic of Mauritania.** Project GCP/MAU/032/SPA. Food and Agriculture Organization (FAO), United Nations.

Velleman, P. (1980). Definition and Comparison of Robust Nonlinear Data Smoothing Algorithms. **J. of the Am. Statistical Association 75:371**

☐ END OF SECTION ■ ☐ END OF REPORT ■

NUUK 18/NOV/2013.

A new look at the Greenland halibut survey on the East Greenland shelf 1998-2012.

R. Hedeholm, S. L. Post and J. Boje

Introduction

Greenland halibut (*Reinhardtius hippoglossoides*) in East Greenland waters (ICES XIVb) is part of a larger stock complex although the actual distribution is unknown (ICES 2013). The East Greenland stock component is currently assessed together with Greenland halibut in ICES areas V, VI, XII. The Greenlandic survey on the East Greenland shelf is part of the assessment model currently used for generating advice; a model which also rests on the Icelandic survey and a standardized CPUE time series from the commercial fishery. In recent years there has been a discrepancy in the assessment with the Greenland survey not following overall model predictions of stock trend. This is a consequence of both CPUE and the Iceland survey increasing, whereas the Greenland survey remains at a time series low (Fig. 1, lower panel). This document represents an evaluation of the Greenland survey and includes a thorough data inspection and alternative approaches to survey analysis.

Method and Results

Survey coverage

The current East Greenlandic survey covers depths from 400m to 1500m. All areas in the distribution area cannot be sampled due to bottom topography and unwanted catch composition (e.g. abundant Porifera). As a result, ICES subdivision Q4 and Q6 are currently not surveyed (Fig 2.), and this clearly leaves a problem as a substantial part of the stock is uncovered, which is revealed by the current fishery distribution (Fig. 3). The highest Greenland halibut densities (t/km^2) found during the survey are in Q5. The average density in Q5 (across all surveyed depths) in 2012 was 1.9 t/km^2 compared to 0.6 t/km^2 in Q2 (the second highest). Q5 is a relatively small area (10.5% of overall survey area), meaning that fluctuations in this area are not highly weighted in the overall survey estimates (all oother areas are larger). The neighbouring strata (Q4 and Q6) are not surveyed and as they potentially include a large proportion of the stock, the lack of sampling in these areas surely causes the stock to be underestimated, but might also make stock variations difficult to detect as much of the dynamic might take place outside the surveyed area. Previously un-surveyed areas in Q4 and Q6 have continuously been investigated during surveys to find suitable conditions. This has mostly been unsuccessful, and starting in 2014 large areas has been excluded from the list of trawlable areas to accommodate efficient survey design. This entails that a discrepancy arises between the trawlable area and the area the estimated fish densities are routinely extrapolated to. Given that Greenland halibut distribution is patchy this can introduce a bias into survey estimates. To assess the effect of this patchiness, the survey estimates were recalculated using new stratum areas that only include fishable area (Table 1). However, the only effect of using the new areas was an expected downward shift in biomass estimates (e.g. a smaller survey area equals less fish), but no overall change in the general pattern (Fig. 4).

As mentioned the current fishery pattern on the Greenland east coast suggests that Greenland halibut distribution is not completely covered by the survey. All of Q4 as well as an area (ICES XIVb1 and XIVb2) north of the currently defined subdivision Q1 remain un-surveyed. ICES XIVb1 and XIVb2 have been fished since 2005, and accounted for 14% of the total ICES XIVb catches in 2012. Any shift in stock distribution towards this region could account for changes in the survey index, and may also partly explain why other used indices show an increasing trend as opposed to the Greenlandic survey. Given the current data it is not possible to address this issue.

Q1-400-600m is the largest stratum in the survey (18.7%) and 28% of the total biomass was estimated to be in this area in 2012. However, the strata had a low density compared to several of the others surveyed and at present no fishery takes place within in the area (Table 2). Given the area's size, it is highly weighted in the calculations, but as this could be considered an unimportant area, it might not reflect the actual stock trend or/and the effect from the fishery. The estimate for Q1 alone shows a slight increase in biomass compared to the beginning of the time series, whereas all other areas shows a decrease; and quite large in the case of Q2 and Q3 (Fig. 7).

Simple restratification

To include un-surveyed areas and evaluate their possible effect on the biomass estimate, we extrapolated fish densities from adjacent areas into the un-surveyed regions (a simple restratification). The fishery is virtually absent in Q6 (Fig. 3), and we assume that the area is not important to overall biomass estimates. However, the large fishery in both Q4 and Q5 suggests that Q4 dynamics could very well be highly connected to Q5 dynamics (Fig. 2). To explore this, Q5 depth strata where expanded to include Q4. This rests on the assumption that fish density in Q5 is representative of the density in Q4, and given the fishery CPUE this is not an unfair assumption, although probably an overestimate (Table 1, Fig. 5). This is of course a great extrapolation of the data, but it might serve as an indicator of the implications it has on the index when leaving such a large area un-surveyed. Especially considering the very large fish densities in Q5 and the relatively small area it represents in the overall biomass estimates (10.5%). The restratification entails that the expanded Q5 constitutes 19% of the survey area. The added area consists of a narrow band along the shelf edge (Fig. 2) and aligns with most of the fishery in the area. By including Q4 a greater proportion

of the fished area is included in the calculation and it is thereby given more weight in the calculation of the total biomass estimate. By doing so, the index should provide a better description of the effect from the fishery and stock trend.
As a result of the restratification, the overall biomass estimate naturally increased (Fig. 6), but although subtle differences are seen in some years (e.g. 2003 and 2012) the overall pattern is the same as with the original stratification. Hence, current estimates remain at a low level.

Strata specific trends

Fig. 7 shows the contribution of each subdivision to the overall biomass estimate and this allows for comparisons of overall trend to area specific changes. Q1 and Q5 estimates remain fairly constant throughout the time series. Q2 shows a steady decline since the beginning of the time series. Similarly, Q3 shows a declining trend, but estimates are highly variable and contribute much of the "noise" to the overall index. Q3 is by far the largest subdivision (36.4% of the total). No such year-to-year variation is seen in other areas, and to evaluate the importance of this variation, Q3 was removed from the analysis. The result is a similar declining trend but with smaller between-year variation (Fig. 8). It is unknown what causes the Q3 variation, but the bottom topography is different from other areas, with the fish to some extent being located in deep "holes" on the shallower shelf plateau and not on the shelf break where most of the other stations are located. These holes may occasionally receive input from other regions, but an unpredictable and variable input would produce the kind of variation seen in the survey. For instance, the largest single year shift in biomass was seen in 2006, and was mostly caused by unusually high Q3 estimates. Only four stations were trawled in Q3 in 2006 (two in the 400-600m stratum and two in the 600-800m stratum) but an estimate increase was seen in both depth strata. The density in 400-600m (0.71 t/km^2) was 428% above average for the time series in that particular stratum. Similarly, the density in 600-800m was 79% above average. The difference was seen in all four hauls, suggesting that the biomass increase was not a sampling artifact, but simply represents a large concentration of fish in that given year. However, it is unlikely that this variation reflects overall population dynamics.
The suggestions here have been addressed individually. Doing the calculation that includes most of the addressed issues was performed. This included 1) disregard Q1 and Q3; 2) expand Q5 to include Q4; 3) exclude non-fishable areas from calculation. The effect of this on biomass estimates is similar to that seen when applying the approaches individually: there is a clear decreasing trend since the beginning of the time series.

Re-stratification by depth only

Some of the subdivision currently used for stratification are either small (i.e. Q5) or very large (i.e. Q1) but the size does not necessarily represent the importance of the area with regard to fish distribution and abundance. Under the assumption that depth is a better predictor of habitat suitability and fish abundance than area, the entire area (ICES XIVb) was divided into depth strata, including un-surveyed regions such as Q4, Q6 and part of Q3. The mean fish density based on all stations taken in the different depth strata was calculated and weighted according to the areas proportion of the total survey area. Biomass was calculated by multiplying this with the depth specific stratum. This way, stations located in small subdivision with high density (i.e. Q5) that were previously downweighted are included with equal weight as stations in very large strata. The shallower part of Q3 that has been mentioned above was not included.
The result is similar to that of previous calculations regarding biomass trend (Fig. 10). There is a decrease since the beginning of the time series, and the current estimate is approximately 50% of the 1998 estimate. In comparison, the currently reported and applied index shows a decrease just above 50%.

Suggestions for survey improvements

Including un-surveyed regions is warranted. Especially Q4, which appears to be fishable based on the distribution of commercial catches. The area north of Q1 has never been surveyed, and since the fishery has become well established in the area, a survey should include this region. To ensure efficiency, Q3 could be down weighted in the survey design (leaving time to survey other areas), as it appears to be a highly variable (and large) stratum, that does not necessarily reflect population trends, but rather sporadic unpredictable events. Similarly, Q1 could be given less attention.

References

ICES. 2013. Report of the North Western Working Group (NWWG), 25 April - 02 May 2013, ICES Headquarters, Copenhagen. ICES CM 2013/ACOM:0076.

Table 1: Description of the used strata for survey calculations. The fishable area and the area currently used for biomass estimation are given for each stratum. The ration indicates how much of the area that is actually trawlable compared to previous used stratum areas.

Stratum	Fishable area (new, km^2)	Previously used area for extrapolation (km^2)	Ratio	Explanation for discrepancy	Average Greenland halibut density (t/km^2) 2010-12
Q1: 400-600m	5824	6975	0.8	Bottom conditions	0.31
Q2: 400-600m	1361	1246	1.1	NA	0.29
Q2: 600-800m	1425	1475	1.0	NA	0.84
Q2: 800-1000m	1870	1988	0.9	NA	0.89
Q2: 1000-1500m	6915	6689	1.0	NA	0.08
Q3: 400-600m	5974	9830	0.6	Bottom conditions	0.11
Q3: 600-800m	2775	3788	0.7	Bottom conditions	0.64
Q3: 800-1000m	420	755	0.6	Bottom conditions	1.44
Q5: 400-600m	989	1819	0.5	Bottom conditions	0.08
Q5: 600-800m	147	257	0.6	Bottom conditions	0.31
Q5: 800-1200m	80	256	0.3	Bottom conditions	4.44
Q5: 1200-1400m	1033	986	1.0	NA	1.80
Q5: 1400-1500m	747	615	1.2	Narrow stratum	0.77
Total	29560	36679	0.8		0.91

Figure 1: Observed (red curve) and predicted (dashed lines) series of the biomass index used as input to the Greenland halibut assessment model. Dashed lines areas are inter-quartile range of the posteriors.

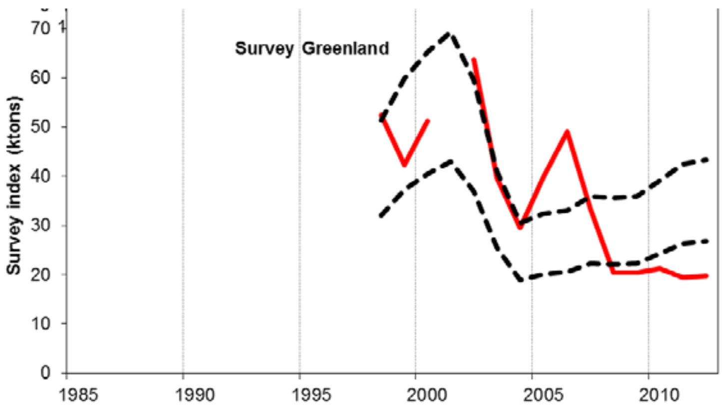


Fig 2: Locations of all successful hauls from 2010 to 2012. Depth contours and subdivision used for stratification are shown.

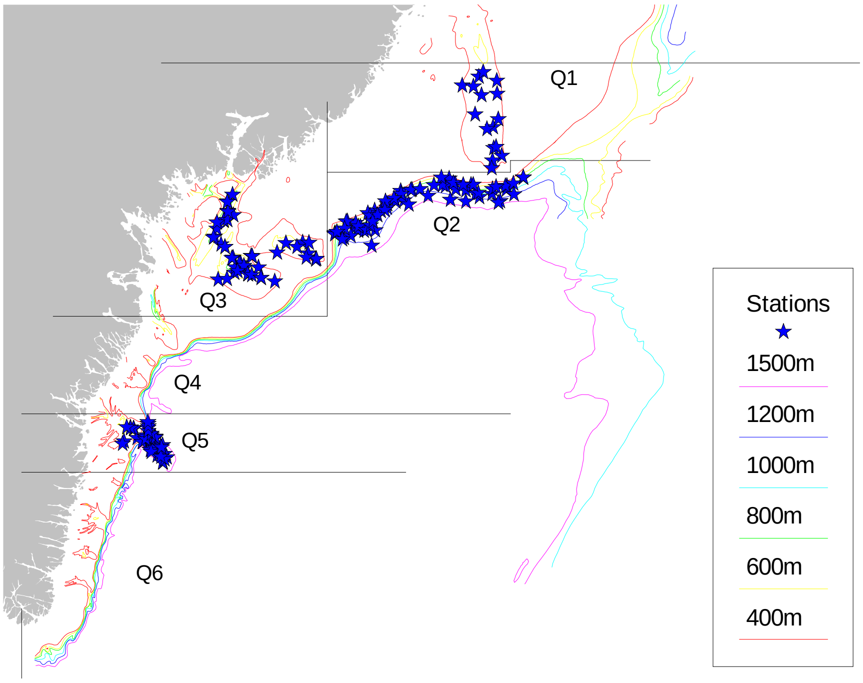


Figure 3: Distribution of the Greenland halibut fishery (effort) in 2012.

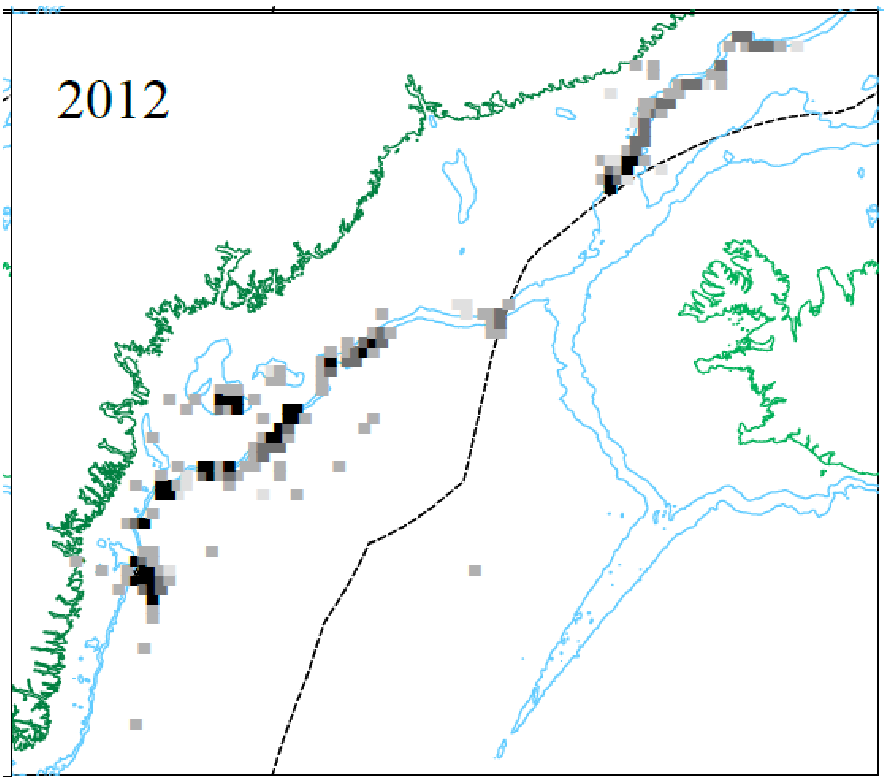


Figure 4: Biomass estimates based on the currently applied stratum areas (original estimates) and biomass estimates based on calculations using only the fishable area (new estimates).

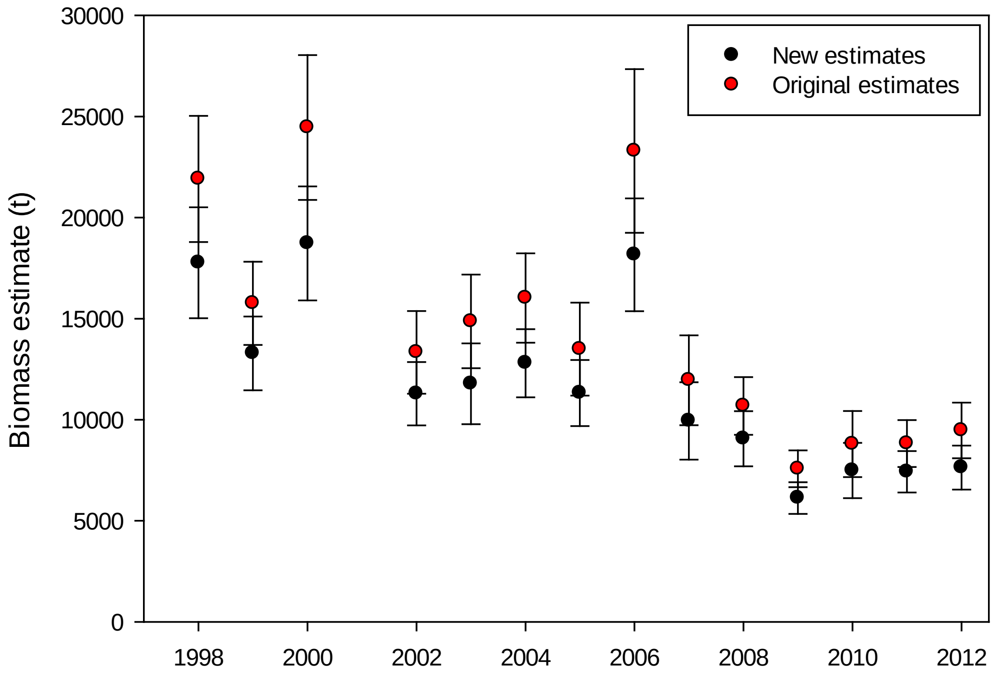


Figure 5: Distribution of 2012 CPUE in the Greenland halibut fishery by statistical square.

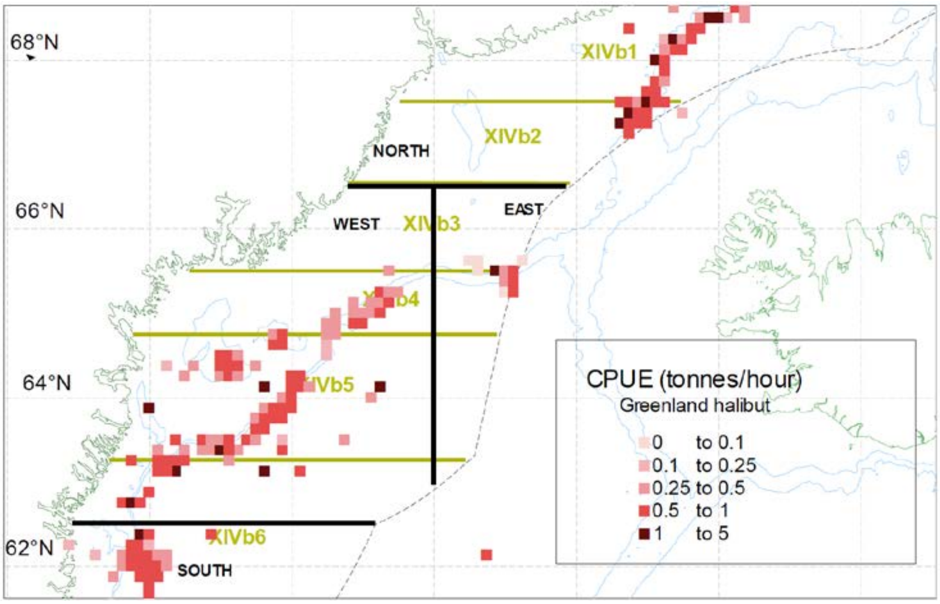


Figure 6: Biomass estimates using the original strata definitions and the approach described, with Q4 added to the Q5 stratum.

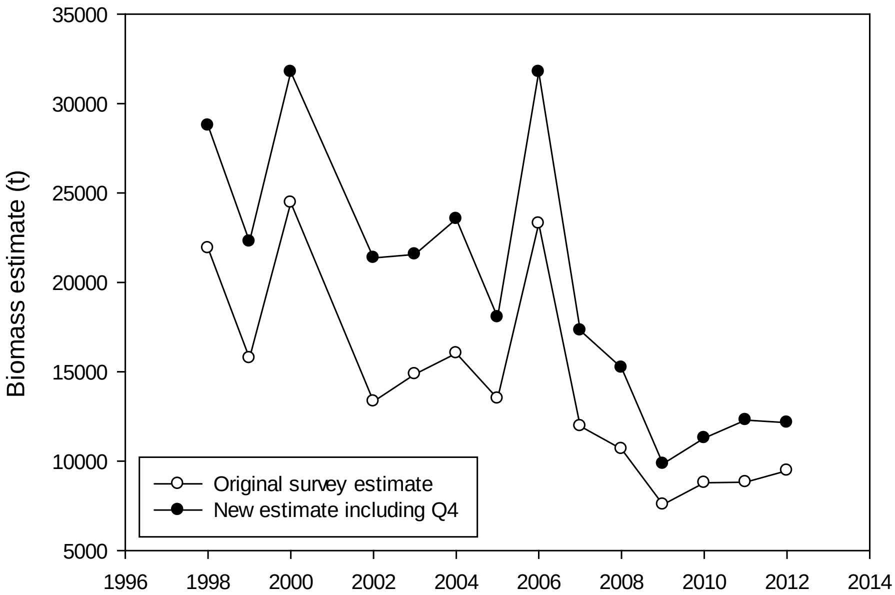


Fig 7: Biomass estimate in the different subdivisions (black line) and the overall survey estimate (grey line).

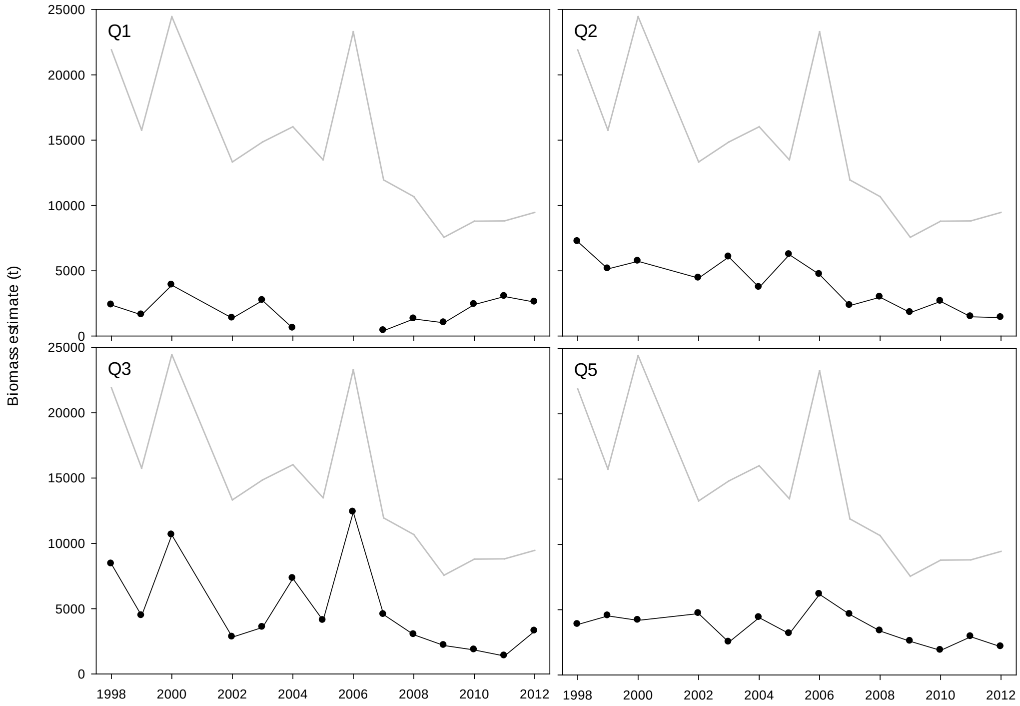


Figure 8: The biomass estimate when area Q3 is removed from the calculations.

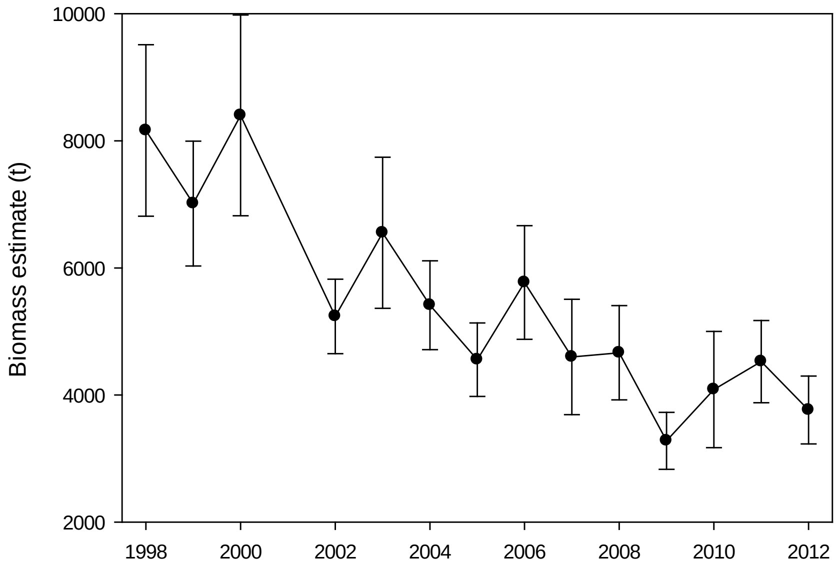


Figure 9: Survey trend (t) using the original calculations (top panel) and applying most things discussed in this document 1) Disregard subdivision Q1 2) Disregard subdivision Q3 and 3) Extend Q5 to include Q4 shelf.

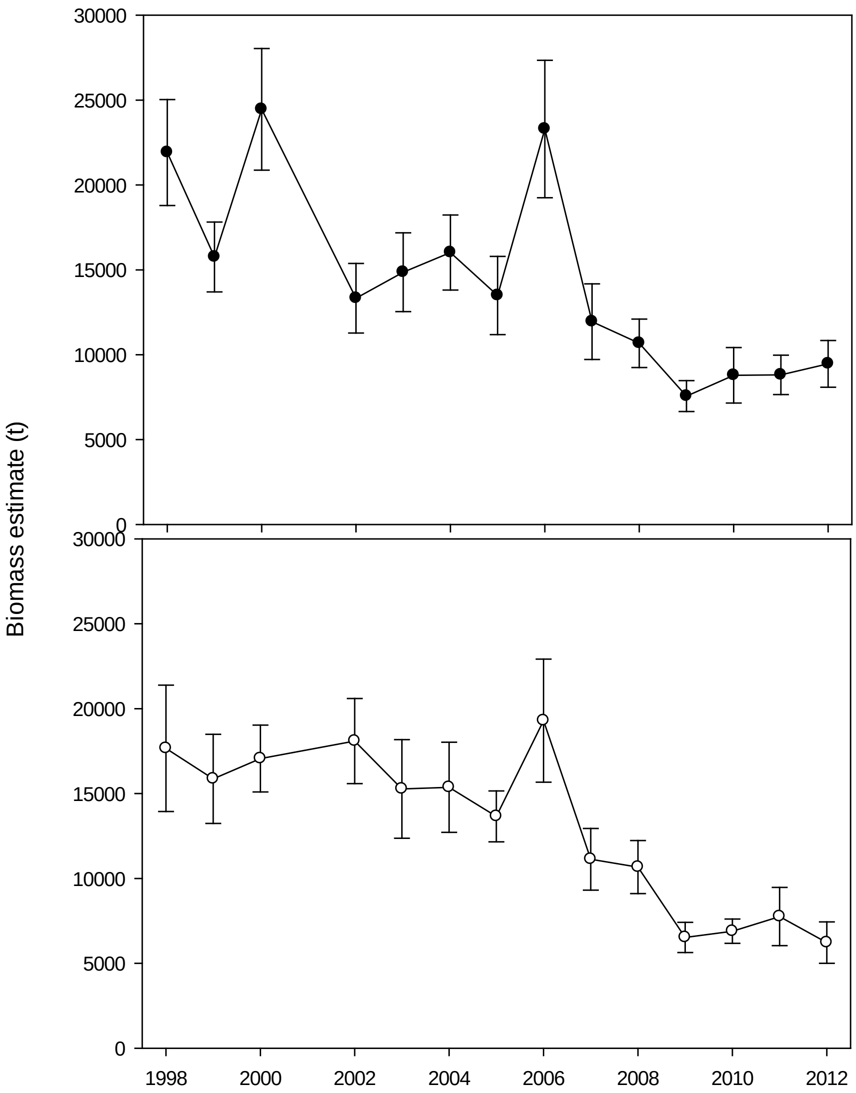
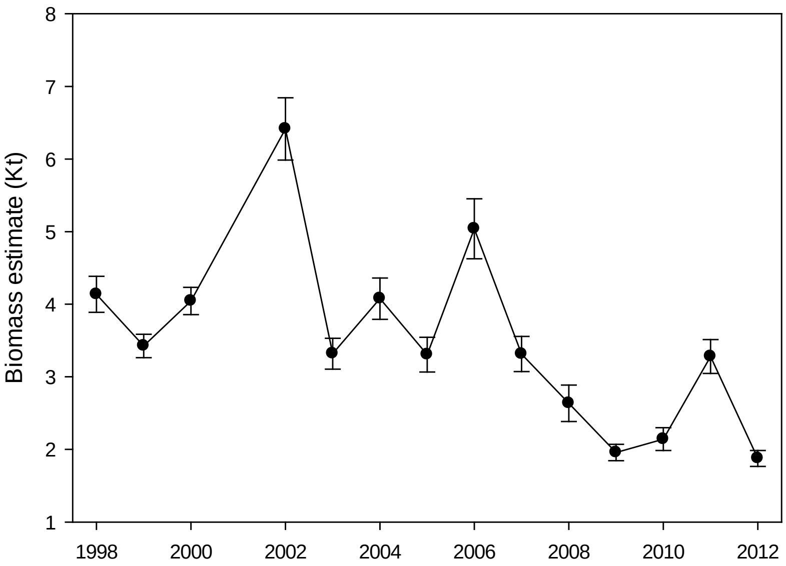


Figure 10: Biomass estimate (Kt) using only depth strata



Constructiong a combined index for Greenland halibut (*Reinhardtius hippoglossoides*) in Subareas V, VI, XII, and XIV from the Icelandic Autumn survey and the

Gudmundur Thordarson

Fisheries Advisory Section
Marine Research Institute, Reykjavík, Iceland
(gudthor@hafro.is)

November 22, 2013

Abstract

A combined index for Greenland halibut is constructed from Greenland deep-water survey (EG) and the Icelandic Autumn Survey (IAGS). These two surveys cover most of the distribution of Greenland halibut in this management unit except the Faroe Islands. The combined index shows shows a very similar overall trend as the index from the Icelandic Autumn Survey.

1 Introduction

Greenland halibut in Subareas V, VI, XII, and XIV is surveyed by three surveys. The Icelandic Autumn survey (IAGS), the Greenlandic Greenland halibut survey (EG) and the Faroe Greenland halibut survey. In many aspects the Icelandic and Greenland Survey are similar and combined they cover most of the known distribution of Greenland halibut in that management area (Figure 1). Apart from the northern most fishing area in the Greenland EEZ the Faroe survey covers the rest of the area. However the Faroe survey design is very different as it is not standardized.

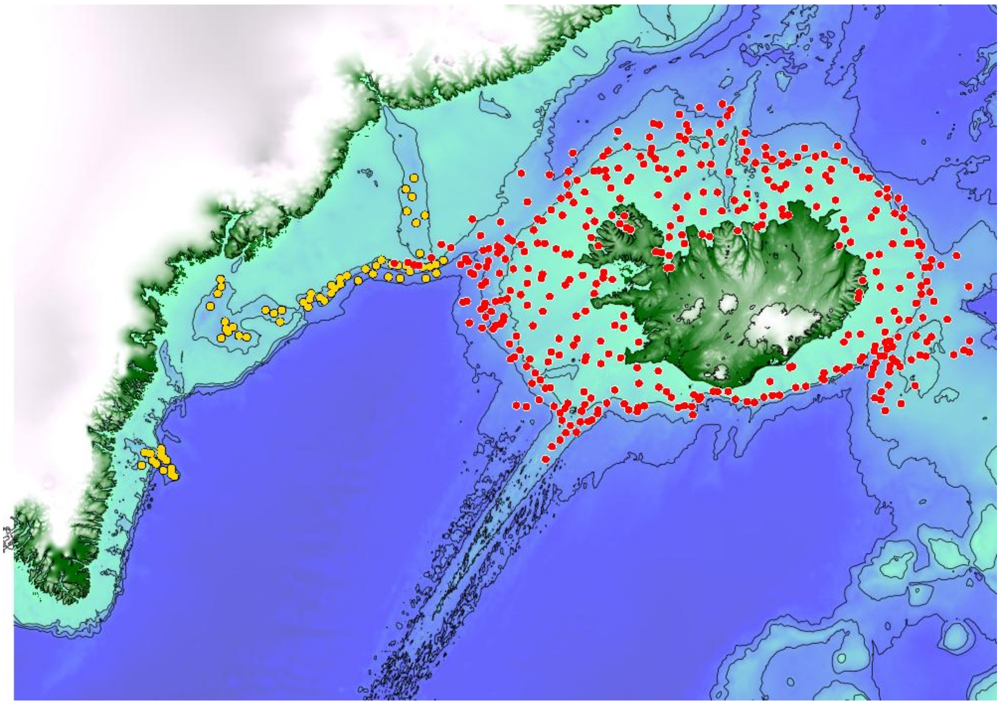


Figure 1: Stations covered in 2012 by the IAGS (red points) and EG (yellow points)

The IAGS and the EG have been used in the Bayesian stock production model currently used for assessing Greenland halibut in the NWWG. The surveys show slightly different trends, specially in the terminal years. This results is that the assessment model follows the IAGS much closer than the EG as the IAGS has closer correlation to the commercial CPUE which seems to a large extend be driving the model. Because of the contradicting signal in the terminal years it is of interest to combine the indices.

In this document an attempt is made to construct one index by combining the Icelandic Autumn survey and the Greenlandic Greenland halibut survey. The critical assumption made is that the catchability, q, in the two surveys is the same. In many ways the surveys are quite similar, they use similar gear (but not the same), they are conducted closely in time (2 months gap) and the survey design is similar (See table 1).

1 Introduction

Table 1: Comparison of the Icelandic Autumn survey and the Greenlandic Greenland halibut survey, (from WGNEACS-2013).

Survey	Survey acronym	IAGS	EG
	Full name	Autumn Groundfish Survey along the continental shelf and slope of Iceland	Greenland halibut survey in East Greenlandic waters
	Nation	Iceland	Greenland
	Month	10	8/9 (until 2008 6)
	Periodicity	annually (except 2011)	annually (except 2001)
	First year of time series	1996/2000	1998
Design parameters	Area	Icel. shelf and slope	East Greenlandic waters from 61°45
	Area coverage	317,000km^2	37,397km^2
	#hauls 0-400m	204	0
	#hauls 401-600m	74	10
	#hauls 601-800m	45	12
	#hauls 801-1000m	30	16
	#hauls 1001-1200m	20	8
	#hauls >1200m	8	6
	Depth range	0-1500m	400-1500
	Total # stations	381	40-55 (depending on ice coverage)
	Design	Stratified random	Buffered stratified random
	Towing speed	3.8 knots	3 knots
	Towed distance	3 nm	2.5 nm
Gear specifications	Gear type	Bottomtrawl	Bottomtrawl
	Gulltoppur	Alfredo III	
	Drawing available	Yes	Yes
	Headrope length	35.6	na
	Groundrope length	22.6	na
	Mesh-size roof	165	140
	Mesh size cod-end	40	30
	Ground gear	Rockhopper	Rockhopper
	Weight of ground gear	2470	na
	Door type / area	Polyice no 8/8m^2	Injector?
	Weight of doors (kg)	2700	2700
	Door spread	120-130	100-150
	Wing spread	15.5/17.8	na
	Sweeps	na	na
Biological sampling	Catch weight	Yes	Yes
	All species identified	Yes	Yes
	Length distribution of all species	Yes	Yes
	Individual weights for deep-water species	Yes	*R. hippoglossoides*
	Sex and maturity for deep-water species	Most species (∼25)	*R. hippoglossoides*
	Stomach content for deep-water species	Some species (15)	No

1 Introduction

2 Exploring the indices

2.1 Calculated indices

In figure 2 total biomass indices from both surveys are plotted as they are normally presented at the NWWG. It should be noted that in the Bayesian Stock Production model the EG index is derived from a glm-model but here is the swept area index. The glm index has a more similar trend as the IAGS than the swept area one. The IAGS shows a decline in biomass from 2001 to 2004 but then a slow increase. On the other hand the EG shows a more or less a continuous decrease from 2002 to 2009 and then very slight increase.

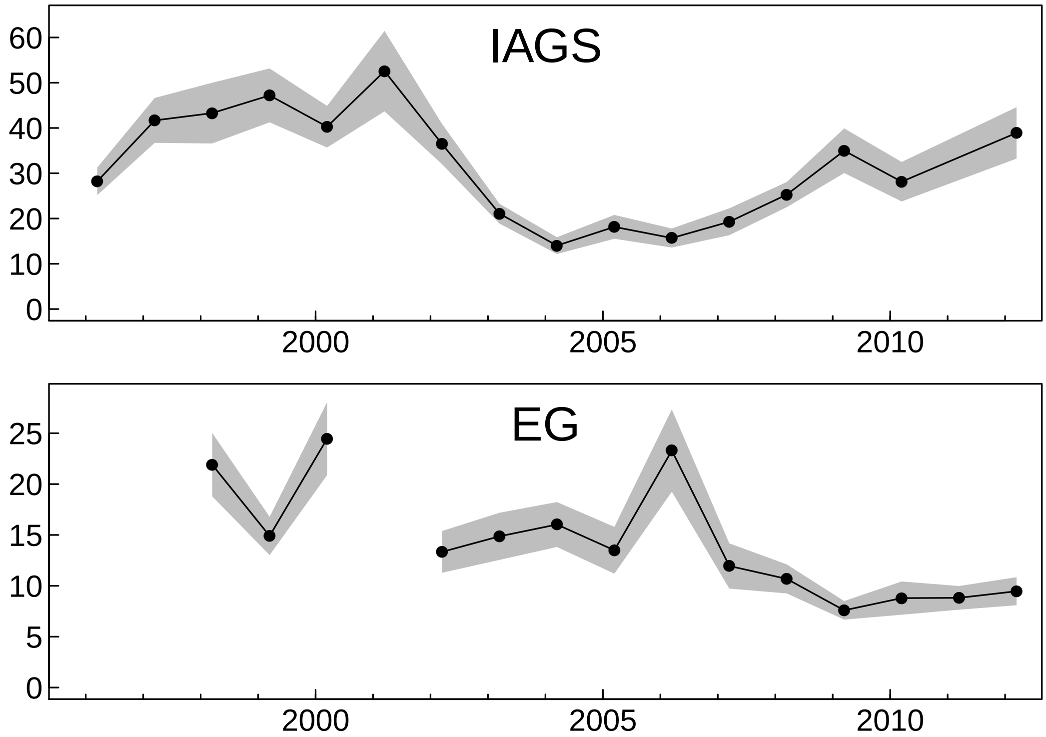


Figure 2: Total biomass index of Greenland halibut from the Icelandic Autumn survey (IAGS) and the Greenlandic Greenland halibut survey (EG). Both indices are swept-area indices based on stratification.

2.2 Raw indices

As the processing of the data, i.e. stratification, calculation routines, can have considerable effect on the index it is of interest to look at the data with minimum processing. Therefore the following raw index is constructed using:

$$rI = \sum(\alpha \times L_i^{\beta}) \times N_i \tag{1}$$

Where rI is 'raw index', L is length in cm, i is the length-group and N_i is the number caught in each length-group. α is set at 0.01 and β at 3.0. So in short there is no standardization of tow-lengths or anything. In figure 3 the raw indices are plotted on top of the calculated indices from figure 2 (All indices scaled with their mean). In the case of the IAGS there is hardly any difference between the raw index and the calculated one.

There is some discrepancy between the EG raw index and the calculated one, specially in the beginning of the time series. However the overall trend is the same and since 2007 the indices are virtually the same.

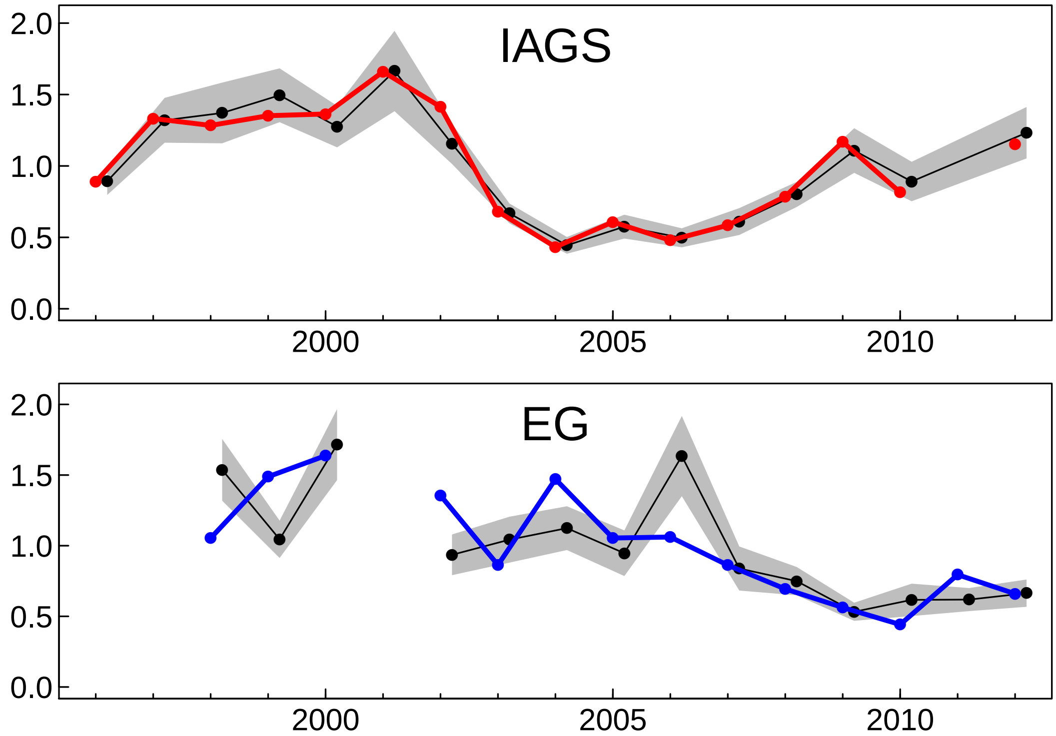


Figure 3: Comparison of trends in total biomass indices of Greenland halibut from the Icelandic Autumn survey (IAGS) and the Greenlandic Greenland halibut survey (EG). The black lines and shaded area are the calculated index ± 1 SE but the red and blue lines are the raw indices.

When looking at the raw indices in absolute terms it can be seen that in the beginning the IAGS raw index was 30 to 50% higher than the EG raw index. However in the period 2003 to 2007 the two indices were roughly on par. After 2007 the difference increases again to similar levels as before 2003 as the IAGS raw index increases the EG raw index has a continuous downward trend from 2004 to 2012 (Figure 4). Adding the two raw indices (black lines and points in figure 4) the resulting combined index has much closer resemblance to the IAGS raw index. This is simply because the IAGS raw index has a much stronger signal (more ups and downs) than the EG raw index and also as for most of the period the IAGS raw index is considerably higher than the EG raw index.

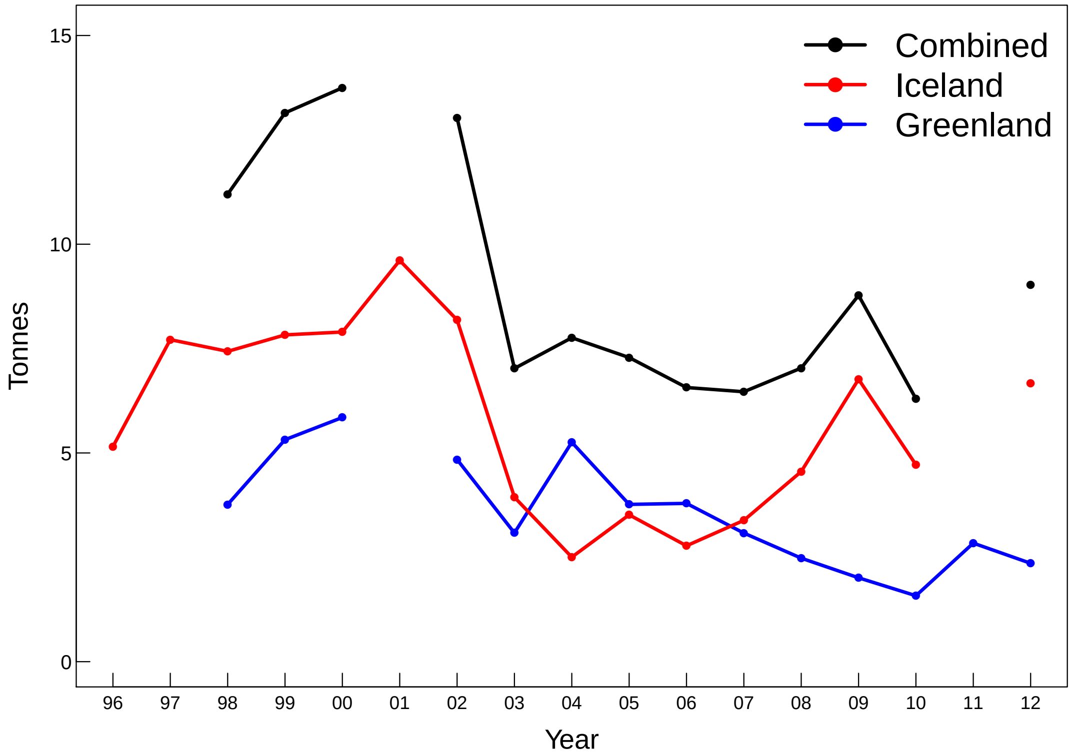


Figure 4: Raw indices from the IAGS (Iceland) and EG (Greenland) and a combined raw index by adding the two raw indices together.

3 A unified stratification scheme for both surveys

As people normally do not believe simple data exploration as done in 2.2 and also that it is not straight forward to assign relative importance to the two indices a unified stratification scheme is presented for the two surveys. The main aim of the scheme was to have rather large stratas, so that they had a good number of stations in them. The second objective was to have the stratas small enough so they would not extrapolate biomass over wast un-surveyed areas. The stratas are plotted in figure 5.

The EG is a much smaller survey than the IAGS so the first aim of having many stations in each strata was not obtained for the EG part (Table 2). This specially applies to the northern most strata (#1) but also to the small stratas in the south (#6 to #8).

Information on the stratas in Icelandic waters, size and number of stations covered each year, is given for the stations in waters less than 400 m depth in table 3 and for stations deeper than 400 m in table 4. The stratas in table 3 (>400 m) are not used in the combined swept index as hardly any Greenland halibut is caught at depths less than 400 m and the EG does not go to shallower waters than 400 m (See table 1).

Table 2: Number of stations covered for each strata by year in the Greenland deepwater survey in 1996 to 2012. Size in nautical square miles of each strata is given in the table header. Green area in figure 5

Strata No	1	2	3	4	5	6	7	8
Size (Nm)	2041	1429	1910	803	2681	235	58	437
Year								
1996	0	0	0	0	0	0	0	0
1997	0	0	0	0	0	0	0	0
1998	5	18	11	3	8	1	3	4
1999	1	18	12	5	6	0	8	4
2000	2	14	12	3	10	1	5	5
2001	0	0	0	0	0	0	0	0
2002	0	15	10	1	3	0	6	5
2003	3	13	9	2	6	0	5	0
2004	2	14	3	7	6	6	4	7
2005	0	18	3	3	7	1	5	9
2006	0	22	4	4	0	2	6	4
2007	2	17	3	7	1	2	6	8
2008	4	16	3	3	6	3	6	4
2009	4	18	4	4	14	2	7	9
2010	2	17	3	2	10	0	4	8
2011	6	14	5	2	13	3	5	11
2012	7	20	7	4	10	5	4	7
2013	0	0	0	0	0	0	0	0

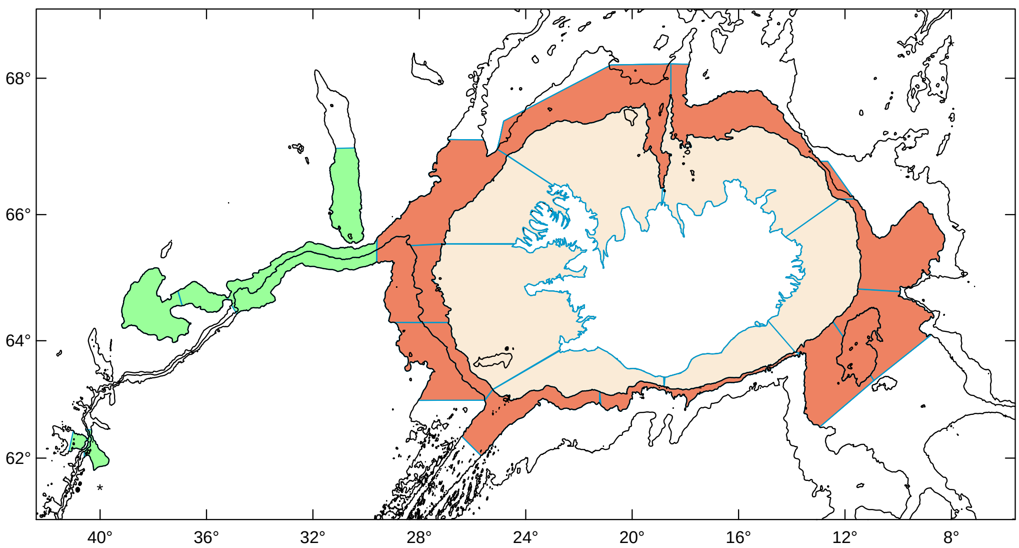


Figure 5: Stratification scheme used for calculating a combined index for Greenland halibut. Stratas in green are covered by the Greenlandic survey and the brown (≥400 m) and pink (<400 m) by the Icelandic Autumn survey

3 A unified stratification scheme for both surveys

Table 3: Number of stations covered for each strata by year in the Icelandic Autumn survey in 1996 to 2012 in waters less than 400 m. Size in nautical square miles of each strata is given in the table header. Pink area in figure 5

Strata No	9	10	11	12	13	14	15
Size (Nm)	4813	14313	4791	3888	7239	9304	9288
Year							
1996	14	32	13	8	27	32	31
1997	17	34	13	8	28	34	32
1998	17	35	14	8	27	33	31
1999	17	35	15	8	28	39	37
2000	21	40	18	9	29	38	38
2001	21	40	17	12	30	34	37
2002	21	39	17	13	30	35	38
2003	21	39	18	11	30	35	39
2004	21	41	18	12	30	35	38
2005	20	40	18	13	30	35	39
2006	21	40	17	13	30	35	39
2007	21	40	17	12	30	34	40
2008	25	43	18	13	34	39	43
2009	25	43	18	13	32	38	41
2010	25	43	18	12	33	38	42
2011	0	0	0	0	0	0	0
2012	24	43	18	12	33	37	42
2013	24	44	17	13	33	38	42

Table 4: Number of stations covered for each strata by year in the Icelandic Autumn survey in 1996 to 2012 in waters deeper than 400 m. Size in nautical square miles of each strata is given in the table header. Brown area in figure 5

Strata No	16	17	18	19	20	21	22	23	24	25	26	27	28
Size (Nm)	868	1715	2273	1205	3166	3294	1407	3808	2095	3778	4737	4248	5787
Year													
1996	21	11	19	5	5	0	0	11	3	5	10	17	18
1997	20	11	20	5	5	0	0	11	3	5	10	18	20
1998	18	12	19	6	5	0	0	12	3	5	10	19	19
1999	21	12	18	6	5	0	0	12	3	5	10	20	22
2000	20	16	18	8	5	16	7	24	7	6	10	19	21
2001	19	16	19	7	5	19	10	24	7	6	10	21	22
2002	21	14	20	8	5	19	10	23	7	6	10	20	22
2003	20	16	18	8	5	19	11	24	7	5	11	20	21
2004	21	17	18	6	5	19	10	23	7	7	10	20	22
2005	21	15	19	7	5	19	9	23	7	7	10	20	21
2006	20	16	17	7	5	19	10	24	7	6	10	20	21
2007	20	17	17	7	5	19	11	23	7	7	10	20	21
2008	20	17	17	7	5	19	9	23	7	7	10	20	21
2009	20	16	18	7	5	19	9	24	7	7	10	20	22
2010	14	13	15	8	4	19	10	19	7	7	10	20	22
2011	0	0	0	0	0	0	0	0	0	0	0	0	0
2012	16	12	15	7	4	19	11	19	7	7	10	21	22
2013	15	13	14	6	4	20	9	19	7	6	10	20	21

3 A unified stratification scheme for both surveys

4 Index calculation

For calculation of indices the Cochran method is used (Cochran 1977). The survey area is split into sub-areas or stratas and an index for each subarea is calculated as the mean number in a standardized tow, divided by the area covered multiplied with the size of the sub-area. The total index is then a summed up estimates from the sub-areas or stratas.

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

$$\bar{Z}_i = \frac{\sum_i Z_i}{N_i} \tag{2}$$

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

$$I_i = \bar{Z}_i \left(\frac{A_i}{A_{tow}} \right) \tag{3}$$

and the sample variance in the i-th stratum:

$$\sigma_i^2 = \left(\frac{\sum_i (Z_i - \bar{Z}_i)^2}{N_i - 1} \right) \left(\frac{A_i}{A_{tow}} \right) \tag{4}$$

where A_i is the size of the i-th stratum in square nautical miles (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:

$$I_{region} = \sum_{region} I_i \tag{5}$$

The variance is:

$$\sigma_i^2 = \sum_{region} \sigma_i^2 \tag{6}$$

and the coefficient of variation is

$$CV_{region} = \frac{\sigma^2_{region}}{I_{region}} \tag{7}$$

5 Combined swept area index

The combined swept area index is presented in figure 6. As the years 2001 and 2011 are missing from the data series it is difficult to see the trends in the data-series. However all indices of biomass decreased after 2000. However the total biomass and biomass larger than 40 cm (proxy for harvestable biomass) have shown some increase since 2006. This is hardly detectable for the SSB proxy (biomass >60 cm).

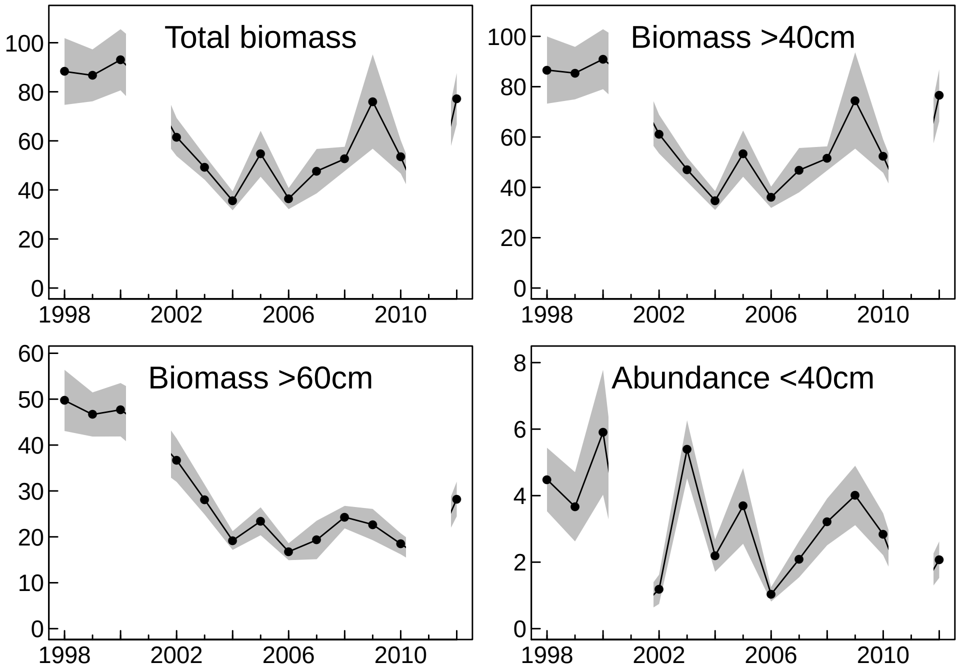


Figure 6: Combined swept area index from the IAGS and EG for total biomass, biomass larger than 40 cm (proxy for harvestable Greenland halibut and biomass larger than 60 cm that is a proxy for SSB and abundance less than 40 cm, a proxy for recruitment.

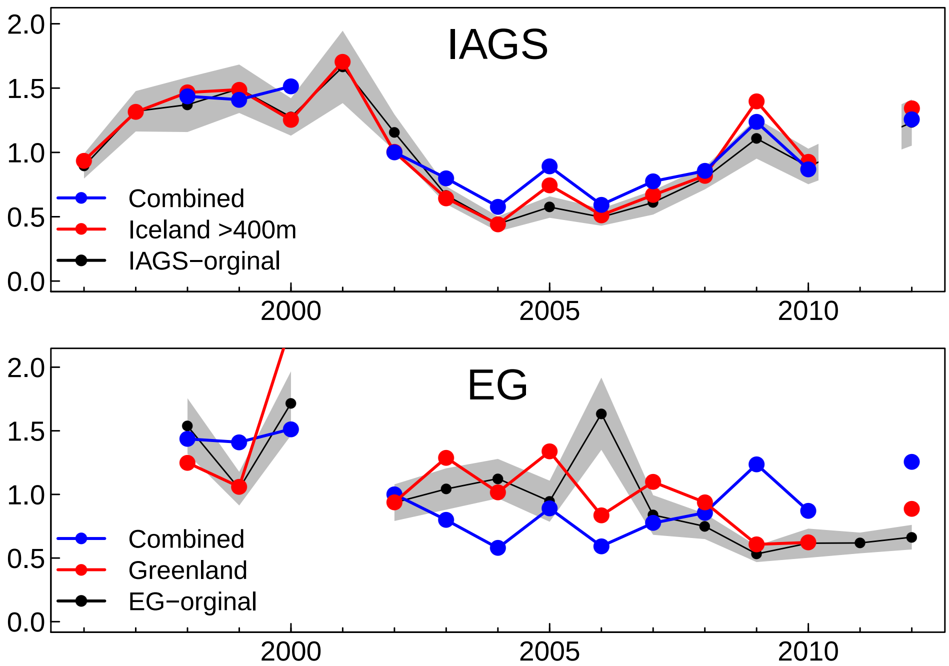


Figure 7: Comparison of the combined index (blue) to the swept area indices (black) normally presented at the NWWG. Also an index using the stratification scheme used for the combined index is presented for Iceland (upper) and for Greenland (lower) as red line and points. (See text for details).

5 Combined swept area index

5.1 Comparing the combined index to the original indices

The combined index seems to be much closer to the IAGS index than the EG index. This can be seen in figure 7 where the indices are standardised and plotted in the same graph. In the upper plot the original IAGS index is plotted with SE. The blue line and points is the combined index and the red line and points is the index for Iceland at depths greater than 400 m using the stratification scheme for the combined index. There is very little difference between the combined index and the one from Iceland. On the other hand the comparison to the original EG-index shows that there is little correlation to the combined index (Figure 7 lower). However the index using the stratification scheme for the combined index for the Greenland area is closely related to the original EG-index.

5.2 Filling up the gaps in the index

As can be seen in figure 6 on page 10 there are two gaps in the combined index. The first one is in 2001 as the EG did not take place. The second gap is in 2011 as the IAGS was canceled due to industrial action by crews of the MRI research vessels. Similarly as the IAGS seems to be driving the combined index (See figure 7) it may be prudent to extend the combined index back to 1996.

A simple approach is used here to fill up these three gaps. It simply involves using the mean of the previous and the following year to interpolate the index over the gap year.

A: The value for the Greenland part of the index in 2001 is the mean of the Greenland combined index in 2000 and 2002. This value is then added to the Icelandic index (>400 m) to get the 2001 value for the combined index (Figure 8a).

B: The value for the Icelandic part of the index in 2011 is the mean of the Icelandic combined index in 2010 and 2012. This value is then added to the Greenlandic index to get the 2011 value for the combined index (Figure 8b).

C: The values for the Greenlandic index in 1996 and 1997 are simply the mean of the values in 1998 and 1999. This approach was used as there was no correlation between the Icelandic and the Greenlandic index that could have been used to extrapolate the values back in time (Figure 8c).

5.3 Indices divided by sex

The combined index was also calculated for each of the sexes (Figure 9). The trends are roughly the same for the sexes, both in biomass and in abundance.

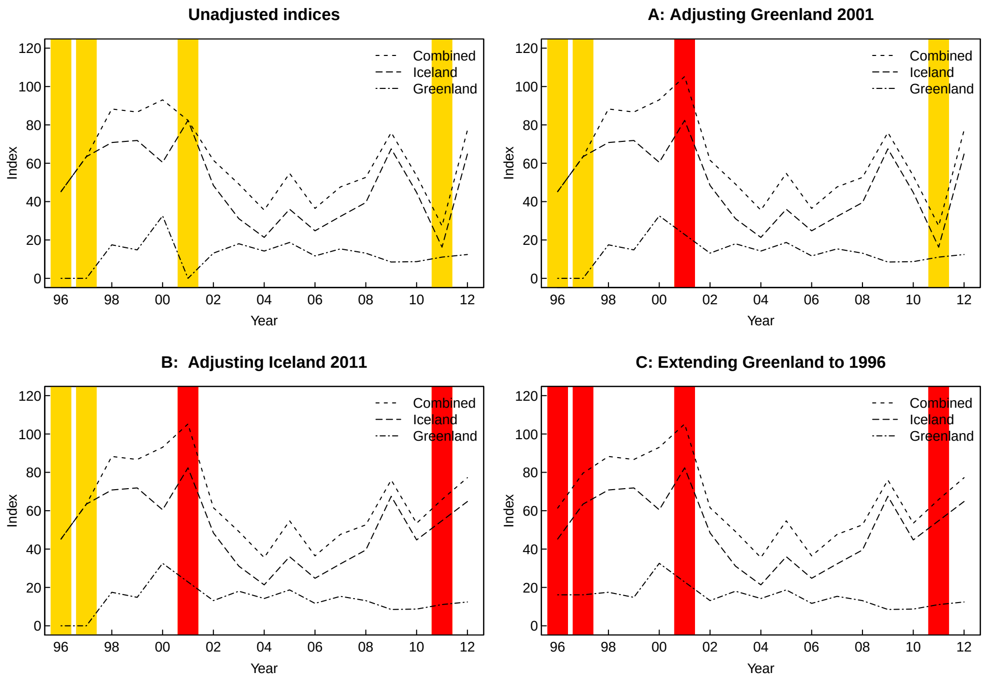


Figure 8: Filling up gaps and extending the Combined index back in time. Yellow blocks show periods of unadjusted index and red of adjusted indices. See text for details

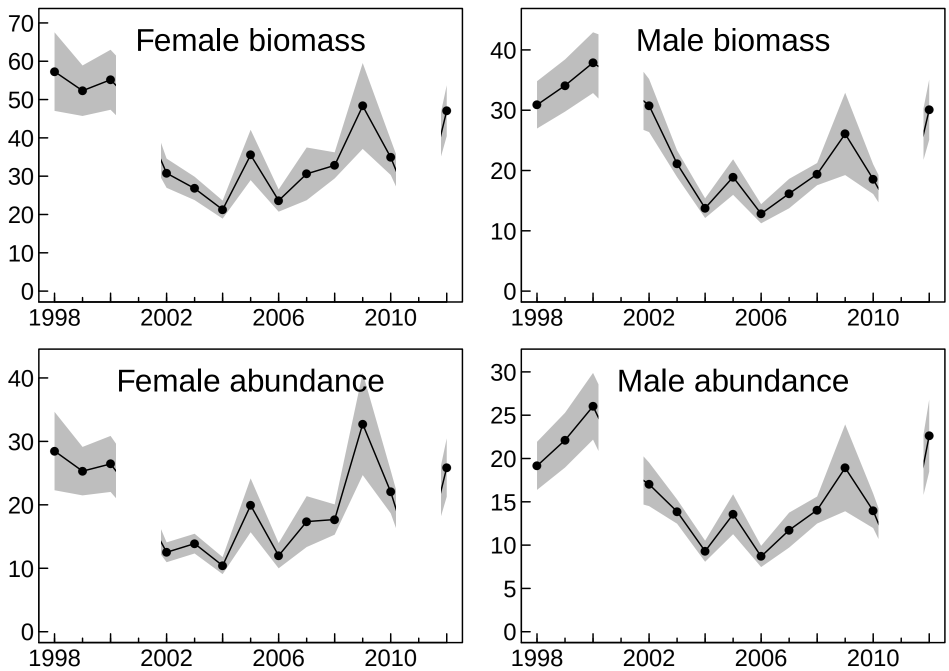


Figure 9: Combined index from IAGS and EG for Females and Males of Greenland halibut.

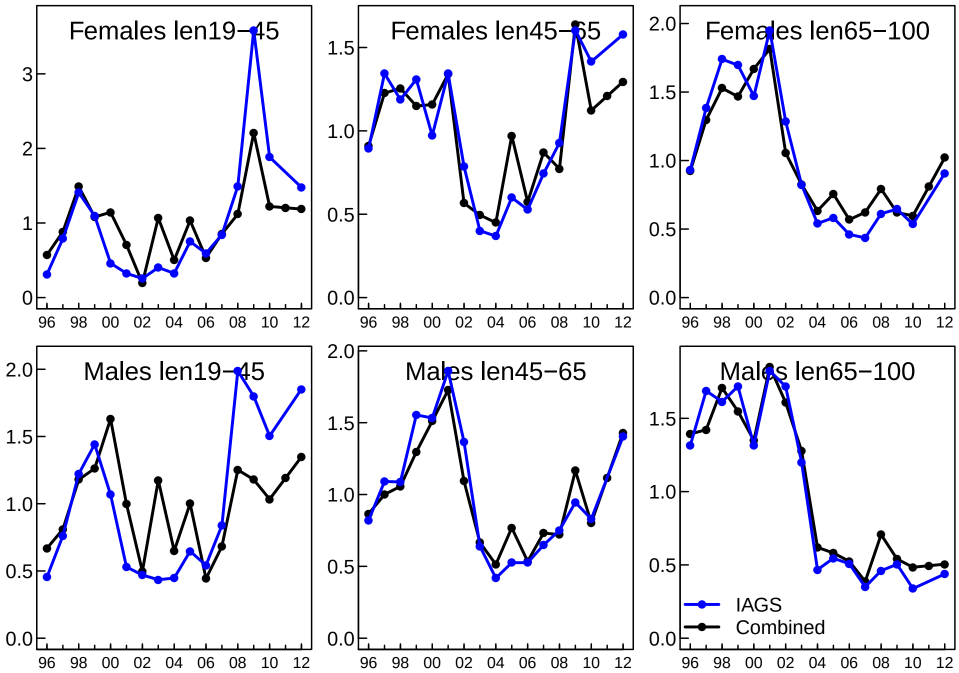


Figure 10: Length dis-aggregated indices by sex for Greenland halibut used in the Gadget model.

6 Sex divided length dis-aggregated indices as input for the Gadget model

In the base model presented in WKBUT2013:WD04 the sex divided length dis-aggregated survey indices used are from the IAGS. In figure 10 the combined dis-aggregated indices are compared to the ones from IAGS. For females it seems that the IAGS index gives higher estimates of abundance for length-groups 19-45 and 45 to 65 than the combined index. The same applies to the smallest length-group of male (19-45cm). For the three remaining length-groups the indices are virtually the same.

It should be noted that 'filling in of the gaps' has been done for the Gadget indices.

WD 11

Some investigations on the Bayesian assessment model for GHL in ICES Div V+XIV

Benchmark November 2013

Carsten Hvingel

Sensitivity to priors

In the Bayesian approach a hypothesis about what the model parameters should look like (their probability density distribution) can be included as "priors". These priors are developed before the data are analyzed and is thus based on any ancillary information available.

The priors for this model are described in WD xx.

P_0, biomass of the initial year

The prior for P_0 (the relative biomass of 1960 equal to the first year of the modeled time series) is given an informative prior which is close to K. The rationale being that there was no fishery prior to 1960 and under the model assumptions K equals the equilibrium stock size in the absence of fishing. Alternative hypotheses with means for P_0 at 0.5, 1 and 1.75 was investigated. The posterior of P_0 is highly sensitive to the setting of the prior (Fig. 1), i.e. the posterior equals the prior as there is little or no information in the data on what this parameter should look like. The trajectory of stock biomass is thus affected as well (Fig. 2). However, the series with the different priors converge over time and once the data (biomass index series) becomes available in 1985 the difference is negligible.

The influence of the P_0-prior on other parameters is small (Fig. 1), however, there is a slight tendency of a more optimistic view on stock production with a lower prior on P_0 (MSY increases see Fig. 1).

Conclusion: Overall the setting of the P_0 prior has little influence on model results and very little or no influence on determining current stock status.

q_x, the catchabilities of biomass index series

There was no external information on these parameters hence non-informative priors were used.

For scaler parameters like the catchabilities (q_{Ice} , q_{Green} and q_{cpue}) a prior uniform on a log scale has been recommended (cf. Gelman et al. 1995, Punt and Hilborn 1997, McAllister and Kirkwood 1998, Hvingel and Kingsley 2006). We are not aware that this has been questioned in the literature.

Conclusion: Priors alternative to the ones used (uniform in log space) would by definition be informative and was therefore not investigated.

σ_x, the error terms

The prior distributions for the error terms associated with the biomass indices (the observation errors) and the modelled biomass (process error) were assigned inverse gamma distributions as error standard deviations typically follow this kind of distribution. The observation errors were informative. The distribution of their standard deviations (≈CV) ranged between 0.06 and 0.26 – the values observed for these data.

We tested the influence of making these priors slightly wider comparable to the priors used in a similar model for shrimp in the Barents Sea. This option didn't change the posteriors for the standard deviations (SD) for the two survey series much (Fig. 1) while the SD for the CPUE series increased somewhat. This implies that the model put less weight in the CPUE series and comparatively more weight on the survey series. As a result the SD on P_t increases slightly and accordingly the uncertainty on the estimate of P_{2013} (Fig 1). The median of P_{2013} remains unchanged. No changes were observed for the other parameters. A standard uninformative prior is used for the process error and was therefore not explored further.

Conclusion: The medians are not sensitive to the choice of priors for the observation errors. However, the uncertainties of stock status estimates did change slightly. To avoid having to choose the priors for the observation error it could be considered to use the series of observed uncertainties calculated for biomass series as a direct data input to the model.

K, carrying capacity

We tested two extreme options to investigate in which directions the model would respond to changes in the *K* prior. The posterior of *K* is sensitive to the prior (Fig. 1) and as the magnitude of K is connected with the scaling of absolute stock size the posteriors for the catchabilities responded as well. However, other parameters are not sensitive and most importantly *MSY* (Fig. 1) and relative stock biomass (Fig 2) are only marginally affected.

Conclusion: There is not a lot of information in the data regarding *K* and its posterior is therefore sensitive to the prior. The model is thus somewhat sensitive to whether the informative prior used is a sensible/realistic one. However, stock status and *MSY* are fortunately not particularly sensitive to the setting of the prior for *K*.

MSY, Maximum Sustainable Yield

A non informative uniform prior was given to *MSY* and was therefore not investigated further. The upper limit was chosen high enough not to truncate the posterior distribution or have any influence on other parameters.

Process errors

The Model assumes time-independent process error. This assumption was investigated by examining annual process errors standardised to the estimated relative biomass (P_t) (Fig. 3). The process errors were variable with maximum values around 30%P_i and a serial correlation of 0.6. This indicated that there are factors other than those included in the model that affects stock dynamics.

This is not so much a problem for the estimates of the historical stock trajectory as these estimates should remain unbiased. However, the serially correlated errors may increase the uncertainty of forward projections. When the occurrence of e.g. a “good year” increases the likelihood of another good year following, the oscillations in the stock may be larger than we predict with the current assumption of independence.

If we were able to include a term for autocorrelated errors in the model and get a good estimate of it from the past behaviour of the system, then we could use that to forecast the future behaviour and would then have a better estimate of the uncertainty of our predictions. We haven’t been able to do that yet.

if process errors are correlated, but we analyse the system as though they are uncorrelated, we will estimate a bigger process-error variance (than we would have estimated with a “clever” autocorrelation term in the model) and will then use that bigger variance in projecting forward, so will have a large uncertainty in predictions anyway.

Conclusion: The autocorrelated error might cause underestimates of uncertainty in model predictions. This is however partly compensated for by the increase in the estimate of the error variance caused by the autocorrelation itself. Furthermore, the observed errors for the most recent period (since 2006) have not been correlated (Fig. 3).

Questions and comments

From NWWG: ”Why does the uncertainty increase when going from estimates of the history of the stock to predictions when the model is a steady state model and everything is calculated in one go”?

Answer: I don’t understand the ‘steady state’ thing, except that they perhaps mean that all parameters of the system – including all those of the stock-dynamic relationships as well as the process error – are considered constant not only throughout past time but also through the present into the future. This applies also to the uncertainties associated with those parameters.

However, we would expect that the uncertainty associated with past estimates of the stock size would be presented by the model as substantially constant, but that future estimates of stock size would have uncertainties that increase progressively into the future because of the compounding of the uncertainties associated with the parameters of the stock-dynamic relationship and also the process error. Past estimates of stock size are locked into the values of the biomass indices. We are repeatedly applying an uncertain stock-dynamic relationship, so any future estimate should have a greater uncertainty than that of the preceding year, and estimates for all future years should have greater uncertainty than the estimate for the present. The *model* might be ‘steady-state’, but the *knowledge* stops at the present moment.

From the review i 2012: ”Given this is a Bayesian technique, it might be good to provide a summary of convergence criteria and metrics for this model”.

Answer: This is done in the WD XX.

From the review i 2012: “The priors on the catchabilities are not uniform in the catchability space. It is not clear how much influence this has on the final estimates. The fact that all the catchability priors are this way may make the catchabilities self-consistent, but influence other predictors, such as production and MSY.

Answer: There is a technical statistical reason to use uniform distributions in log-space as uninformative priors for the catchabilities (see section on priors above). They are made like that in order not to convey information to other parameters in the model e.g. MSY.

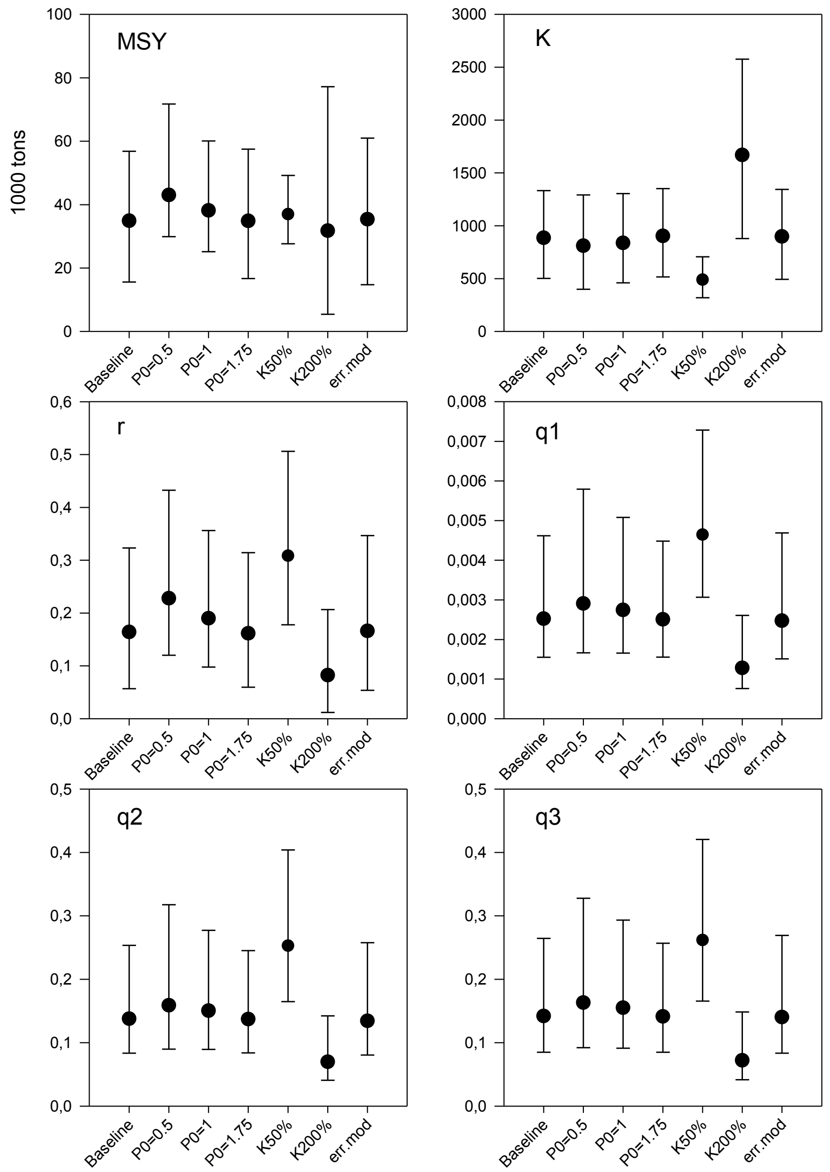


Fig 1. distributions of model parameters (one panel for each parameter: dot is the median and error bars is 90% confidence interval) in response to selected variations of the informative priors. “Baseline” is the 2013 assessment model; “P0=0.5, 1, 1.75” is priors with a variance similar to that of the 2013 model but with means set to 0.5, 1, 1.75 respectively; “K50%, 200%” is a prior equal to 0.5 and 2 times the prior used in the 2013 model; err.mod is slightly less informative priors on observation error equal to those used in Hvingel 2012. Figure continues on next page...

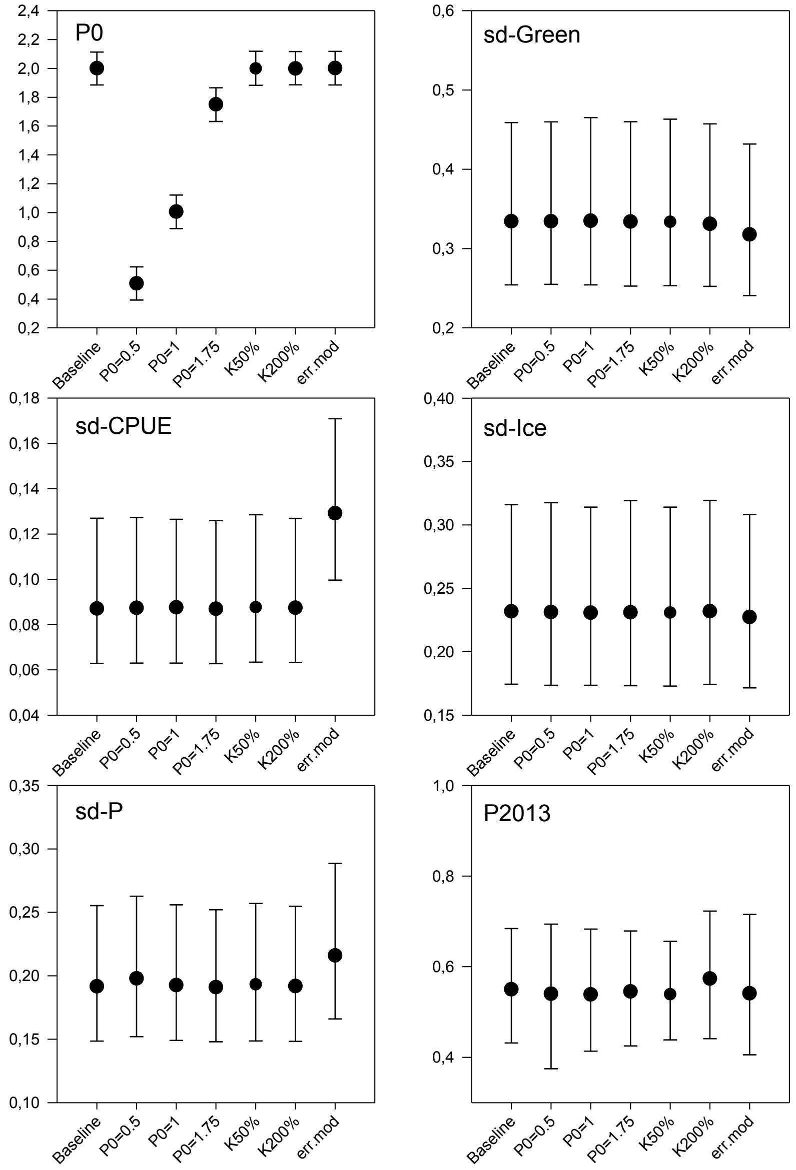


Fig. 1. ...continued

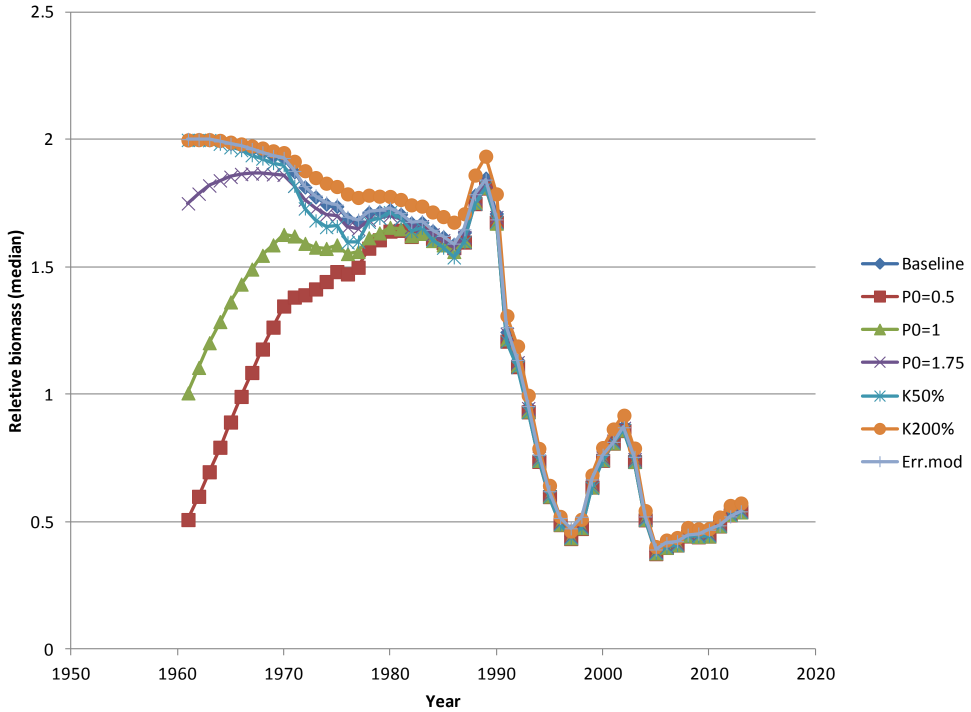


Fig. 2. Modelled relative biomass (median P) in response to selected variations of the informative priors. "Baseline" is the 2013 assessment model; "P0=0.5, 1, 1.75" is priors with a variance similar to that of the 2013 model but with means set to 0.5, 1, 1.75 respectively; "K50%, 200%" is a prior equal to 0.5 and 2 times the prior used in the 2013 model; err.mod is slightly less informative priors on observation error equal to those used in Hvingel 2012.

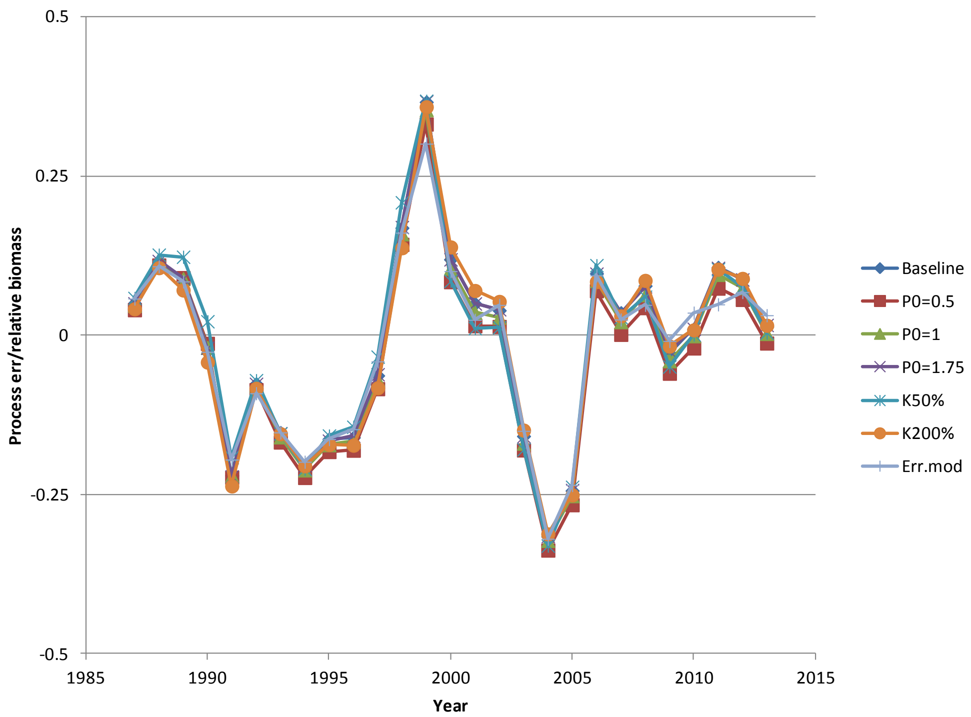


Fig. 3. Process error standardised to annual estimated stock biomass. “Baseline” is the 2013 assessment model; “P0=0.5, 1, 1.75” is priors with a variance similar to that of the 2013 model but with means set to 0.5, 1, 1.75 respectively; “K50%, 200%” is a prior equal to 0.5 and 2 times the prior used in the 2013 model; err.mod is slightly less informative priors on observation error equal to those used in Hvingel 2012.

A study on the possible scenarios for the exploratory gadget stock assessment model for Greenland halibut (*Reinhardtius hippoglossoides*) in Subareas V, VI, XII, and XIV

Bjarki Þór Elvarsson

Fisheries Advisory Section
Marine Research Institute, Reykjavík, Iceland
(gudthor@hafro.is)

Do not cite without authors permission

November 25, 2013

Abstract

This document describes the results from model alternatives tested in the exploratory Gadget stock assessment of Greenland halibut.

1 Model scenarios

In this analysis the Growth scenarios considered in WD-02 contrasted in terms of the fit to data, projected biomass and predicted yields. Furthermore these scenarios are combined with scenarios on abundance indices described in WD-01. A listing of the possible model alternatives are shown in table 1. Alternative Atl.1:2 is the base case described in WD-04. The parameters for each of the model alternatives in were estimated in the fashion as the base case and their respective fit to data and biomass estimates were contrasted.

	Alt.1:1	Alt.1:2	Alt.1:3	Alt.1:4	Alt.2:1	Alt.2:2	Alt.2:3	Alt.2:4	Alt.5:1	Alt.5:2
Growth scenario	SC1	SC2	SC3	SC4	SC5	SC1	SC2	SC3	SC4	SC5
Index scenario	I1	I1	I1	I1	I1	I2	I2	I2	I2	I2

Table 1: An overview of the model alternatives considered in this analysis. Growth scenerios 1 to 4 represent the unaltered Norwegian growth data (SC1), scaled Norwegian data (SC2), Icelandic age estimates (SC3) and scaled Icelandic age estimates respectively. SC5 respresents no data arising from aging. Similarly index scenarios 1 and 2 represent the autumn survey index in Va and the combined index from Va and East Greenland respectively.

2 Results

An overview of the final fit, i.e the fit after applying the iterative reweighting, to the various components is shown in table 2. The base case alternative did not show obvious model discrepancies when compared other alternatives. Fit to abundance indices is illustrated in figures 1, 2 and 3. It can be seen, that although the models can follow the observed survey index, the final estimate does not. Fit to length distributions is illustrated in figures 4 to 9. The ratio of females in the commerical catches is shown in figure 10.

Growth estimates are shown in figure 11. Estimated recruitment is shown in figure 14, ana there is little obvious correlation between model alternatives. The estimated fishing mortality is illustrated in figure 15, where a notable differnce between male and females is observed in some model alternatives. Figures 12 and 13 show the estimated biomass according to the model alternatives. Broad patterns appear to be similar, however terminal year estimated appear to vary between alternatives, see table 3 for exact values. Figure 16 show the estimated yield per recruit curves by model alternative. It appears that $F_{0.1}$ varies between 0.11 up to 0.23, while F_{max} is between 0.25 and upwards. Figure 3 shows the total landings per year and catch projections using $F_{0.1}$ as estimated by each model variant.

Model prognosis is shown in table 3.

3 Discussion

Overall the model alternative seem to show a similar pattern, both in respect to the data and estimated biomass. However they appear to differ substantially in respect to estimated growth and projected catches. This may be attributed to differences in the survey index for females in 44.5 to 64.5 cm which respresent a bulk of the commercial catches.

A harvest control rule based on F_{max} appears in this case to be illsuited for this particular stock. Both due to the fact it is illdetermined and more importantly F_{max} is higher than the current F in all cases. When projecting the stock status using F_{max} the estimate SSB is reduced from current levels in all cases.

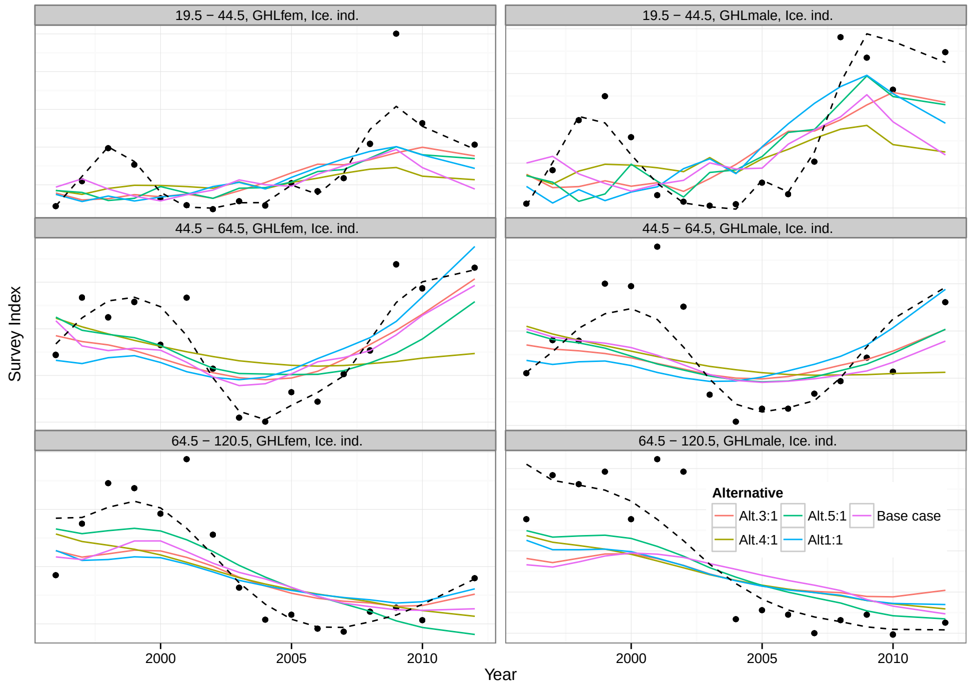


Figure 1: Abundance indices based on the autumn survey in Va (length aggregated and divided by sex). Points denote the observed values, solid lines final fit from the various model alternatives and broken lines fit from the best fit from the iterative reweighting (explained in the WD-04).

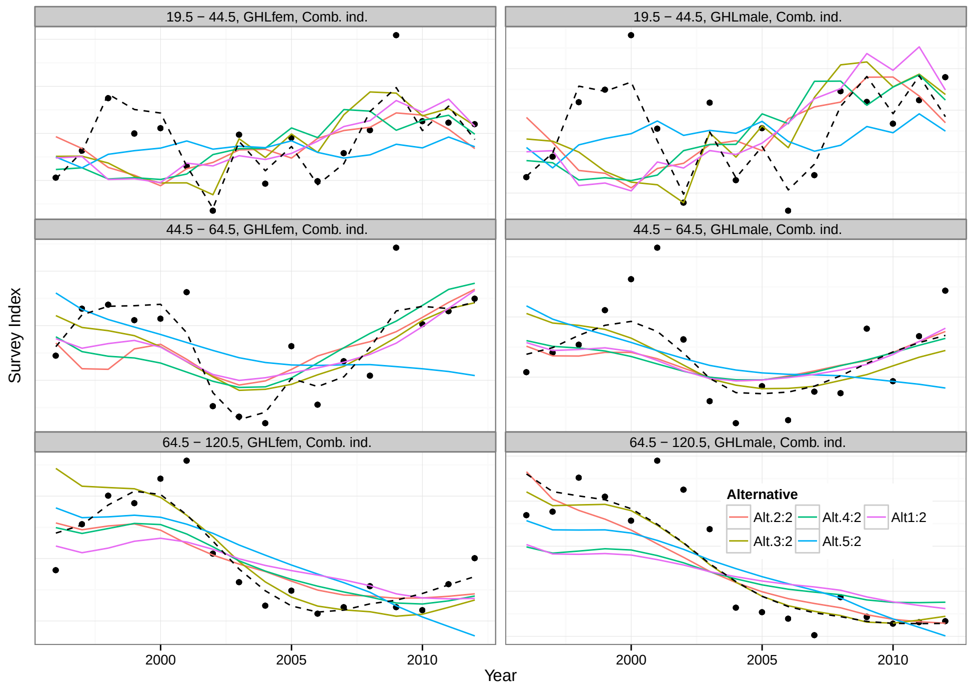


Figure 2: Combined abundance indices from the autumn survey in Va and East-Greenland (length aggregated and divided by sex). Points denote the observed values, solid lines final fit from the various model alternatives and broken lines fit from the best fit from the iterative reweighting (explained in the WD-04).

3 Discussion

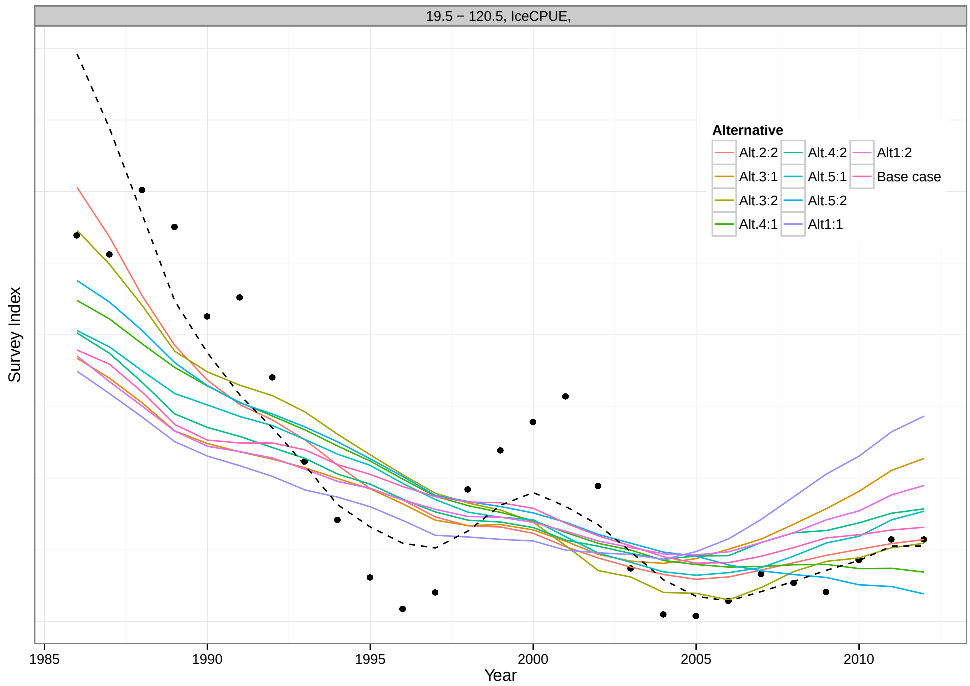


Figure 3: Commerial CPUE series. Points denote the observed values, solid lines final fit from the various model alternatives and broken lines fit from the best fit from the iterative reweighting (explained in the WD-04).

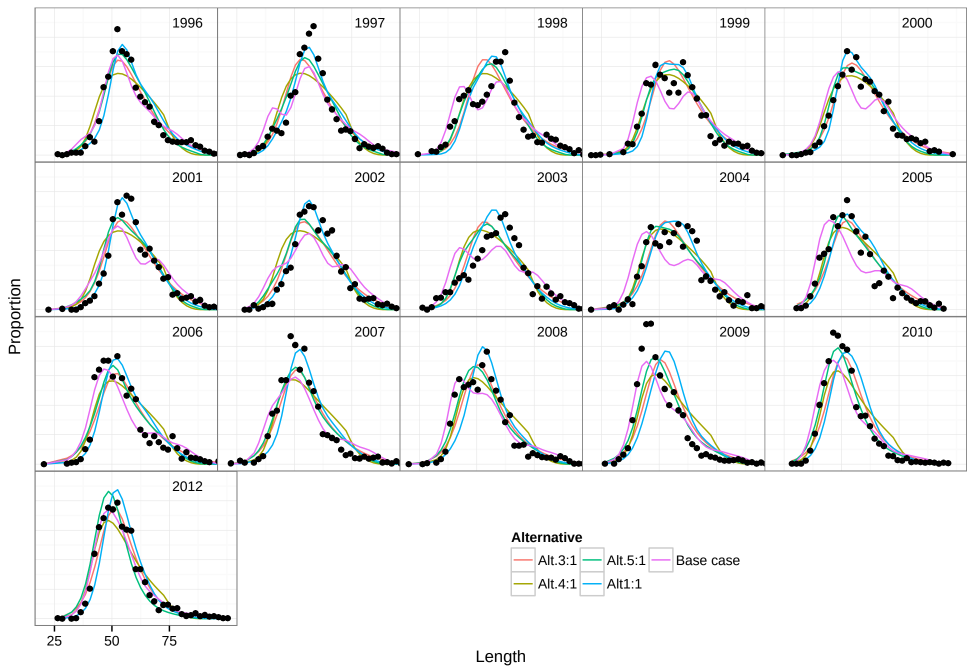


Figure 4: Female length distribution from survey in Va. Points denote the observed values, solid lines final fit from the various model alternatives.

3 Discussion

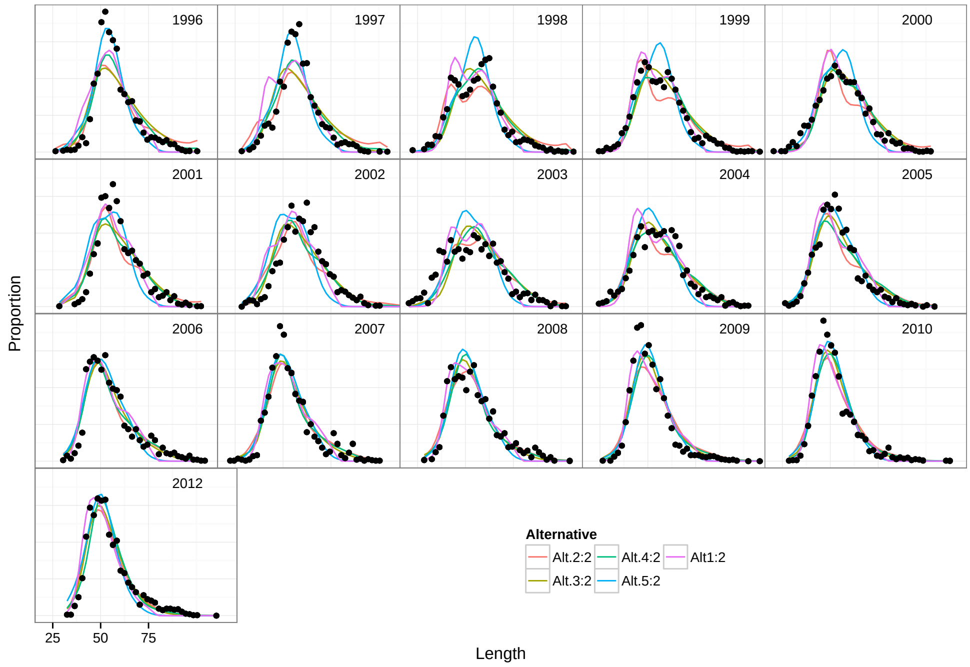


Figure 5: Female length distribution from the combined survey. Points denote the observed values, solid lines final fit from the various model alternatives.

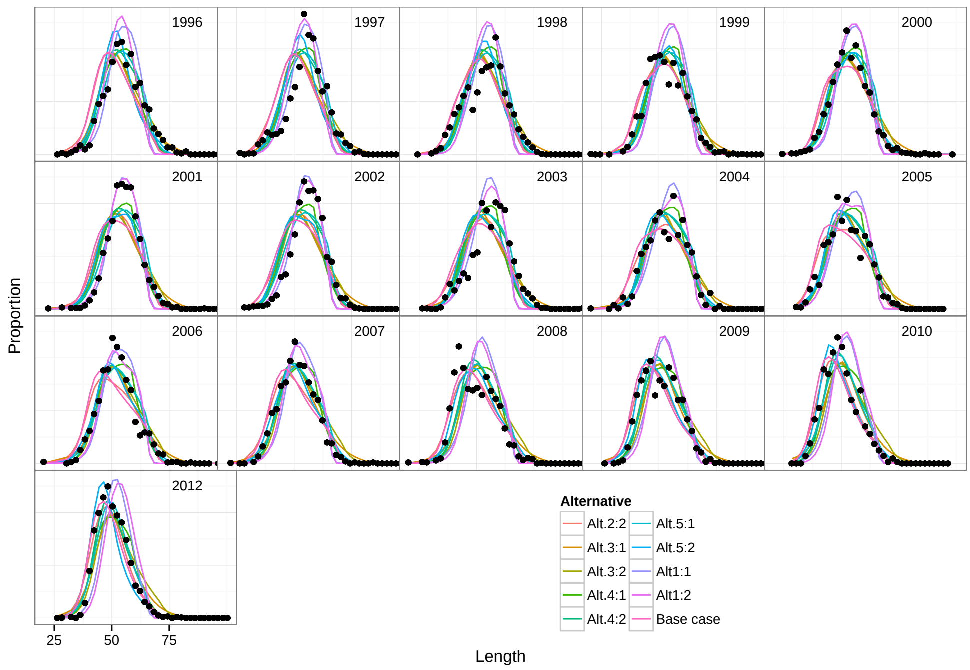


Figure 6: Male length distribution from survey. Points denote the observed values, solid lines final fit from the various model alternatives.

3 Discussion

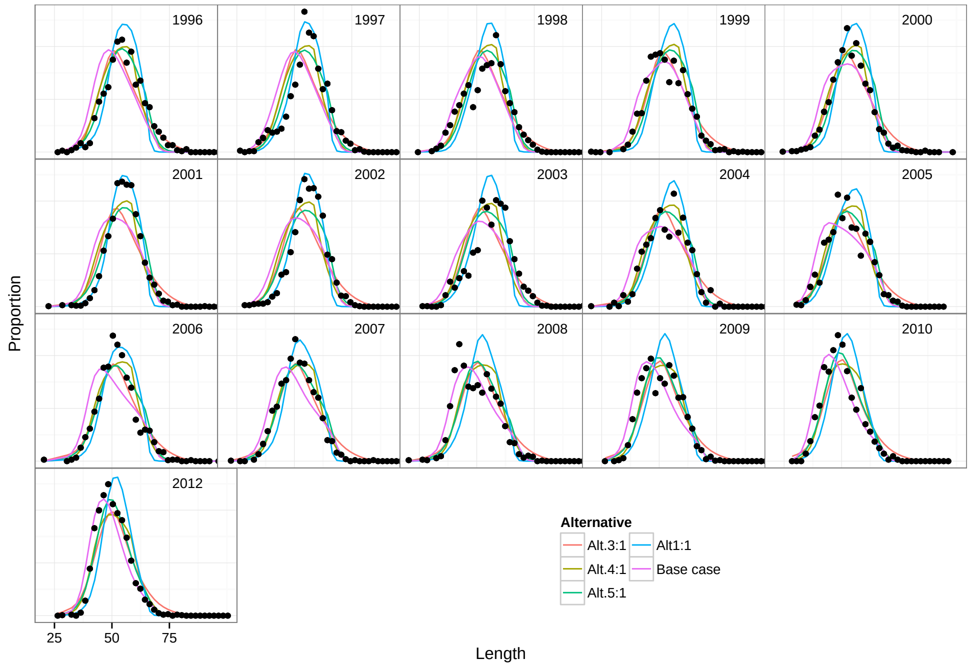


Figure 7: Male length distribution from survey in Va. Points denote the observed values, solid lines final fit from the various model alternatives.

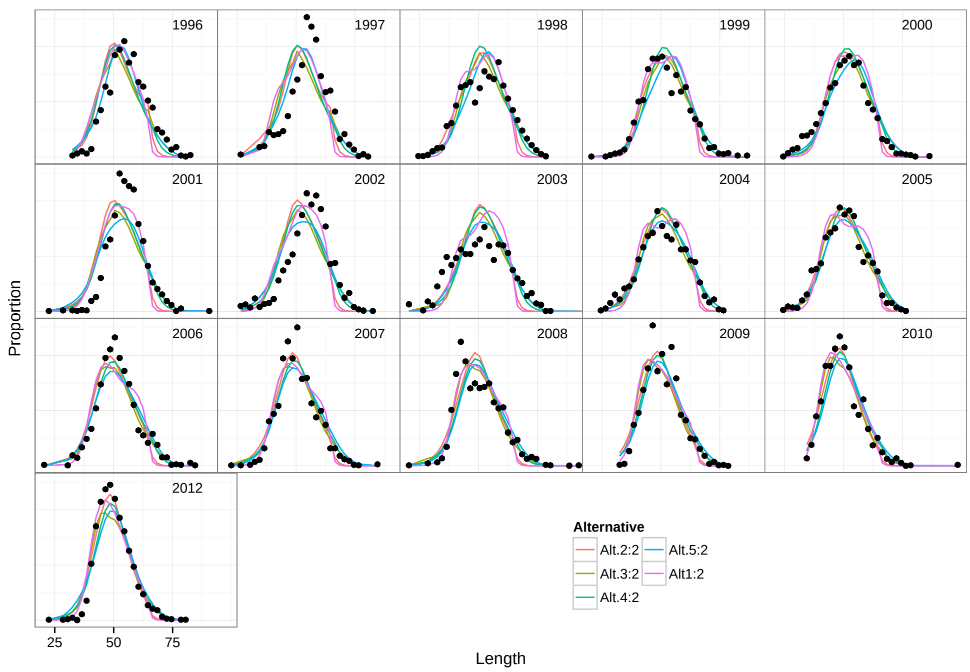


Figure 8: Male length distribution from the combined survey. Points denote the observed values, solid lines final fit from the various model alternatives.

3 Discussion

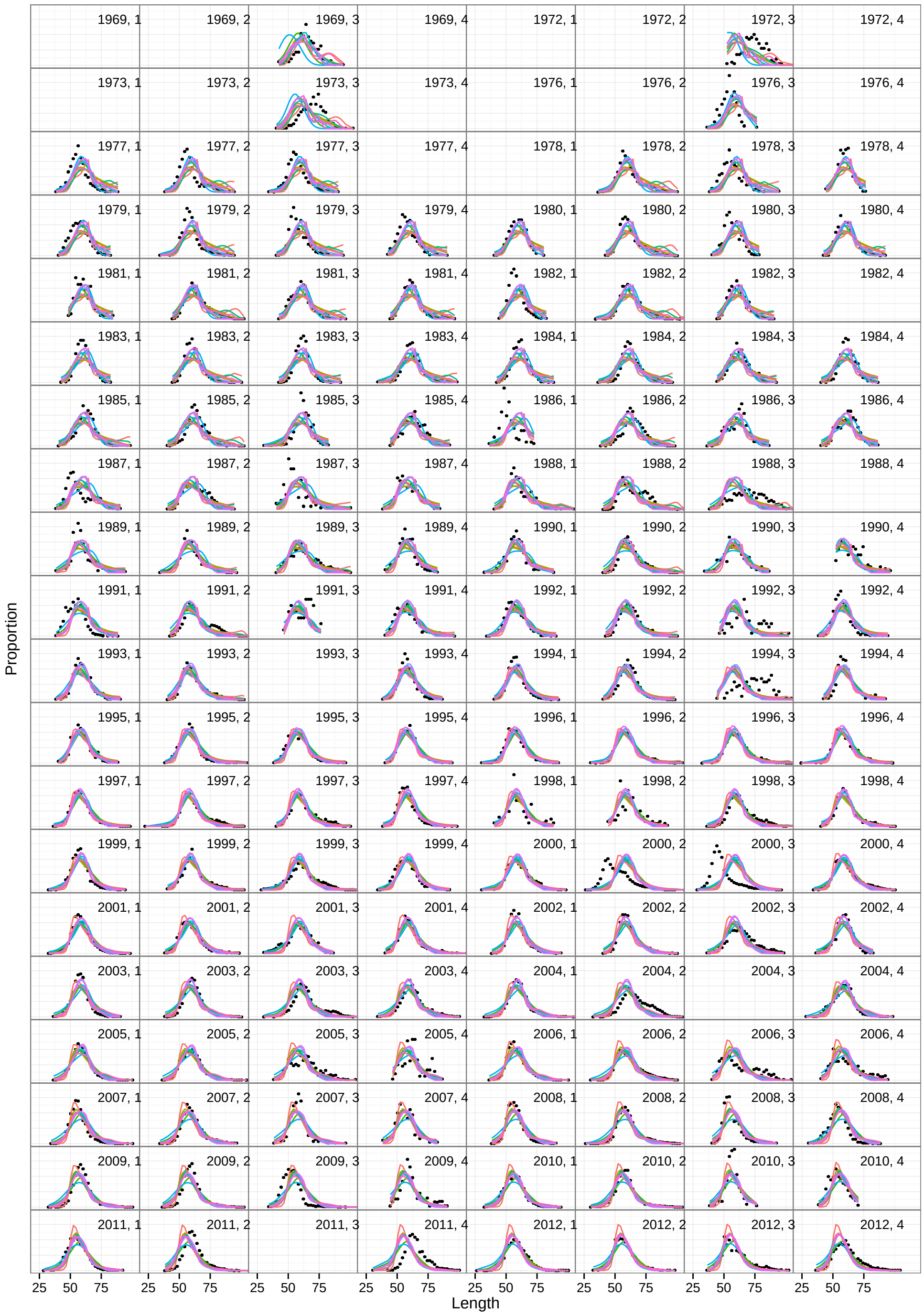


Figure 9: Length distribution from commerical catches. Points denote the observed values, solid lines final fit from the various model alternatives. Figure legends are omitted.

3 Discussion

Alternative	SexRatio-IceTrawl.lik	FemSmh-ML.lik	MaleSmh-ML.lik	Female-SmhLD.lik	IceTrawl-LD.lik	Male-SmhLD.lik	FemSmh-2045.si	FemSmh-4565.si	FemSmh-65120.si	MaleSmh-2045.si	MaleSmh-4565.si	MaleSmh-65120.si	VaCPUE-.lik	fALDc	mALDc
Alt1:1	2145	213.600	177.400	0.082	1.600	0.143	6.458	2.094	2.064	4.807	2.709	3.168	3.567		
Alt1:2	2425	8.658	55.430	0.072	1.839	0.090	5.817	1.526	1.483	3.644	1.532	1.349	1.914		
Base case	2623	55.850	23.750	0.088	1.715	0.137	6.250	1.674	1.727	3.904	1.834	3.782	2.285		
Alt.2:2	2630	17.840	51.580	0.074	1.658	0.111	5.398	1.364	1.420	3.471	1.504	2.170	2.177		
Alt.3:1	2615			0.067	1.681	0.096	5.682	1.663	1.715	3.474	2.181	3.793	2.830	4.713	6.618
Alt.3:2	2380			0.063	1.875	0.084	3.656	1.704	2.167	3.325	1.521	0.942	1.954	4.707	6.615
Alt.4:1	1901			0.085	1.690	0.080	6.633	2.823	2.058	3.580	2.435	3.122	1.944	7.656	12.300
Alt.4:2	2567			0.067	1.631	0.062	3.622	1.698	1.714	2.919	1.891	1.800	1.892	6.866	11.450
Alt.5:1	1951			0.051	1.615	0.063	5.650	1.906	2.047	3.715	2.058	2.187	2.078		
Alt.5:2	2596			0.065	1.665	0.099	5.316	2.032	2.005	3.001	2.078	2.171	2.207		

Table 2: The final fit to each of the likelihoodhood components of the various model alternatives. Note that the survey indices and growth indices are only directly comparable within respective scenarios.

3 Discussion

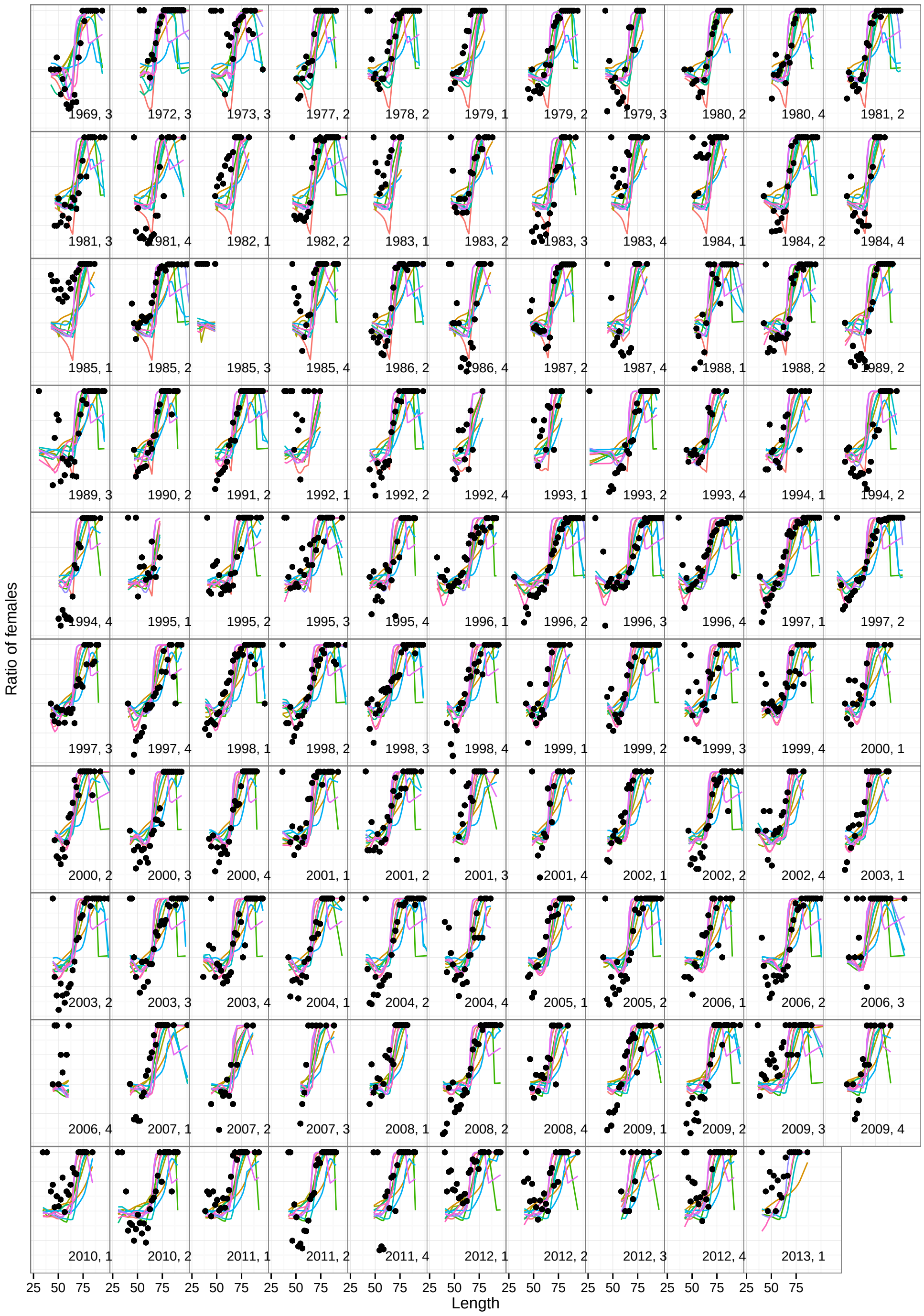


Figure 10: Ratio of females in commercial catches by length. Points denote the observed values, solid lines final fit from the various model alternatives. Figure legends are omitted.

3 Discussion

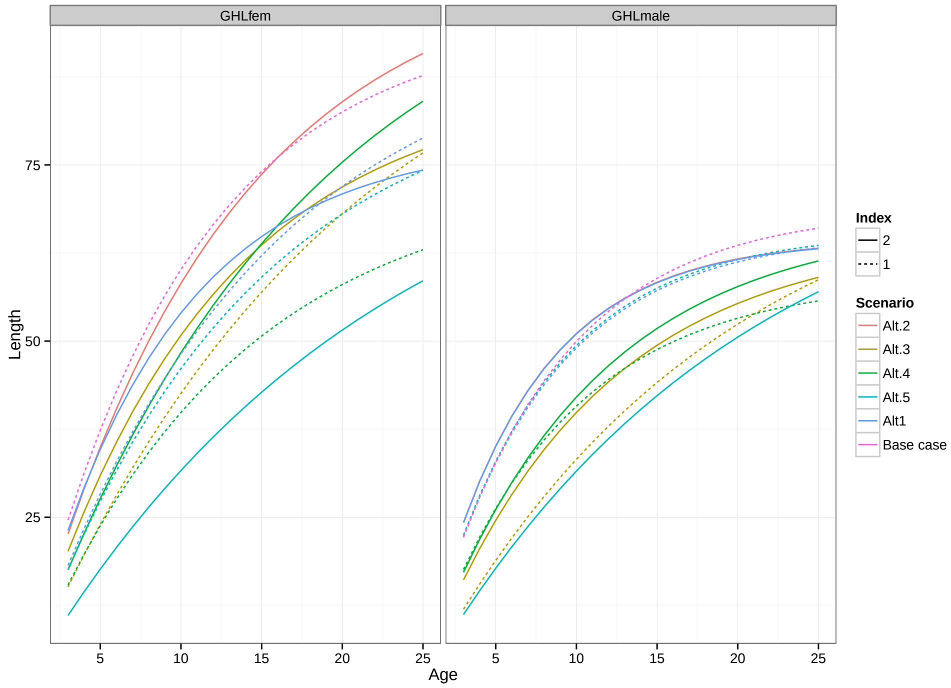


Figure 11: Estimated growth of the Greenland halibut by sex in the various model alternatives, based on model parameters.

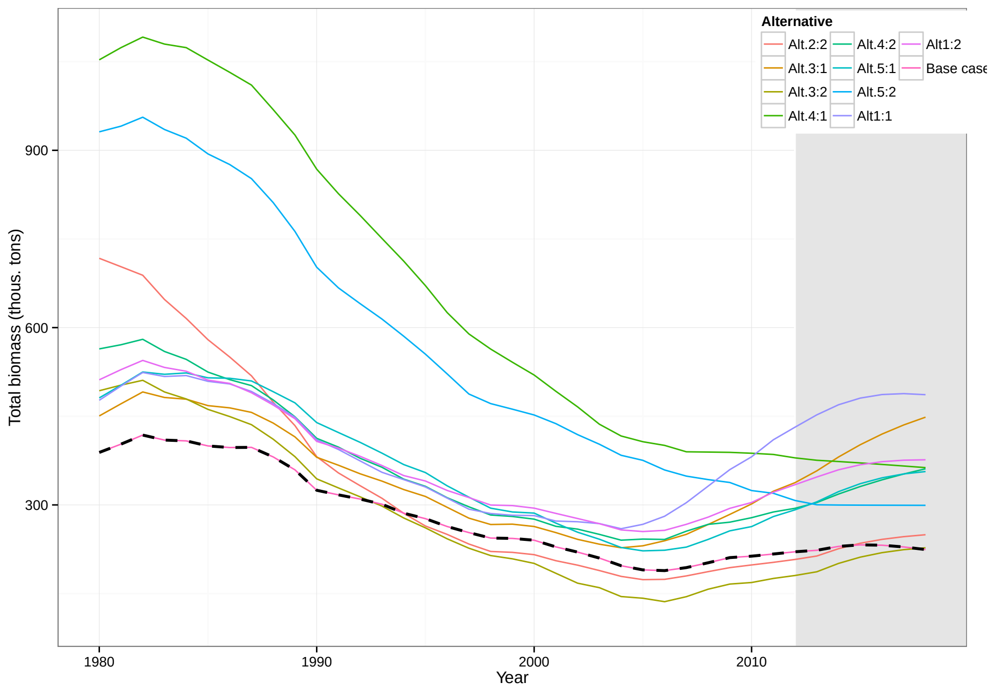


Figure 12: Estimated total biomass with predictions after 2012 based on average recruitment in the last three years. The stock status is based on $F_{0.1}$, $F_{current}$ and F_{max}.

3 Discussion

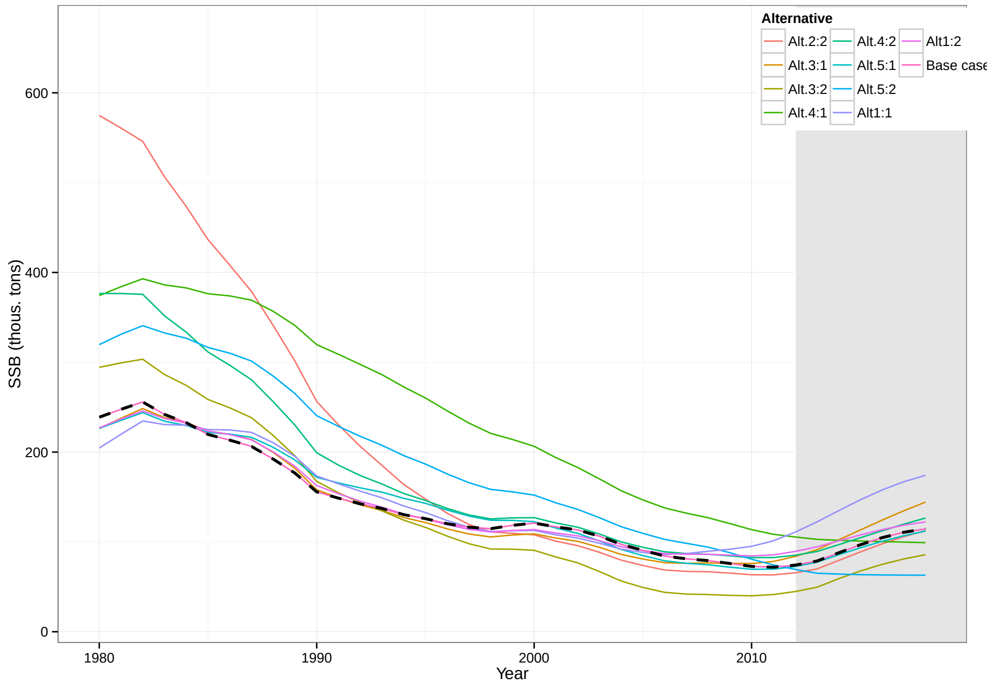


Figure 13: Estimated spawning stock biomass with predictions after 2012 based on average recruitment in the last three years. The stock status is based on $F_{0.1}$, $F_{current}$ and F_{max}.

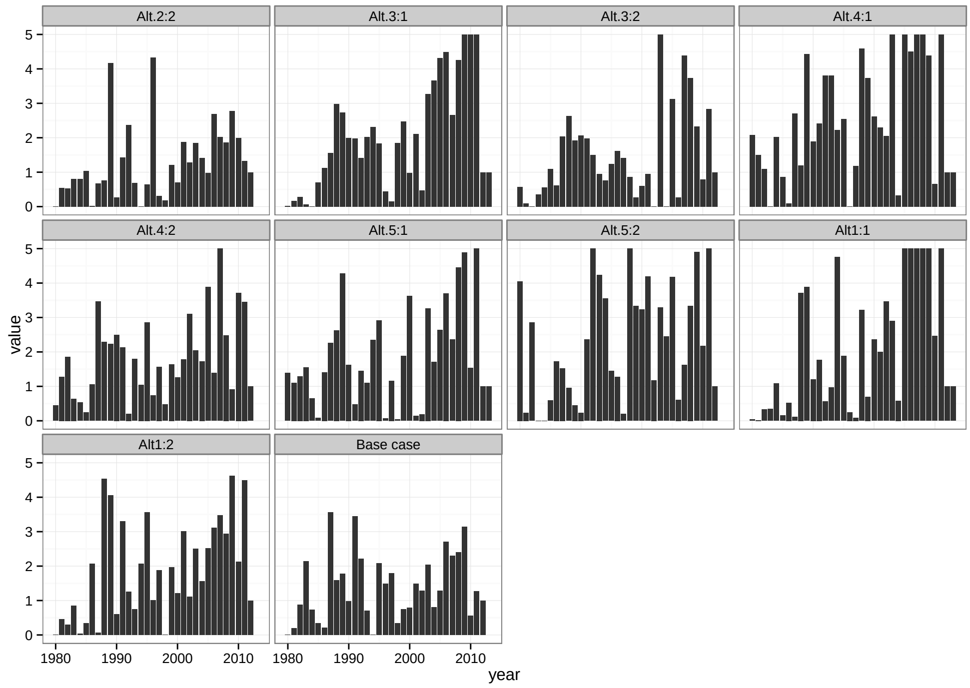


Figure 14: Estimated female recruitment by model alterntive.

3 Discussion

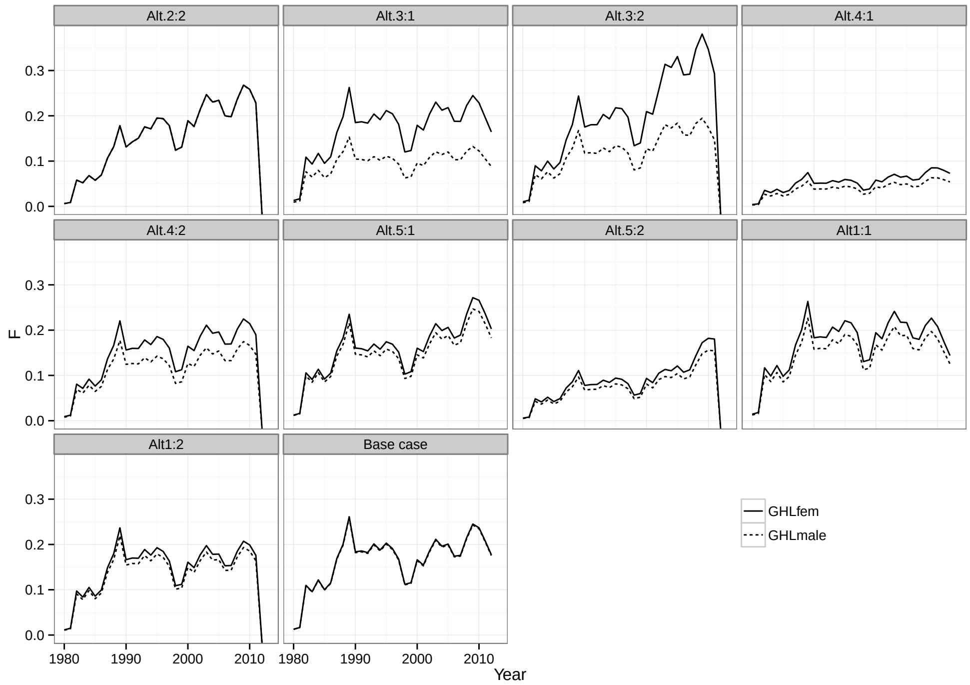


Figure 15: Estimated fishing mortality by model alternative.

3 Discussion

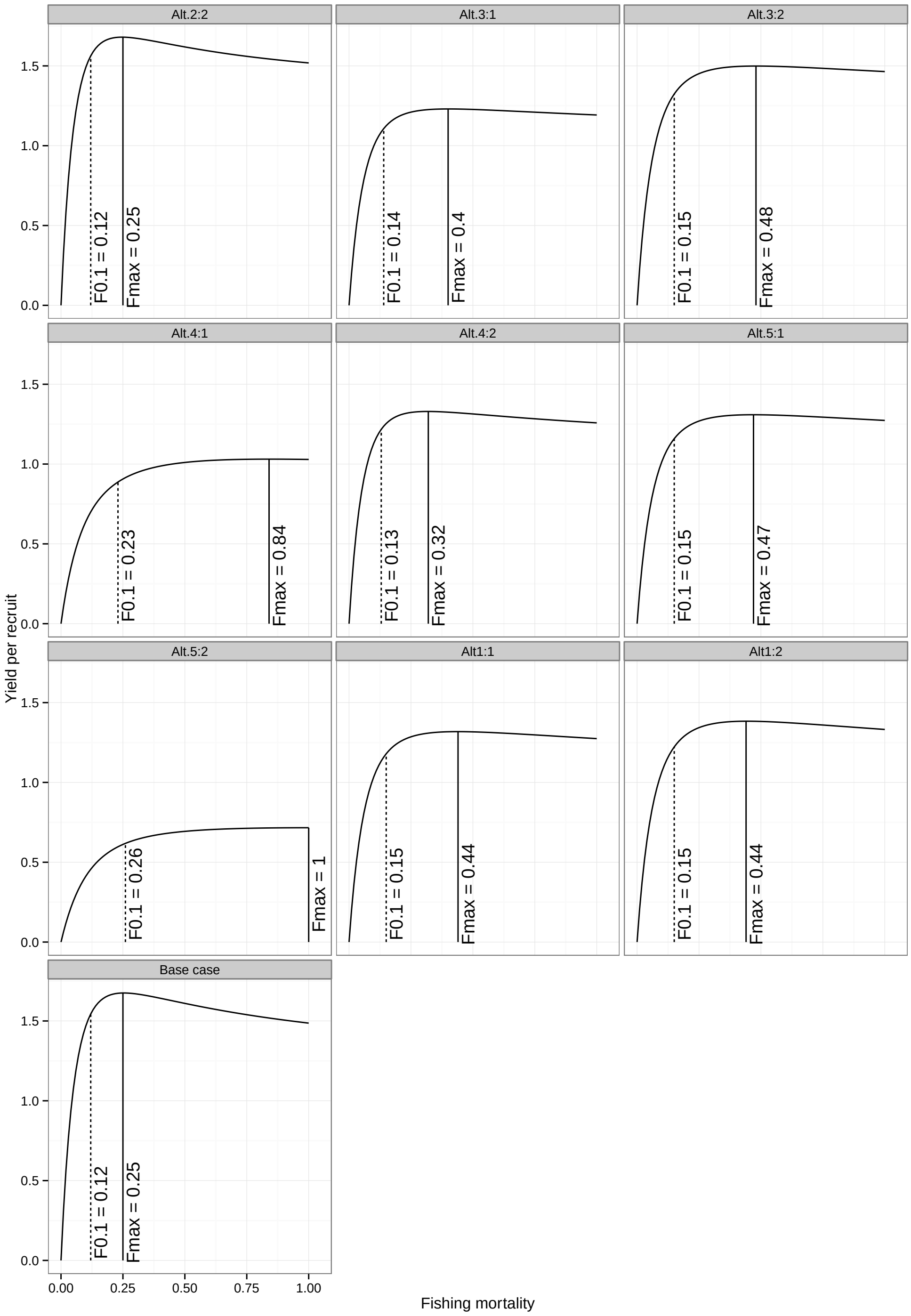


Figure 16: Estimated yield per recruit by model alternative.

3 Discussion

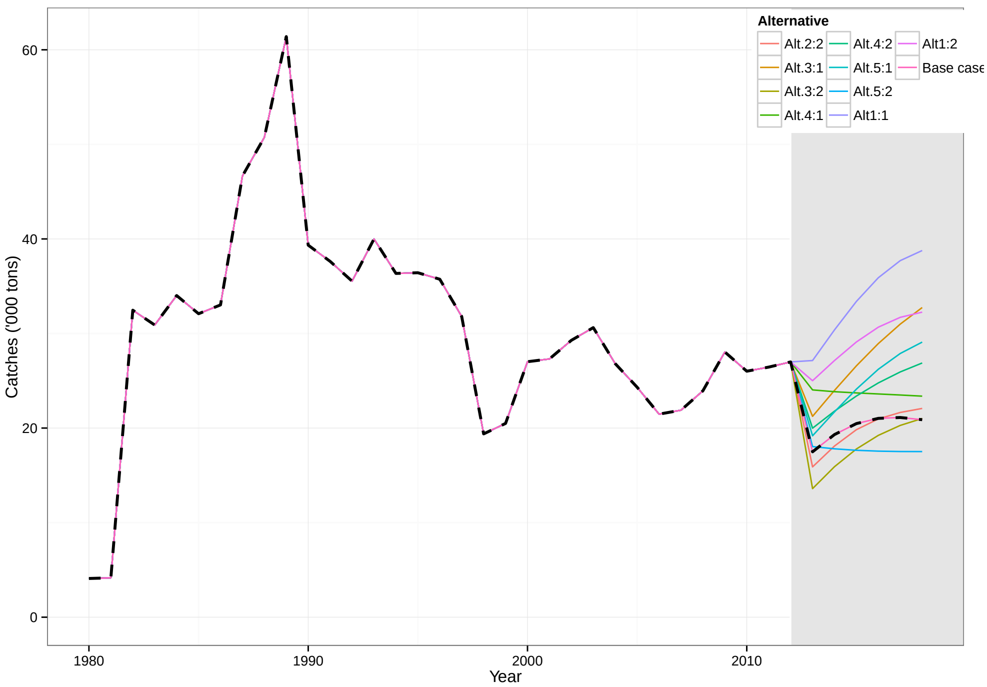


Figure 17: Total landings projected after 2012 within the model alternatives using $F_{0.1}$

3 Discussion

Alternative	Biomass 2012	Biomass 2014	Harv. biomass 2012	Harv. biomass 2014	SSB 2012	SSB 2014	Catch 2012	Catch 2014
Alt.1:1	431.594	469.466	218.161	274.296	110.849	134.738	26.995	30.378
Alt.1:2	334.274	359.438	179.485	211.028	89.361	101.183	26.995	27.139
Base case	220.734	229.821	135.361	162.750	74.110	87.811	26.995	19.312
Alt.2:2	207.732	225.926	118.731	146.340	65.578	79.285	26.995	18.098
Alt.3:1	337.718	381.124	155.769	193.578	83.745	102.178	26.995	23.981
Alt.3:2	180.589	201.044	85.858	110.511	44.717	58.992	26.995	15.911
Alt.4:1	379.599	373.412	198.997	196.309	105.501	101.789	26.995	23.845
Alt.4:2	294.289	318.410	159.956	184.625	85.152	96.857	26.995	21.787
Alt.5:1	291.709	322.490	133.967	166.554	72.572	85.635	26.995	21.709
Alt.5:2	307.501	299.825	135.441	127.522	69.400	64.190	26.995	17.804

Table 3: Comparision of projected catches and stock status by model alternatives

3 Discussion

A production model of Greenland halibut (*Reinhardtius hippoglossoides*) in Faroese waters

Petur Steingrund, Faroe Marine Research Institute

Abstract
A production model is performed for Greenland halibut in Faroese waters. The model was tuned with either the CPUE from the research vessel “Greenland halibut trip” or with the CPUE from the commercial single trawlers. The intrinsic growth rate was fixed and obtained from tagging studies. The results of the two model runs were very similar, giving a biomass of Greenland halibut in Faroese waters 1995-2012 ranging between 15 and 29 thousand tonnes. The exploitation rate (catch/biomass) ranged from 0.05 to 0.25. If the CPUE series of the trawlers was extended to 1983, by a correlation with the March survey, the production model gave slightly higher biomasses and lower exploitation ratios, but was not able to follow the rapid changes in CPUE in the first half of the series. Even though the production model was able to explain the stock development during the 1995-2012 period under the assumption that the population dynamics was governed by only the intrinsic growth rate and the catch, the possibility cannot be ruled out that the biomass of Greenland halibut in Faroese waters is influenced by the exchange with other areas, for example Iceland/east Greenland.

Introduction
The populations of Greenland halibut in east Greenland, at Iceland and at the Faroe Islands are considered to belong to the same stock. In principle, stock assessments of Greenland halibut should focus on the whole stock, i.e., be based on data from all the areas, and this is certainly the main goal in this benchmark. However, given the great difficulties to age-read the otoliths of Greenland halibut, and the poor information about the individual growth from other sources (e.g. tagging studies), it is a very difficult task to assess the stock size of Greenland halibut in the East Greenland-Iceland-Faroe area, as well as in other areas.

A more simple approach is to assess the size of local populations of Greenland halibut, as long as it can be shown that the exchange of individuals with other areas is limited (or not extensive), and when there is knowledge about certain parameters of the local population, such as individual growth. The area around the Faroe Islands seems to be suitable for such an approach, since tagging studies (WD-03) show that the immigration is limited (two out of 36 individuals) and that there is an estimate of the growth rate obtained from tagging studies.

A lot of length measurements of Greenland halibut have been performed on the research vessel “Greenland halibut trip”. A visual inspection of the length distribution by year indicated no clear pattern of year classes going through the fishery, although a more thorough analysis is needed. Therefore, an age-based approach to assess the biomass of Greenland halibut in Faroese waters was not possible at the moment, but a production model is presented instead, which is based on catch-per-unit effort (CPUE) time series, time series of catch, and estimates of the intrinsic growth rate of the population.

Materials and methods

CPUE

When using CPUE as a relative measure of biomass, it is necessary to show that a large part of the population is covered by the fishing gear (horizontally and vertically). We used data from data-storage-tagged fish to show that this was the case. Details about the tagging experiments are provided in Working Document 3 in this benchmark.

The CPUEs were obtained from two sources, the research vessel “Greenland halibut trip”, which is conducted in May-June each year since 1995, and from the commercial single trawlers. The Greenland halibut trip is not as rigidly standardized as usual surveys, but the main fishing area is determined (i.e., has to be covered) as well as the timing of the year, and the main goal of the trip is to get a CPUE measure of Greenland halibut in Faroese waters. Also, the trip cannot be terminated if the catch is low. Within these limits, the skipper is allowed to perform tows where he wants and the duration of the hauls, which is normally 3-6 hours. The trawl is a star trawl, the doors are of the Thyborøn type, and the distance between the trawl doors is 120 meters. The mesh size in the codend is 135 mm. The headrope is approximately 5 meters above the bottom. There have been only minor changes in the gear during the years. The catch is sampled in a scientific way. The catch of all species is measured by direct weighting and subsamples are taken for length measurements, individual weight measurements, and, for a minor part (500 indivduals), also determination of sex and maturity stage, and otoliths are collected.

The commercial single trawlers are trawling in deep (> 150 m) waters all around the Faroes and the banks south-west of the Islands. They target many fish species, such as redfish, Greenland halibut, and blue ling. In this analysis, the area east of 8^{o} W and south of 63^{o} N was selected (i.e. the SW-banks and the Icelandic ridge were skipped) in order to cover the area where there is a well-defined and large (200 m high) mixed layer between the upper warm (> 6^{o} C) Atlantic water and the lower cold (~0^{o} C) Arctic water. The years after 1995 were selected because the logbooks by then had got the format used today. Only vessels attending the fishery for many years (> 5 years) or still operating were included in the analysis – in order to minimize the parameters to be estimated by the GLM-model used (see later). The 400-600 m depth interval was selected because data-storage-tagged Greenland halibut usually were found there.

Both CPUE series were treated by a General Linear Model (GLM). For the research vessel, the Greenland halibut catch per hour (dependent variable) was square-root transformed, and back-transferred afterwards, when the model was run. The reason for using a square-root transformation rather than a log transformation was that the latter was quite influenced by very low catches (a difference between 10 and 20 kg per tow gave the same effect as a difference between 100 and 200 kg per tow) and the back-transformation could sometimes give quite high or low values. The square-root transformation was considered to be better even though there were occasional outliers (not removed). The independent variables were year, area (3 of them), all categorical variables, and depth (continuous variable).

Since the CPUE series were quite short, I extended the trawler CPUE series back to 1983 by applying a regression analysis with Faroese spring survey (March) 1991-2001. Although the correlation was not strong, the approach was taken because the March survey showed very high

CPUEs in the 1980s. After 2001 there was no correlation between the trawlers and the March survey, and the reason is unknown.

The catch rates for the commercial trawlers were also square-root transformed, for similar reasons as above. The independent variables were: year, month, area (statistical squares of 30 x 30 nautical miles), all these categorical variables, and depth (continuous variable).

The GLM was run on the statistical package “Systat”. The independent variables were set to an “effect” coding.

Production model
The traditional production model: $B_{y+1} = B_y + rB_y\ (1\text{-}K/B_y) - catch_y$ was used, where “B” is the biomass of the population at year “y” or “y+1”, and “r” is the intrinsic growth rate of the population. The model was fitted by the CPUE series, i.e., by minimizing the difference between B = scaling factor x CPUE and the production model. The intrinsic growth rate (r) was obtained from the tagging studies. They showed that Greenland halibut of ~60 cm grew 3.3 cm in length per year (Working Document 3 in this benchmark), which corresponded to a rate of 0.188, i.e., the observed round weight of a fish of 63.3 cm minus the weight of a fish of 60 cm divided by the weight of a 61.7 cm (actually 5 mm were added to these lengths because the lengths in the tagging studies were rounded down to the nearest whole centimetre whereas the lengths on the research vessel were measured in millimetres). When the growth rate was known, there were only two parameters to be estimated: the initial biomass and the scaling factor. The minimization process was performed in MS Excel Solver.

Results
Data-storage-tagged Greenland halibut at the Faroes usually occupied water with temperatures between zero and four degrees Celcius (Figure 1), corresponding to depths between 400 and 600 metres (Figure 2) – over 80 % of the time.

Data-storage-tagged individuals frequently performed changes in depth, but these could only with certainty be grouped as pelagic swimming in 3 % of the cases. This result was obtained by comparing the average swimming speed required to swim along the bottom slope when covering this change in depth with the critical long-term sustainable swimming speed of one body length per second.

Therefore, the depth range covered by the research vessel “Greenland halibut trip” (Figure 3) is appropriate to cover the main distribution of Greenland halibut in Faroese waters. The hauls of the commercial trawlers were, therefore, also constrained to the 400-600 m depth interval and the eastern part (east of 8 degrees West, see Figure 3) on the Faroe Plateau.

The GLM analysis showed that the area was not significant for the research vessel “Greenland halibut trip”, i.e., only two explanatory variables (year and depth) were needed in the model (Appendix 1). For the trawlers, all the explanatory variables: year, month, square and depth were significant (Appendix 2).

The production model fitted each of the two CPUE tuning series quite well (Tables 1 and 2, Figures 4 and 5), and gave very similar results with regards to the biomass of Greenland halibut in Faroese waters. The biomass 1995-2012 fluctuated between 15 and 29 thousand tonnes, and the exploitation ratio (catch divided by biomass) fluctuated between 0.05 and 0.25.

Using the extended trawler CPUE series to tune the production model, the fit was poor for the first half of the time series, but still good for the later half (Figure 6). The biomass estimate for the later half of the series was slightly higher than for the short trawler CPUE series.

Discussion

Given the difficulties to estimate the absolute biomass of the whole stock of Greenland halibut that are spread over the area from East Greenland, Iceland and Faroe Islands, I have chosen a more simple approach to estimate the biomass of Greenland halibut in Faroese waters, as a starting point.

Data-storage-tagged Greenland halibut occupied depths of 400-600 m most of the time. Moreover, they were probably close to the bottom most of the time, as judged by the few (3 %) incidents of pelagic behaviour, where the swimming speed required to swim the vertical range along the bottom slope exceeded one body length per second. It is impossible to tell from these data, however, that Greenland halibut are not swimming off the bottom, only that they had been able to cover the depth range by swimming along the bottom slope, if they wanted. Nevertheless, the data indicate that a bottom trawl at the 400-600 m depth interval is a good tool to estimate the density of Greenland halibut in Faroese waters.

The GLM of the two CPUE series gave the same impression, that the biomass was lowest in the middle of the 1995-2012 period. The research vessel CPUE was quite simple to handle statistically, because only “year” and “depth” were significant explanatory variables. There was no need to take account of vessel, timing of the year or area, because these things were standardized already. Hence, the research CPUE series gave little room for fiddling. The trawler CPUE series was based on much more hauls, but there were more variables to account for: vessel, year, month, square and depth (“year” is the interesting variable in our context here). The model was, therefore, much more flexible than the GLM of the research vessel CPUE. It may, for example, be asked why it was necessary to use two variables to describe the location (statistical square and depth), and excluding one of them would change the development over time in such a way that the increase in the latest year would be steeper than in the adopted GLM run. Clearly, more work is needed on this issue.

The production model was easy to fit to the CPUE series and three parameters had to be fitted (initial stock size, the scaling factor of CPUE to biomass and the carrying capacity). The growth rate was fixed at 0.188, based on the tagging results, but future runs could allow the growth rate to be somewhere in the 95 % confidence interval (obtained in Working Document 3).

The production model assumes that the population dynamics of Greenland halibut in Faroese waters is governed only by the intrinsic growth rate and the catch. Although the results seem reasonable (the production model followed the CPUE series well), the possibility exists that the population size is governed by other factors, e.g. the exchange of individuals between the Faroe area and the rest of the stock.

The extended CPUE series (trawlers – March survey back to 1983) showed that density of Greenland halibut was high at the Faroes in the 1980s, as was seen at Iceland. The production model was not able to capture the high, and rapidly fluctuating CPUEs of Greenland halibut in the 1983-94, which is a common problem for production models.

The carrying capacity was estimated at some 51-77 thousand tonnes, indicating a maximum sustainable yield of half of this amount, i.e., 25-39 thousand tonnes. However, the carrying capacity is difficult to estimate precisely from these short time series with the long-lived Greenland halibut.

Acknowledgments

I thank the crew on the research vessel “Magnus Heinason” and on Faroe Marine Research Institute for their work in all stages of the process to get the data used in this working document. Also many thanks to the partners in the Nordic DST project, and especially the Norwegian team, which allowed their share of the tags to be deployed in Faroese waters.

Table 1. Greenland halibut in Faroese waters. Output from the production model when tuned with the CPUE of the research vessel "Greenland halibut trip". The biomass was expressed in two ways: 1) biomass = scaling factor x CPUE, and 2) biomass$_{y+1}$ = biomass$_y$ + intrinsic growth rate x biomass$_y$ (1-biomass$_y$/K). The intrinsic growth rate (r), here approximated by the somatic growth, was fixed and obtained from tagging studies. These models were fitted to each other by minimizing the sum of the squared residuals (shown in red). MS Excel Solver found the corresponding initial biomass (in 1994), the carrying capacity, and the scaling factor (all shown in gray).

Carrying capacity K:	76537.69	Sum relative residuals^2
Scaling factor to biomass:	191.3569	1.17E+00
Initial biomass:	24427.84	

	GLM-model (sq-transformation) Trawlers kg/hour	Catch "C" in Vb (tonnes)	Biomass, scaled from CPUE (tonnes)	B y+1 = B + rB(1-B/K)-C	Relative residual^2	Ratio Catch to biomass
1994		1032				
1995	163.25	3832	31239	26517	0.03	0.14
1996	94.91	6469	18161	25937	0.09	0.25
1997	128.37	4870	24564	22685	0.01	0.21
1998	98.27	3825	18804	20810	0.01	0.18
1999	102.05	2694	19528	19828	0.00	0.14
2000	102.11	5079	19540	19891	0.00	0.26
2001	79.74	3951	15260	17575	0.02	0.22
2002	77.95	2694	14917	16164	0.01	0.17
2003	114.30	2459	21872	15863	0.14	0.16
2004	62.25	1771	11912	15764	0.06	0.11
2005	57.38	892	10980	16341	0.11	0.05
2006	47.90	873	9166	17861	0.24	0.05
2007	53.76	1060	10287	19557	0.22	0.05
2008	118.98	1759	22769	21230	0.01	0.08
2009	132.23	1739	25303	22349	0.02	0.08
2010	118.11	1413	22602	23579	0.00	0.06
2011	104.00	1489	19901	25228	0.04	0.06
2012	198.16	2162	37920	26912	0.17	0.08
2013	183.98					
Average		2724	19707	20783		0.13
Growth per year (r)		0.187646				

The CPUE in 2010 was the average of the CPUE in 2009 and in 2011.

Table 2. Greenland halibut in Faroese waters. Output from the production model when tuned with the CPUE of the commercial trawlers.

			Carrying capacity K:	76835.26	Sum relative residuals^2	
	GLM-model (sq-transformation)		Scaling factor to biomass:	392.8423	3.35E-01	
	Trawlers kg/hour	Catch "C" in Vb (tonnes)	Initial biomass:	28799.35		

			Biomass, scaled from CPUE (tonnes)	B y+1 = B + rB(1-B/K)-C	Relative residual^2	Ratio Catch to biomass
1994		5225				
1995	70.73	3832	27785	26953	0.00	0.14
1996	52.10	6469	20467	26404	0.05	0.24
1997	57.56	4870	22613	23187	0.00	0.21
1998	49.43	3825	19420	21355	0.01	0.18
1999	55.10	2694	21646	20424	0.00	0.13
2000	64.64	5079	25394	20543	0.06	0.25
2001	45.14	3951	17735	18289	0.00	0.22
2002	42.89	2694	16849	16953	0.00	0.16
2003	45.68	2459	17947	16738	0.01	0.15
2004	41.90	1771	16460	16735	0.00	0.11
2005	31.14	892	12232	17421	0.09	0.05
2006	44.76	873	17582	19057	0.01	0.05
2007	40.28	1060	15825	20873	0.06	0.05
2008	54.58	1759	21442	22665	0.00	0.08
2009	66.18	1739	25998	23905	0.01	0.07
2010	61.78	1413	24270	25256	0.00	0.06
2011	75.19	1489	29536	27024	0.01	0.06
2012	87.18	2162	34248	28823	0.04	0.08
2013						
Average		2724	21525	21811		0.13
Growth per year (r)		0.187646				

Table 2. Greenland halibut in Faroese waters. Output from the production model when tuned with the CPUE of the commercial trawlers extended back to 1983.

Carrying capacity K:	51193.19
Sum relative residuals^2	2.42E+00
Scaling factor to biomass:	455.1624
Initial biomass:	52470.94

	GLM-model (sq-transformation) Trawlers kg/hour	Catch "C" in Vb (tonnes)	Biomass, scaled from CPUE (tonnes)	B y+1 = B + rB(1-B/K)-C	Relative residual^2	Ratio Catch to biomass
1982		1032				
1983	120.31	1436	54760	51193	0.00	0.03
1984	70.97	3065	32303	49757	0.12	0.06
1985	81.29	2126	37001	46954	0.04	0.05
1986	99.38	940	45235	45558	0.00	0.02
1987	138.52	1043	63047	45559	0.15	0.02
1988	160.06	969	72853	45457	0.36	0.02
1989	123.89	1606	56389	45443	0.06	0.04
1990	65.28	1282	29714	44795	0.11	0.03
1991	56.10	1662	25535	44564	0.18	0.04
1992	66.73	2269	30374	43985	0.10	0.05
1993	46.84	4434	21320	42878	0.25	0.10
1994	29.79	5225	13559	39751	0.43	0.13
1995	70.73	3832	32193	36193	0.01	0.11
1996	52.10	6469	23714	34351	0.10	0.19
1997	57.56	4870	26200	30003	0.02	0.16
1998	49.43	3825	22501	27463	0.03	0.14
1999	55.10	2694	25080	26027	0.00	0.10
2000	64.64	5079	29422	25734	0.02	0.20
2001	45.14	3951	20548	23056	0.01	0.17
2002	42.89	2694	19522	21483	0.01	0.13
2003	45.68	2459	20794	21128	0.00	0.12
2004	41.90	1771	19071	20998	0.01	0.08
2005	31.14	892	14172	21551	0.12	0.04
2006	44.76	873	20371	23000	0.01	0.04
2007	40.28	1060	18336	24504	0.06	0.04
2008	54.58	1759	24844	25841	0.00	0.07
2009	66.18	1739	30122	26484	0.02	0.07
2010	61.78	1413	28120	27143	0.00	0.05
2011	75.19	1489	34222	28123	0.05	0.05
2012	87.18	2162	39681	29012	0.14	0.07
Average		2503	31033	33933		0.08
Growth per year (r)		0.187646				

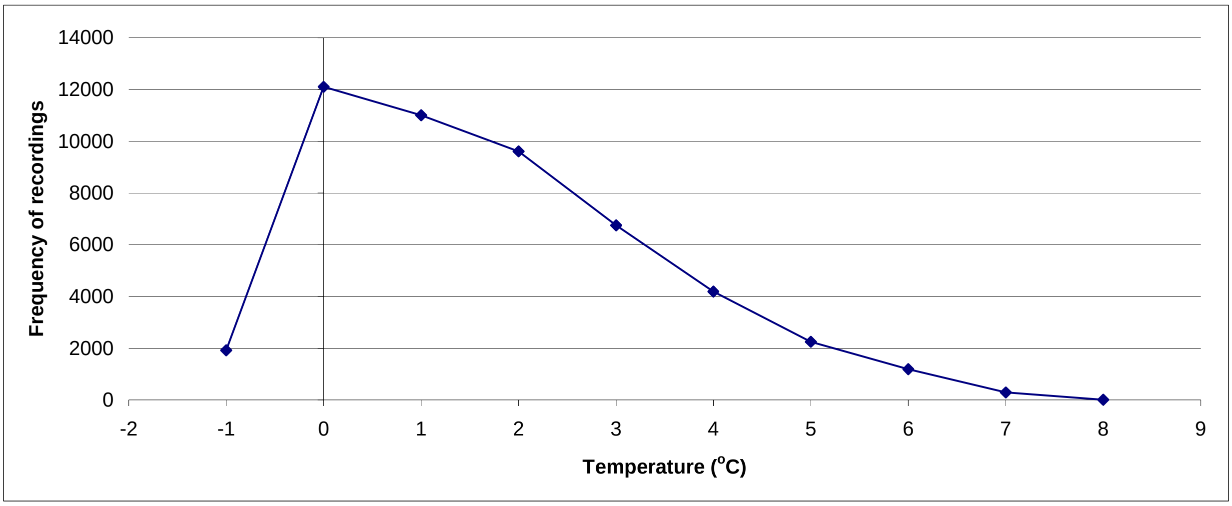


Figure 1. Data-storage-tagged Greenland halibut in Faroese waters 2002-2013. Frequency of recordings in temperature bins. Note Greenland halibut usually occupy waters with temperatures between 0 and 4 °C.

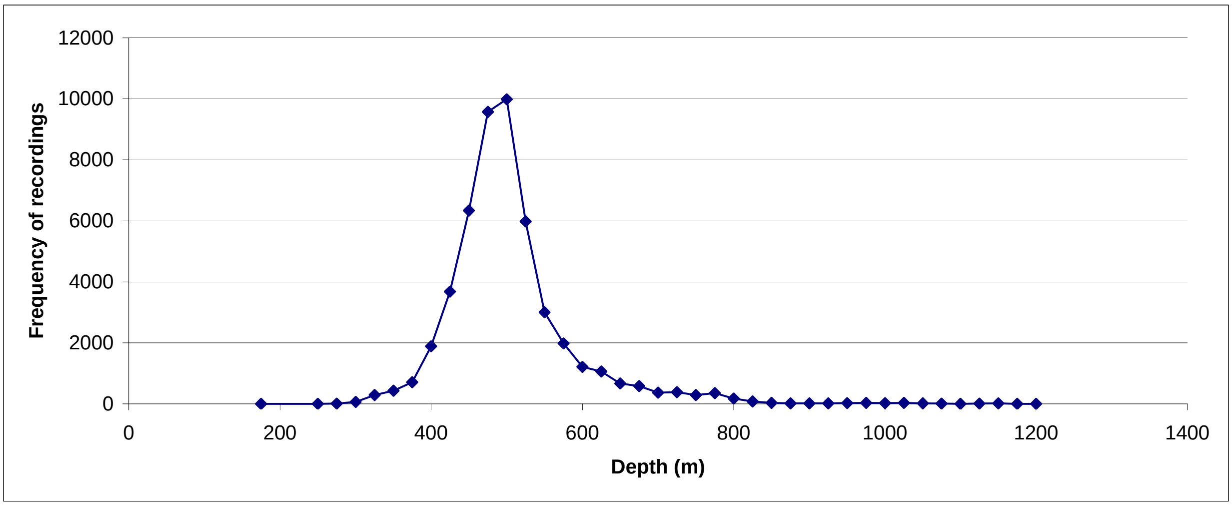


Figure 2. Data-storage-tagged Greenland halibut in Faroese waters 2002-2013. Frequency of recordings in depth bins. Note that Greenland halibut usually (88 %) occupy depths between 400 and 600 m.

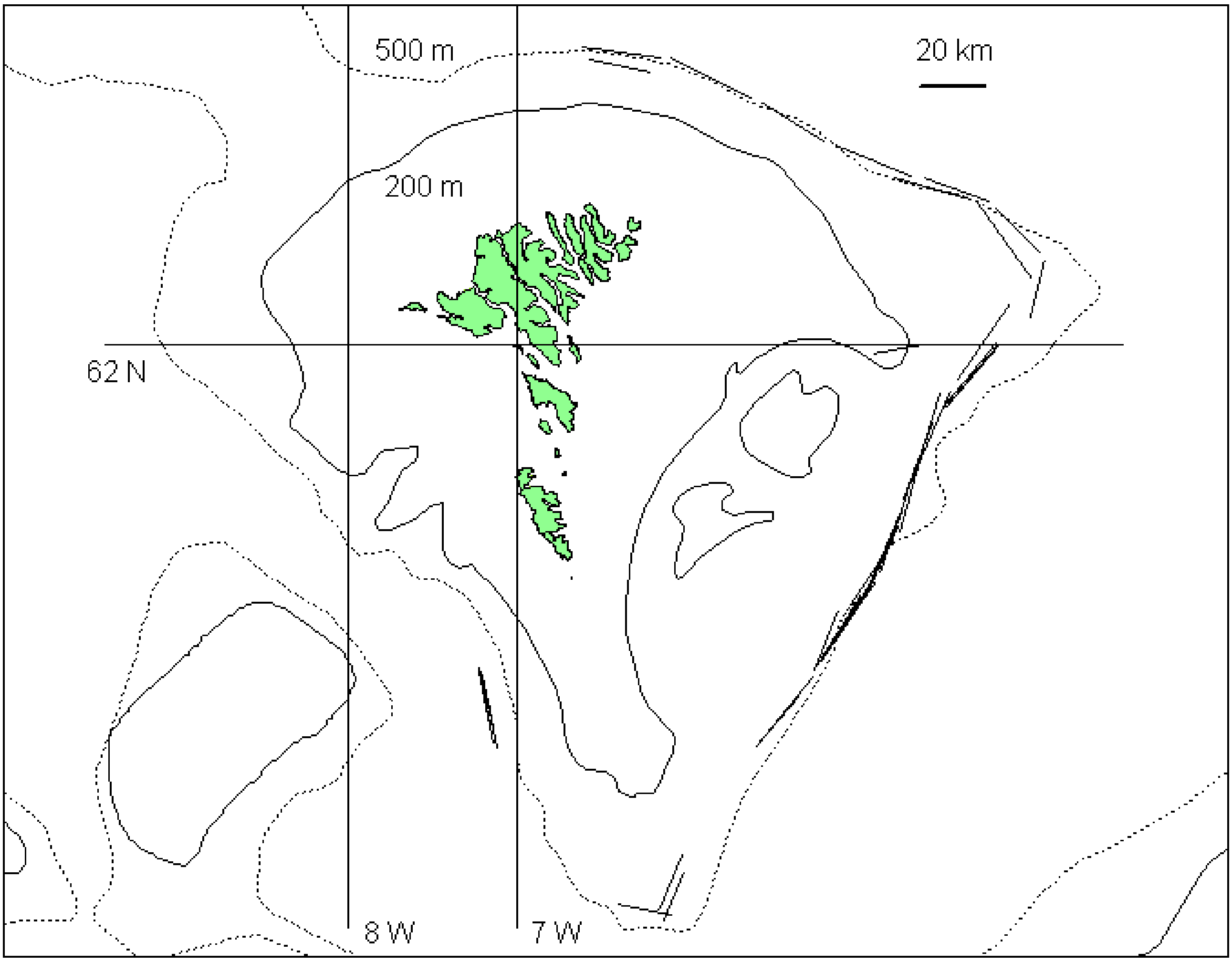
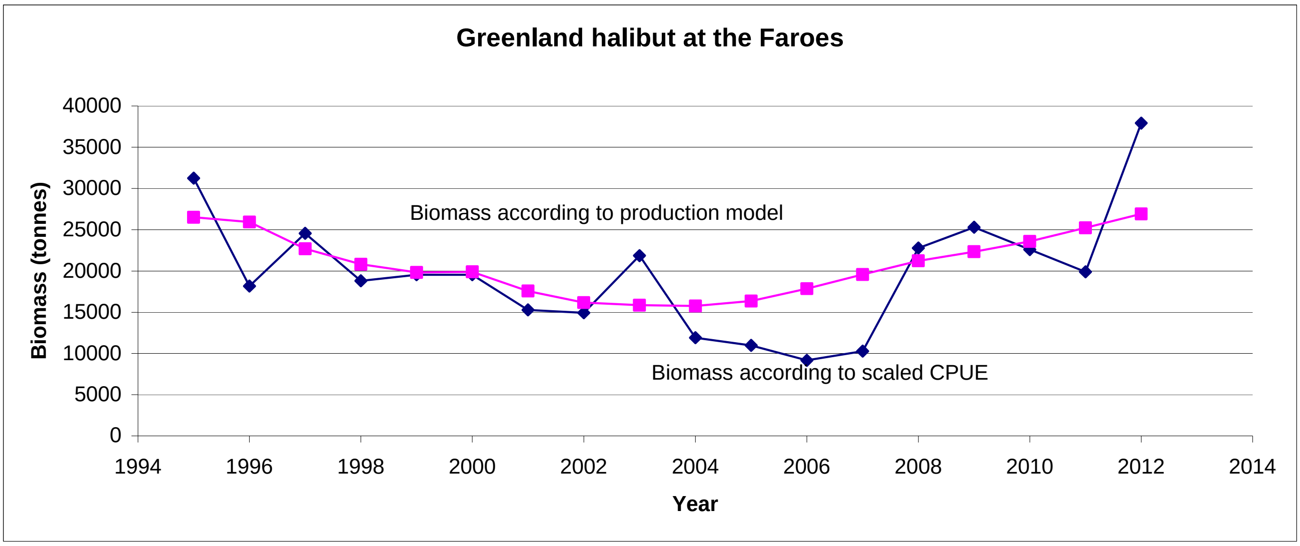


Figure 3. The location of the hauls in the Greenland halibut trip in 2007. Note that most hauls were occupied in the 400-600 m depth interval.



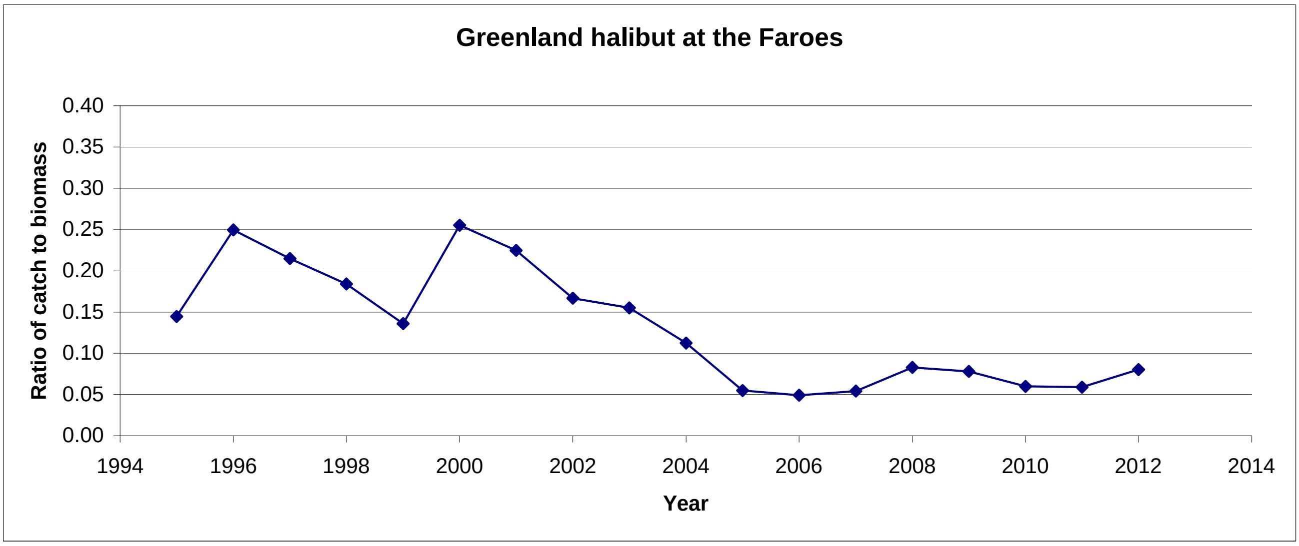
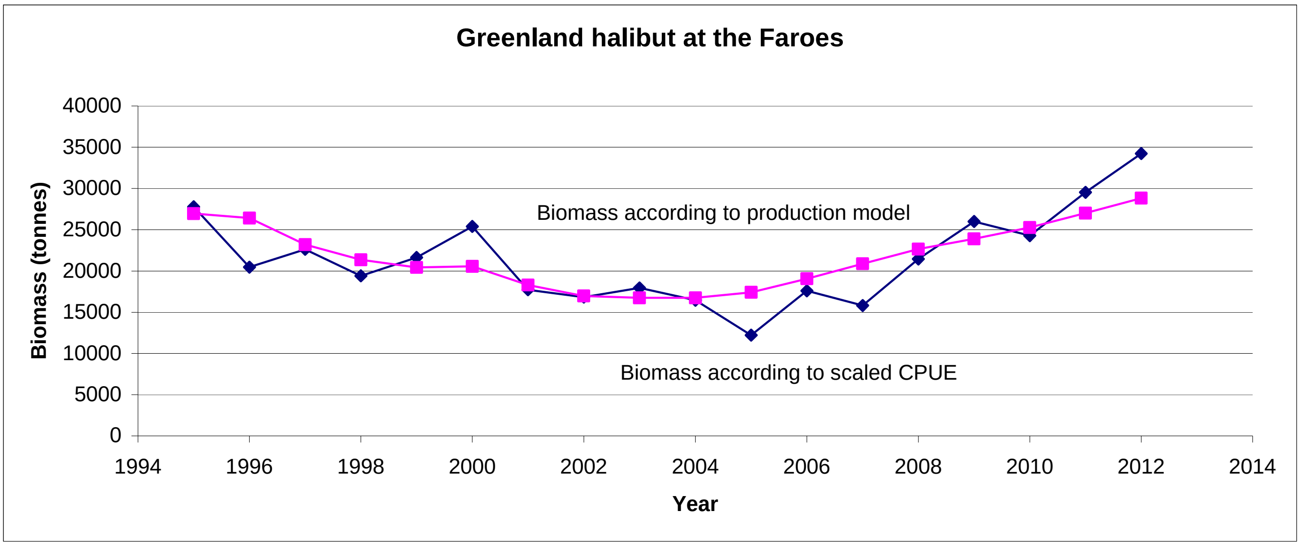


Figure 4. Greenland halibut in Faroese waters. Results from a production model using the CPUE from the research vessel "Greenland halibut trip" in May-June 1995-2013, treated by a GLM-model, and the catch. The CPUE in 2010 (only 1 haul taken) was taken as the average value for 2009 and 2011. The intrinsic growth rate was set at 0.188, as obtained from the tagging experiments.



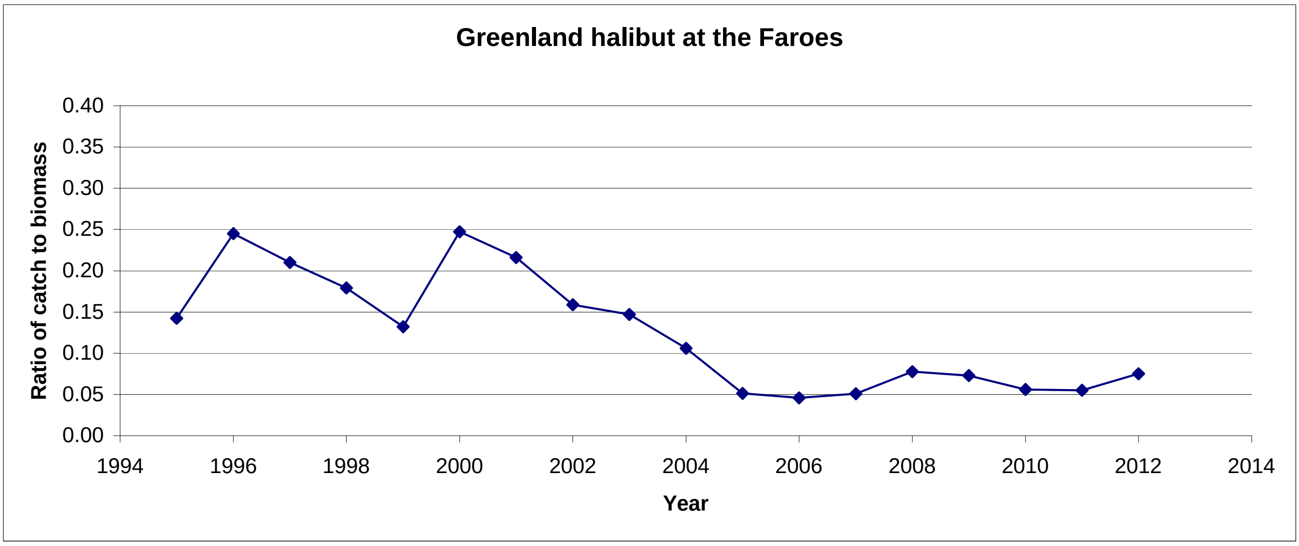
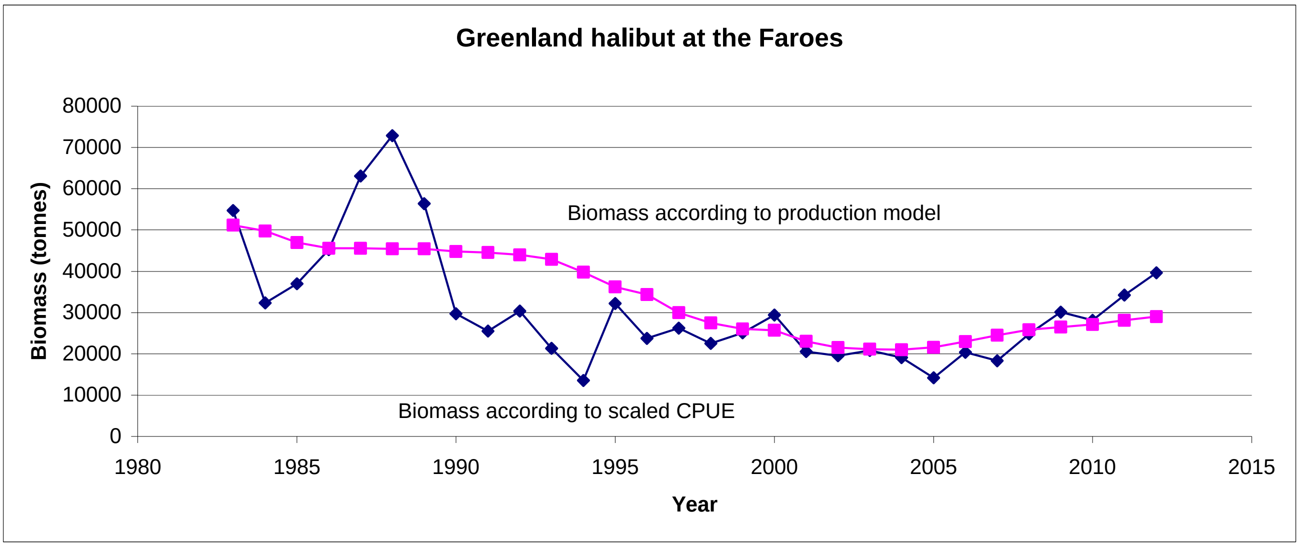


Figure 5. Greenland halibut in Faroese waters. Results from a production model using the CPUE from the commercial single trawlers 1995-2013, treated by a GLM-model, and the catch. The intrinsic growth rate was set at 0.188, as obtained from the tagging experiments.



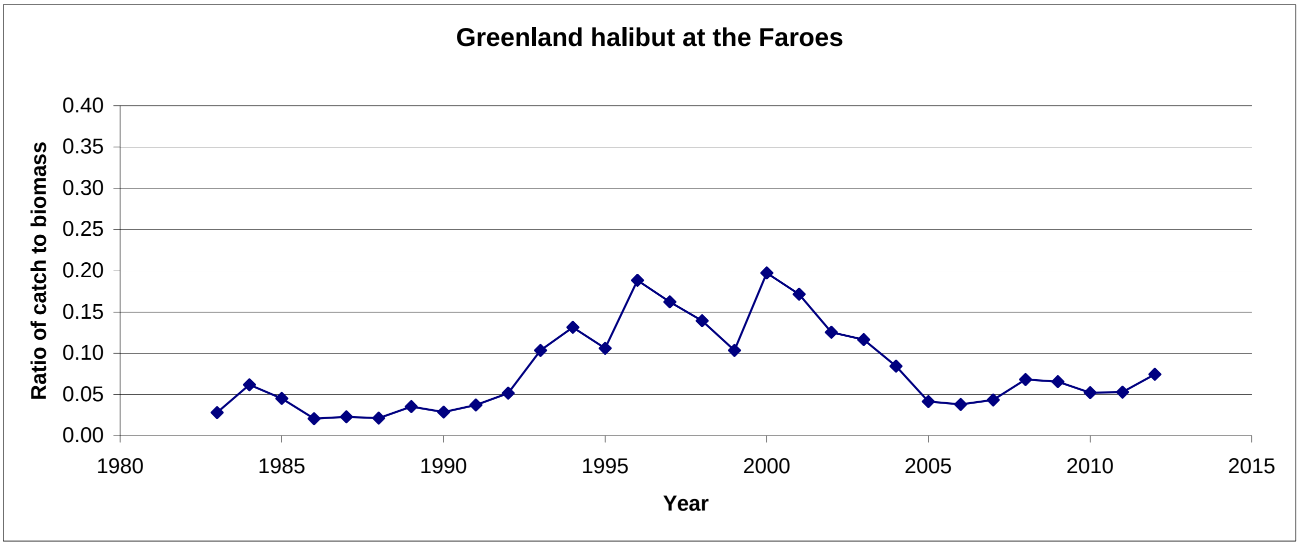


Figure 6. Greenland halibut in Faroese waters. Results from a production model using the CPUE from the combined March (1983-1990) and trawler (1991-2012) CPUE index and the catch. The intrinsic growth rate was set at 0.188, as obtained from the tagging experiments.

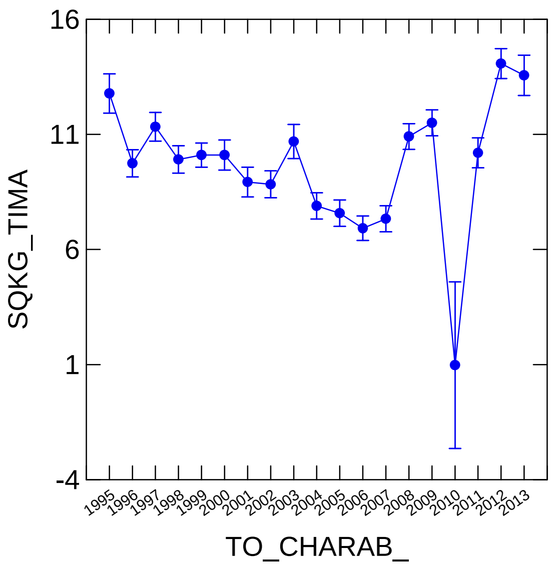
Appendix 1. Statistical output (package “Systat”) from the GLM model with the research “Greenland halibut trip”.

(“TO_CHARAB_” = year, “SQKG_TIMA” = Greenland halibut kg per hour, square root transformed, “Dypi” = depth).

```
Effects coding used for categorical variables in model.

Categorical values encountered during processing are:
TO_CHARAB_ (19 levels)
       1995,     1996,     1997,     1998,     1999,     2000,     2001,
       2002,     2003,     2004,     2005,     2006,     2007,     2008,
       2009,     2010,     2011,     2012,     2013

Dep Var: SQKG_TIMA   N: 633   Multiple R: 0.569   Squared multiple R: 0.324

                               -1
Estimates of effects  B = (X'X)  X'Y
                           SQKG_TIMA

   CONSTANT                      -9.056

   TO_CHARAB_ 1995                3.126
   TO_CHARAB_ 1996                0.092
   TO_CHARAB_ 1997                1.680
   TO_CHARAB_ 1998                0.262
   TO_CHARAB_ 1999                0.452
   TO_CHARAB_ 2000                0.454
   TO_CHARAB_ 2001               -0.721
   TO_CHARAB_ 2002               -0.822
   TO_CHARAB_ 2003                1.040
   TO_CHARAB_ 2004               -1.760
   TO_CHARAB_ 2005               -2.075
   TO_CHARAB_ 2006               -2.730
   TO_CHARAB_ 2007               -2.319
   TO_CHARAB_ 2008                1.257
   TO_CHARAB_ 2009                1.848
   TO_CHARAB_ 2010               -8.673
   TO_CHARAB_ 2011                0.548
   TO_CHARAB_ 2012                4.427

   DYPI                           0.040


Analysis of Variance
Source            Sum-of-Squares   df  Mean-Square     F-ratio       P

TO_CHARAB_              2364.663    18      131.370      10.072       0.000
DYPI                    1101.989     1     1101.989      84.488       0.000

Error                   7995.477   613       13.043

----------------------------------------------------------------------------------------------------

Adjusted least squares means
                           Adj. LS Mean          SE       N
  TO_CHARAB_  =1995              12.777        0.852      18
  TO_CHARAB_  =1996               9.742        0.592      40
  TO_CHARAB_  =1997              11.330        0.622      34
  TO_CHARAB_  =1998               9.913        0.594      37
  TO_CHARAB_  =1999              10.102        0.523      48
  TO_CHARAB_  =2000              10.105        0.652      31
  TO_CHARAB_  =2001               8.930        0.649      31
  TO_CHARAB_  =2002               8.829        0.586      38
  TO_CHARAB_  =2003              10.691        0.738      24
```

TO_CHARAB_	=2004	7.890	0.569	41
TO_CHARAB_	=2005	7.575	0.574	41
TO_CHARAB_	=2006	6.921	0.533	46
TO_CHARAB_	=2007	7.332	0.565	41
TO_CHARAB_	=2008	10.908	0.557	42
TO_CHARAB_	=2009	11.499	0.564	41
TO_CHARAB_	=2010	0.978	3.619	1
TO_CHARAB_	=2011	10.198	0.650	31
TO_CHARAB_	=2012	14.077	0.651	31
TO_CHARAB_	=2013	13.564	0.877	17

Least Squares Means



```
*** WARNING ***
Case           75 is an outlier        (Studentized Residual =        5.619)
Case          180 is an outlier        (Studentized Residual =        4.284)
Case          534 is an outlier        (Studentized Residual =        4.079)

Durbin-Watson D Statistic          1.586
First Order Autocorrelation        0.206
```

Appendix 2. Statistical output (package “Systat”) from the GLM model with the single trawlers.

(“orka” = trawling hours, “dypi” = depth, “puntur” = area square).

```
Data for the following results were selected according to:
      (ORKA_OK = 1) AND (DYPI_400_600 = 1) AND (DYPI_OK = 1)

Effects coding used for categorical variables in model.

Categorical values encountered during processing are:
YEAR (22 levels)
       1991,     1992,     1993,     1994,     1995,     1996,     1997,
       1998,     1999,     2000,     2001,     2002,     2003,     2004,
       2005,     2006,     2007,     2008,     2009,     2010,     2011,
       2012
MONTH (12 levels)
          1,        2,        3,        4,        5,        6,        7,
          8,        9,       10,       11,       12
PUNTUR$ (22 levels)
   DD6, DD7, DD8, DE5, DE6, DE7, DE8, DF4, DF5, DF6, DF7, DF8, DG4, DG5, DG6,
   DG7, DG8, DI4, DI5, DI6, DI7, DI8

Dep Var: SQRSVKATIMA   N: 9544   Multiple R: 0.635   Squared multiple R: 0.403

                               -1
Estimates of effects  B = (X'X)  X'Y
                           SQRSVKATIMA

   CONSTANT                    -19.026

   YEAR       1991               0.209
   YEAR       1992               0.888
   YEAR       1993              -0.437
   YEAR       1994              -1.822
   YEAR       1995               1.129
   YEAR       1996              -0.063
   YEAR       1997               0.306
   YEAR       1998              -0.250
   YEAR       1999               0.142
   YEAR       2000               0.759
   YEAR       2001              -0.562
   YEAR       2002              -0.732
   YEAR       2003              -0.521
   YEAR       2004              -0.807
   YEAR       2005              -1.701
   YEAR       2006              -0.591
   YEAR       2007              -0.934
   YEAR       2008               0.107
   YEAR       2009               0.854
   YEAR       2010               0.580
   YEAR       2011               1.391

   MONTH      1                 -0.166
   MONTH      2                  0.026
   MONTH      3                  0.845
   MONTH      4                  0.001
   MONTH      5                  0.548
   MONTH      6                  4.416
   MONTH      7                  2.365
   MONTH      8                 -0.816
   MONTH      9                 -2.075
   MONTH      10                -2.368
   MONTH      11                -1.976

   PUNTUR$    DD6               -0.778
   PUNTUR$    DD7               -1.224
   PUNTUR$    DD8               -8.858
   PUNTUR$    DE5                0.345
   PUNTUR$    DE6                0.338
   PUNTUR$    DE7               -1.122
   PUNTUR$    DE8               -0.944
   PUNTUR$    DF4                3.188
   PUNTUR$    DF5                1.637
```

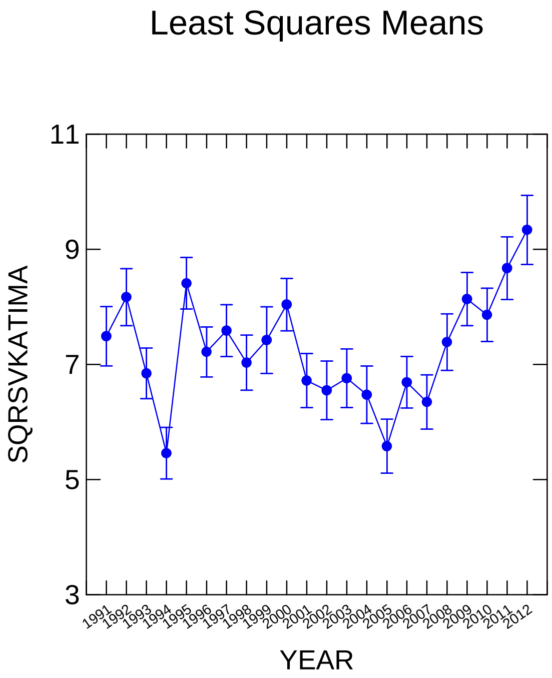
PUNTUR$	DF6	1.500
PUNTUR$	DF7	5.426
PUNTUR$	DF8	-1.930
PUNTUR$	DG4	5.305
PUNTUR$	DG5	1.981
PUNTUR$	DG6	-1.085
PUNTUR$	DG7	-7.034
PUNTUR$	DG8	-1.474
PUNTUR$	DI4	5.689
PUNTUR$	DI5	1.500
PUNTUR$	DI6	1.304
PUNTUR$	DI7	0.421
B_DYPI		0.055

Analysis of Variance

Source	Sum-of-Squares	df	Mean-Square	F-ratio	P
YEAR	6611.452	21	314.831	14.833	0.000
MONTH	37945.511	11	3449.592	162.520	0.000
PUNTUR$	15288.990	21	728.047	34.300	0.000
B_DYPI	41333.946	1	41333.946	1947.359	0.000
Error	201410.150	9489	21.226		

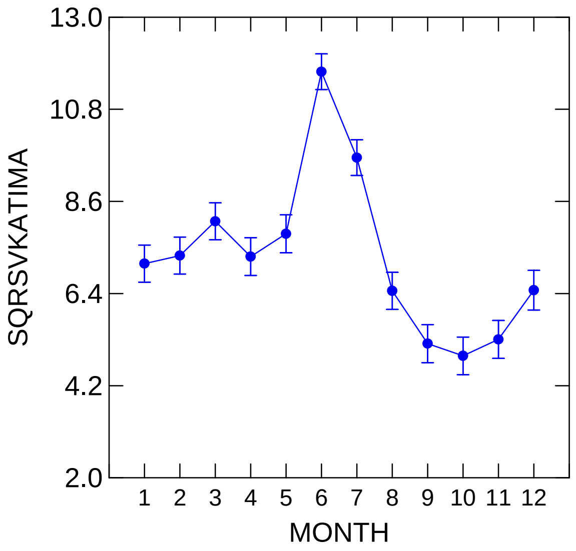
Adjusted least squares means

		Adj. LS Mean	SE	N
YEAR	=1991	7.490	0.514	200
YEAR	=1992	8.169	0.495	276
YEAR	=1993	6.844	0.439	755
YEAR	=1994	5.458	0.449	620
YEAR	=1995	8.410	0.448	621
YEAR	=1996	7.218	0.434	1161
YEAR	=1997	7.587	0.451	644
YEAR	=1998	7.031	0.479	356
YEAR	=1999	7.423	0.579	128
YEAR	=2000	8.040	0.454	608
YEAR	=2001	6.719	0.470	411
YEAR	=2002	6.549	0.510	242
YEAR	=2003	6.759	0.509	246
YEAR	=2004	6.473	0.499	273
YEAR	=2005	5.580	0.469	424
YEAR	=2006	6.690	0.447	665
YEAR	=2007	6.347	0.471	400
YEAR	=2008	7.388	0.491	298
YEAR	=2009	8.135	0.461	445
YEAR	=2010	7.860	0.463	487
YEAR	=2011	8.671	0.546	169
YEAR	=2012	9.337	0.601	115



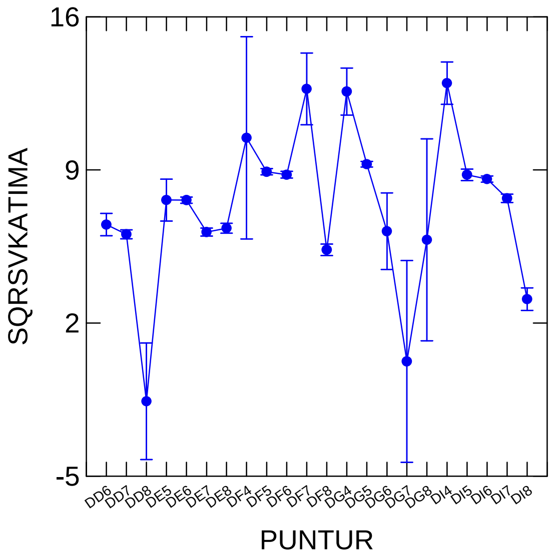
MONTH	=1	7.115	0.443	726
MONTH	=2	7.307	0.441	804
MONTH	=3	8.126	0.443	795
MONTH	=4	7.282	0.450	641
MONTH	=5	7.829	0.453	472
MONTH	=6	11.697	0.425	1616
MONTH	=7	9.646	0.427	1549
MONTH	=8	6.465	0.444	731
MONTH	=9	5.205	0.454	549
MONTH	=10	4.913	0.449	656
MONTH	=11	5.305	0.452	602
MONTH	=12	6.480	0.474	403

Least Squares Means



PUNTUR$	=DD6	6.503	0.511	83
PUNTUR$	=DD7	6.057	0.201	607
PUNTUR$	=DD8	-1.577	2.665	3
PUNTUR$	=DE5	7.626	0.957	24
PUNTUR$	=DE6	7.619	0.140	1192
PUNTUR$	=DE7	6.159	0.179	719
PUNTUR$	=DE8	6.337	0.230	521
PUNTUR$	=DF4	10.469	4.625	1
PUNTUR$	=DF5	8.918	0.142	1152
PUNTUR$	=DF6	8.781	0.154	968
PUNTUR$	=DF7	12.706	1.641	8
PUNTUR$	=DF8	5.351	0.262	364
PUNTUR$	=DG4	12.586	1.074	19
PUNTUR$	=DG5	9.262	0.126	1578
PUNTUR$	=DG6	6.196	1.751	7
PUNTUR$	=DG7	0.247	4.613	1
PUNTUR$	=DG8	5.807	4.617	1
PUNTUR$	=DI4	12.970	0.967	25
PUNTUR$	=DI5	8.780	0.262	329
PUNTUR$	=DI6	8.585	0.140	1221
PUNTUR$	=DI7	7.702	0.189	639
PUNTUR$	=DI8	3.093	0.513	82

Least Squares Means




```
----------------------------------------------------------------------------------------------------
*** WARNING ***
Case          146 is an outlier        (Studentized Residual =       5.599)
Case         1188 is an outlier        (Studentized Residual =       6.023)
Case         1189 is an outlier        (Studentized Residual =       5.030)
Case         1190 is an outlier        (Studentized Residual =       6.491)
Case         1333 is an outlier        (Studentized Residual =       7.784)
Case         1335 is an outlier        (Studentized Residual =       6.174)
Case         6549 is an outlier        (Studentized Residual =       7.593)
Case         6588 is an outlier        (Studentized Residual =       6.083)
Case         6594 is an outlier        (Studentized Residual =       5.845)
Case         6609 is an outlier        (Studentized Residual =       5.260)
Case         6715 is an outlier        (Studentized Residual =       6.984)
Case         6752 is an outlier        (Studentized Residual =       6.489)
Case        12514 is an outlier        (Studentized Residual =       7.067)
Case        12835 is an outlier        (Studentized Residual =       8.529)
Case        13857 is an outlier        (Studentized Residual =       5.060)
Case        13863 is an outlier        (Studentized Residual =       5.982)
Case        18856 is an outlier        (Studentized Residual =       7.073)
Case        18858 is an outlier        (Studentized Residual =       6.948)
Case        18859 is an outlier        (Studentized Residual =       6.755)
Case        18864 is an outlier        (Studentized Residual =       7.248)
Case        18865 is an outlier        (Studentized Residual =       7.143)
Case        19166 is an outlier        (Studentized Residual =      15.887)

Durbin-Watson D Statistic          1.291
First Order Autocorrelation        0.354
```

Working Document # 14

Benchmark Workshop on Greenland Halibut Stocks 2013

Assessment of the Barents Sea Greenland halibut stock using the stochastic version of the production model

S. Bakanev

Introduction

Production approach to modelling of the Greenland halibut stocks is applied for population occurring in the areas of Greenland, Iceland and the Faroese Islands (June, 2007; Boje et al., 2012). At that, the assessment is made allowing for a precautionary approach and a calculation of risks to exceed the management limiting reference points. The results of such study serve as recommendations for international management of the Greenland halibut stock in the adjacent waters of Greenland, Iceland and the Faroese Islands.

For the first time, this work attempts to estimate the Barents Sea Greenland halibut stock dynamics using a production approach. The primary population parameters were calculated with regard for their stochastic nature, and the risks to exceed the management limiting reference points were estimated.

Material and methods

The production model of stock estimation (Schaefer, 1954) was realized within the framework of the Bayesian Approach to model the system of state space (Hvingel and Kingsley, 2006; Schnute, 1994), when a parameter vector (θ) defines the stock dynamics. Posteriori distribution for model parameters $p(\theta|data)$ is estimated taking into account as the prespecified (prior) values of parameters $p(\theta)$, as the observation data $p(data|\theta)$, by means of the Bayes theorem (1763):

$$p(\theta \mid data) \propto p(data \mid \theta)\, p(\theta) \qquad [1]$$

Posteriori parameter values are estimated by the Markov Chain Monte Carlo statistical procedure (MCMC), realized in the OpenBUGS software environment (Spiegelhalter et al. 2004). The equation of the relationship of stock biomass in t-year and the following t+1 year is described through the digital form of the population growth logistic model involving fishing mortality, maximal sustainable yield (*MSY)*, and the intrinsic growth rate (*r*; Fletcher, 1978):

$$B_{t+1} = B_t - C_t + 4MSY\frac{B_t}{K}\left(1-\frac{B_t}{K}\right), \qquad [2]$$

where K – the environmental carrying capacity or the virgin biomass (thou.t), B_t - the exploitable biomass at the start of year t (thou.t), C_t – the catch by all gear-types during year t (thou.t, Table 1).

To diminish uncertainty appearing when estimating catchability (a parameter scaling indices with biomass) the exploitable biomass at the start of year t, (B_t) is expressed through a relative index, P_t, by means of dividing by B_{MSY}, the biomass at which MSY is achieved (Hvingel and Kingsley 2006). At that, the equation describing the biomass dynamics with regard for a process error is as follows:

$$P_{t+1} = \left(P_t - \frac{C_t}{B_{MSY}} + \frac{2\,MSY\,P_t}{B_{MSY}}\left(1-\frac{P_t}{2}\right)\right)\cdot \exp(\nu_t) \qquad [3]$$

where P_t – the relationship of the biomass in t-year and the biomass corresponding to the level of MSY ($P_t=B_t/B_{MSY}$). Within the range of varying stock biomass (B), a relative P-value equaled to 1 will be corresponding to $B_t = B_{MSY}$, and $P=2$ corresponds to $B_t = 2B_{MSY}$. Calculation error in estimation of modeled abundance (v) has normal distribution with average 0 and standard deviation σ_v^2.

Unobserved variable P_t may be expressed through an observed index of relative abundance ($Index_t$), i.e. the index calculated using the results from the research survey or CPUE:

$$Index_t \sim q_{index} B_{MSY} P_t \cdot \exp(k) \qquad [4]$$

The relationship of index and a real biomass value is expressed through the catchability coefficient, q_s, and e^k is the error in abundance index measurement having a normal distribution with average 0 and a standard deviation of $\sigma_k{}^2$ (Haddon, 2001).

Table 1 Catch (thou. t) and indices (standard units) of the Greenland halibut abundance in the Barents Sea in 1964-2012.

(GLM – standardized catch-per-unit-effort of Russian fleet, NOR1 – catch per effort of low-tonnage Norwegian vessels, NOR2 – catch per effort of large tonnage Norwegian vessels, NOR – abundance index from the Norwegian survey, RUS - abundance index from the Russian survey, ECO - abundance index from the ecosystem survey)

Year	Catch, ktons	GLM	NOR1	NOR2	NOR	RUS	ECO
1964	40,391	1,71	-	-	-	-	-
1965	34,751	1,52	-	-	-	-	-
1966	26,321	1,48	-	-	-	-	-
1967	24,267	1,54	-	-	-	-	-
1968	26,168	1,60	-	-	-	-	-
1969	43,789	1,61	-	-	-	-	-
1970	89,484	1,48	-	-	-	-	-
1971	79,034	1,38	-	-	-	-	-
1972	43,055	1,34	-	-	-	-	-
1973	29,938	1,38	0,34	-	-	-	-
1974	37,763	1,39	0,36	-	-	-	-
1975	38,172	1,35	0,38	-	-	-	-
1976	36,074	1,29	0,33	-	-	-	-
1977	28,827	1,26	0,33	-	-	-	-
1978	24,617	1,29	0,21	-	-	-	-
1979	17,312	1,30	0,28	-	-	-	-
1980	13,284	1,34	0,32	-	-	-	-
1981	15,018	1,39	0,36	-	-	-	-
1982	16,789	1,40	0,41	-	-	-	-
1983	22,147	1,36	0,35	-	-	-	-
1984	21,883	1,35	0,32	-	-	42,88	-
1985	19,945	1,42	0,37	-	-	44,70	-
1986	22,875	1,35	0,37	-	-	25,92	-
1987	19,112	1,34	0,35	-	-	15,34	-
1988	19,587	1,33	0,31	-	-	16,89	-
1989	20,138	1,32	0,26	-	-	11,48	-
1990	23,183	1,25	0,27	-	-	10,06	-
1991	33,32	1,21	0,24	-	-	11,61	-
1992	8,602	1,07	0,46	0,72	-	11,84	-
1993	11,933	-	0,79	1,22	-	18,81	-
1994	9,226	-	0,77	1,27	-	20,14	-
1995	11,734	1,40	1,03	1,48	-	13,49	-
1996	14,347	1,59	1,45	1,82	14,20	9,00	-
1997	9,41	1,20	1,23	1,6	16,98	16,40	-
1998	11,893	1,33	0,98	1,35	26,72	28,10	-
1999	19,517	1,69	0,82	1,77	50,70	23,75	-
2000	14,437	1,88	1,38	1,92	25,59	34,44	-
2001	16,307	2,01	1,18	1,57	33,96	41,8	-
2002	13,161	1,64	1,07	1,82	37,40	27,05	-
2003	13,578	1,97	0,86	2,45	43,56	43,66	-
2004	18,8	1,54	1,16	1,79	42,61	55,50	11,09
2005	18,834	1,68	1,3	2,29	33,56	42,03	12,84
2006	17,897	1,60	0,96	2,09	37,02	60,09	22,00
2007	15,237	1,63	-	-	23,85	71,56	24,00
2008	13,778	1,56	-	-	23,15	81,59	26,31
2009	12,996	1,95	-	-	31,49	62,95	29,13
2010	15,221	2,14	-	-	-	86,86	42,77
2011	16,337	2,22	-	-	-	82,90	37,94
2012	15.00	2,16	-	-	-	63,00	42,33

The used indices were (Table 1):

1) annual standardized catch per effort of the main Russian fishing vessel types (GLM_t) in 1964-2012;
2) annual catch per effort of the Norwegian low-tonnage vessels ($NOR1_t$; reference) in 1973-2006;
3) annual catch per effort of the Norwegian large tonnage vessels ($NOR2_t$; reference) in 1993-2006;
4) annual index of abundance from the Norwegian survey (NOR_t; reference) in 1996-2009;
5) annual index of abundance from the Russian survey ((RUS_t; reference) in 1984-2012;
6) annual index of abundance from the Russian survey (ECO_t; reference) в 1984-2012.

In terms of using several abundance indices in the estimate the equation [4] is transformed into the equation typesetting:

$$
\begin{aligned}
GLM_t &\sim q_{GLM} B_{MSY} P_t \cdot \exp(\sigma_{\mathrm{GLM}}{}^2), \\
NOR1_t &\sim q_{NOR1} B_{MSY} P_t \cdot \exp(\sigma_{\mathrm{NOR1}}{}^2), \\
NOR2_t &\sim q_{NOR2} B_{MSY} P_t \cdot \exp(\sigma_{\mathrm{NOR2}}{}^2), \\
NOR_t &\sim q_{NOR} B_{MSY} P_t \cdot \exp(\sigma_{\mathrm{NOR}}{}^2), \\
RUS_t &\sim q_{RUS} B_{MSY} P_t \cdot \exp(\sigma_{\mathrm{RUS}}{}^2), \\
ECO_t &\sim q_{RUS} B_{MSY} P_t \cdot \exp(\sigma_{\mathrm{RUS}}{}^2),
\end{aligned}
\qquad [5]
$$

where q_{GLM}, q_{NOR1}, q_{NOR2}, q_{NOR}, q_{RUS}, q_{ECO} – the coefficients of proportionality (catchability) of relevant abundance indices, GLM_t, $NOR1_t$, $NOR2_t$, RUS_t and ECO_t. At that, the errors in index abundance measurement have a normal distribution with average 0 and standard deviations $\sigma_{GLM}{}^2, \sigma_{NOR1}{}^2, \sigma_{NOR2}{}^2, \sigma_{NOR}{}^2, \sigma_{RUS}{}^2, \sigma_{ECO}{}^2$.

According to the above discussed equations in order to make a model it is necessary to estimate such parameters as the catchability coefficients, the virgin biomass (maximal possible biomass under the lack of fishery or K, the environmental carrying capacity), maximal surplus production or maximal sustainable yield (*MSY*), the initial abundance value (B_1), as well as the error standard deviation values.

Currently, there are no reliable data on the catchability coefficients for indices of catch per unit effort in the fishery of the Barents Sea Greenland halibut. Also, there are no true data on the absolute biomass of the commercial stock in the Barents Sea and coefficients scaling this biomass to indices calculated by trawl surveys.

When there is no preliminary information about a parameter, one of the variants to solve the problem may be using a uniform distribution as the prior one (when all possible outcomes of a random value have equal probabilities). In this case, the distribution of catchability coefficient will be only limited by its physics, i.e. it will be equally within the range of values from 0 to 1. In accordance with foreign authors, in this case, the distribution of catchability coefficient is more preferable to express in the logarithmic scale. Mathematically, this less informative prior is accepted to write down as: $\ln(q) \sim \text{dunif}((-10;1)$, where dunif is a uniform distribution, from 10 to 1 (Table 2; Punt and Hilborn, 1997; McAllister and Kirkwood, 1998; Gelman et al., 1995).

A choice of maximal possible abundance of population with the lack of fishery (*K*, the environmental carrying capacity) was estimated with regard for the following assumptions. In recent years, according to the data from the trawl surveys of PINRO, the fishing stock was estimated at 200-450 thousand t. Taking into account a good stock status in recent years and a comparatively low fishery press, as well as a quite high uncertainty of estimates obtained by instrumental methods, the lower bound of possible *K*-value may correspond to the maximal estimate of survey allowing for an error. The survey error or a variation coefficient usually varies at the level of 25-50%. Thus, the lower bound of a prior distribution of *K* was initially adopted at the level of 500-700 thou.t. At that, the distribution of possible *K*-values corresponded to low informative and it was adopted as normal with a moda of 1,000 thou.t and a dispersion of 300, at which *K* was within the range of 800-1,200 t with a 95% probability (Table 2). Besides, the runs of model with different parameters of the dispersion and moda values equaled to 250 thou.t and 500 thou.t were made in order to estimate model sensitivity.

Table 2 Input data of model (distribution: dunif – uniform; dnorm – normal, dgamma - gamma)

Parameter			Prior	
Name	Symbol		Type	Distribution
Maximum sustanable yield	MSY		reference	dunif(1, 200)
Carrying capacity	K		low informative	dnorm(1000,300)
Initial biomass	P_1		informative	dnorm(1.5, 0.071)
Catchability coefficient for GLM	q_{GLM}		low informative	ln(qGLM)~dunif(-3,1)
Catchability coefficient for NOR1	q_{NOR1}		low informative	ln(qNOR1)~dunif(-3,1)
Catchability coefficient forNOR2	q_{NOR2}		low informative	ln(qNOR2)~dunif(-3,1)
Catchability coefficient for NOR	q_{NOR}		low informative	ln(qNOR)~dunif(-3,1)
Catchability coefficient for RUS	q_{RUS}		low informative	ln(qRUS)~dunif(-3,1)
Catchability coefficient for ECO	q_{ECO}		low informative	ln(qECO)~dunif(-3,1)
Error for GLM	$1/sigma_{GLM}^2$		low informative	dgamma(2.5,0.03)
Error for NOR1	$1/sigma_{NOR1}^2$		low informative	dgamma(2.5,0.03)
Error for NOR2	$1/sigma_{NOR2}^2$		low informative	dgamma(2.5,0.03)
Error for NOR	$1/sigma_{NOR}^2$		low informative	dgamma(2.5,0.03)
Error for RUS	$1/sigma_{RUS}^2$		low informative	dgamma(2.5,0.03)
Error for ECO	$1/sigma_{ECO}^2$		low informative	dgamma(2.5,0.03)
Process error	$1/sigma_P^2$		low informative	dgamma(2.5,0.03)

In accordance with the equation [5] *MSY*-parameter is mainly defined by the environmental carrying capacity, *K*. Assuming this, the density distribution of probabilities of *MSY* possible values has been chosen with regard for *K* distribution. The uniform distribution of *MSY* was assigned within the limits of 1 to 200 thou.t. The lower bound was specified with consideration for more pessimistic estimate of the stock productivity. The upper bound was set to be high so that biologically plausible posterior distribution of the parameter entirely entered into the prior one.

The adequacy of information about a stock status before fishery is usually lower after its start and the annual collection of fishery statistics and biological data ([24] Doubleday, Rivard, 1981; [25] Seber, 1982; [26] Helser, Hayes, 1995; [27] Perry, Smith, 1994). As a rule, it is allowable that $B_1 \approx K$ (or P_1=2), i.e. that the stock is maximal, and, in this period, fishery has no essential impact on the stock dynamics. The biomass in 1964 (the start year in the assessment) cannot be equal to *K*, since the fishery was also active in the previous years. However, the fishing press in those years may be considered as moderate ([28] Smirnov, 2006), therefore, the initial biomass was chosen in the range of 0,5**K* to 1**K*. A low informative prior with a normal distribution of P_1~ dnorm(1,5; 0,071), moda of 1,5 and dispersion of 1, under which P was in the range of 1 to 2 with 95% probability was used. There is no priori information about the accuracy of the error in the abundance index measurement $(\sigma_{GLM}{}^2, \sigma_{NOR1}{}^2, \sigma_{NOR2}{}^2, \sigma_{NOR}{}^2, \sigma_{RUS}{}^2, \sigma_{ECO}{}^2)$ and model abundance (σ_v^2) estimation. A possible value of this parameter may be within a wide range of values with probable distribution of $1/\sigma_v^2 \sim dgamma(0.001, 0.001)$ ([15] Hvingel, Kingsley, 2006).

Results

The calculations using a Shefer's production model were made in order to estimate biomass dynamics, population production and management reference points for the Barents Sea Greenland halibut stock. The algorithm was adjusted to 500,000 iterations. The model runs with different adjustment and parameter start values were made to analyze the stability of model decisions and sensibility to changes of parameters. There were made four runs of model with the following input abundance indices:

1) a full set of indices including *GLM*, *NOR1*, *NOR2*, *NOR*, *RUS*, *ECO*;
2) *NOR1*, *NOR2*, *NOR*, *RUS*, *ECO*, as well as a *GLM*-index with shorter time series for 1995-2012;
3) *NOR1*, *NOR2*, *NOR*, *RUS*, as well as a number of *GLM*-indices divided into two time series, 1964-1992 and 1995-2012;
4) A set of survey indices including *NOR*, *RUS*, *ECO* without Russian and Norwegian indices of catch per effort.

The analysis of model run results has showed that *K* is estimated within the range of 810 to 1,139 thou.t, B_{MSY} – of 405 to 570 thou. t and MSY – of 23 to 47 thou. t. At that, the biomass for the estimated year, B_{2012}, is assessed within a wide range of 700 to 1,400 thou.t. Under various model runs, the stock dynamics is similar, but values themselves vary within the limits of 100-700 thou.t (in accordance with Figure 2).

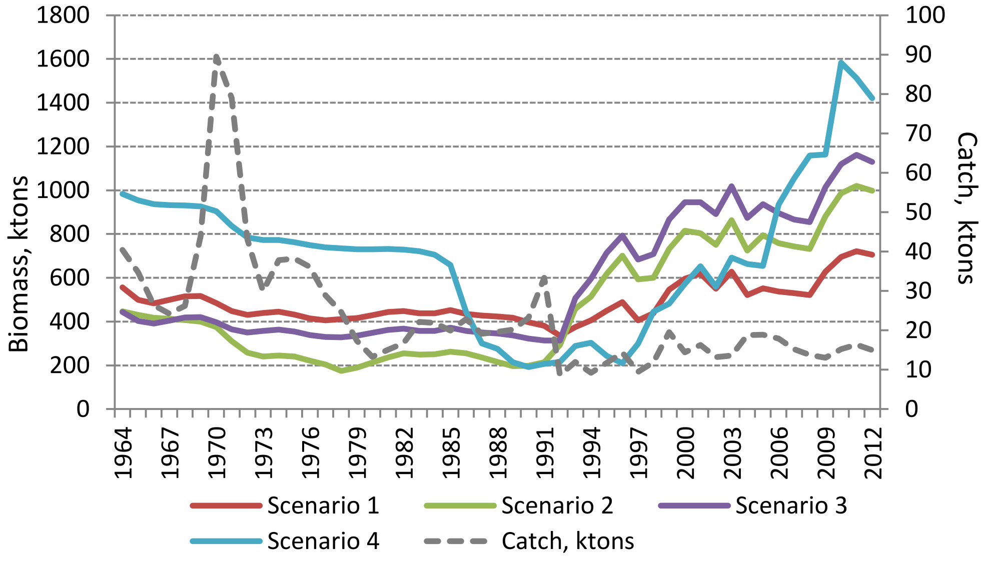


Figure 2 Dynamics of annual catch and modelled stock of the Barents Sea Greenland halibut in 1964-2012 under the different variants of input data.

The biomass estimate is maximal when only using the survey indices which have increased significantly recently. All the calculation variants indicate that, in the 21 century, the stock biomass was higher than in the last one. During the calculations without regard for fishing efficiency indices more variable dynamics was noticed (Variant 4). That was conditioned by more conservative variability of fishing indices in the course of the survey period. It should be noticed that the dynamics of early survey period is quite stable that is a result of adjusting model to the only index of abundance in this period (*GLM*). At that time, the index of Russian fishery efficiency (*GLM*) has no significant changes in the dynamics despite the big yields in the 1970s.

The results of model runs showed that the first variant with regard for all the available input data gave more conservative estimates of biomass in the late years. Taking that into consideration the parameters of that run were chosen for further research of model behavior. The posterior parameters of the model are presented in Table 3. *MSY* is estimated at the level of 25 thou.t, that corresponds to F_{MSY} equaled to 0.06. In other words, the maximal sustainable yield accounts for 6% from the biomass at which the surplus production is at the maximal level.

Table 3 Mean, standard deviation, median and bounds of 50% and 95% deviations of model parameter distributions

Parameter	Mean	St. Dev.	2,5%	25,0%	Median	75,0%	97,5%
K	786.1	288.8	313.8	523.2	810.7	1007	1299
MSY	23.45	8.736	9.133	15.62	24.59	30.03	38.36
B_{MSY}	393.1	144.4	156.9	261.6	405.4	503.6	649.3
q_{GLM}	0.003745	0.008927	0.002268	0.002722	0.003108	0.003571	0.005026
q_{NOR1}	0.008419	0.07034	9.22E-04	1.03E-03	0.001159	0.001363	0.003412
q_{NOR2}	0.005778	0.03857	2.38E-03	0.002889	0.003315	0.003856	0.005564
q_{NOR}	0.06392	0.105	0.03845	0.04868	0.05558	0.06414	0.08906
q_{RUS}	0.06389	0.0212	4.04E-02	0.05104	0.05994	0.07126	0.1083
q_{ECO}	0.03659	0.01776	0.003314	0.03144	0.03883	0.04648	0.0663
$1/sigma_{GLM}^2$	0.06842	0.1638	0.03397	0.0431	0.04938	0.0571	0.09988
$1/sigma_{NOR1}^2$	0.5989	0.5877	0.4063	0.4663	0.5043	0.5491	0.8373
$1/sigma_{NOR2}^2$	0.1744	0.194	0.1096	0.1404	0.1584	0.1795	0.236
$1/sigma_{NOR}^2$	0.2844	0.1178	0.1975	0.2406	0.2698	0.3058	0.4178
$1/sigma_{RUS}^2$	0.5309	0.07498	0.4051	0.4835	0.5263	0.5745	0.6875
$1/sigma_{ECO}^2$	0.5969	0.6645	0.2162	0.2767	0.3237	0.4105	2.496
$1/sigma_{P}^2$	0.1498	0.0265	0.1087	0.1294	0.1465	0.1672	0.2081
P_1	1.756	1.064	0.7405	1.087	1.421	2.291	3.275
F_{MSY}	0.05952	0.004475	0.0515	0.05669	0.05913	0.06144	0.07067

In order to study model sensitivity to change of the main parameter, *K*, the runs with different parameters of its distribution were made (Table 4). The results of the runs have shown that the choice of different parameters of *K* distribution give significant biases in posteriori estimates that indicates the stock estimate is mainly based on our expert judgment concerning the maximal stock size under the lack of fishery, i.e. *K*, and not on the input data. So, with change of 95% interval, under a constant moda of 1,000 thou.t of priori distribution, *K*, median *MSY*-values vary within the range of 20 to 31 thou.t.

Table 4 Sensitivity of central parameter estimates (25, 50, and 75 percentiles of their posterior distribution) to changes of the prior for carrying capacity, *K*. MSY = Maximum Sustainable Yield, P_{2012} is the stock biomass in 2012 relative to B_{msy}.

Prior distribution							Aposterior distribution					
Carrying capacity (K, ktons)					K (ktons)			MSY (ktons)			P2012	
Distribution	2,5%	Median	97,5%	2,5%	Median	97,5%	2,5%	Median	97,5%	2,5%	Median	97,5%
dnorm(1000,300)	796,5	999,4	1203,0	523,2	810,7	1007	15,62	24,59	30,03	1,402	1,81	2,721
dnorm(1000,600)	591,8	998,6	1405,0	687,0	847,4	878,8	17,69	19,84	21,22	1,703	1,913	2,139
dnorm(1000,900)	387,7	997,9	1608,0	774,9	920,3	1067,0	24,89	30,59	33,6	1,257	1,464	1,718
dnorm(500,300)	295,9	499,3	702,5	438,7	460,5	482,1	19,75	20,74	21,64	2,054	2,282	2,542
dnorm(750,300)	162,5	748,7	1337,0	547,0	740,6	995,3	20,73	25,99	49,31	1,4	1,955	2,543
dnorm(1500,300)	911,3	1499,0	2090,0	1149,0	2156,0	2714,0	13,49	32,99	39,63	0,347	0,594	1,148

To evaluate reliability of the results obtained the calculations with the input data sets were made allowing for different time periods. At that, the current estimate with data before 2012 was compared to those ones obtained with the data restricted by the previous years of the research down to 2002 (in accordance with Figure 3). In so doing, the biomass values significantly varied depending on the last year in data time series. The range of biomass value discrepancies reached 150-200 thou. t in different runs.

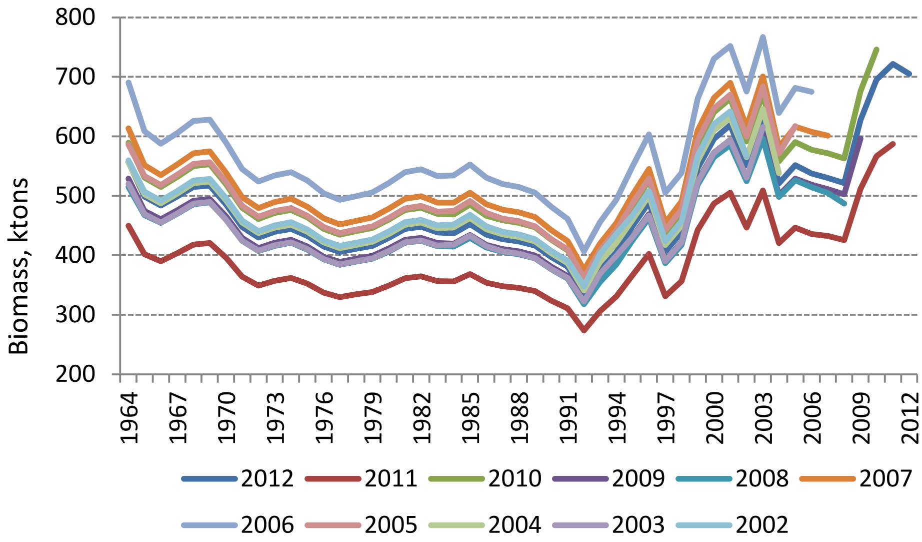


Figure 3 Retrospective dynamics of the Barents Sea Greenland halibut modelled stock when choosing the terminal year of 2002 to 2012.

The analysis of deviations between actual and calculated values of abundance indices shows that there is a minor bias of the estimate in relation to *GLM*-index towards higher model values in 1964-1992 (Table 5). An actual index is lower than the modeled one by 2-7%.

Table 5 Deviations (%) of actual abundance indices from the calculated values with using production model to estimate the Barents Sea Greenland halibut stock in 1964-2012.

Year	GLM	NOR1	NOR2	NOR	RUS	ECO
1964	-1,06					
1965	-2,04					
1966	-1,46					
1967	-0,53					
1968	-0,21					
1969	-0,04					
1970	-2,08					
1971	-1,04					
1972	0,12					
1973	1,25	-49,82				
1974	0,87	-43,07				
1975	0,22	-31,88				
1976	0,40	-45,54				
1977	0,16	-42,35				
1978	0,68	-126,83				
1979	0,60	-72,19				
1980	0,18	-55,38				
1981	0,91	-43,01				
1982	0,54	-26,61				
1983	-0,22	-45,11				
1984	-0,31	-58,28			38,92	
1985	0,69	-41,71			39,35	
1986	0,31	-36,10			-0,44	
1987	0,65	-41,43			-66,81	
1988	1,14	-58,30			-50,23	
1989	1,94	-85,66			-117,35	
1990	1,47	-70,46			-136,56	
1991	2,34	-83,80			-96,39	
1992	2,94	15,44	-54,52		-69,80	
1993		45,10	-1,68		-19,22	
1994		39,04	-5,71		-20,53	
1995	0,56	49,47	-0,59		-99,42	
1996	4,71	60,90	10,90	-91,48	-225,64	
1997	-4,92	61,75	15,90	-32,85	-48,33	
1998	-2,28	48,15	-7,65	8,81	6,49	
1999	-0,08	22,79	-2,32	40,12	-37,86	
2000	1,77	50,00	-2,80	-29,27	-3,62	
2001	4,45	39,24	-30,62	-1,22	11,29	
2002	-4,05	40,35	-0,31	18,17	-22,01	
2003	1,44	15,42	15,08	19,93	13,86	
2004	-4,89	47,94	3,51	32,04	43,74	-82,38
2005	-1,40	50,85	20,19	8,71	21,38	-66,67
2006	-3,97	35,12	14,76	19,33	46,40	5,16
2007	-0,52			-23,50	55,60	14,26
2008	-3,63			-25,16	61,69	23,04
2009	0,50			-10,70	40,28	16,40
2010	-0,77				52,03	36,90
2011	-0,68				47,82	26,14
2012	-1,27				32,94	35,35

The modelled values of *NOR1*-index are considerably higher than the actual ones in 1973-1991 and lower than the real values in the following years, that is indicative of a weak correspondence of modelled stock dynamics to the actual index. The same results were obtained when analyzing the index of Russian bottom survey (*RUS*). The figure shows dynamics of actual abundance indices and range of 50% confidence interval of their model estimates (according to Figure 4). The dynamics correspondence of less variable GLM-index is quite satisfied. Low correspondence of actual values and model ranges for the other abundance indices is a result of both a great variability of factual values of indices and a weak conformity of index dynamics inter se. The model has described recent significant positive trends in *RUS* and *ECO*-indices as more smoothed, in better compliance with GLM-index behavior in these years.

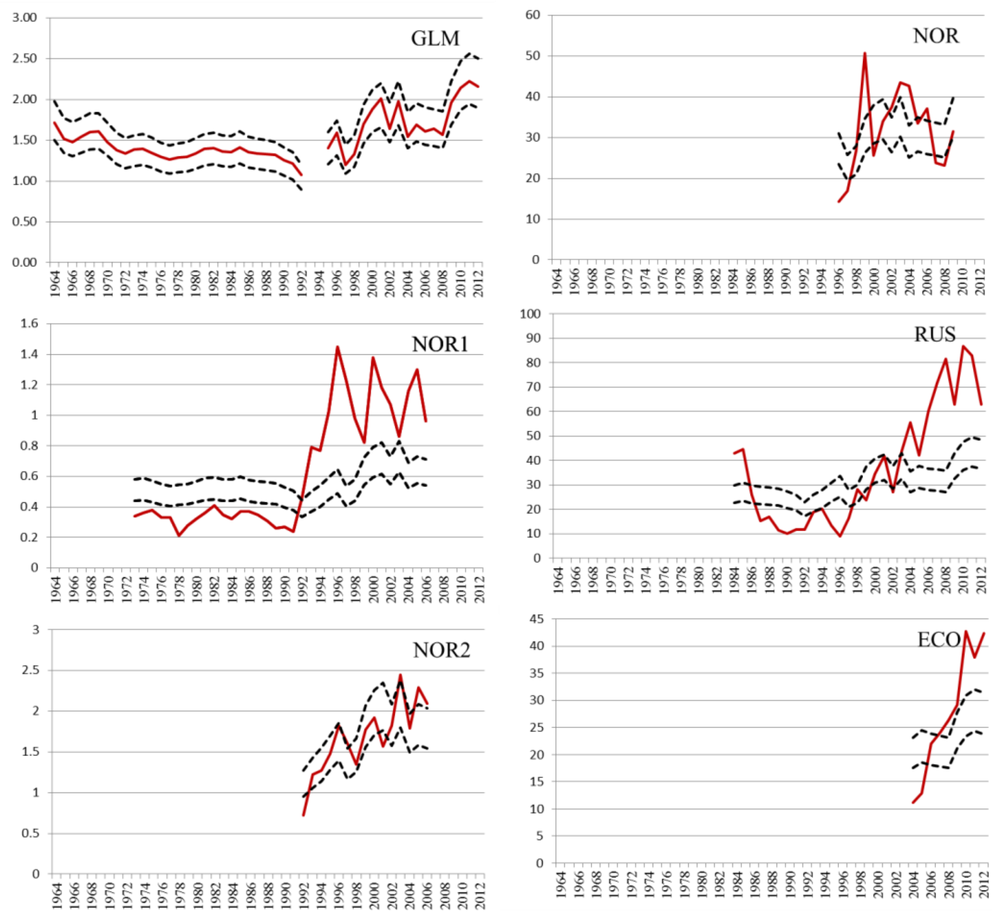


Figure 4 Dynamics of Greenland halibut actual abundance indices (red line) and limits of 50% confidence interval (dashed lines) of their model estimates.

In order to analyze the relationship of the stock dynamics and fishing intensity a zonal diagram was plotted at the beginning (in accordance with Figure 5). The abscissa axis, along which a relative biomass had been plotted was divided into three segments by two points corresponding to the population threshold state, B_{MSY} and B_{lim}. The parameter, B_{MSY}, a target management reference point, equals to 405 thou.t in accordance with the production model. On the abscissa axis showing a relative biomass the value, B_{MSY}, corresponds to 1. The B_{lim}-parameter is a boundary reference point lower of which the stock state is considered as unfavourable. In our work, B_{lim}-value equals to 30% of B_{MSY}, that is in keeping with the fishery regulation scheme for the North-East Atlantic when estimating the stocks of fish and invertebrates with the use of the production models (NAFO, 2004). The biological sense of this management reference point corresponds to the definition of overfishing by recruitment, i.e. the population state when the recruitment cannot compensate the total loss of the stock cause of the low abundance of spawners (Ricker, 1979).

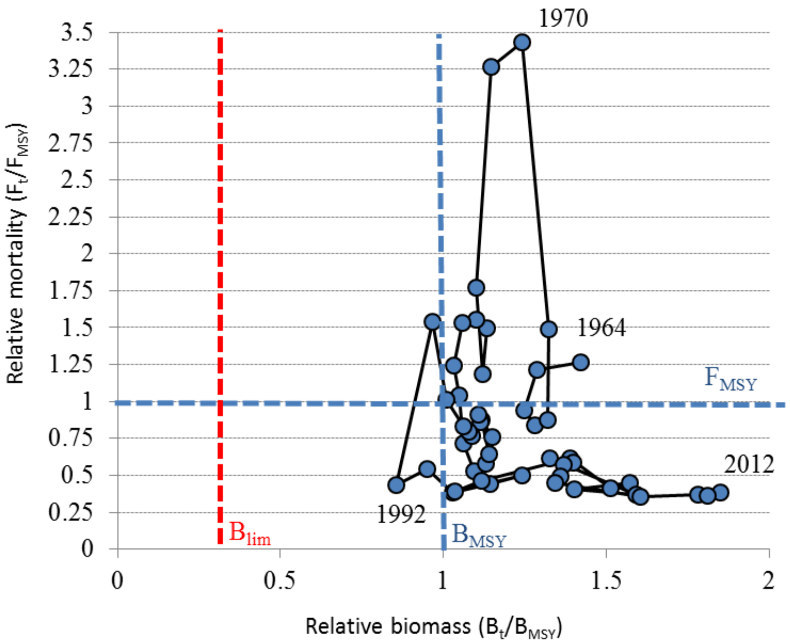


Figure 5 Annual relationship of relative biomass (B_t/B_{MSY}) and annual mortality (F_t/F_{MSY}) in the management area zones for the Barents Sea Greenland halibut stock in 1964–2012.

To estimate the population exploitation intensity the ordinate axis showing a relative mortality (F_t/F_{msy}) is divided into two segments by the point corresponding to F_{lim}-reference point. The F_{lim} is a boundary value the exceeding of which may lead to the stock collaps. In our work, F_{lim}-value is taken to be equal to F_{msy}, that agrees with the adopted scheme of fishery regulation in the North Atlantic when estimating stocks of fish and invertebrates with the use of the production models (NAFO, 2004).

The trajectory of the relationship of median estimates, (B_t/B_{MSY}) and (F_t/F_{MSY}), (in compliance with Figure 4) starts from 1964, when the biomass was quite high (1,5*B_{MSY}), and the exploitation exceeded the threshold level of F_{MSY}. In 1970–1971, fishing mortality significantly increased with minor reduction in biomass. The stock biomass in the following years is estimated to be higher than B_{MSY}; the fishing mortality varies within the range of 0.5 to 1.5. In 1991-1993, biomass was lower than B_{MSY}, but much higher than B_{lim}. Later, with commercial fishery under a ban, the stock biomass grew and fishing intensity decreased; the points corresponding to these years are grouped in the right lower corner of the diagram. 2010–2012 was a period of maximal biomass and low exploitation.

Taking into consideration a high probability of the stock size being at the level which was quite higher than the biomass corresponding to B_{MSY}, the risk of the biomass reduction towards the level of under this optimal one was very small in 2002-2012 (<1%; Table 6). The risk-analysis of the stock size in the prognostic years (2013-2020) under the catch of 0 to 30 thou.t indicated that probability of the stock size being under the threshold levels (B_{MSY}, B_{lim}) was also minor (less than 1%). The increase of possible annual catch to 50 thou.t will reduce the biomass to B_{MSY} only to 2020 (in accordance with Figure 6). It should be noticed that the stock production at the level of the stock estimation in 2012 is low, since its size considerably exceeds B_{MSY}. At that, the surplus production is estimated at 4.7 thou.t. In accordance with the production model, the annual catch exceeding 4.7 thou. t will inevitably reduce the biomass in the prognostic years.

Table 5 Greenland halibut stock biomass estimates and risks of exceeding management reference points (%) in 2002-2012

Parameter/Year	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Biomass (B, ktons)	551	628	521	551	537	530	522	627	695	722	705
Relative biomass ($P=B/B_{MSY}$)	1,4	1,6	1,3	1,4	1,4	1,4	1,3	1,6	1,8	1,9	1,8
Probability of falling below B_{lim} $(0.3B_{msy})$	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%
Probability of falling below B_{trig} $(0.47B_{msy})$	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%
Probability of exceeding F_{msy}	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%

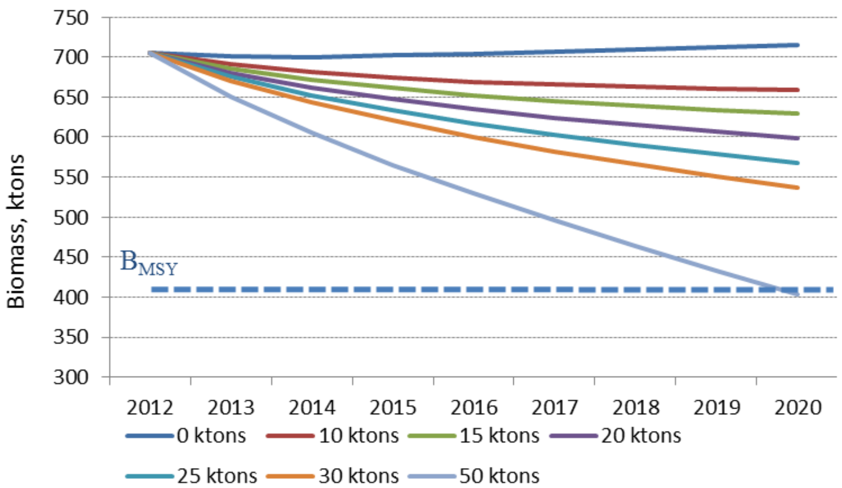


Figure 6 Prognostic dynamics of the Barents Sea Greenland halibut stock with different annual yield (dashed line – the level of B_{MSY}).

Figure 7 shows that the model ability to determine an equilibrium production curve is not great. The estimation of *MSY* requires more significant influence of fishery on the stock. But, it is possible to assume that, with our view of environmental carrying capacity and available data on the intensive exploitation in 1964–2012, it can be within the range of 20–30 thou.t. Probably, the Barents Sea Greenland halibut population reacts to fishery, but so far the available data and estimation procedures haven't allowed the reaction to be defined. Probably, the production reserves of the stock may provide the real high rate of its exploitation with the appearance of strong year-classes and, at the same time, they will permit the population reaction on increasing fishing efforts to be tracked.

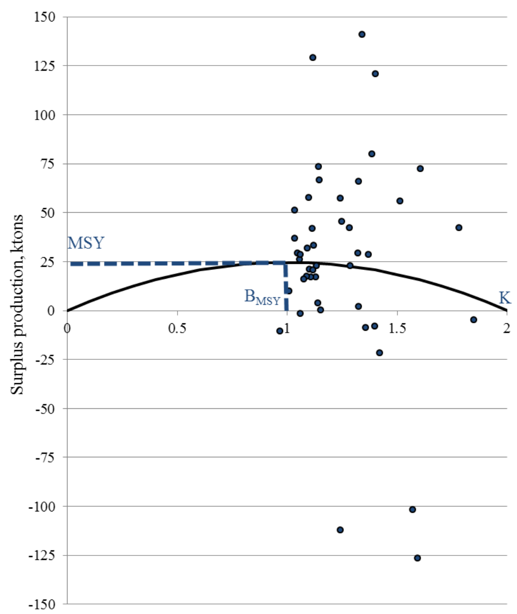


Figure 7 Dependence of production on the stock biomass calculated using model parameters (parabola) and *GLM*-indices taking into account coefficients of catchability and catch (points). The parabola vertex corresponds to the maximal surplus production (*MSY*) under B_{MSY}-biomass.

Conclusion

The analysis made by us showed that the attempts to forecast exact balanced catch are linked to a great risk to have a false real picture. Obviously, a role of stock estimation does not consist in guessing the best *MSY*-value. It should ensure the aid to the system of fishery management in order to react to different natural fluctuations. The role of the stock assessment is not to determine the optimal values of static fishing effort and catches balanced, but to evaluate the responses of harvested populations and the fishermen on the control solutions and other impacts.

Currently, there are two trends supported by calculations, initial data and expert opinion: insignificant fishing press in the last 10 years and simultaneous increase in the commercial stock abundance. Undoubtedly, the main reason of abundance increase is a presence of strong year-classes which compensates the total mortality. The question about the role of fishing mortality decrease in this increase has been discussed recently. The right recruitment estimates and value of environmental carrying capacity will make it possible to use in the optimal way the results of calculations by the production model in future.

However, despite the high uncertainty, this variant of a model combining the flexibility of the Bayesian approach with the traditional production one, currently provides the analytical alternative for the existing methods to assess the Greenland halibut stock. A combined approach takes into account the errors of observations and allows us to associate the equation of the population dynamics with the observed indices of abundance, derived from the surveys, and fishing efficiency. Thanks to this, in some research periods, different additional parameters may be integrated into the model. The Bayesian method may include additional information as the priory distributions of different parameters into the model thus filling in unavailable input data which often occur in fishery biostatistics. Probabilistic estimates also permit us to calculate the risk to exceed this or that management reference point that makes model attractive for using in making management decisions.

REFERENCES

Boje J, C. Hvingel and R. Hedeholm An assessment of the resource of Greenland halibut (*Reinhardtius hippoglossoides*) off East Greenland, Iceland and the Faroe Islands. ICES North-Western Working Group. – WD#29. – 2012. – 21 p.

Doubleday W.G., Rivard D. Bottom trawl surveys. Can. Spec.Publ. Fish. Aquat. Sci. 58, 1981.– 273 p.

FAO. Precautionary approach to fisheries. FAO Technical Paper, 350/2. 1996. – 210 p.

Fletcher, R.I. 1978. Time-dependent solutions and efficient parameters for stock-production models. *Fisheries Bulletin, 76: 377–388*.

Gelman, A. Carlin, J.C., Stern, H., and Rubin, D. B Bayesian Data Analysis. Chapman & Hall, New York. 1995. – 525 p.

Gulland J.A. Manual of methods for fish stock assessment. Part I. Fish population analysis// FAO Man.Fish.Sci. – N.4. – 1964.– 154 p.

Haddon M. Modelling and quantitative methods in fisheries. Chapman & Hall/CRC Washington, D.C. 2001 – 406 p.

Helser T.E. and Hayes D.B. Providing quantitative management advice from stock abundance indices based on research surveys. Fish. Bull., U.S. 93, 1995 – P. 290–298.

Hilborn, R., Walters, C.J., Quantitative Fisheries Stock Assessment: Choice, Dynamics and Uncertainty. Chapman & Hall, New York, 1992. – 570 p.

Hvingel, C., Kingsley M.C.S. A framework to model shrimp (Pandalus borealis) stock dynamics and quantify risk associated with alternative management options, using Bayesian methods. ICES J. Mar. Sci. 63. 2006, P. 68–82.

June H. C. The use of surplus production models and length frequency data in stock assessments: Explorations using Greenland halibut observations. The United Nations University. Fisheries Training Programme, 2007. – 51 p.

McAllister, M. K., Kirkwood G. P. Bayesian Stock assessment: a review and example application using the logistic model. ICES Journal of Marine Science, V. 55. – 1998. P. 1031–1060.

Perry R.I. and Smith S.J. Identifying habitat associations of marine fishes using survey data: An application to the NW Atlantic. Can. J. Fish. Aquat. Sci. 51, 1994. – P. 589–602.

Punt, A., and Hilborn, R. Fisheries stock assessment and decision analysis: the Bayesian approach. Reviews in Fish Biology and Fisheries, V.7. – 1997. – P. 35–63.

Schnute, J.T. A General Framework for Developing Sequential Fisheries Models// Can. J. Fish. Aquat. Sci.– Vol. 51.–1994.– P. 1676–1688.

Seber G.A.F. The Estimation of Animal Abundance and Related Parameters, 2nd edn. Macmill an Publishing Co., New York, NY. – 1982. – 654 p.

Smirnov O.V. 2006. Greenland halibut from the Norwegian-Barents Sea population. Murmansk: PINRO Press, 2006. 113 p. (in Russian)

Spiegelhalter, D.J., A. Thomas, N.Best. WinBUGS version 1.3 User Manual. MRC Biostatistics Unit, Inst. of Public Health, Cambridge, England. 2000. – 167 p.

Exploratory GADGET stock assessment of NEA Greenland halibut (*Reinharditius hippogossoides*)

Daniel Howell, Elvar H. Hallfredsson, Tone Vollen and Åge Fotland

Institute of Marine Resarch, Norway.

Abstract

This document describes an exploratory stock assessment of NEA Greenland halibut in Subareas I and II using the GADGET model. Due to complication data gathering and preparations some simplifying assumptions had to be made. Still, the model is able to follow trends in the tuning data and the fit to other data-sets is good. The main challenge in terms of the model is growth assumptions and age distributions, as well as to incorporate different (possibly conflicting) tuning series. The model estimates that the total biomass of fish length 45cm+ in 2012 was around 800Kt, slightly down on a peak of 850Kt in 2009. These results are similar, though not identical, to "scenario 1" from the stochastic production model in WD14. It should be noted that this length category is only just within the fishery (20% of fully selected for the trawl, 5% for the gilfleet). Choice of a higher length cut off, or a choice to multiply biomass at length by overall selectivity for that length, would give lower absolute levels, and slightly altered trends.

Introduction

The Northeast Arctic (NEA) Greenland halibut is found along the continental slope of Norway north of 61° N. The distribution area extends into the Arctic area north and east of Svalbard (Fig. 1).

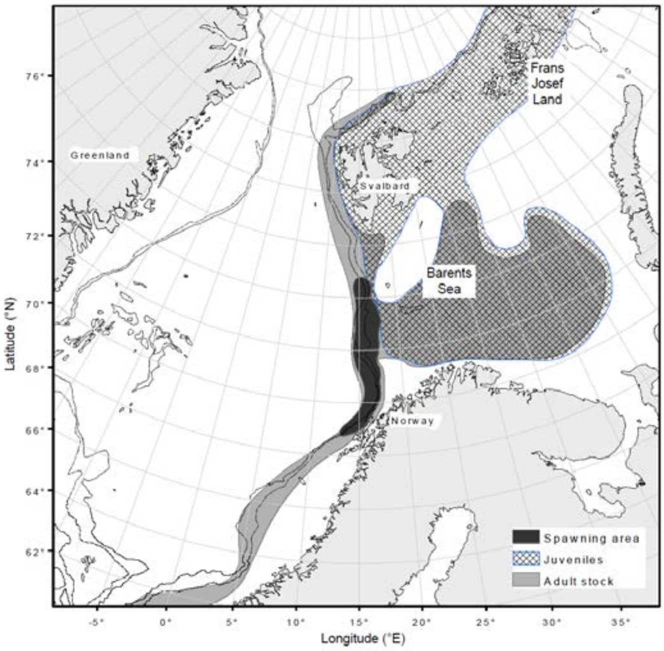


Figure 1. Distribution of Northeast Arctic Greenland halibut. The most important adult area is along the slope from 600–900 m. The area north and east of Svalbard towards the Franz Josef Land and into the northern Kara Sea is the most important juvenile area even though some juveniles are found in the central Barents Sea (from Høines and Gundersen 2008).

Exploitation of NEA Greenland halibut increased rapidly in the 1970s and 1980s, and as a consequence strong regulations were introduced in 1992. Landings from 1992 to 2009 were around 13000 t, basically artisanal and research quota. In 2009 ban against targeted Greenland halibut fishery was cancelled and landings have increased to around 20000 t in 2012. Norway gets 51% of TAC, Russia 45% and 4% are for other nations in the Fisheries Protection Zone around Svalbard.

Sexual dimorphism of Greenland halibut in maturation and distribution is a factor to be taken into account. Along the slope area, where adults and both spawning grounds and main fishing grounds are found, proportion of females is highly length dependent. This can be seen in data from the Norwegian survey, which covers the continental slope area from 68-80°N in autumn (figure 2). Minimum size regulation for Greenland halibut landings is 45 cm.

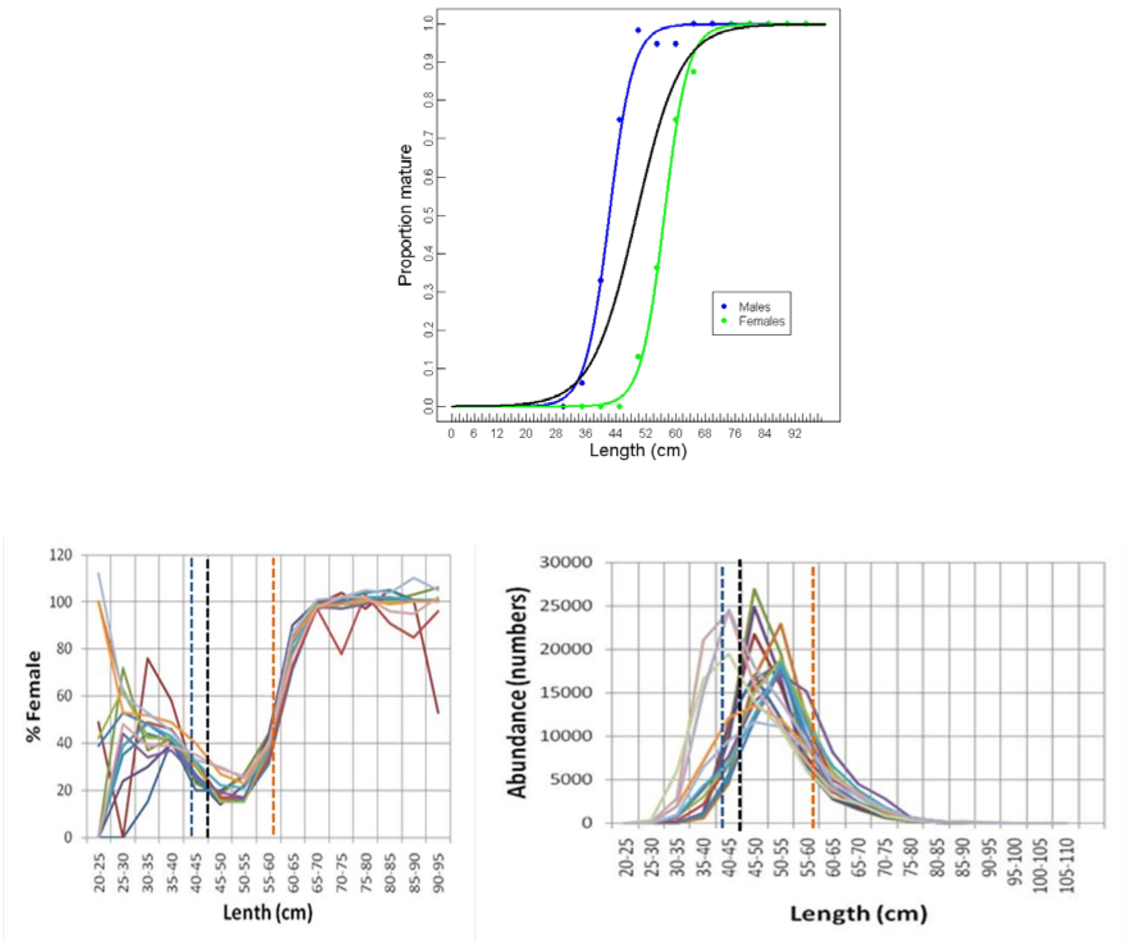


Figure 2. Greenland halibut maturity ogives (upper panel). Proportion females and length distributions from the Norwegian slope survey 1992-2009 (lower panels). Dashed lines show L50 maturity for males (blue, = 42 cm) females (brown, = 57 cm), and minimum landing size (black, = 45 cm).

Age readings are challenging for Greenland halibut and suspicion of bias in the traditional age readings have called for revision of assessment strategy for a while (Albert etal 2005). New aging methods have been in development in i.a. in Norway, Canada and USA (ICES WKARGH 2011). Due to uncertainties in age reading and limited amounts of age readings by the new aging methods available at present in this model work main emphasis is on length data.

Gadget is the "Globally applicable Area Dis-aggregated General Ecosystem Toolbox", which is a statistical model of marine ecosystems. Gadget is an age-length structured forward simulation model, coupled with an extensive set of data comparison and optimisation routines. Processes are generally modelled as dependent on length, but age is tracked in the models, and data can be compared on either a length and/or age scale. The model is designed as a multi-area, multi-fleet model, capable of including predation and mixed fisheries issues, however it can also be used on a single species basis. Gadget models can be both very data- and computationally- intensive, with optimisation in particular taking a large amount of time (Thordarson and Elvarsson WKBUT WD4). Worked examples, detailed manual and further information on Gadget can be found on www.hafro.is/gadget. In addition the structure of the model is described in Begley & Howell (2004), and a formal mathematical description is given in Frøysa et al. (2002).

Using a Gadget model for a species such as Greenland halibut has two advantages. First, Gadget can fit to length data directly, increasing the amount and quality of data that can be used in model tuning. Secondly, because the model produces a biological process-based simulation, the flexibility exists to investigate a wide range of sources of uncertainty. These include, but are not limited to, different tuning data sets, different age reading methodologies, assumptions about growth rates.

The present model is a single-area model, single-species model, with a split by sex and maturity into four separate “population groups”. The intention is to allow for differences in growth between males and females, and differences in maturation, although at present no differences have been implemented between the mature and immature components. Two composite fleets have been defined, one based an asymmetrical dome-shaped trawl selectivity, and one on a “S-shaped” gilfleet selectivity. In addition the base case has a single trawl survey (modelled with a dome shaped selectivity). It should be noted that “selectivity” goes beyond gear selectivity, and encompasses all factors that affect the chance that a fish of a particular size will end up caught. In the model work NEA Greenland halibut is defined to have distribution within in ICES area I and II.

Material and methods

NEA Halibut Gadget model

An age-length structured Gadget model has been constructed for the NEA Halibut. The model runs from 1992 to 2012, with quarterly time steps. The stock is split by gender and maturity. Growth is modelled as Von Berthanlanffy model with externally estimated parameters, based on the “new” age reading methodology recommended in WKARGH (growth is further discussed in Hallfredsson WKBUT WD 16). Length-weight relationship are based on data from the Norwegian Slope survey and are fixed through time for all years, with no annual variations. Separate parameters are used for female and male growth curves. (Females: a=1.4E-6 and b=3.47. Males: a=5.7E-6 and b=3.12). Natural mortally is set at 0.1. No SSB-recruitment relationship is used, rather the number of recruits per year is directly estimated. Two combined fleets are used: one for gilfleet (and handline and longline) and one for trawl (and other gears). Catch in tonnes by sex was available for both fleets, length distributions by sex were taken from the Norwegian data. Total survey index and length distributions from the Norwegian slope survey were also used as tuning data. No other surveys have so far been included. Examining length distributions indicated that both the survey and the trawl had dome shaped selectivity, and this was modelled using asymmetric domes for each fleet. The gillfleet was the only fleet to fully select the largest individuals, and an S-shaped curve was used for this fleet. The fact that the gillfleet catches larger fish than the trawl gives the model the data required to estimate the dome on the smaller selectivity fleets.

The model fit reasonably well to the overall survey index, and to the sex-aggregated length distributions in the commercial catches. However there were discrepancies when examining the sex-disaggregated fit. This indicates that there is a sex-selection effect over that due to length, and this should be incorporated in the model.

Maturation is a simple knife edge function and maturation takes place once per year. Males and females have different parameters. It should be noted that the process modelled in an L50-type approach is that of becoming mature, not the proportion mature in the population at a given time. The L50 estimated here would thus be different (higher) than L50 for proportion mature if a more sophisticated maturation function were to be employed. Due to focus on ageing and selectivity issues, as well as uncertainty around choice of surveys to include, no further investigation has been conducted on maturity in this document, and the mature-immature split will not be presented.

Growth

In the present work growth is based on age readings with one of the new aging methods that were recommended by the 2011 workshop on age reading of Greenland halibut (WKARGH)(further discussed in Hallfredsson WKBUT 2013 WD 16).

Fleets

Catch data were split into two fleets. Longline/gillnet fleet includes landings from gillnet, longline and handline. Trawl fleet includes landings from bottom trawl, purse_seine and danish_seine.

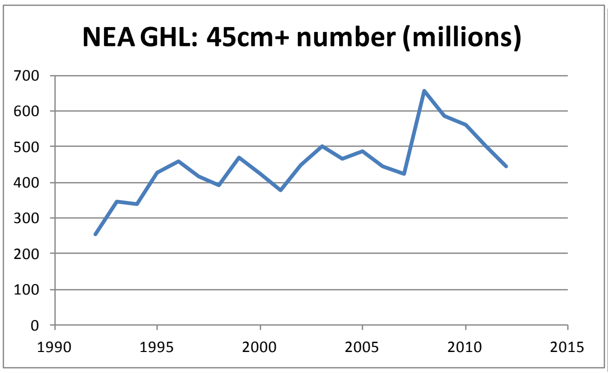
The following simplifications and assumptions were implemented;

- Norwegian length data from the catches included very small fish in a few years. This is unlikely to be real and fish smaller than 20 cm was removed. Under an assumption of constant selectivity through time, the inclusion of this data would result in a poorly fitting selection to the majority of the data. This issue needs further investigation.
- Obvious outlayers were found in length distribution of females in 2012, quarter 2 and 3, fleet.trawl were corrected. Females length 73 an 82 cm were very high and were recalculated as the mean of previous and next length group.
- Russian catch data 1992-2012 (by fleet and quarter) were split on sex based on Norwegian data.
- Landings from other nations were added to the Norwegian trawl fleet and split on quarter and sex accordingly.

Results

It should be noted that the results presented here are for fish of 45cm+. This is the length category at which fish begin to enter the fishery, and is the minimum landing size. However, this length category is only just within the fishery (20% of fully selected for the trawl, 5% for the gilfleet). Choice of a higher length cut off, or a choice to multiply biomass at length by overall selectivity for that length, would give lower absolute levels, and slightly altered trends. Choosing a cutoff of 50cm reduced the biomass in 2012 by around 10% and the numbers by around 15%. Examining the impact of using the selectivity to report biomass has not been done, but would reduce the figures significantly.

Using all fish of 45+cm as a proxy for "exploitable biomass", the Gadget model has produced a population rising from around 250 million individuals and 400 thousand tonnes in 1992 to a peak of 650 million individuals and 850 thousand tonnes in 2009, declining to around 450 million individuals and 800 thousand tonnes by 2012 (Figure 3). The peak in numbers occurs in 2008, the peak in biomass in 2010. These biomass results are compatible with the results from the production model, and are slightly higher than scenario 1 from the production model, and slightly lower than scenario 2.



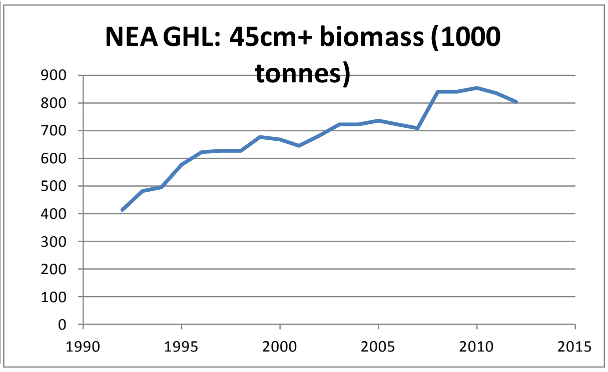


Figure 3. Number (left) in millions and total 5+ biomass (right) in 1000 tonnes at the 1st January each year.

Diagnostics

Recruitment

As currently formulated the model has no age-based tuning data. Thus, annual recruitment values are estimated only using length distributions, and this is insufficient to precisely allocate the recruitment to a particular year. This can be seen in Figure 4 where the recruitment is unrealistically variable. Thus, results from the model are best examined by length, with age-based outputs being poorly constrained by the data. A moving average shows the overall trend in recruitment, which is likely to be more constrained by the data. However the actual value per year should not be considered reliable unless age-based data is included in the tuning process, and is thus not reported here beyond the example for recruitment at age 5.

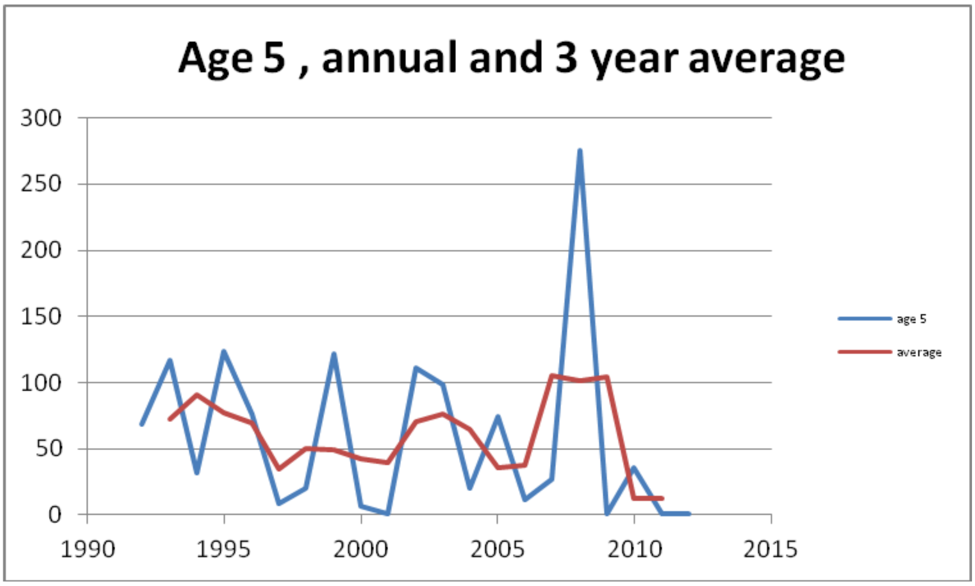


Figure 4. Estimated annual recruitment (at age 5) in millions, and a three year moving average.

Catch estimation

The model has been constructed with an estimated effort parameter governing the fishing effort for each of the two “fleets”, and a “catch in tonnes” tuning dataset. In other words the data on catch in tonnes is assumed to be a tuning dataset rather than absolute truth. This has been done because in a situation with uncertainties in the selectivity, a slight mismatch between the modelled and real selectivities can result in an artificially high modelled population in order to produce enough fish to match the extremes of the distribution, and can make optimisation difficult. Allowing slight flexibility in the modelled level of the catch avoids this. It can been seen in Figure 5 that the modelled annual catch in tonnes is always within 2% of the actual data, and we therefore consider that this estimation has not adversely affected the modelled catches. It should be noted that there is no data to estimate *bias* in the reported catch, this procedure is merely concerned with allowing for slight *variance*.

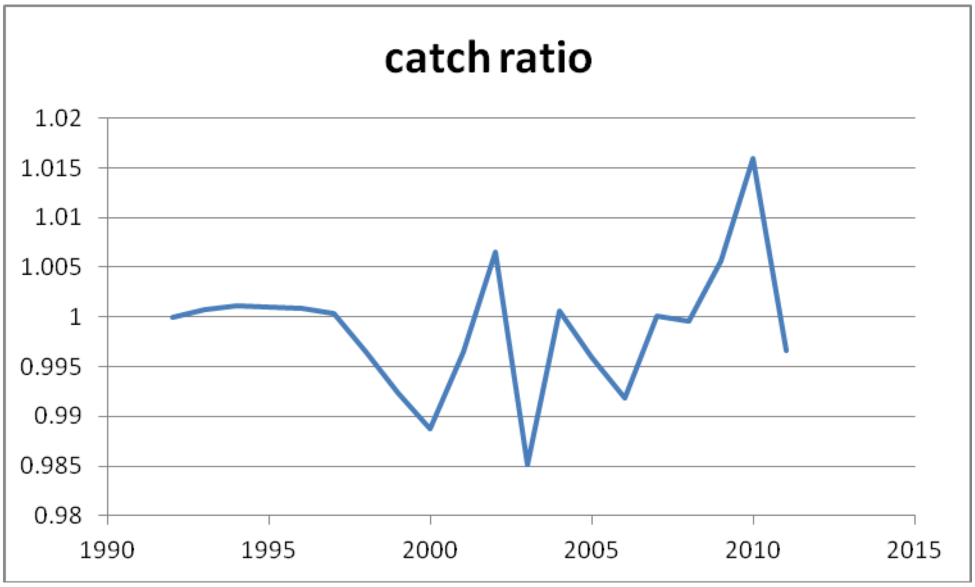


Figure 5. Ratio of modelled catch in tonnes divided by recorded catch in tonnes, per year. Note that all scale is ±2%.

Choice of selectivity functions

As mentioned in the model description, the “selectivity” for each fleet is a function of more than simply physical gear selectivity. Fishing behaviour, spatial and temporal distributions, fish behaviour, and other factors all contribute. Based on an examination of the length distributions (Figure 6), it can be seen that the gillnet and trawl fleets have a similar maximum length for the males caught, but that there are much larger females in the gillfleet than the trawl. It is therefore clear that the trawl must have a dome shaped selectivity, avoiding the largest fish. A similar effect is seen for the Norwegian survey trawl.. It is possible that a similar effect is happening for the gillfleet, however there is no data available to estimate this, as there is no other fleet that catches the largest fleet. We have therefore used an asymmetric dome shaped selectivity for the trawl and the Norwegian survey, and a flat topped “S-shaped” selectivity for the gillfleet. The survey is estimated to have a very sharply rising selectivity with a peak selectivity at around 45cm, the gilfleet has a l50 at around 59cm, and the peak of the trawl selectivity is at around 52cm.

It has been assumed that there is no sex-selectivity beyond that implicit in using length selective fisheries on a species with sexual dimorphism in growth. As discussed below, this assumption seems to be incorrect, and should be addressed.

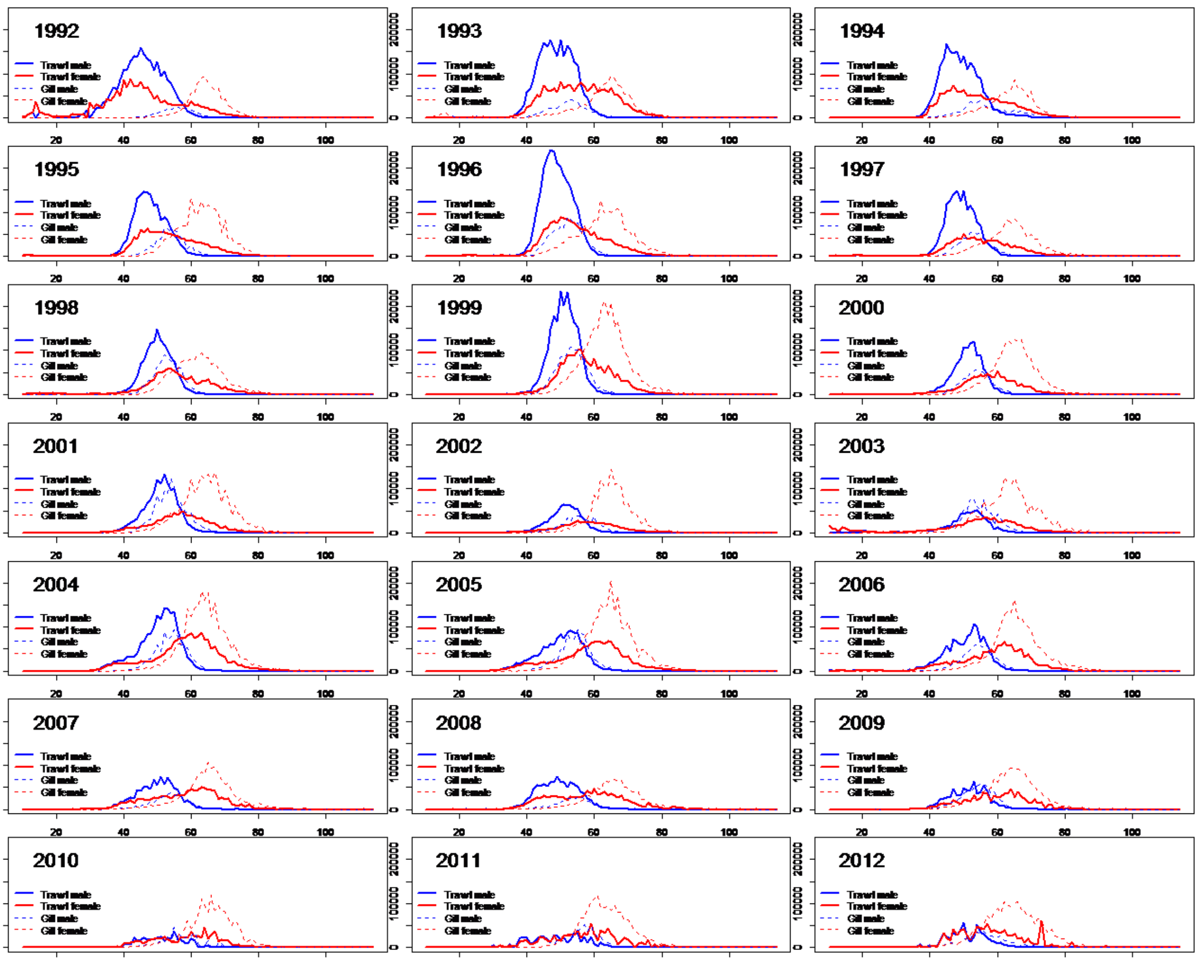


Figure 6. Annual length distributions in the Norwegian catch. Solid line is trawl, dotted line is gilfleet. Blue is male, red is female.

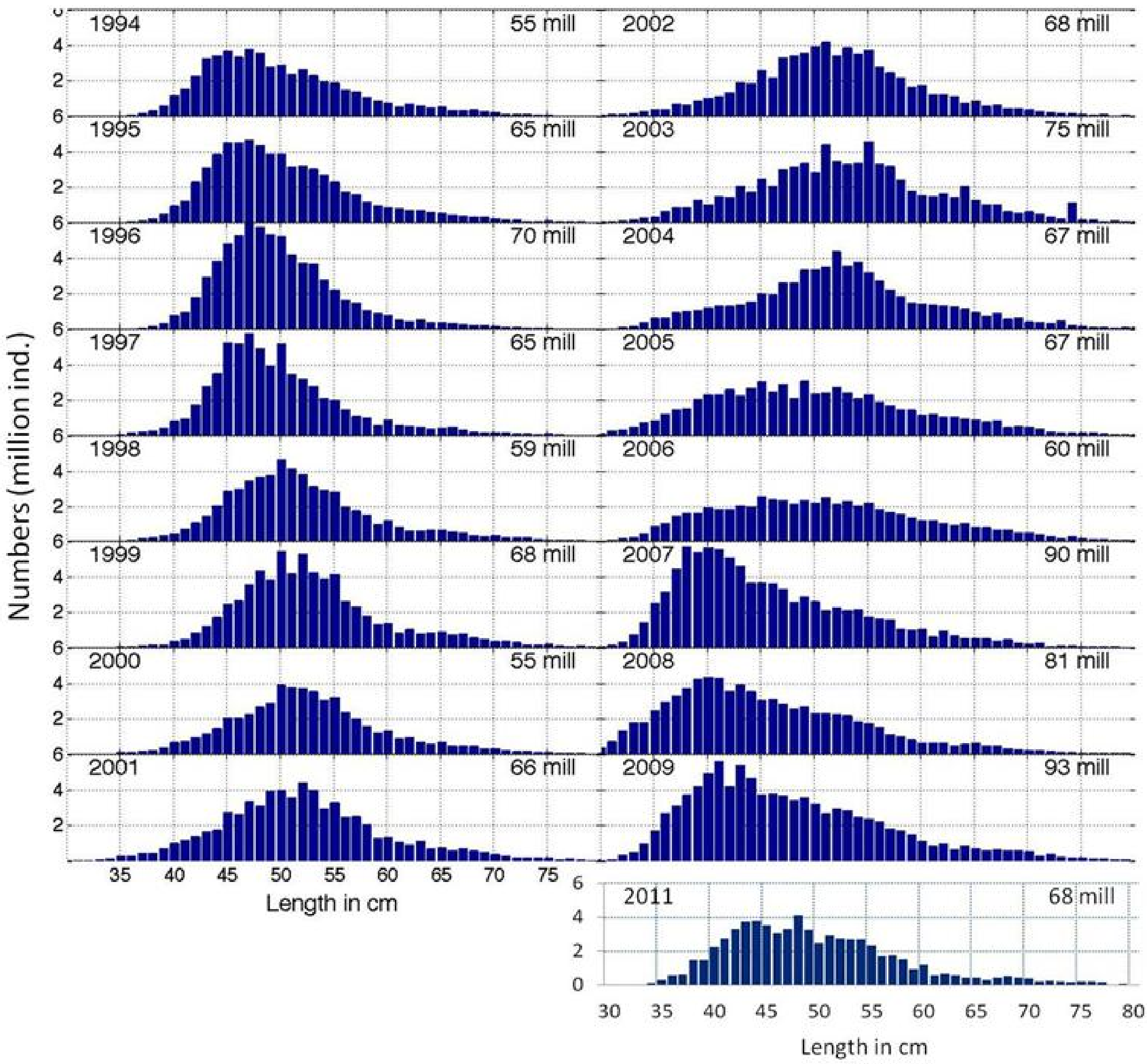
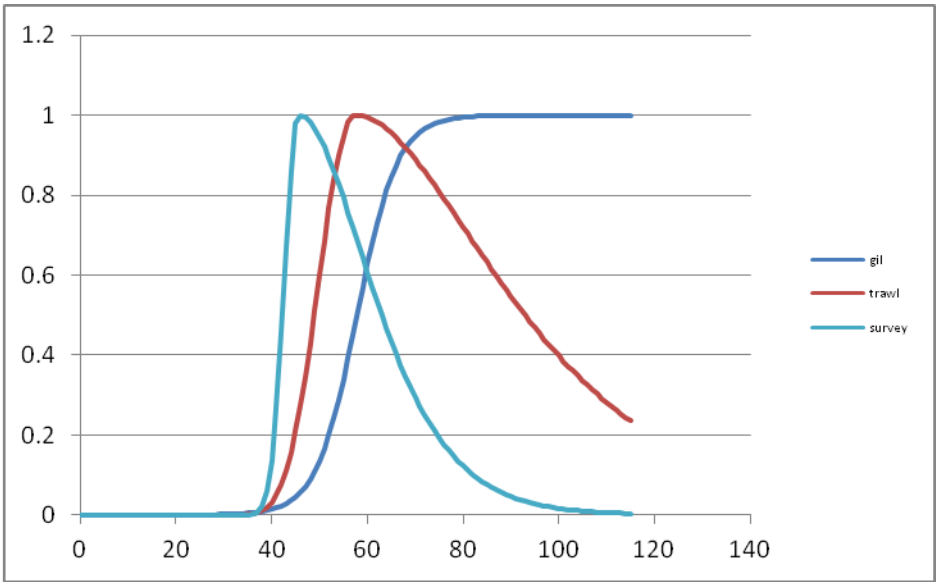


Figure 7. Annual length distributions (male and female combined) in the Norwegian slope survey and survey index in numbers



Figue 8. Estimated selectivity of the three fleets (commercial trawl, commercial gillnet and survey trawl) within the model

Sensitivity to trawl survey selectivity

Using a S-shaped selectivity for the commercial trawl is clearly a bad match with the data (see Figure 6), and a dome shaped trawl is required. However it is not so clear cut for the survey trawl, where there are few fish over 80cm, but there are significant numbers up to this level (Figure 7). Using dome shaped selectivities can be in general be dangerous, since the model can have too much freedom, allowing large numbers of unsampled bigger fish. Therefore choosing a dome shaped function needs to be done with care.

Using the dome shaped selectivity produces a better overall fit to the data (lower optimisation “likelihood” score, and better match on the length distributions). The population trends are similar under the two assumptions, but the biomass is c. 100 million tonnes lower under the S-shaped assumption (figure 9).

It may actually be that this issue could be better resolved by allowing for a sex-dependent selectivity

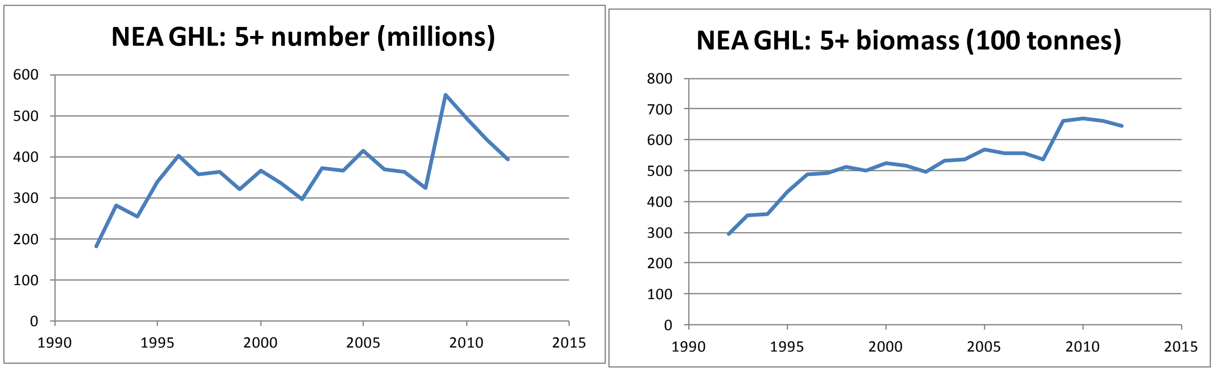


Figure 9. Number and biomass under an assumption of S-shaped trawl selectivity

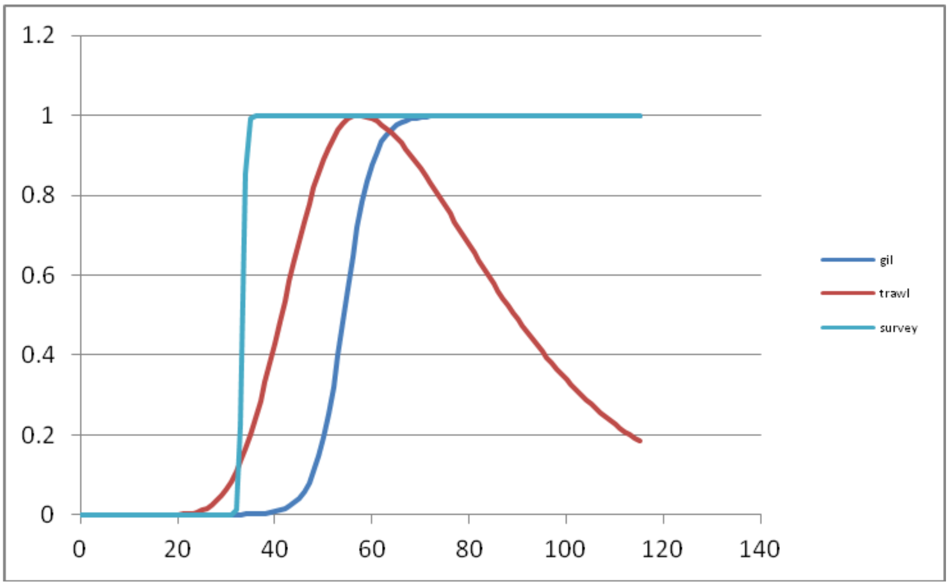


Figure 10. Estimated fleet selectivities using a S-shaped trawl selectivity

Fit to the survey and fleets

The fit to the total survey index is rather close for all fish combined (Figure 11), with the model underpredicting the number of males and overpredicting the number of females prior to around 2003. This suggests that there may be a slight selectivity difference between males and females which is not accounted for in the current model. The fit to the length distributions in the fleets and surveys is shown in Figures 12-14. The fits are relatively good for the fleets, but notably poor for the survey. In particular the model overpredicts the number of small fish prior 2004, with a much better fit thereafter. This may indicate an overall change in the effective survey selectivity around this date. These figures present the combined sex fits to the fleets. As noted the fit worsens when examined on a per sex basis. This is not presented here, merely noted as further work is required on the sex selectivity in the fleets and especially the survey,

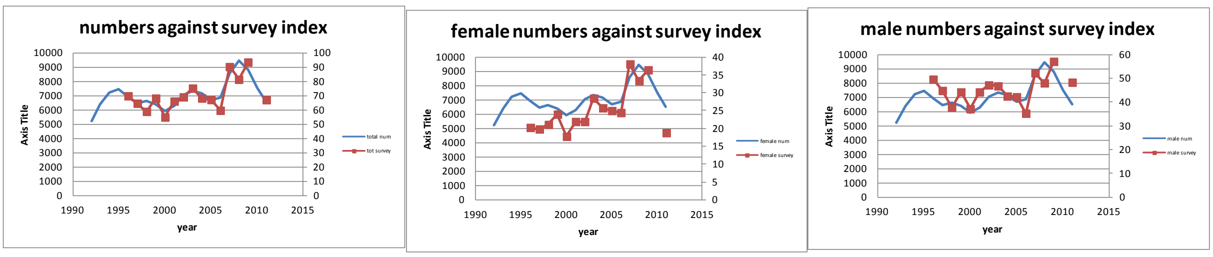


Figure 11. Fit to survey index, Gadget results in blue, survey data in red.

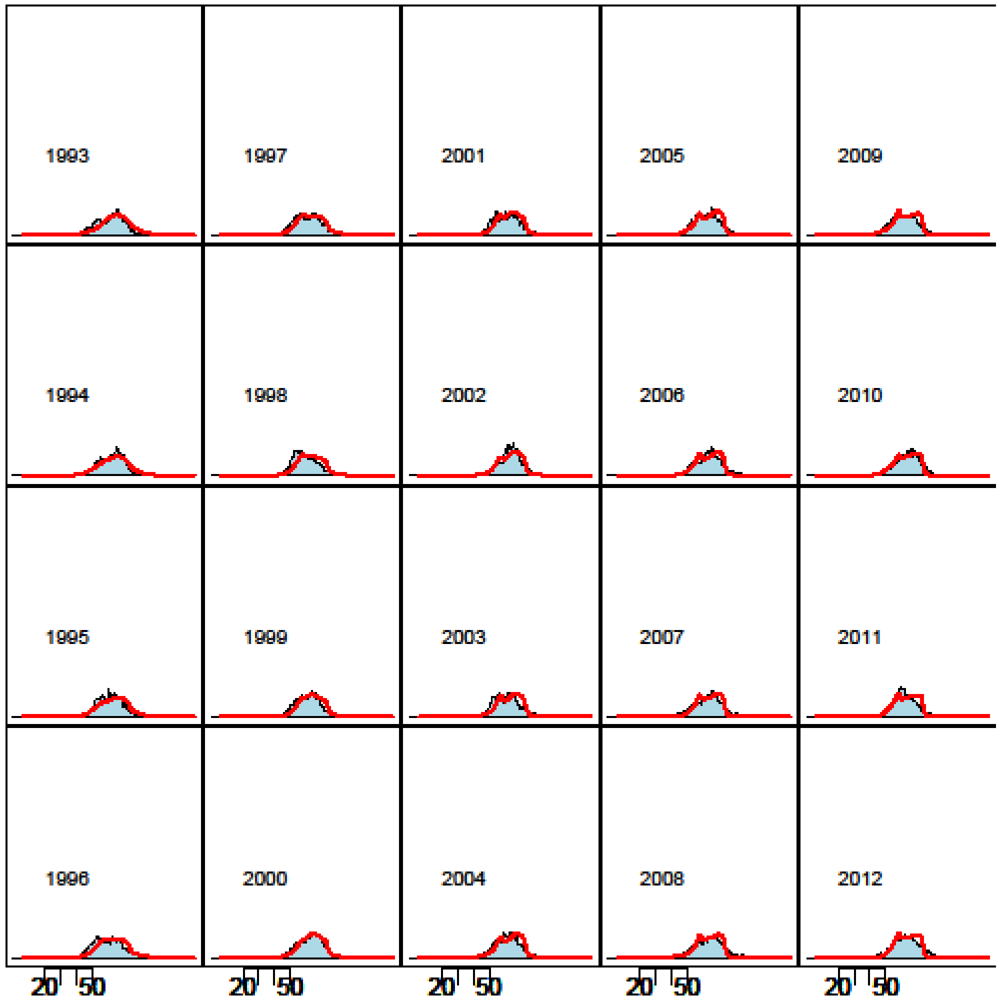


Figure 12. Annual fit to gilfleet, sexes combined. Blue is data, red is model.

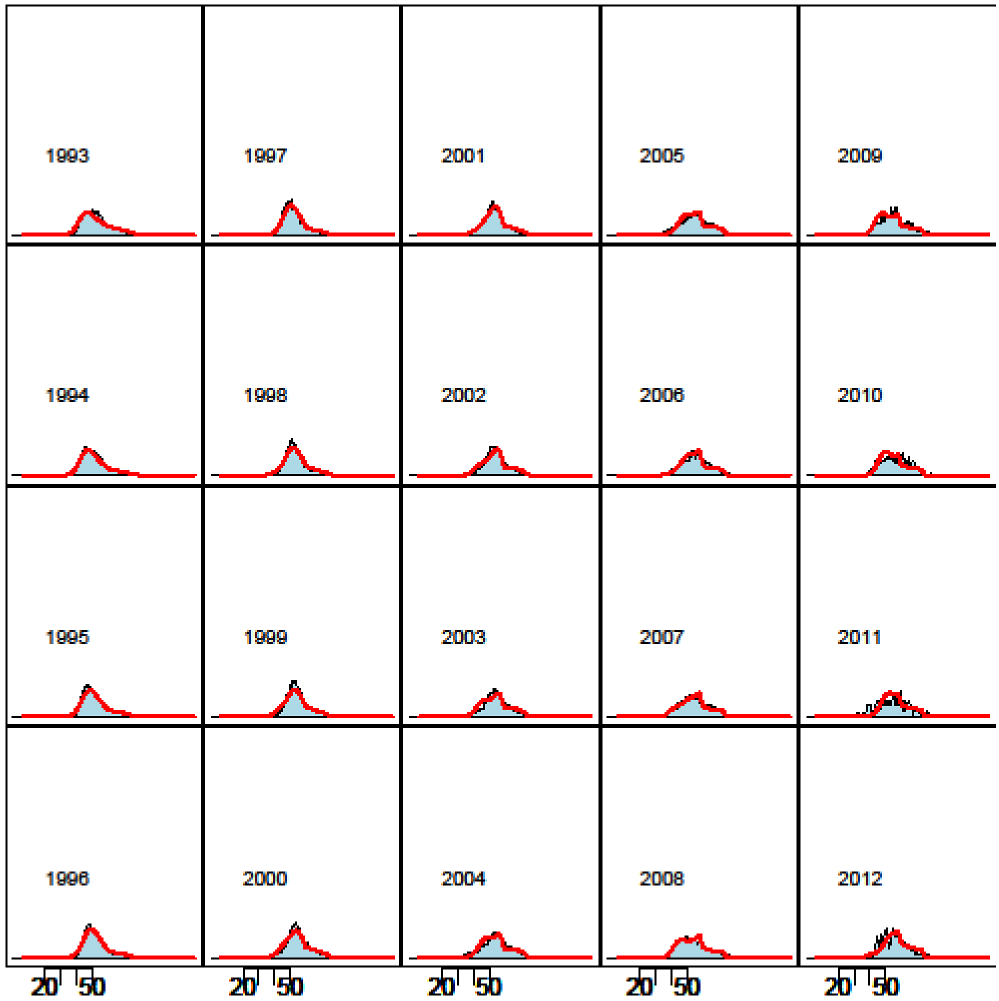


Figure 13. Annual fit to trawl fleet, sexes combined. Blue is data, red is model.

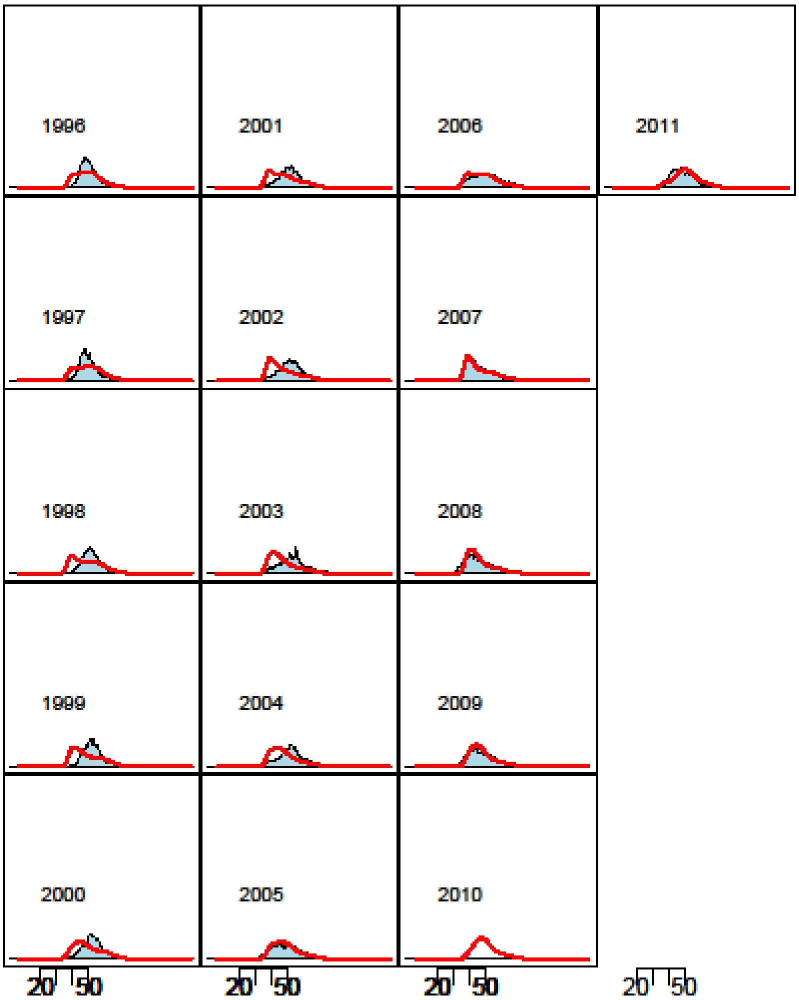


Figure 14. Annual fit to the Norwegian survey. Blue is data, red is model. Note that there is no survey in 2010.

Discussion

In general the model results represents a consistent model, with reasonable fit to the data series.It is clear that the age distributions suffer from a lack of age data in the tuning series. The length data is sufficient to fit the overall length structure of the population, but is not sufficiently discriminating to identify the detailed age structure of the population, or the annual recruitments. Care must therefore be taken when interpreting the results by age. One major issue that arises from the analysis here, it that for the survey, and potentially for the commercial catches, there appears to be sex-dependent selectivity. This needs to be included in the model and the results examined.

The model has been designed to be the starting point for further work on analysing the uncertainties around this stock. Further details are in the next section.

Further work

In general, we consider that the model results represents a consistent model, with reasonable fit to the data series, and could form the basis of an assessment model and act as a simulation tool to evaluate the impacts of the different uncertainties on our understanding of the stock. However, there are a number of issues that remain to be addressed. It is clear that the age distributions suffer from a lack of age data in the tuning series. The length data is sufficient to fit the overall length structure of the population, but is not sufficiently discriminating to identify the detailed age structure of the population, or the annual recruitments. Care must therefore be taken when interpreting the results by age. One would want to directly include age-length data within the model to address this. A second issue is that there appears to be sex-dependent selectivity. This needs to be included in the model and the results examined. A further obvious area of work is to replace the assumption of fixed growth, and allow estimation of growth rates based on different age reading datasets. In this case one could also attempt to estimate if there are identifiably differences between immature and mature individuals. In all cases the model allows the impact of these different choices on the population model to be examined. A further obvious are of work is replace the assumption of fixed growth, and allow estimation of growth rates based on different age reading datasets. In this case one could also attempt to estimate if there are identifiably differences between immature and mature individuals. In all cases the model allows the impact of these different choices on the population model to be examined.

One of the key reasons for producing such a model is to provide a platform to investigate the uncertainties around this stock. Due to complication in data gathering and preparations, little time was available to perform such work prior to the benchmark meeting, and a simplified base case model has been derived using only Norwegian biological samples, and a single survey - the Norwegian Slope Survey in autumn (ICES acronym: NO-GH-Btr-Q3).

One example of the analysis of uncertainties can be seen in the length distribution analysis behind the choice of dome selectivity for the trawl fleet. Obvious further work includes using the biological information from the Russian catches, and examining the impacts of using the Russian autumn survey (RU-BTr-Q4) and the Ecosystem survey in the Barents Sea (see Hallfredsson et al. ICES AFWG 2013 WD17) as alternative or additional tuning series. Preliminary analysis has been presented here, but this needs to be analysed further, with more alternative tuning series included.

References

Albert, O. T., A.-B. Salberg, Å. S. Høines, and A. Harbitz. 2005. Bias in age reading of Greenland halibut calls for new assessment strategy. Working Document for ICES Arctic Fisheries Working Group, Murmansk 19-28 April 2005:1-20.

Begley, J. & Howell, D. (2004). An overview of Gadget, the globally applicable area-disaggregated general ecosystem toolbox. ICES CM, 1–15.

Frøysa, K., Bogstad, B. & W Skagen, D. (2002). Fleksibest–an age-length structured fish stock assessment model. Fisheries Research, 55, 87–101.

Høines, Å. S., and A. C. Gundersen. 2008. Rebuilding the Stock of Northeast Arctic Greenland Halibut (*Reinhardtius hippoglossoides*). J. Northw. Atl. Fish. Sci., Vol. 41: 107–117 41:107-117.

A note on growth of Greenland halibut, and status of age readings by new age reading method in Norway.

Elvar H. Hallfredsson

Not to be cited without prior reference to the author

Introduction

Age determination of Greenland halibut is challenging and new methods of aging have been in development in later years. In 2011 an ICES workshop recommended identification of annual zones in Greenland Halibut otoliths should preferably be done 1) along the longest growth axis of the whole right otoliths, or 2) towards the proximal edge of the sectioned left otoliths (ICES WKARGH 2011) . Both alternatives give slower growth than traditional aging method. In Norway a method based on alternative 1 has been developed and is from here referred to as "new aging method", while the traditional aging method will be referred to as "old aging method".

Purpose of this document is to examine shortly the growth of Greenland halibut according to the new and the old aging methods. Also in a GADGET model work at IMR in advance of ICES benchmark of Greenland halibut (WKBUT 2013) (Howel etal ICES WKBUT 2013 WD 15), parameters from von Bertallanfy's (VBF) growth function were used as fitted by the solver function in Excel and the assumption that t_0=0. This fit shows to be slightly different from one done with NLS (nonlinear (weighted) least-squares) in the statistical packaged R. Parameter estimates based on both of these methods are given and visualised.

Results and discussion

Status of age readings with new aging method

As the new aging method has been under development in recent years and routine aging has newly started limited amounts of age-length data based on aging with this method are available. At present in total1568 specimens of Greenland halibut have been aged with the new method, all were collected at the Norwegian continental slope survey in autumn in chosen years. From the survey sampling in 2001, 2007 and 2011 a subsample was drawn for aging, while reading is complete for the survey in 2009 (table 1).

Different methods for model fit

Table 2 gives von VBF parameters that were used in GADGET model base run for NEA Greenland halibut at WGBUT, and figure 1 shows the corrisponding growth curves. Assuming t_0=0 the VBF curve was fitted by the solver function in Excel (see http://www.solver.com/content/basic-solver-algorithms-and-methods-used). In the base run the VBF parameters used were fitted only by the 2009 survey data as these were available in due time. VBF parameters from same type of calculations on Russian age-length data from 2008 to 2012 are also given (table 2, figure 1).

In later effort to further scrutinise the VBF growth of Greenland halibut the NLS function in R was utilized, and it gave slightly different VBA parameter values for the 2009 Norwegian data with t_0=0 (table 3) compared to the solver fit (table 2). The difference is unlikely to be of big importance for other calculations based on these parameters. It is however apparent that the assumption that t_0=0 affects the shape of the estimated VBF curve considerably (table 3, figure 2). In table 3 it can also be seen that estimates for Linf and K for males in 2009 were statistically significant when t_0=0, but not when t_0 is also estimated.

New vs. old aging method

To examine difference between old and new aging methods data from all available aging with the new method are compared to Russian age readings with the old method in table 3, and figure 3 and 4. The old aging method gives considerably faster growth for both males and females.

Age readings with both new and old method are available for 200 specimens from the 2001 Norwegian slope survey data (figure 5). The conclusion is again indicating faster growth with old aging method. It should be noted that a part of the procedure in the new aging method as practiced presently in Norway is to collect and keep the otoliths in liquid and frozen. Thus when it comes to the aging the otolith is wet. The otoliths from 2001 are stored dry and this may have some effect on the aging. Also the age reader was relatively inexperienced in the new aging method and this may increase the variance in aging. More work is thus needed if good direct comparison of new and old method applied on the same specimen is desired.

Tables

Tabel 1. Numbers aged by new aging method in Norway at present, from the Norwegian slope survey.

Survey year	2001	2007	2009	2011
Numbers aged	200	324	749	295

Table 2. Parameters of growth curves that were thested in IMR GADGET model runs for NEA Greenland halibut on the 2013 ICES benchmarc meeting for Greenland halibut stocs.

	VBF Parameters	Russian 2008-2012	Norwegian 2009
Female	Linf	106	73
	K	0.09	0.15
Male	Linf	74	58
	K	0.16	0.24

Table 3. Estimates of parameters in von Bertalanffy's growth function as fitted by the NLS function in R.

	Formula	VBF						VBF, t0=0					
			Estimate	Std. Err	t value	Pr(>|t|)			Estimate	Std. Err	t value	Pr(>|t|)	
Norwegian	Females	Linf	97	11	8.9	<200E-16	***	Linf	72	2	45.4	<2e-16	***
Slope survey	N=415	K	0.058	0.015	4.0	7.46E-05	***	K	0.151	0.007	21.7	<2e-16	***
2009		t0	-3.91	1.03	-3.8	0.000169	***	---					
New aging method	Males	Linf	243	653	0.4	0.7099		Linf	54	1	48.2	<2e-16	***
	N=334	K	0.011	0.038	0.3	0.7627		K	0.272	0.016	16.6	<2e-16	***
		t0	-10.71	5.91	-1.8	0.0709	.	---					
	Both sexes	Linf	126	26	4.8	1.75E-06	***	Linf	66	1	58.5	<2e-16	***
	N=749	K	0.033	0.012	2.9	0.00447	**	K	0.175	0.006	27.0	<2e-16	***
		t0	-6.43	1.22	-5.3	1.82E-07	***	---					
Russian data	Females	Linf	128	2	78.7	<2e-16	***						
2008-2012	N=844	K	0.059	0.001	52.9	<2e-16	***						
Old aging method		t0	-1.19	0.02	-56.8	<2e-16	***						
	Males	Linf	115	2	48.5	<2e-16	***						
	N=716	K	0.067	0.002	33.1	<2e-16	***						
		t0	-1.16	0.03	-41.6	<2e-16	***						
	Both sexes	Linf	130	1	88.1	<2e-16	***						
	N=1560	K	0.057	0.001	61.1	<2e-16	***						
		t0	-1.23	0.02	-73.5	<2e-16	***						
Norwegian data	Females	Linf	98	10	9.5	< 2e-16	***						
2001, 2007, 2009	N=844	K	0.046	0.011	4.3	1.86E-05	***						
and 2011		t0	-5.95	1.19	-5.0	0.000000635	***						
New aging method	Males	Linf	83	15	5.7	0.000000021	***						
	N=716	K	0.049	0.020	2.5	0.013268	*						
		t0	-7.95	2.14	-3.7	0.000216	***						
	Both sexes	Linf	119	19	6.3	3.96E-10	***						
	N=1560	K	0.029	0.008	3.6	0.000336	***						
		t0	-8.64	1.25	-6.9	6.07E-12	***						
	Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1												

Figures

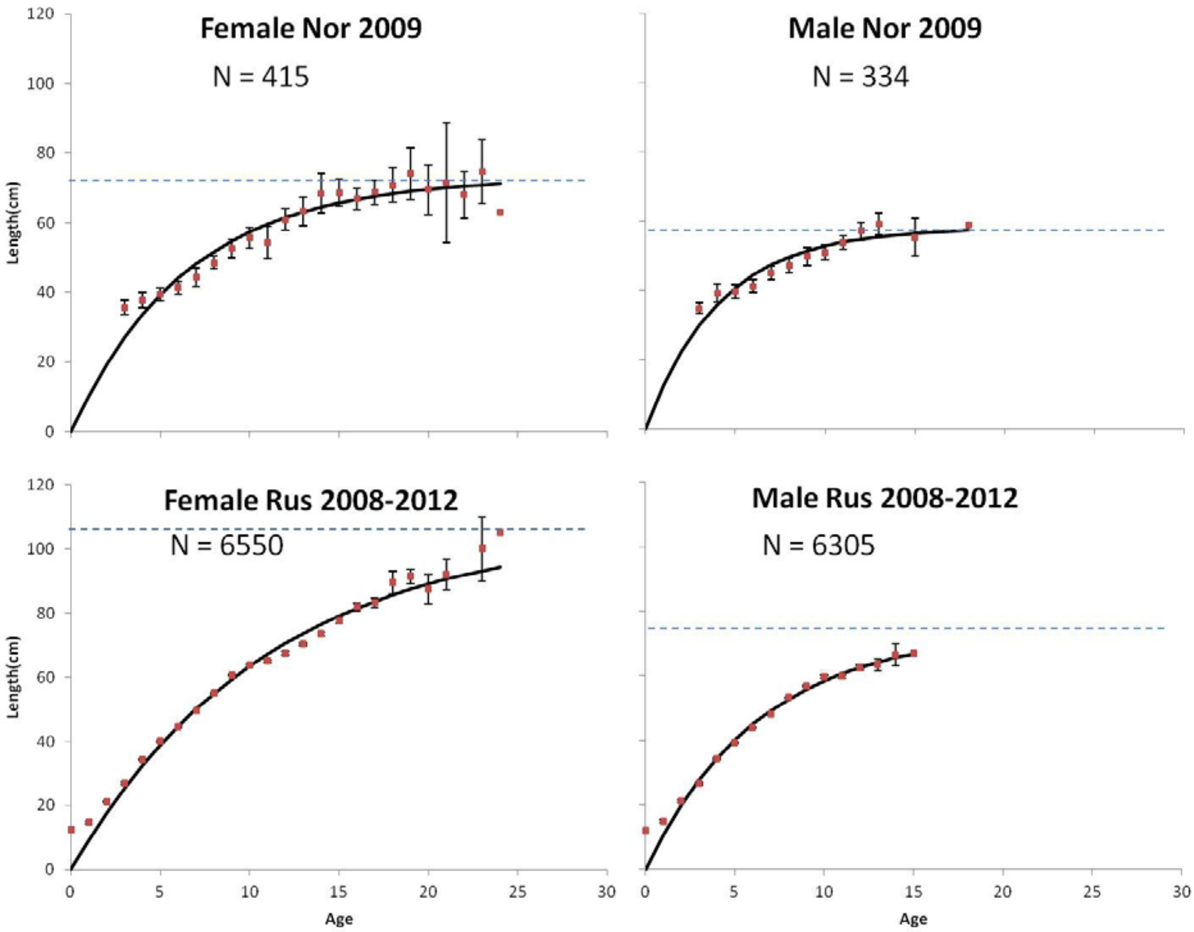
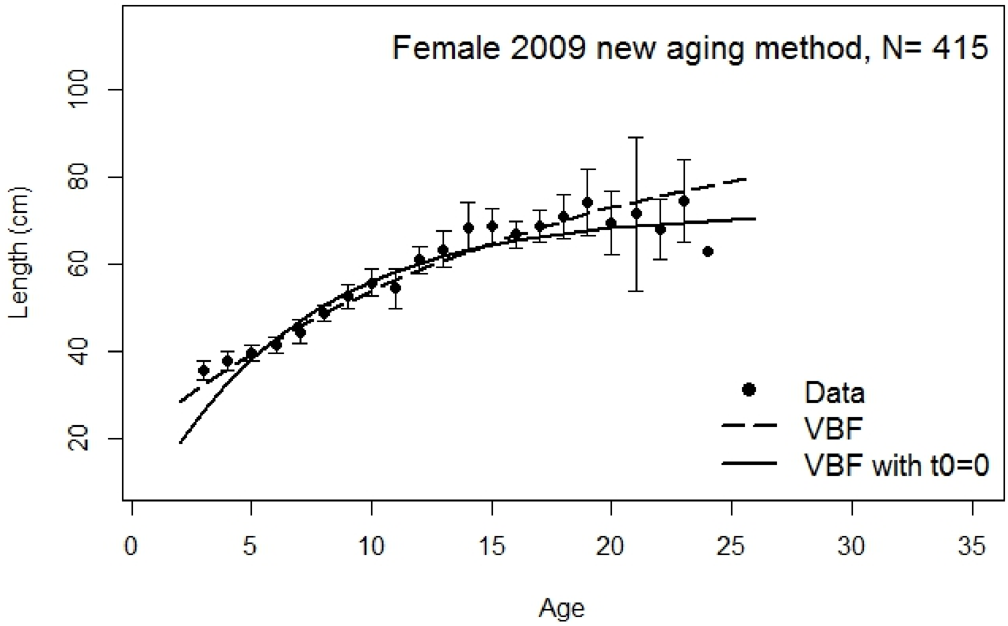


Figure 1. Growth of Greenland halibut acording to new aging method deveoloped in Norway (upper panels), and acording to traditional ageing method by Russian age readers (lower panels). Von Bertalanffy growth curves are shown (assumption t0=0 and fitted by the solver function in Excel) .



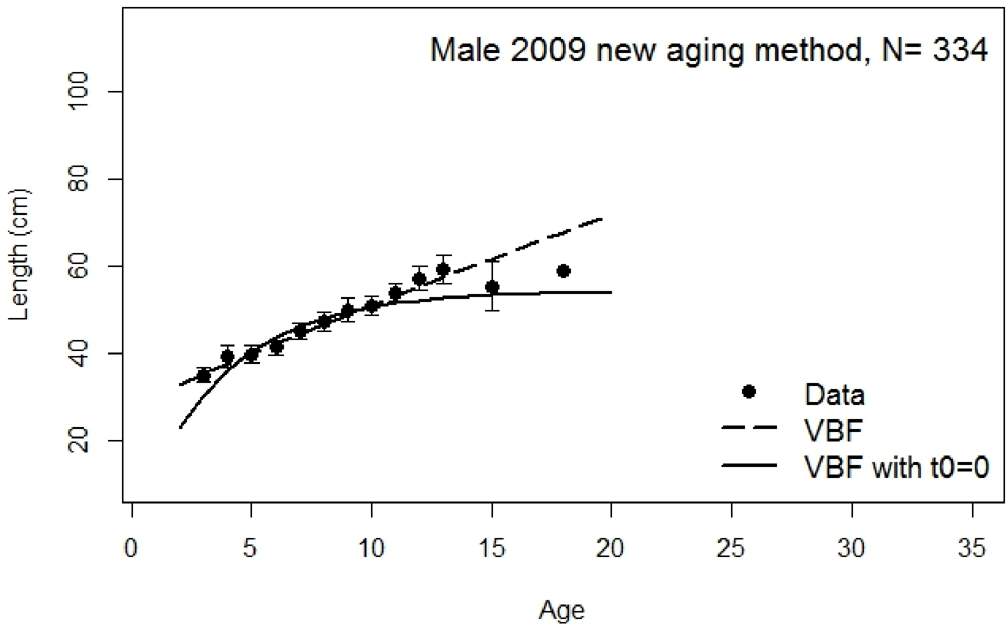
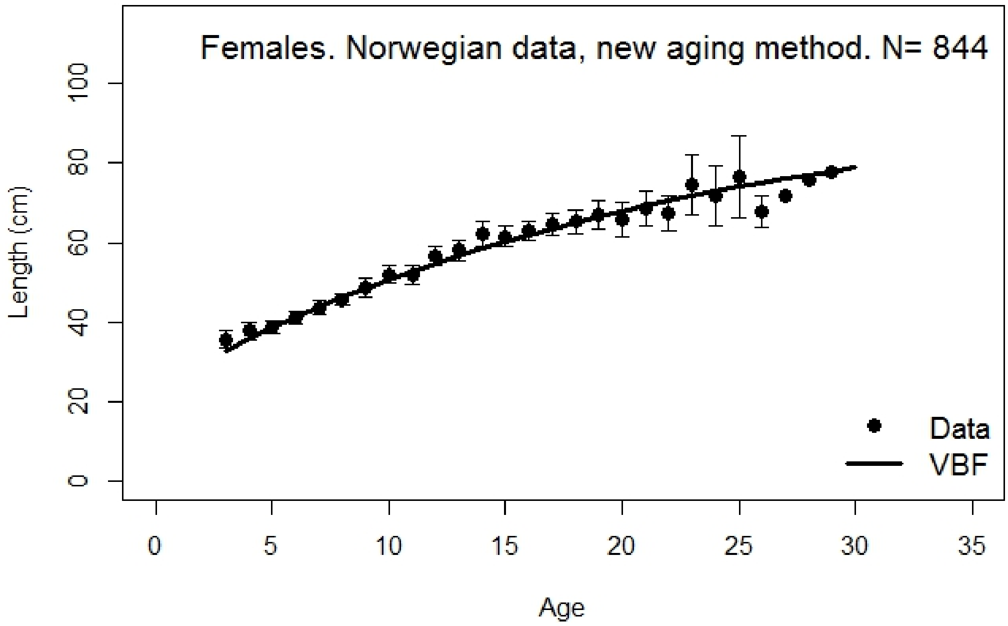


Figure 2. Growth of Greenland halibut in the Norwegian slope survey in 2009, with von Bertalanffy growth functions (Fitted by the NLS function in the statistical pacage R). Solid line shows growth curve where t0=0.



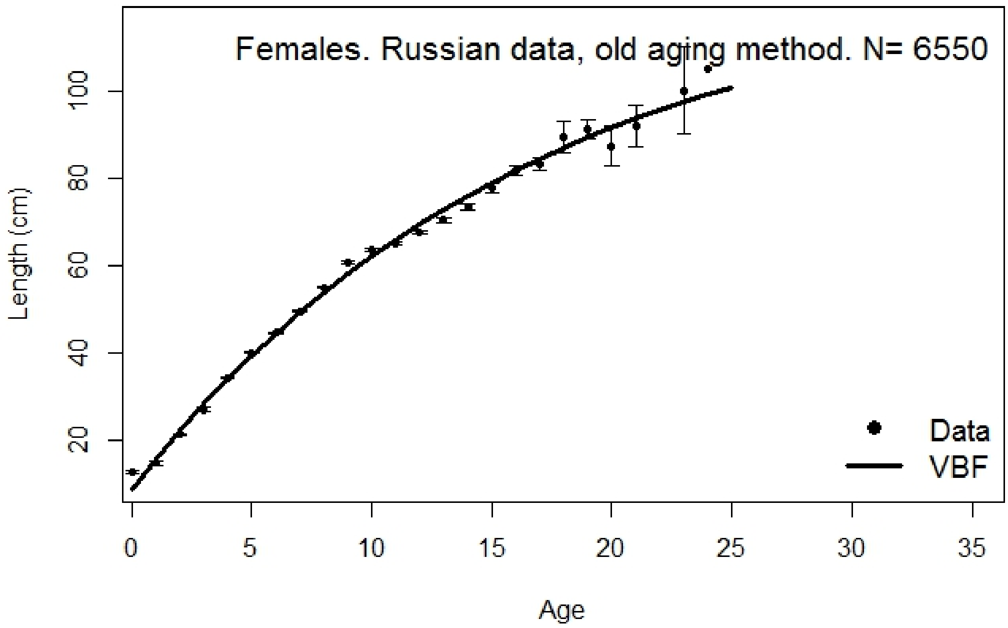
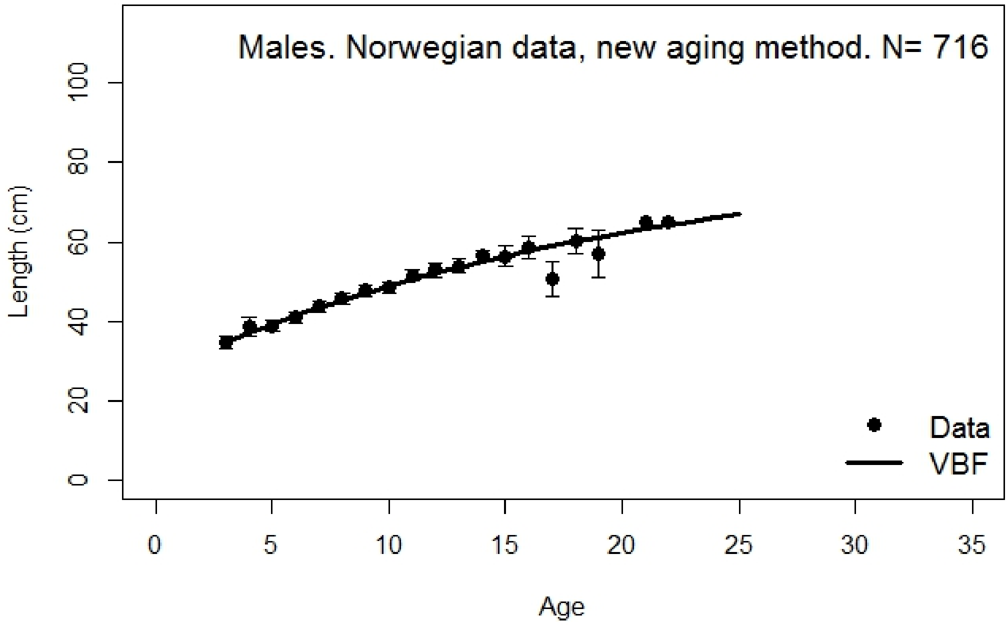


Figure 3. Growth of female Greenland halibut based on all currently available age readings by new aging method (upper panel) and based on Russian data from 2008-2012 and old aging method (lower panel). VBF growth functions fitted by the NLS function in R.



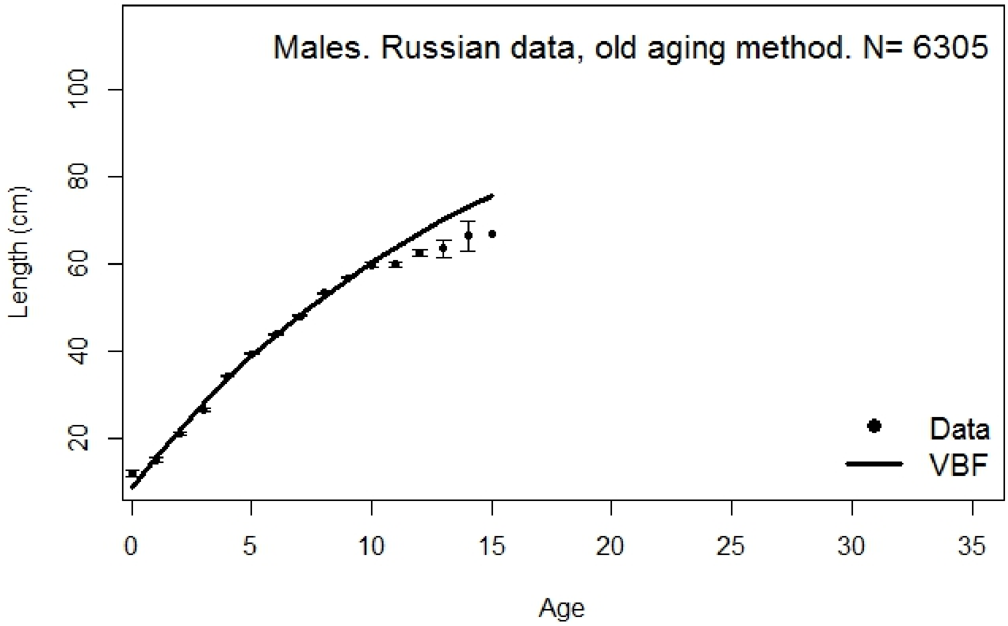


Figure 4. Growth of male Greenland halibut based on all currently available age readings by new aging method (upper panel) and based on Russian data from 2008-2012 and old aging method (lower panel). VBF growth functions fitted by the NLS function in R.

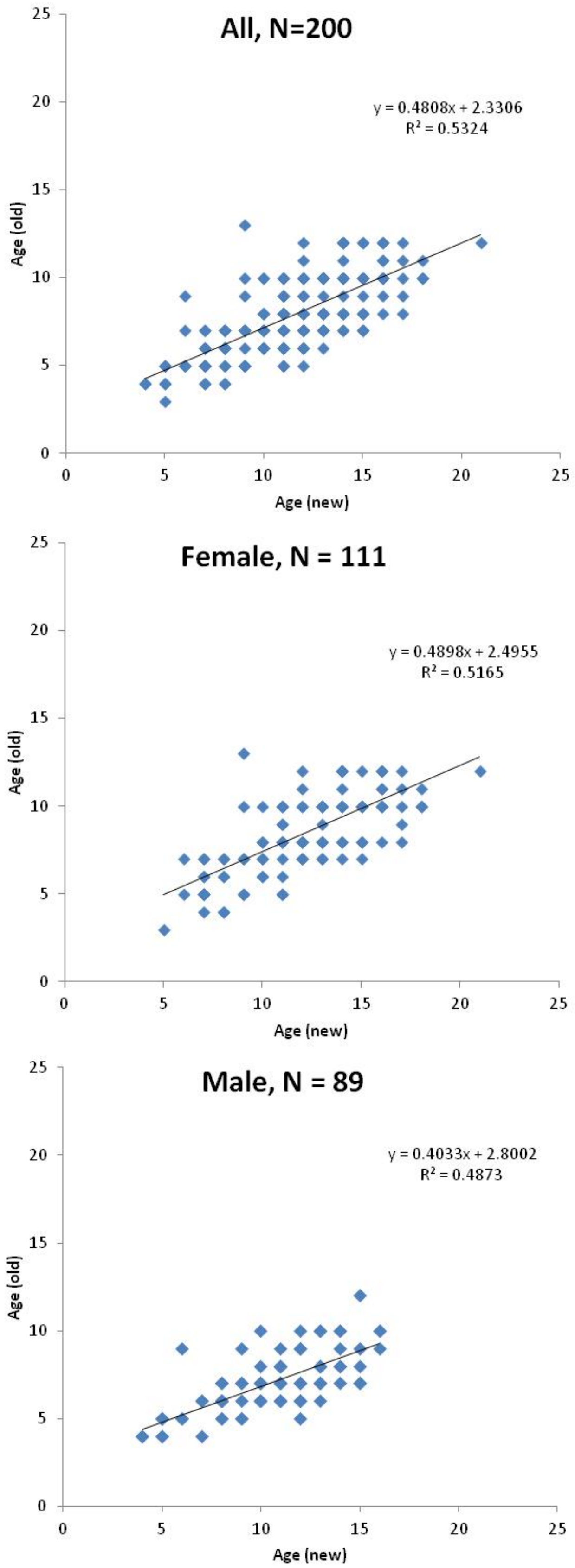


Figure 5. Age readings of Greenland halibut with old vs. new aging method in Norway. Data from Norwegian Slope survey in 2001. Also shown are linear regressions.

Greenland halibut V+XIV

Biology, Fishery and Assessment 2013

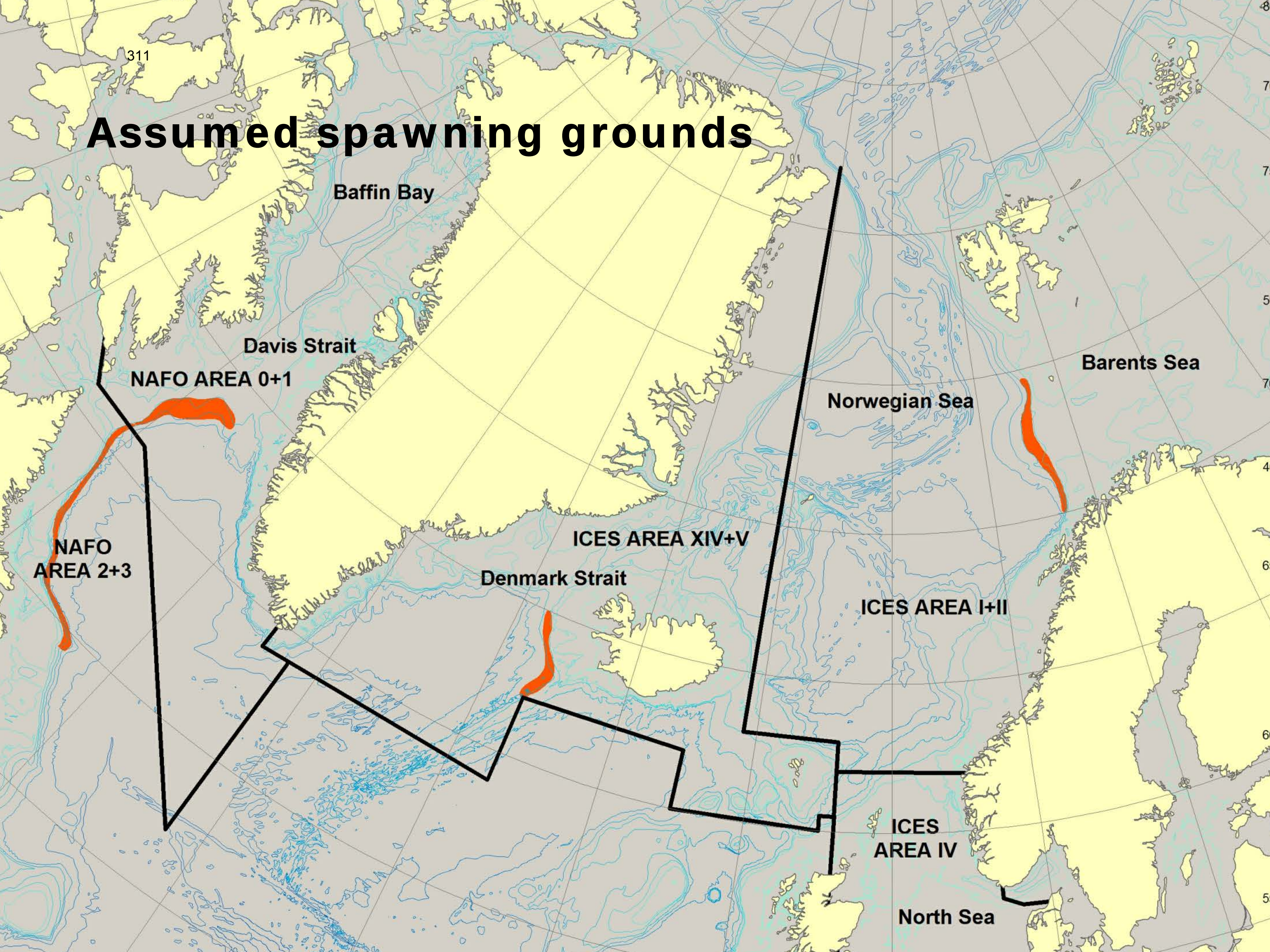
Jesper Boje, Rasmus Hedeholm &
Gudmundur Thordarson

DTU Aqua
National Institute of Aquatic Resources

Biology

- Distributed widely in North Atlantic at 200-2000m
- 2 ICES stocks and 2(4) NAFO stocks, stock definitions unclear
- Slow growing, annual growth revised
- Mature late (50-70 cm), maturation difficult to assess in field
- Spawning poorly mapped, assumed to take place in winter/early spring
- Long drifting period of eggs and larvae
- Nursery grounds poorly known for the NWWG stock
- Fish enter fishery at age 5-6
- Both immature and mature fish perform long migrations
  - Mainly an eastward migration
  - East Greenland – Iceland – Faroe islands
  - Iceland – Barent Sea (NEA stock)
- When becomming adult fish moves to deeper waters
- Fishery mainly exploits adults 800-1000 m

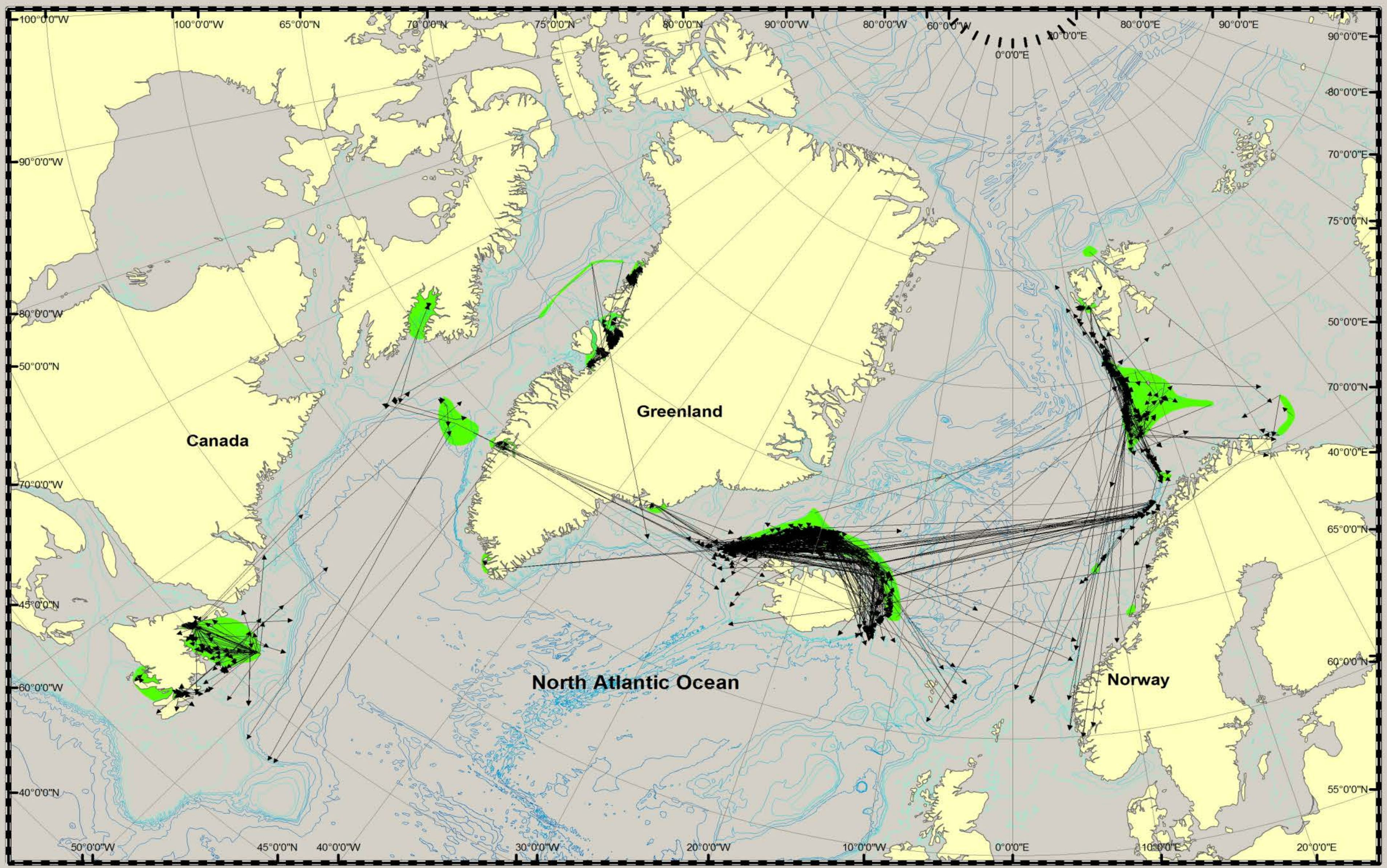
Assumed spawning grounds



Biology

- Distributed widely in North Atlantic at 200-2000m
- 2 ICES stocks and 2(4) NAFO stocks, stock definitions unclear
- Slow growing, annual growth revised in later years
- Mature late (50-70 cm), maturation difficult to assess in field
- Spawning poorly mapped, assumed to take place in winter/early spring
- Long drifting period of eggs and larvae
- Nursery grounds poorly known for the NWWG stock
- Fish enter fishery at age 5-6
- Both immature and mature fish perform long migrations
  – Mainly an eastward migration
  – East Greenland – Iceland – Faroe islands
  – Iceland – Barent Sea (NEA stock)
- When becomming adult fish moves to deeper waters
- Fishery mainly exploits adults 800-1000 m

Migrations

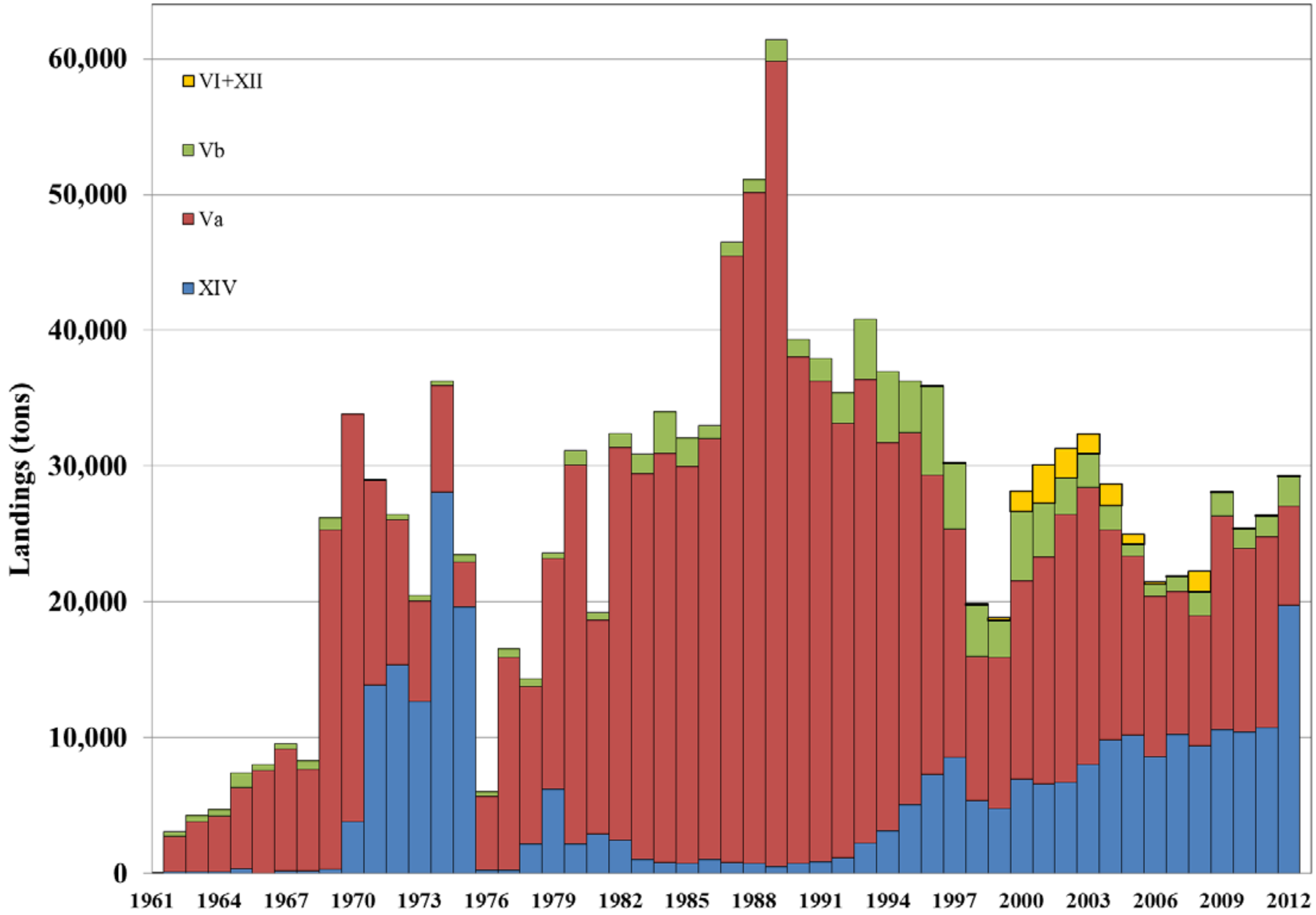


Canada
Greenland
North Atlantic Ocean
Norway
100°0'0"W
65°0'0"N
70°0'0"N
75°0'0"N
80°0'0"N
90°0'0"W
80°0'0"W
0°0'0"E
80°0'0"E
90°0'0"E
70°0'0"E
75°0'0"N
50°0'0"E
40°0'0"E
65°0'0"N
60°0'0"N
55°0'0"N
50°0'0"N
60°0'0"W
45°0'0"N
40°0'0"N
50°0'0"W
40°0'0"W
30°0'0"W
20°0'0"W
10°0'0"W
10°0'0"E
20°0'0"E

Biology

- Distributed widely in North Atlantic at 200-2000m
- 2 ICES stocks and 2(4) NAFO stocks, stock definitions unclear
- Slow growing, annual growth revised in later years
- Mature late (50-70 cm), maturation difficult to assess in field
- Spawning poorly mapped, assumed to take place in winter/early spring
- Long drifting period of eggs and larvae
- Nursery grounds poorly known for the NWWG stock
- Fish enter fishery at age 5-6
- Both immature and mature fish perform long migrations
  - Mainly an eastward migration
  - East Greenland – Iceland – Faroe islands
  - Iceland – Barent Sea (NEA stock)
- When becomming adult fish moves to deeper waters
- Fishery mainly exploits adults 800-1000 m

Landings



VI+XII
Vb
Va
XIV
Landings (tons)
60,000
50,000
40,000
30,000
20,000
10,000
0
1961
1964
1967
1970
1973
1976
1979
1982
1985
1988
1991
1994
1997
2000
2003
2006
2009
2012

Fishery

- Conducted by large trawlers, single trawlers > 1000 Hp
  - In Greenland EEZ 17 trawlers in 2012
  - In Iceland EEZ 19 trawlers in 2012
  - In Faroese EEZ approx xx trawlers

- Bottom trawl – rock hopper - mesh size 140 mm codend

- Onboard freezing

- Fishery conducted all seasons – main bulk of catches is Jan-June in Va and spring-summer in XIV

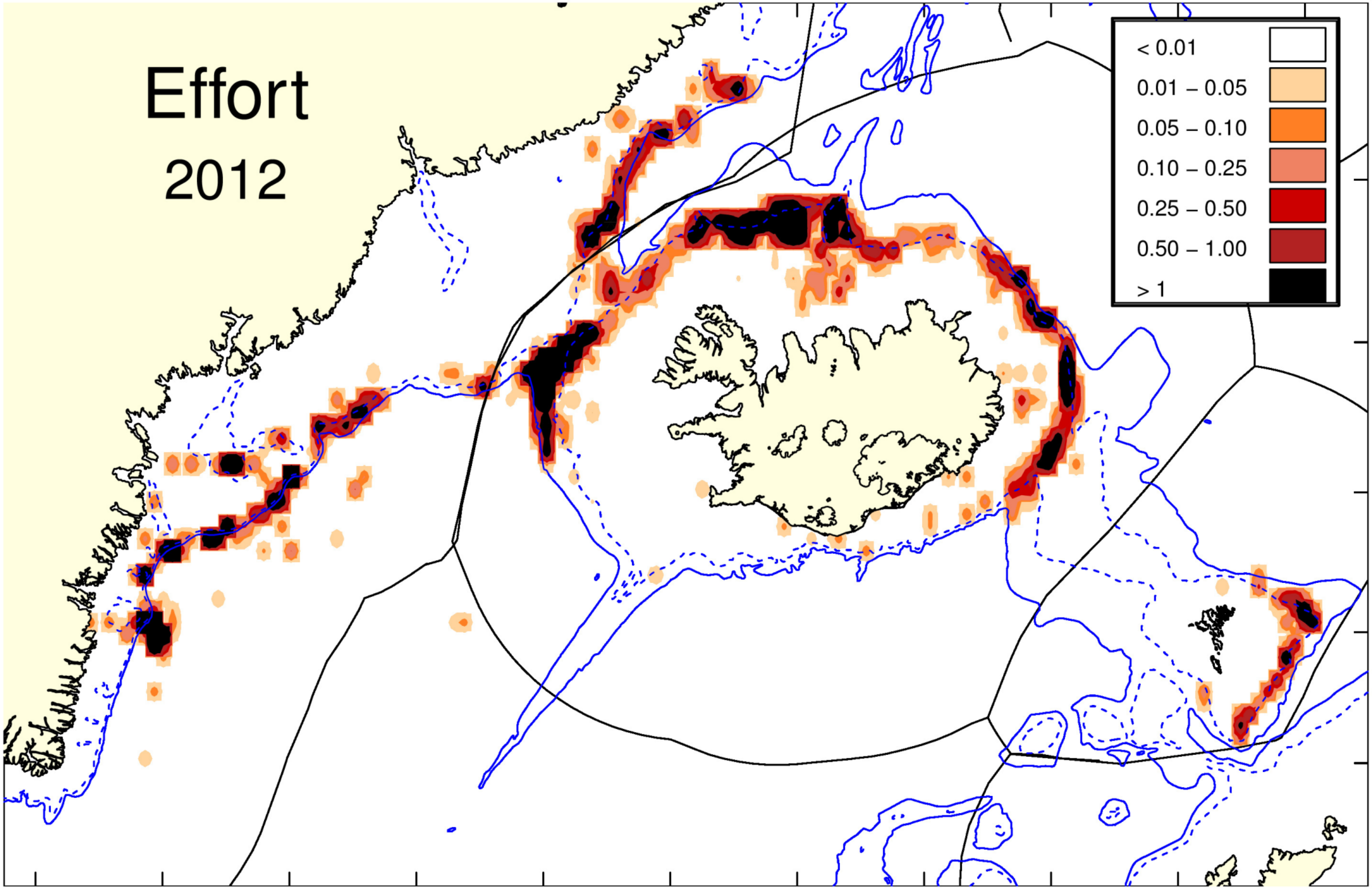
Management

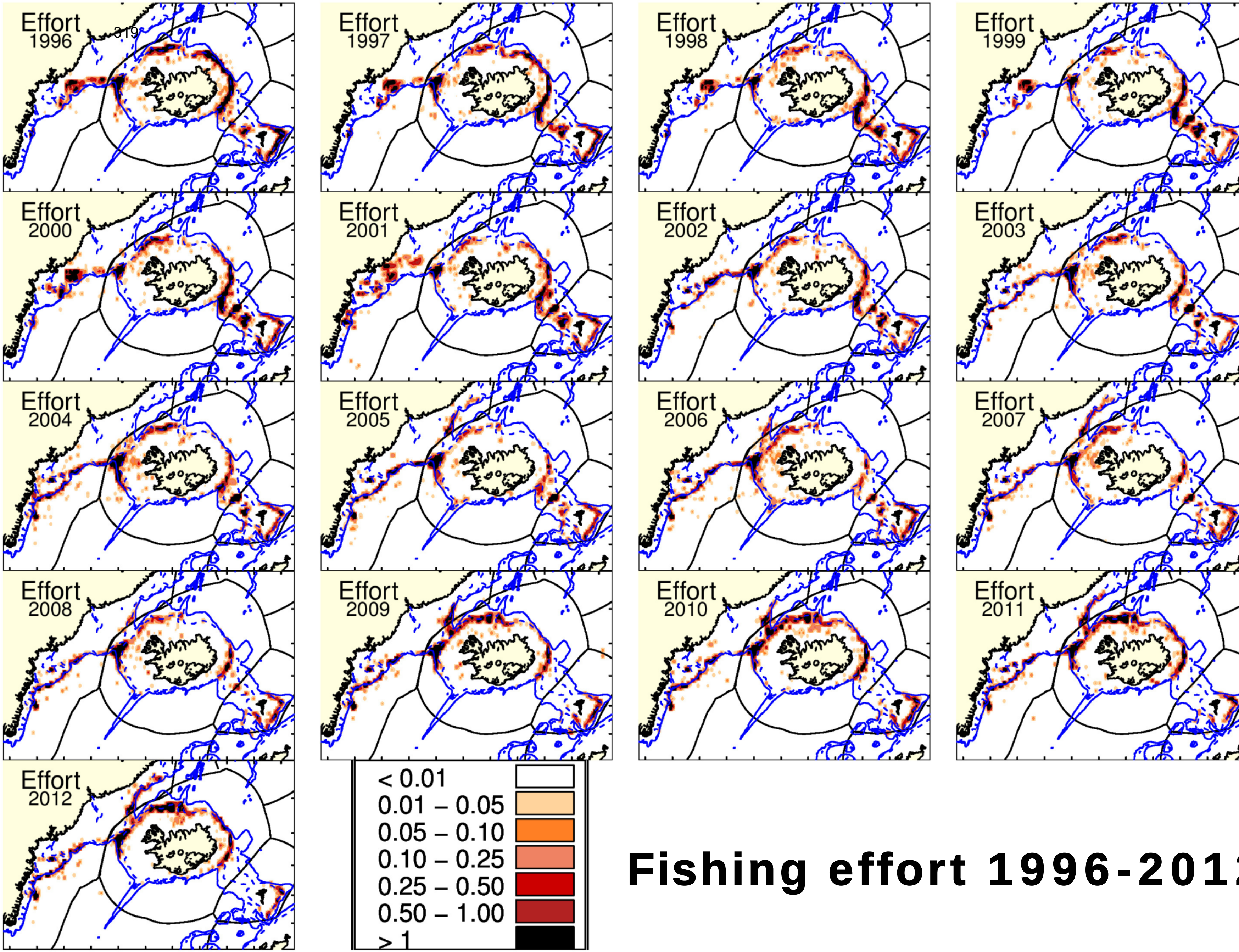
- TAC regime in Iceland and Greenland; Effort regime in Faroe Islands

- Prior to 2012 no common management was in place; Greenland, Iceland and Faroe Island set autonomous quotas; most often these quotas in total was 200% of the ICES TAC advice

- Since 2012 Iceland and Greenland agreed for shared usage of the stock. This agreement provides that TAC in 2013 will be 26 thous. tonnes but would decrease by 15% in 2014

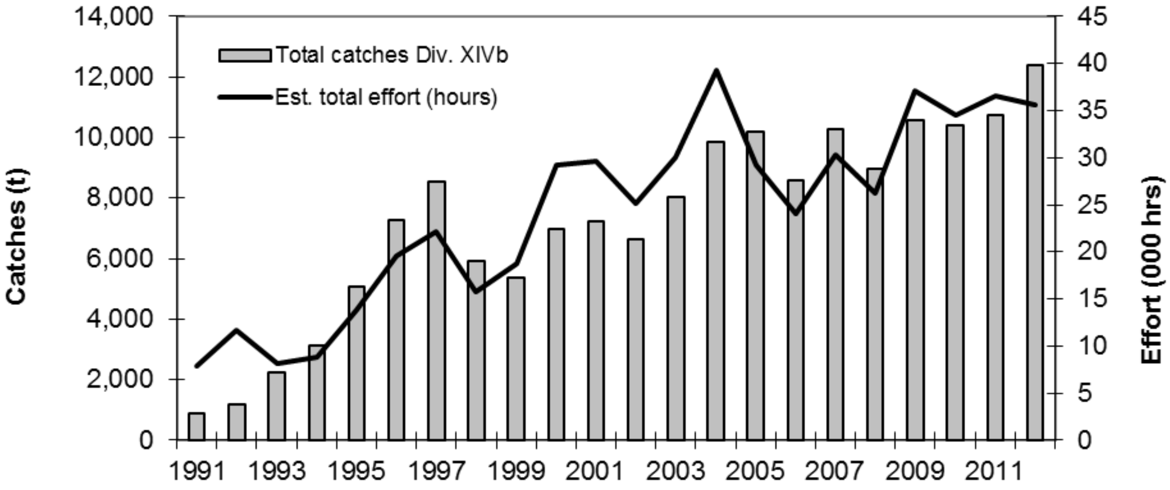
- The nations agreed to develop a harvest control rule (HCR) for Greenland halibut that would be adopted in 2015.


Effort
2012
< 0.01
0.01 – 0.05
0.05 – 0.10
0.10 – 0.25
0.25 – 0.50
0.50 – 1.00
> 1

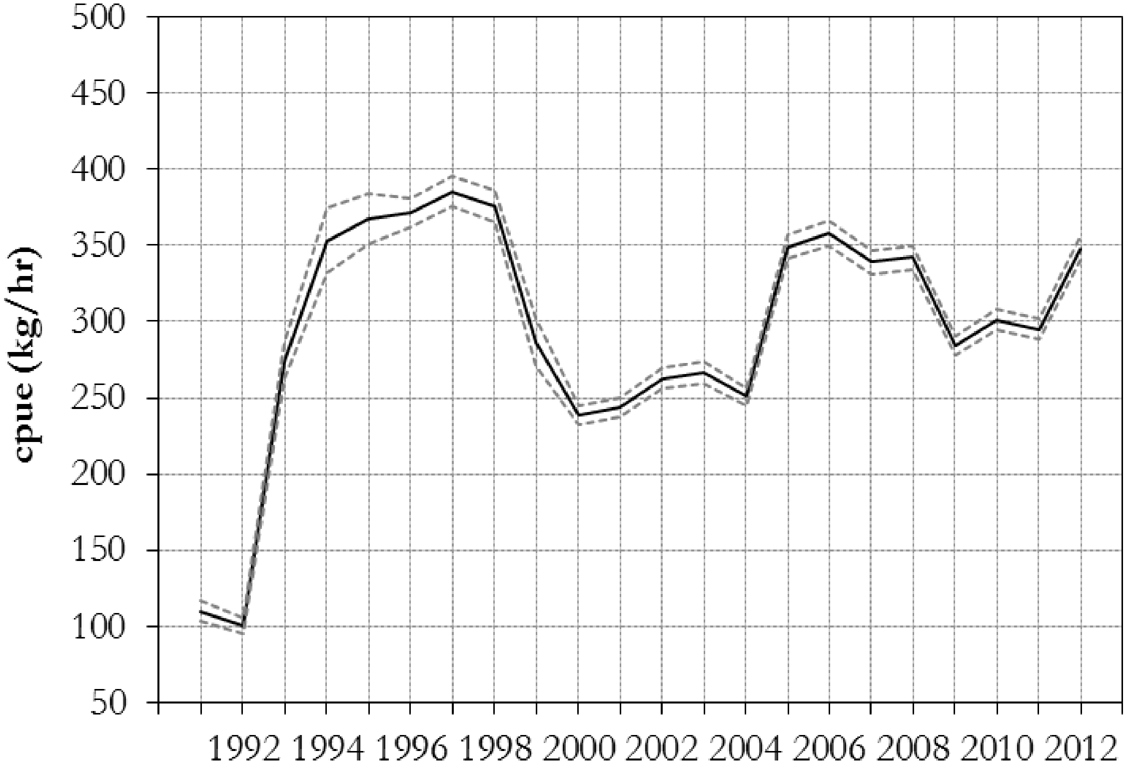


Fishing effort 1996-2012

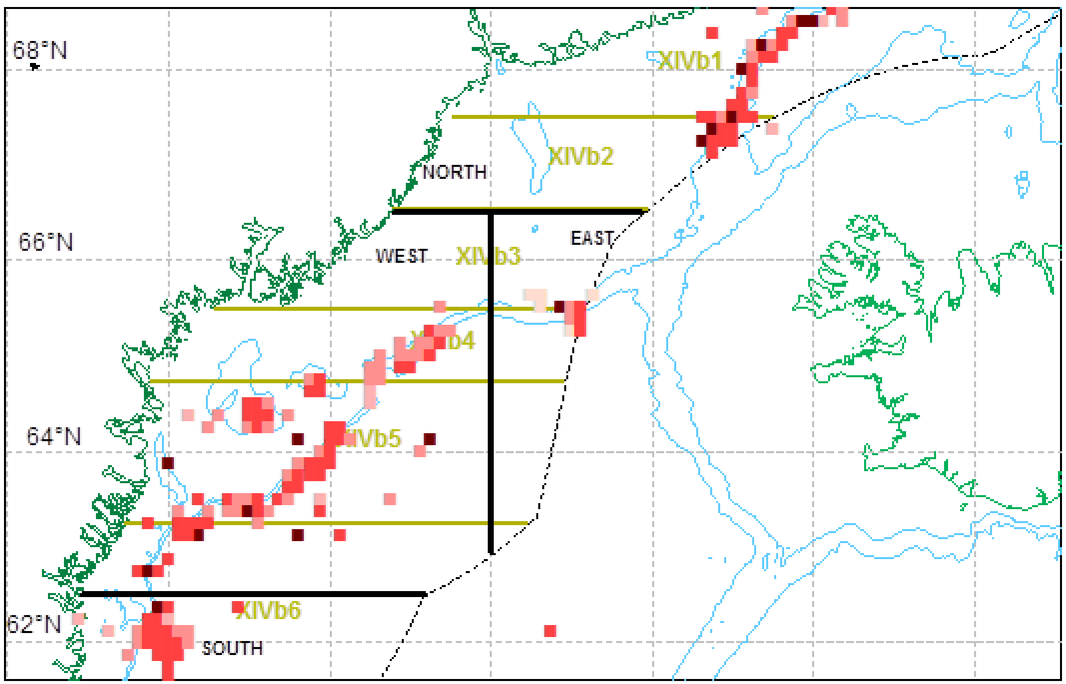
East Greenland - XIV

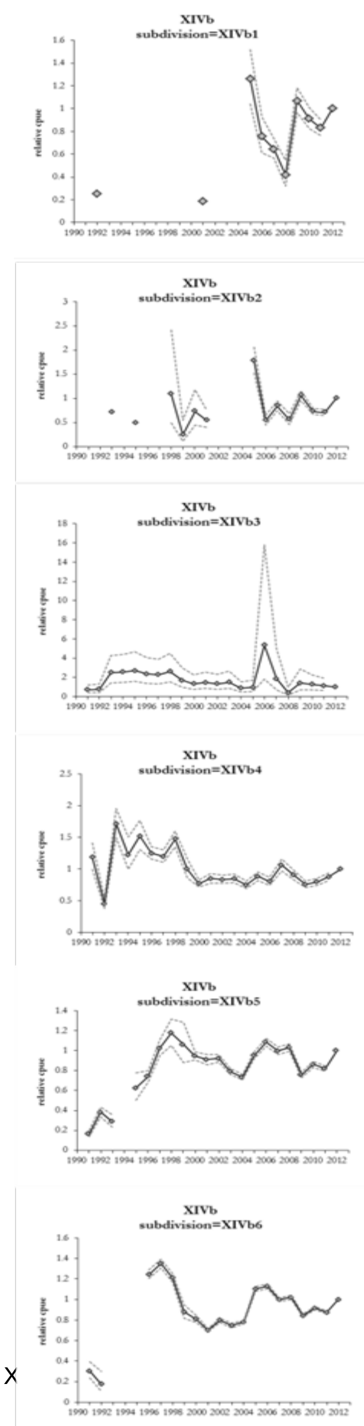


Standardised (CPUE) in XIV (East Greenland)

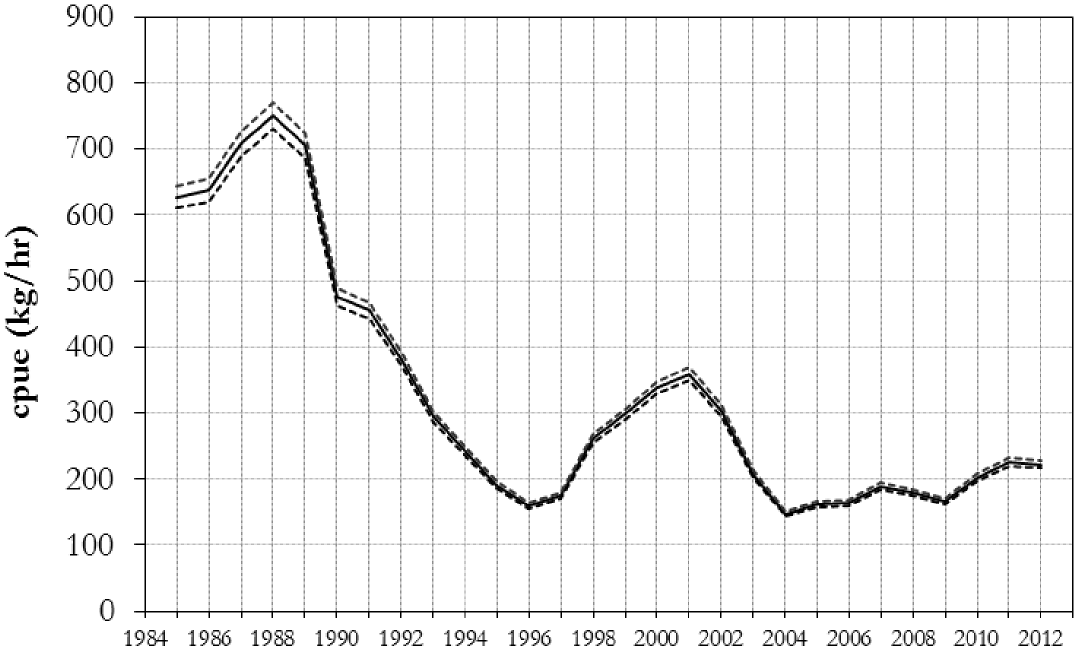


Standardized (CPUE) in XIV (East Greenland) by subdivisions from north to south

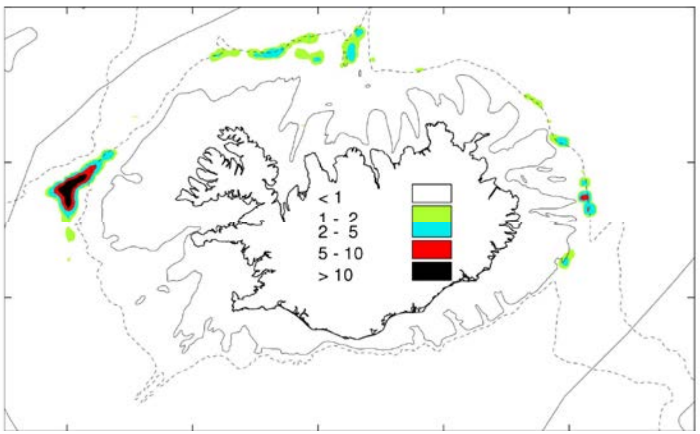




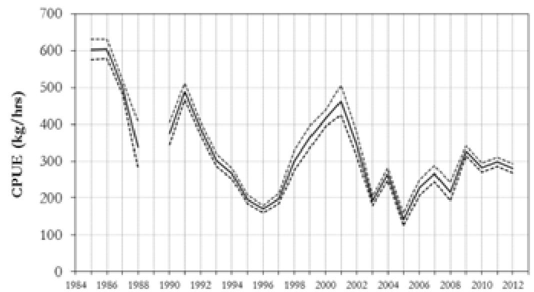
Standardised CPUE in Va (Iceland)



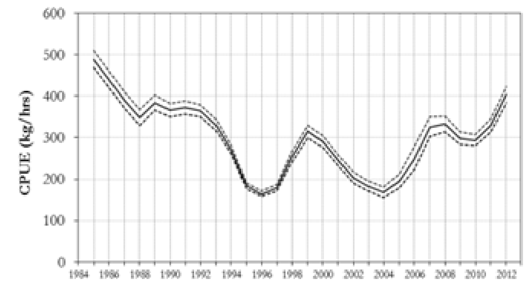
Standardised CPUE in Va (Iceland)



Va - North

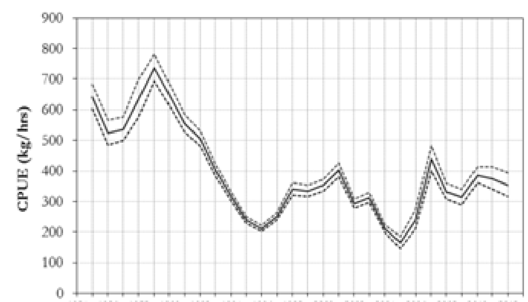


Va - East

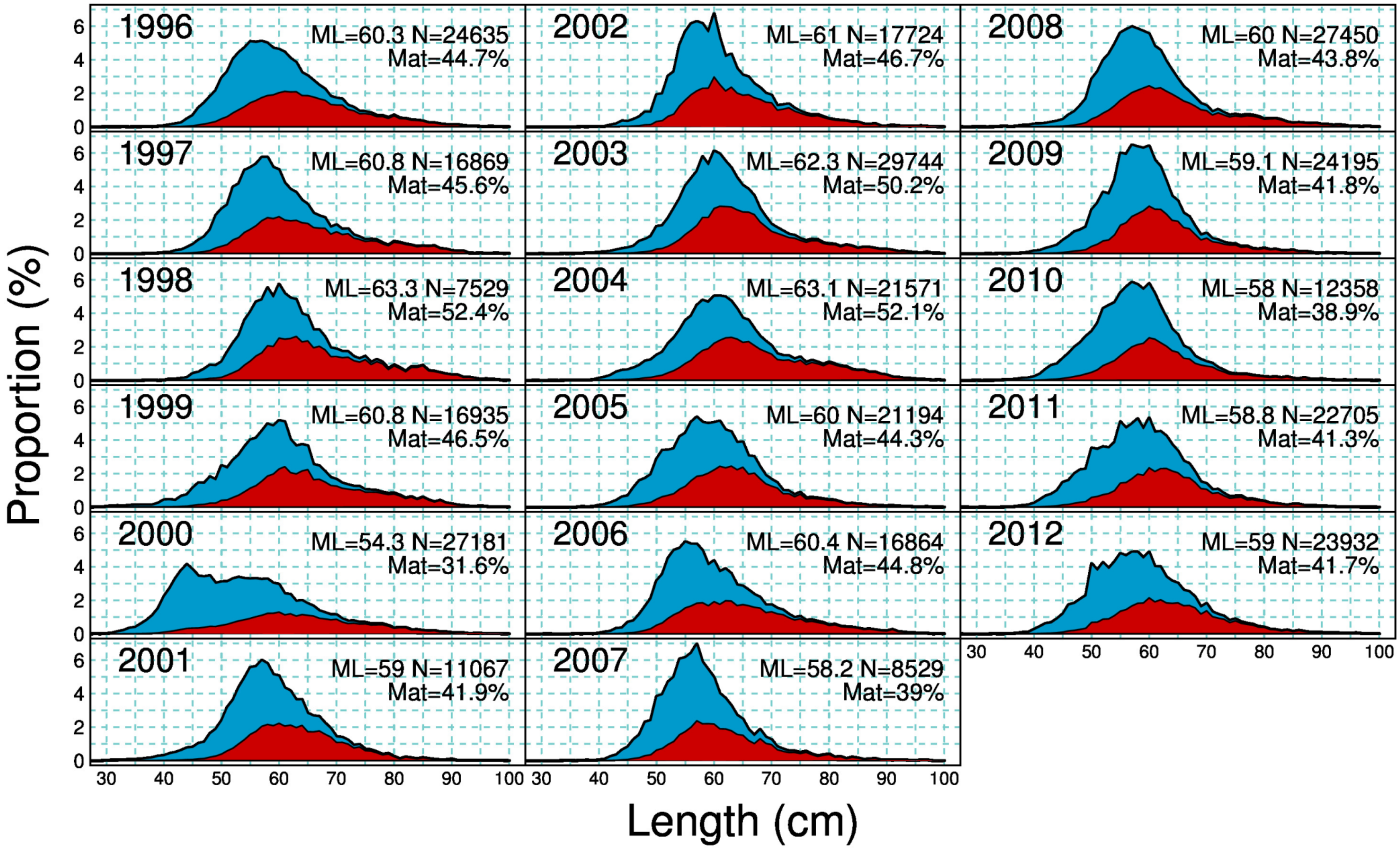


Va - West

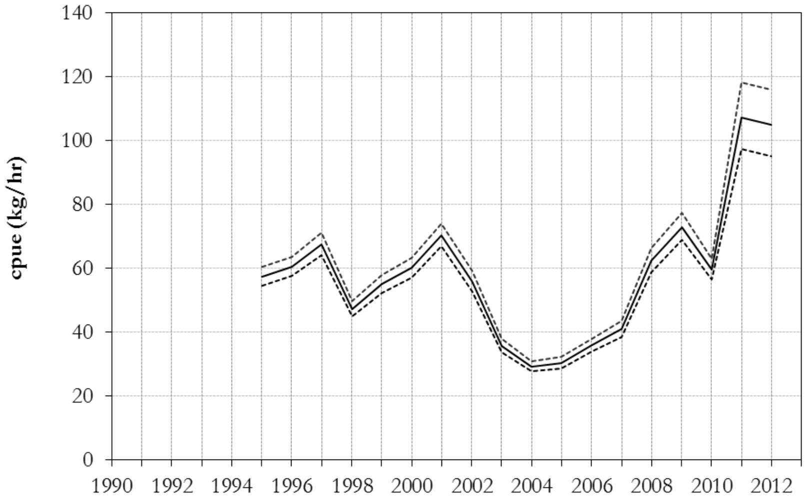
Va - South-East

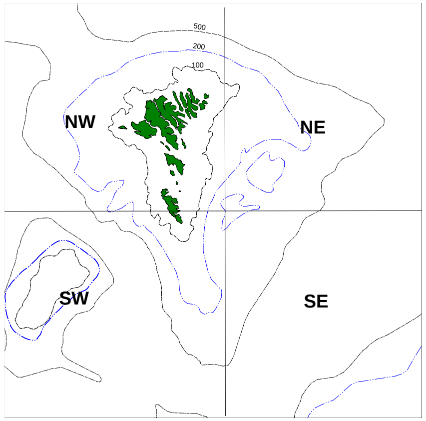


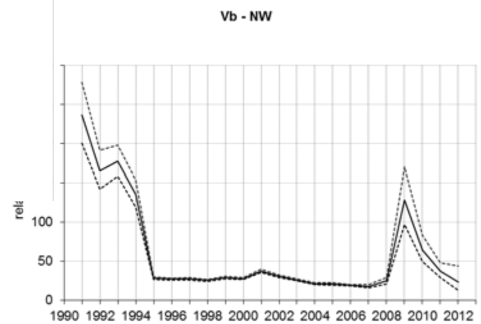
The fishery in Va
Catch composition

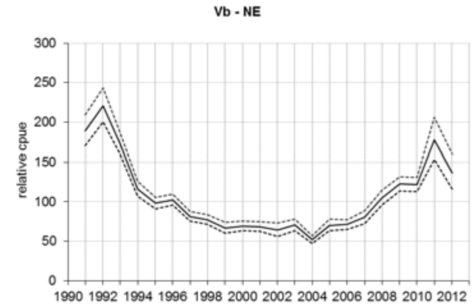


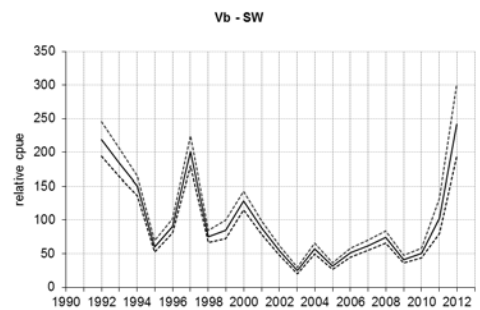
The fishery in Vb, standardised CPUE

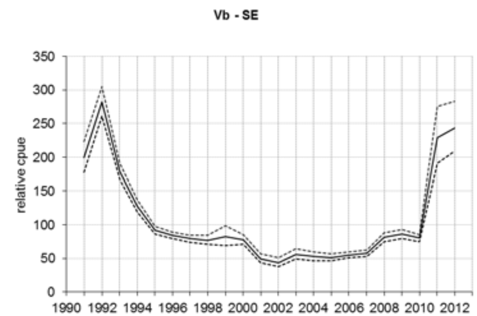




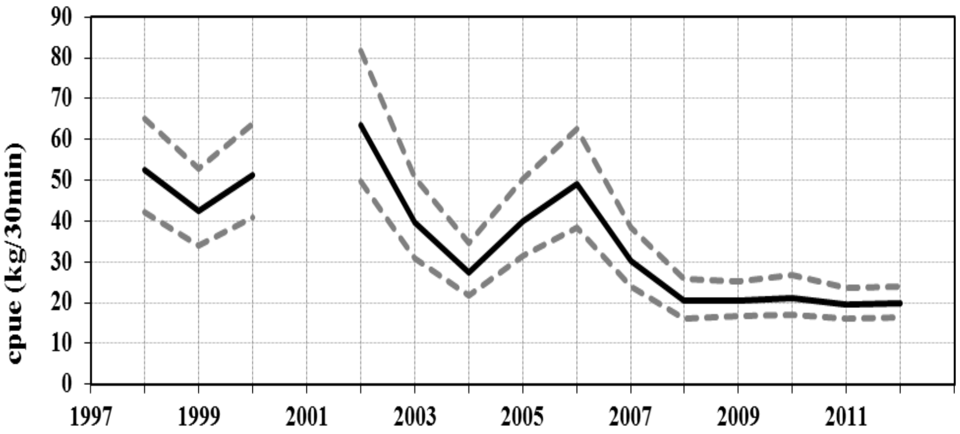


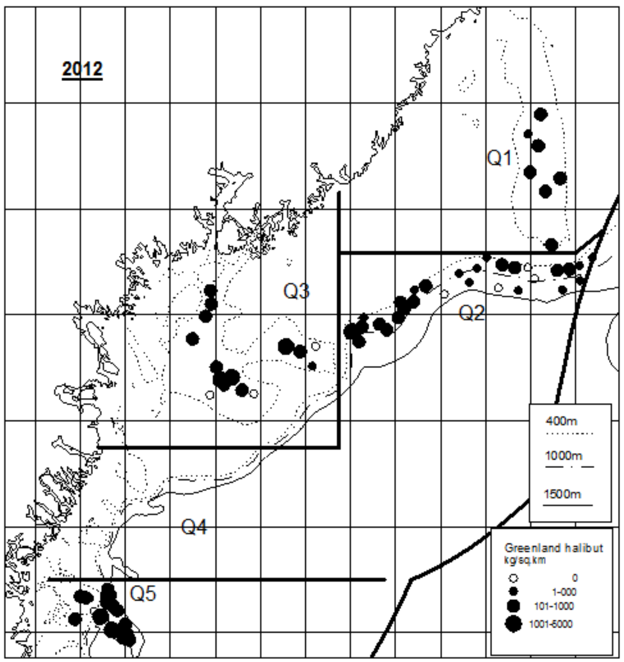




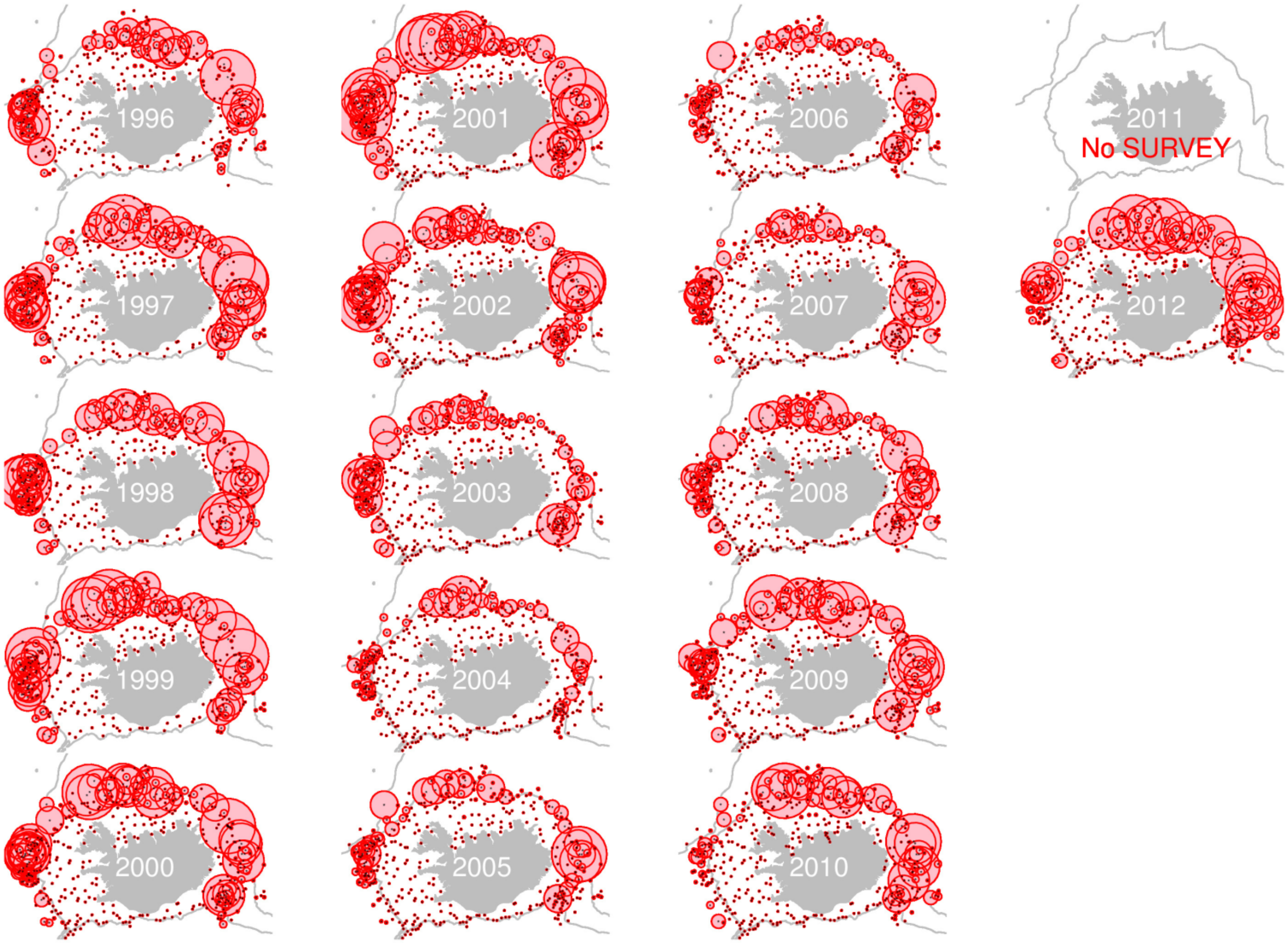


Survey in XIV

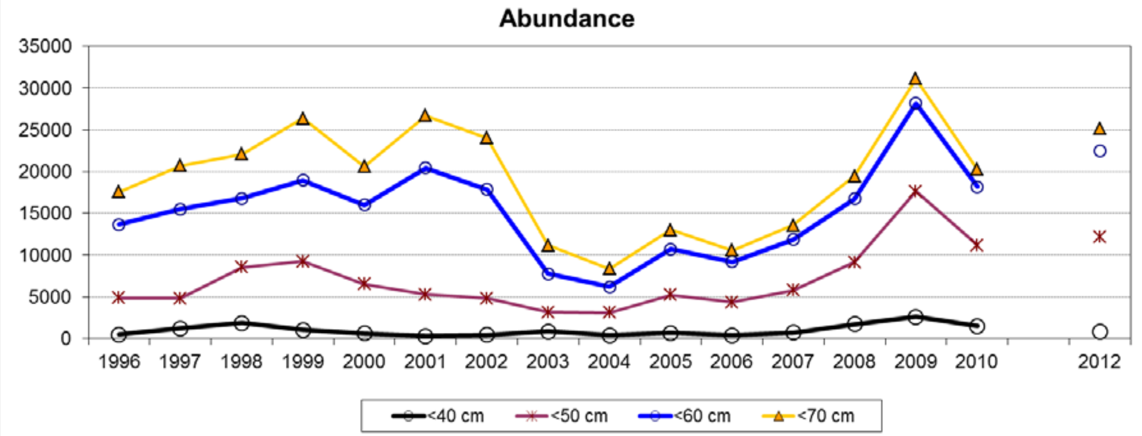


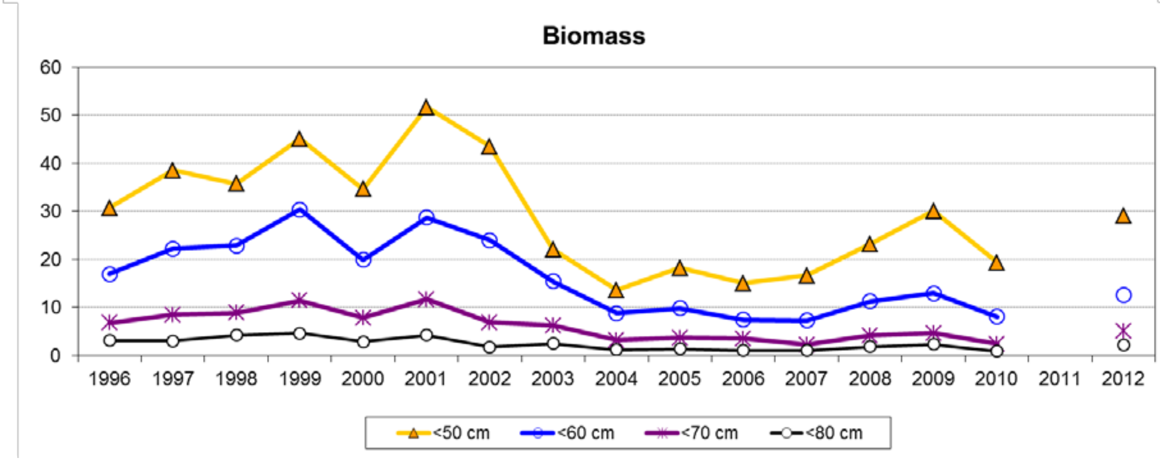


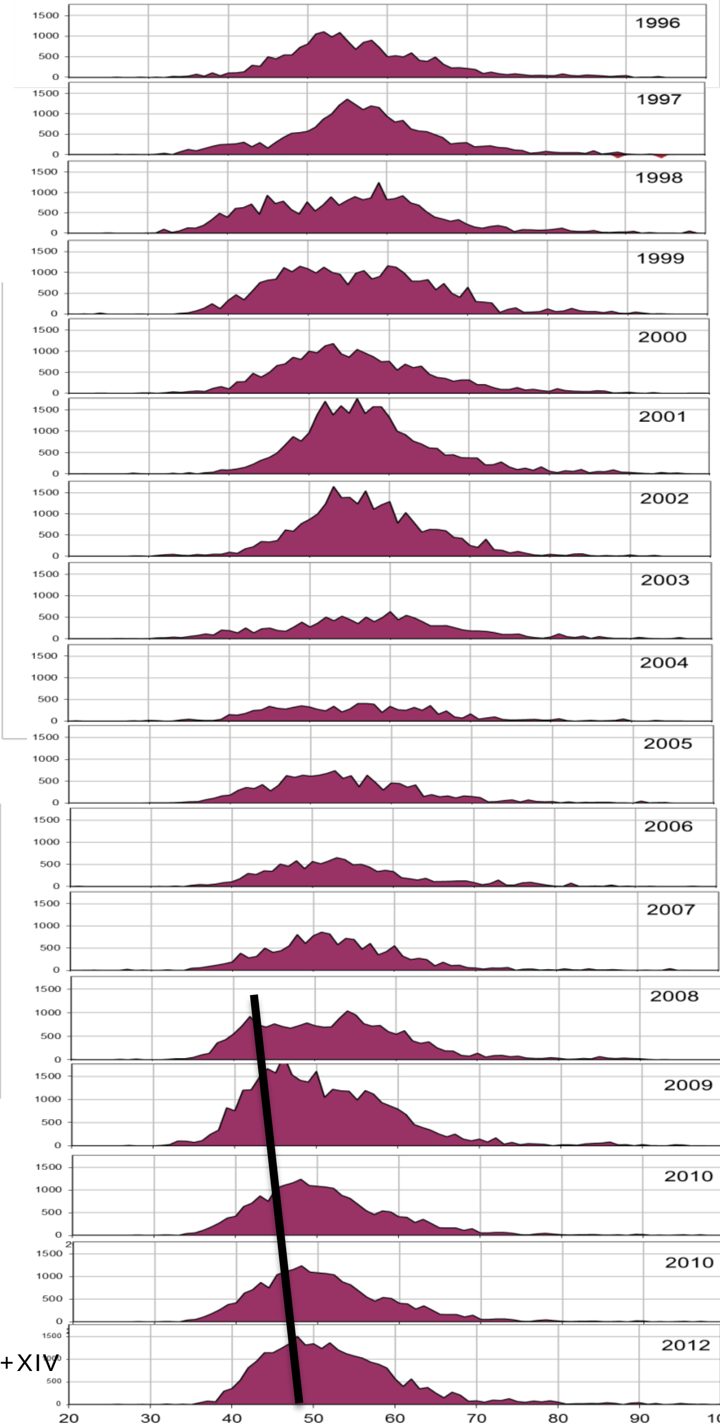
Survey Va - fall



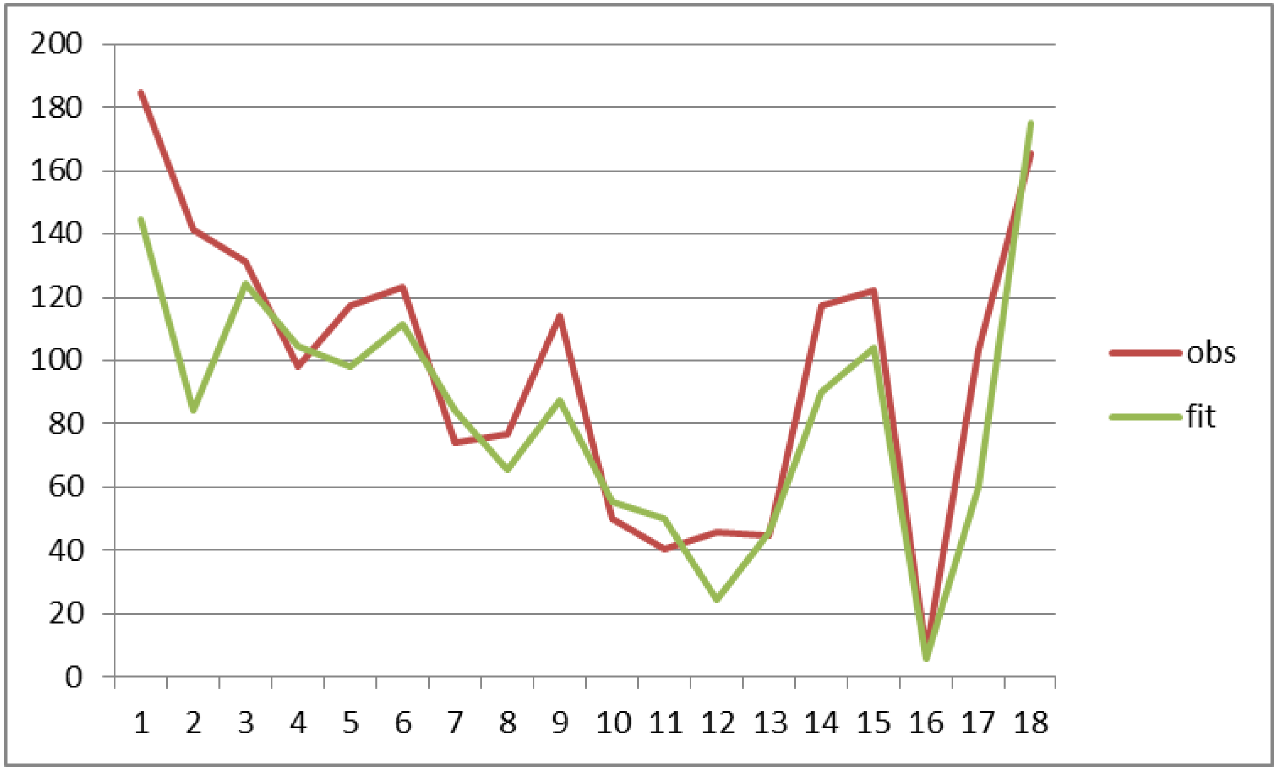
Survev Va - fall







Vb survey


200
180
160
140
120
100
80
60
40
20
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
obs
fit

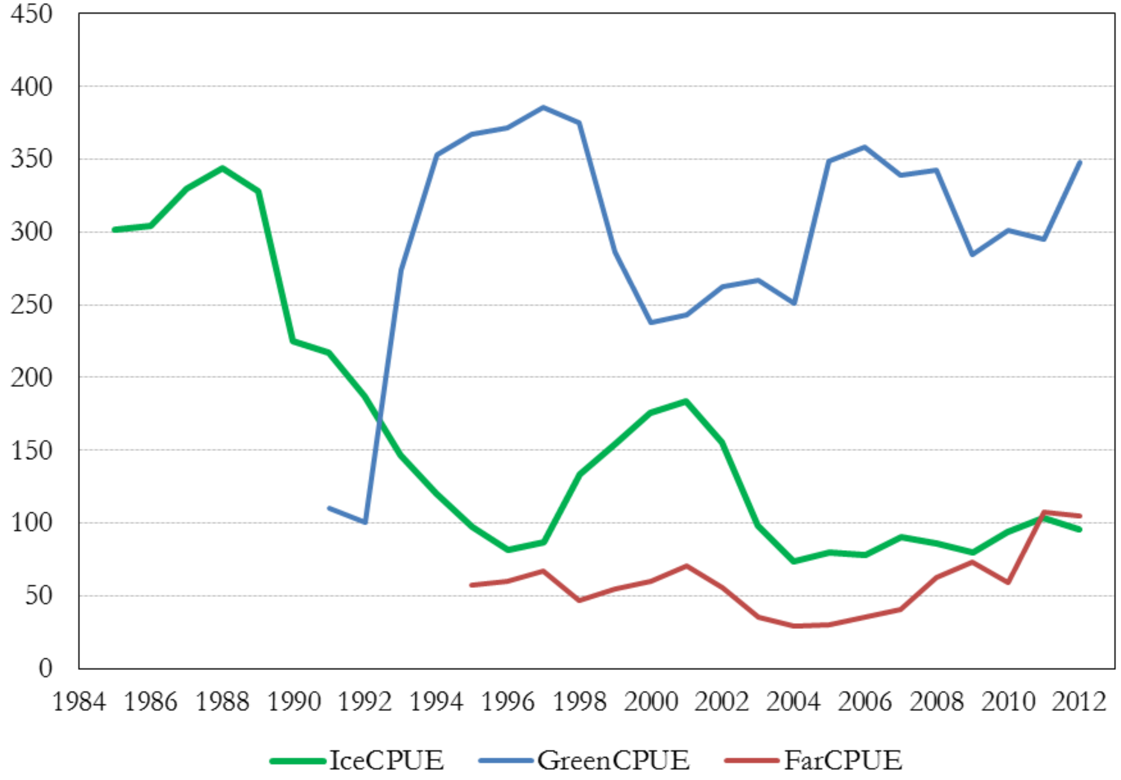
Stock prod model in Bayesian framework

Same settings since 2008

Input data:

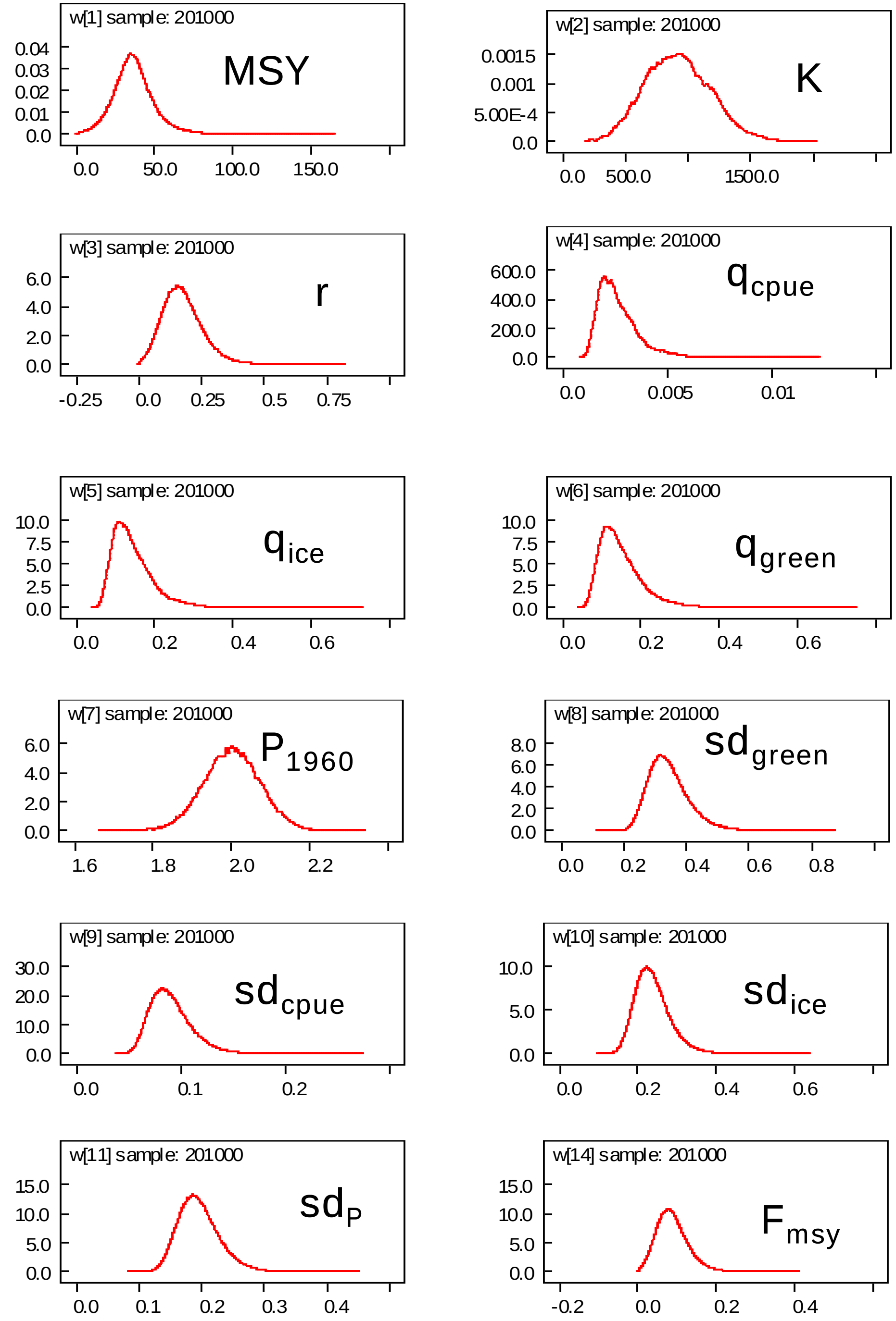
- –Landings 1961-2012 in V,VI,XII and XIV
- –Greenland Survey indices 1998-2012
- –Iceland Fall survey 1996-2012, no survey 2011
- –Icelandic fishery cpue index 1985-2012

CPUE trends conflict



333

Parameter estimates

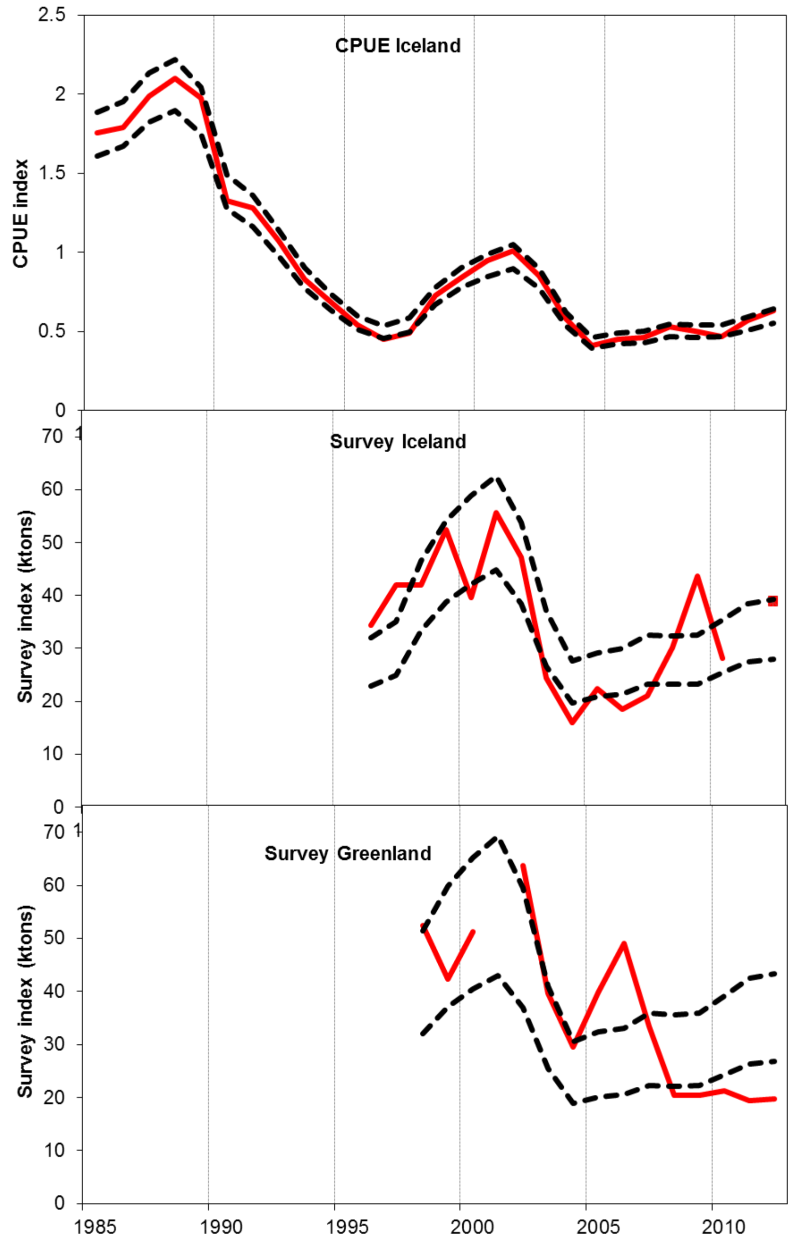


Parameter estimates

	Mean	sd	25%	Median	75%
MSY (ktons)	36	13	28	35	43
K (ktons)	881	243	704	869	1040
r	0.18	0.09	0.12	0.17	0.23
q_{cpue}	3E-03	1E-03	2E-03	3E-03	3E-03
q_{Ice}	0.15	0.05	0.11	0.13	0.17
q_{Green}	0.17	0.06	0.13	0.16	0.20
P_{1985}	1.58	0.12	1.51	1.59	1.67
P_{2010}	0.49	0.06	0.44	0.48	0.53
σ_{Ice}	0.31	0.06	0.27	0.31	0.35
σ_{cpue}	0.10	0.02	0.08	0.09	0.11
σ_{Green}	0.24	0.05	0.20	0.23	0.26
σ_{P}	0.20	0.03	0.17	0.20	0.22

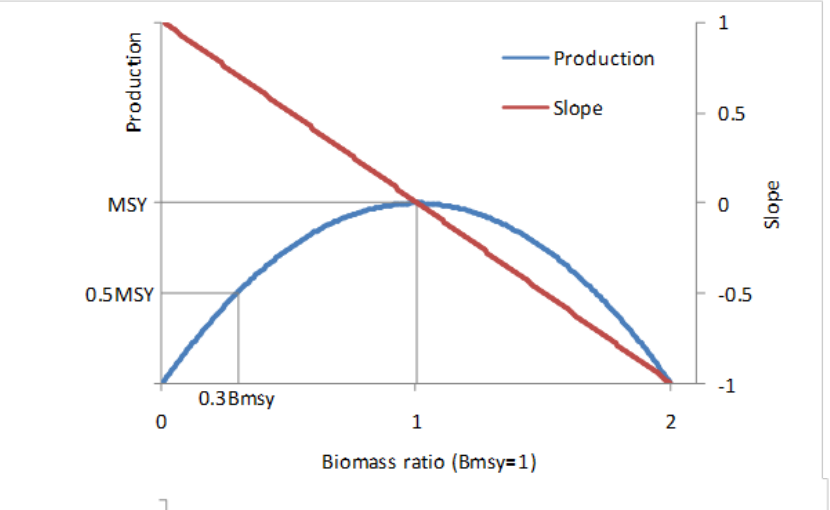
Model performance

- 25-75 model percentiles and observed indices



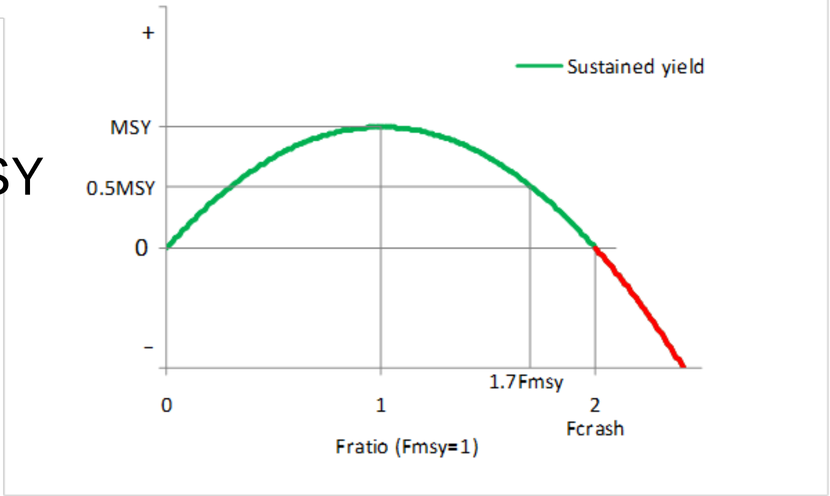
Defined reference points

- Fmsy (F/Fmsy=1)
- Bmsy (B/Bmsy=1)

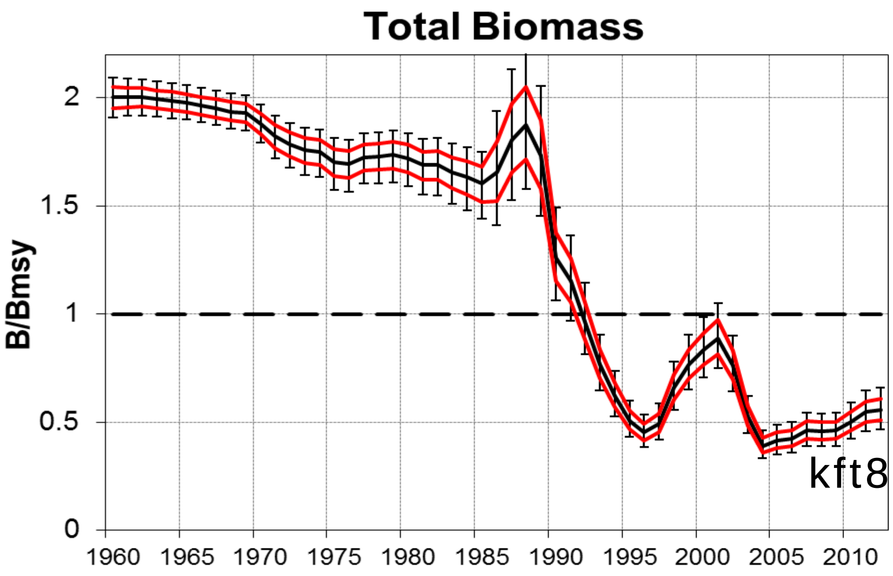


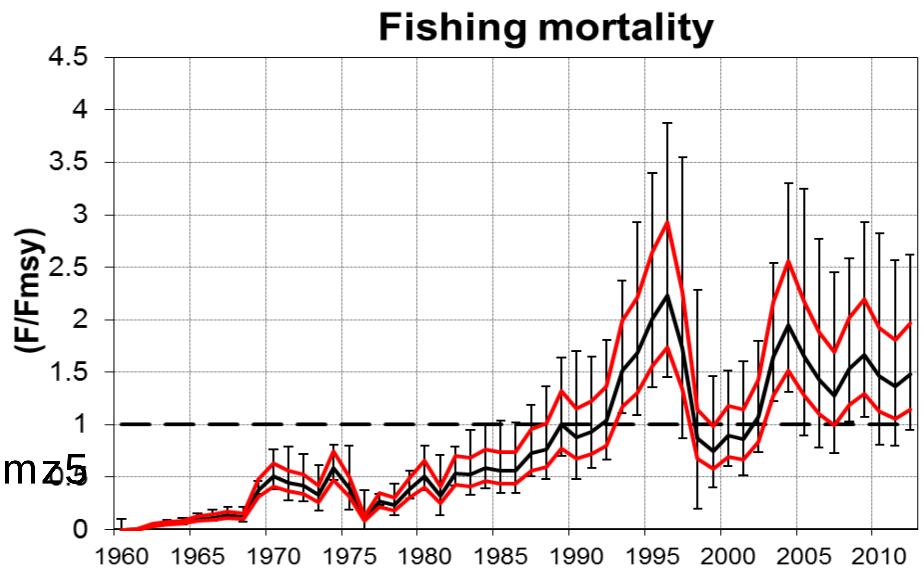
Candidate reference points

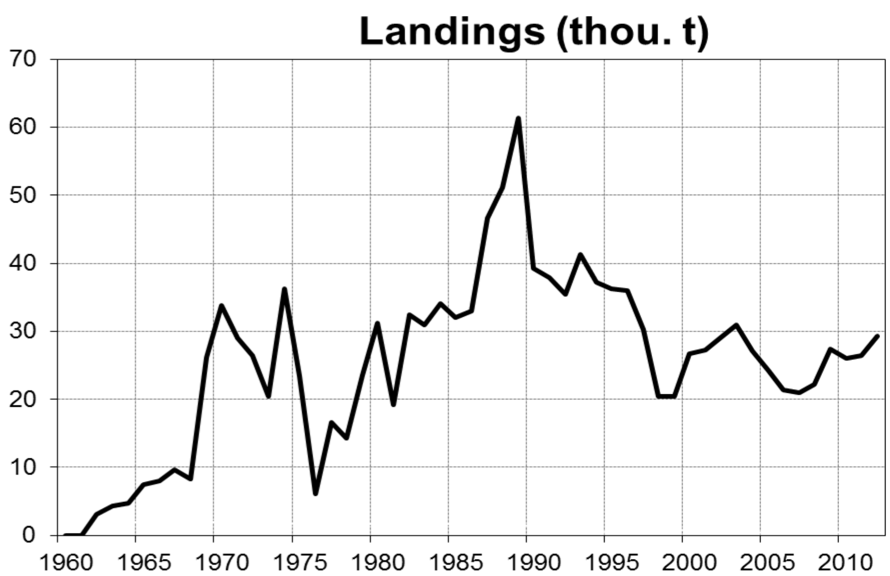
MSY Btrigger=30-50%Bmsy~0.5-0.7MSY



Stock summary







2013 catches of 25000 t

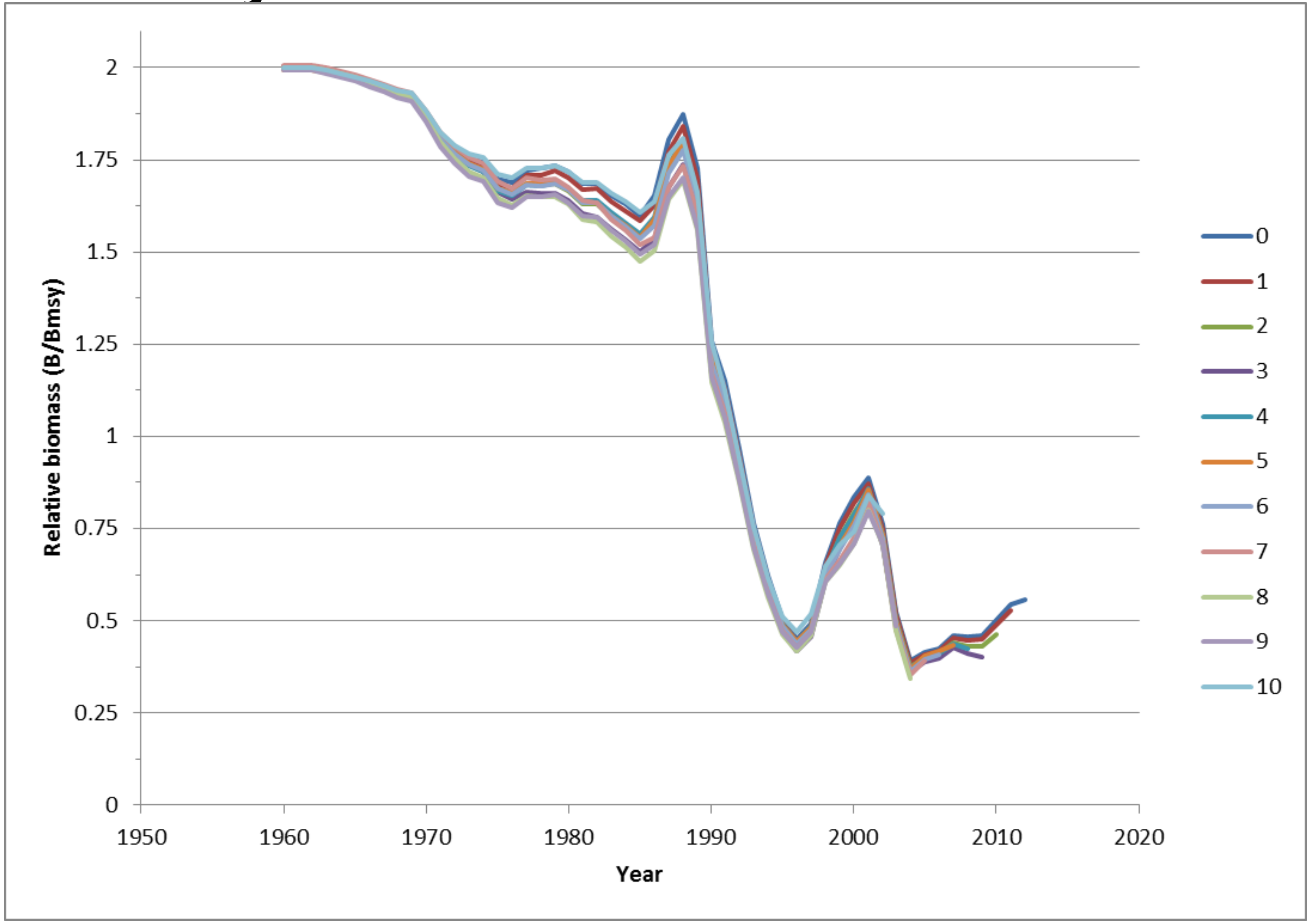
Status	2012	2013
Risk of falling below $B_{msy\_trigger}$	0%	0%
Risk of falling below B_{MSY}	100%	99%
Risk of exceeding F_{MSY}	85%	69%
Risk of exceeding F_{lim}	37%	26%
Stock size (B/Bmsy), median	0.56	0.57
Fishing mortality (F/Fmsy),	1.50	1.25
Productivity (% of MSY)	80%	81%

Conclusions

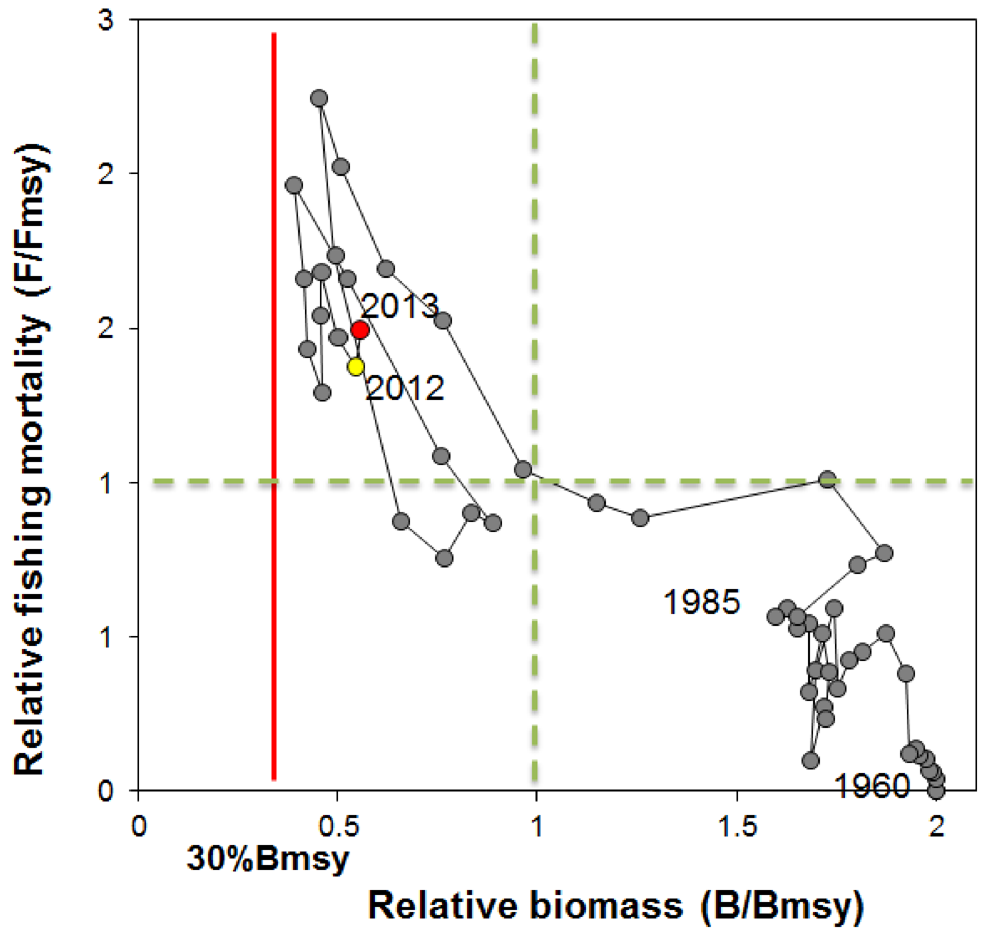
Stock status 2012

- Stock size:
  - Stock biomass 0.56*Bmsy* (median)
  - 100% probability of being below *Bmsy*
  - 0-2% risk of being below *Blim*
- Stock production:
  - MSY = 28 – 44 ktons (inter-quartile range)
  - Actual ≈ 0.8*MSY (median)
- Exploitation:
  - 30 ktons
  - 1.5**Fmsy* (median)
  - 37% risk of exceeding *Flim*

Retro analysis



Stock / fishery trajectory



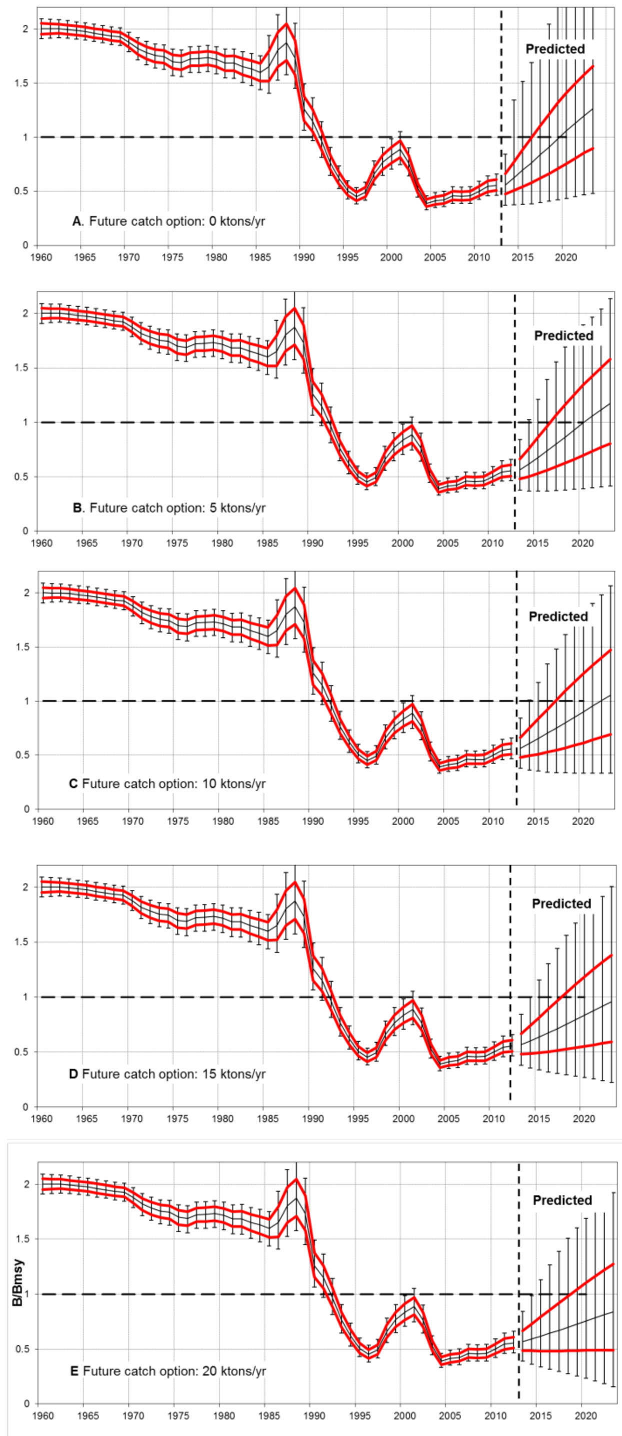
Stock status and man. opt. 2014

Status	2012	2013 *
Risk of falling below $B_{msy\_trigger}$	0%	0%
Risk of falling below B_{MSY}	100%	99%
Risk of exceeding F_{MSY}	85%	69%
Risk of exceeding F_{lim}	37%	26%
Stock size (B/Bmsy), median	0.56	0.57
Fishing mortality (F/Fmsy),	1.50	1.25
Productivity (% of MSY)	80%	81%

*Predicted catch in 2013 = 25ktons

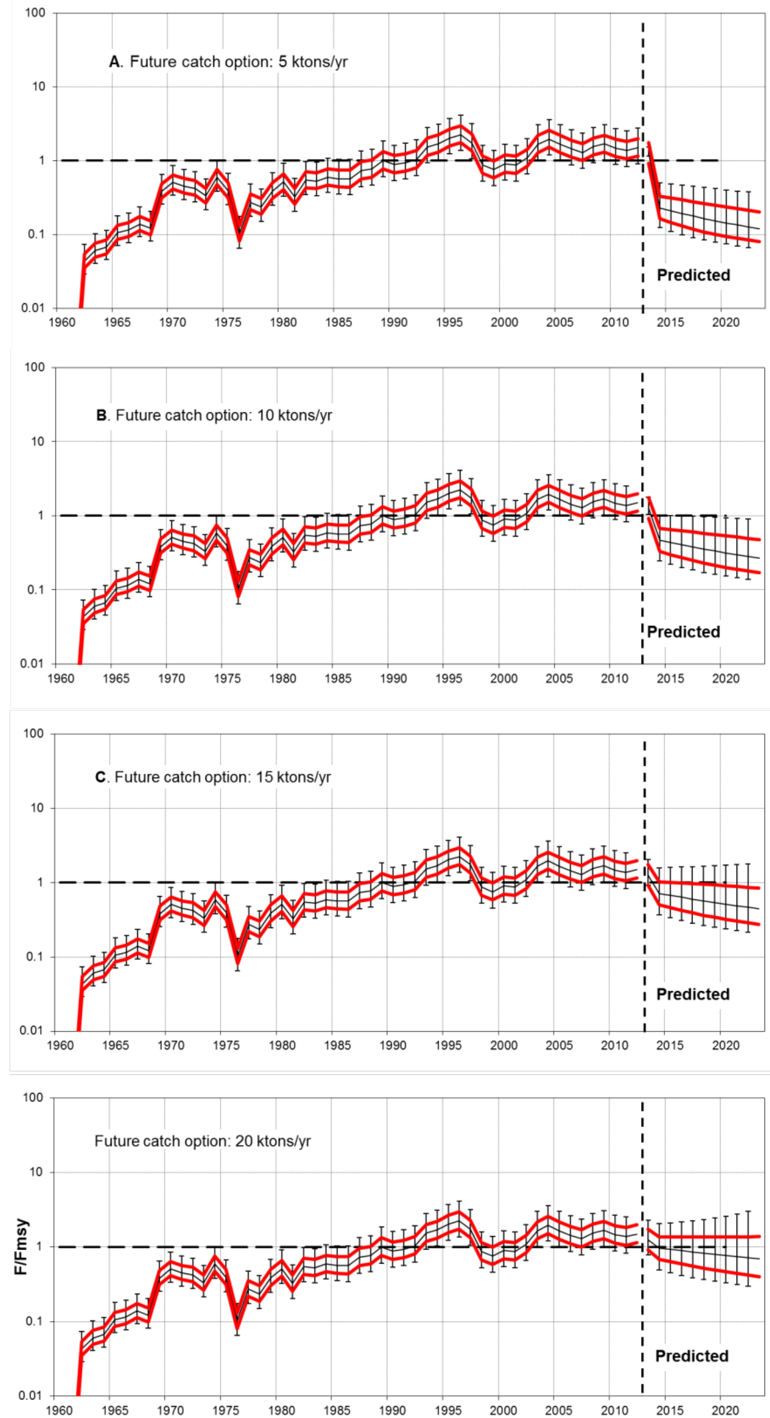
Catch option 2014 (ktons)	0	5	10	15	20	30
Risk of falling below $30\%B_{MSY}$	1%	1%	1%	2%	1%	4%
Risk of falling below B_{MSY}	94%	94%	95%	95%	95%	97%
Risk of exceeding F_{MSY}	-	2%	10%	27%	47%	81%
Risk of exceeding F_{lim}	-	1%	3%	8%	15%	43%
Stock size (B/Bmsy), median	0.63	0.62	0.61	0.60	0.59	0.55
Fishing mortality (F/Fmsy),	0.00	0.23	0.47	0.71	0.97	1.56
Productivity (% of MSY)	86%	85%	85%	84%	83%	80%

Biomass at diff. catch options

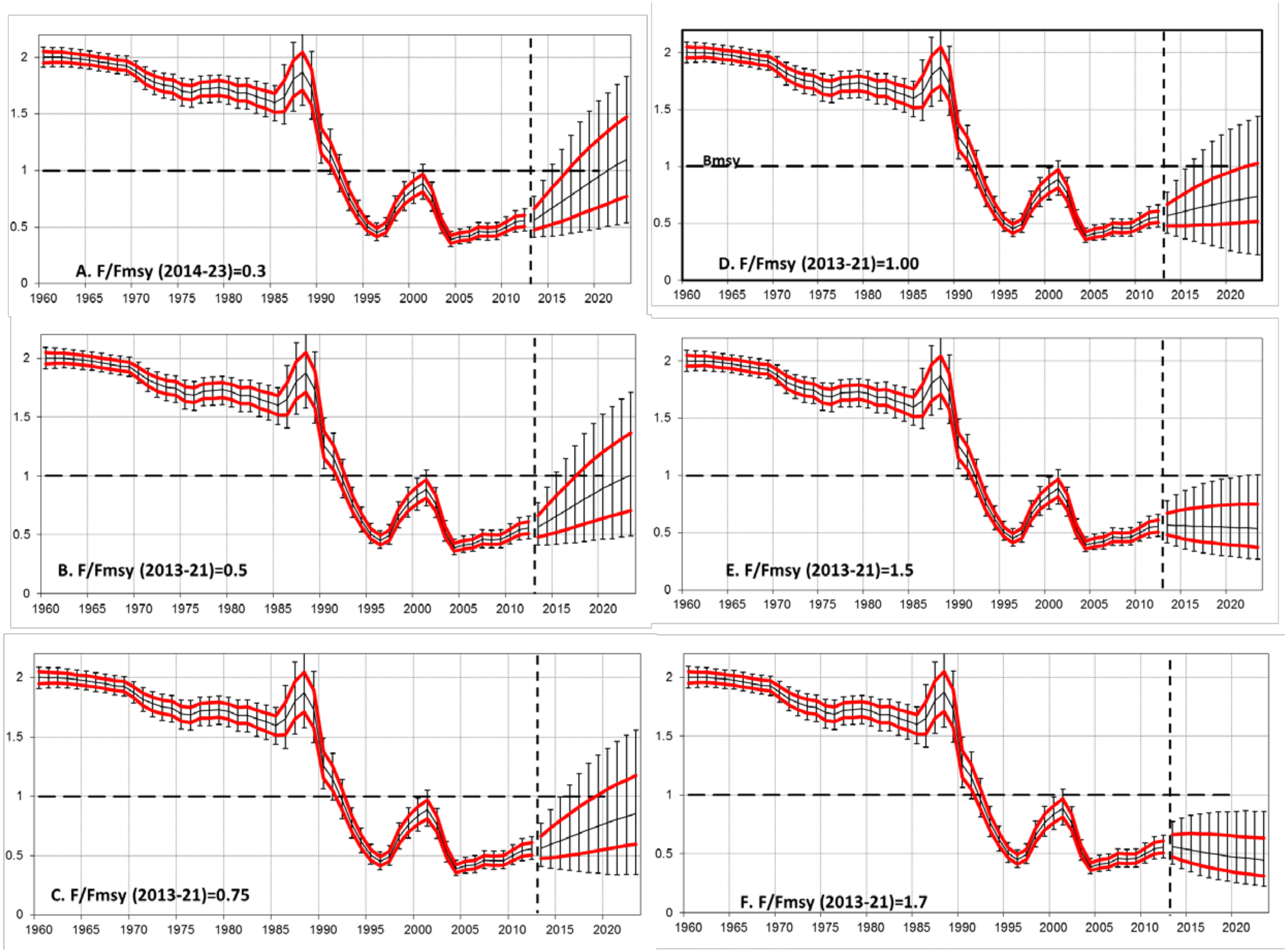


343

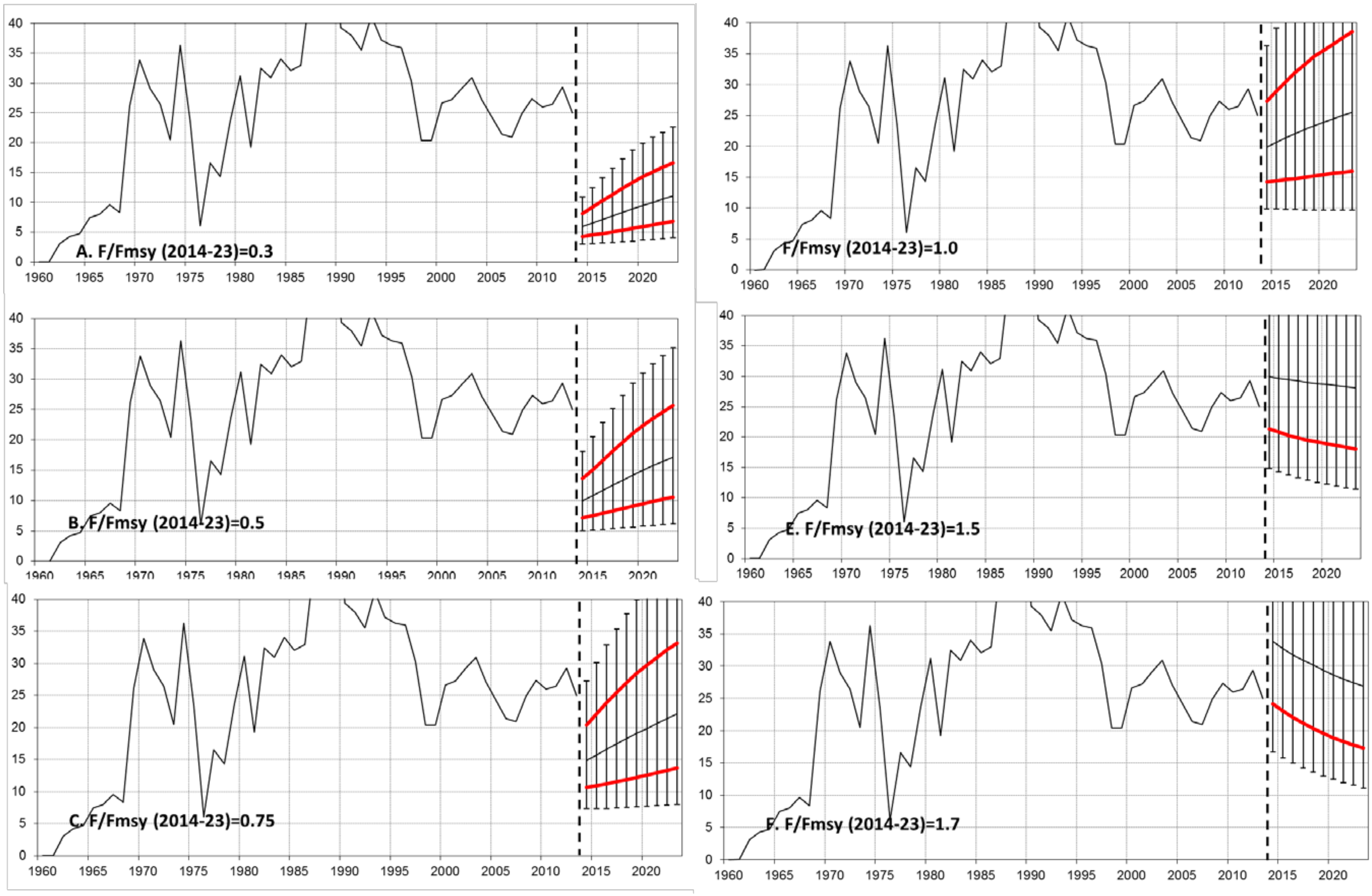
F at diff. catch options



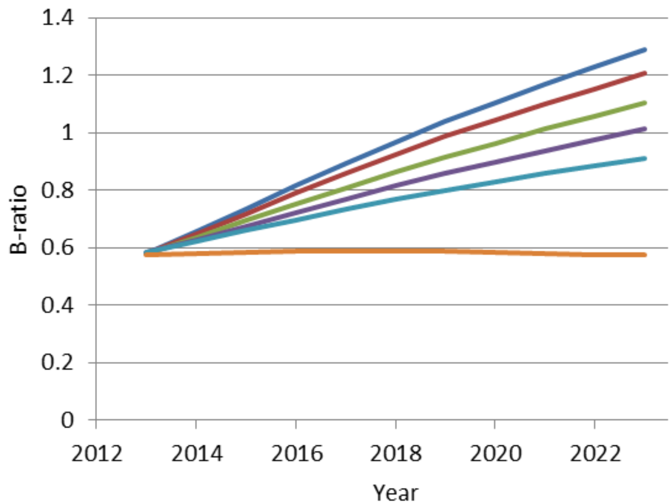
Biomass at diff. F options

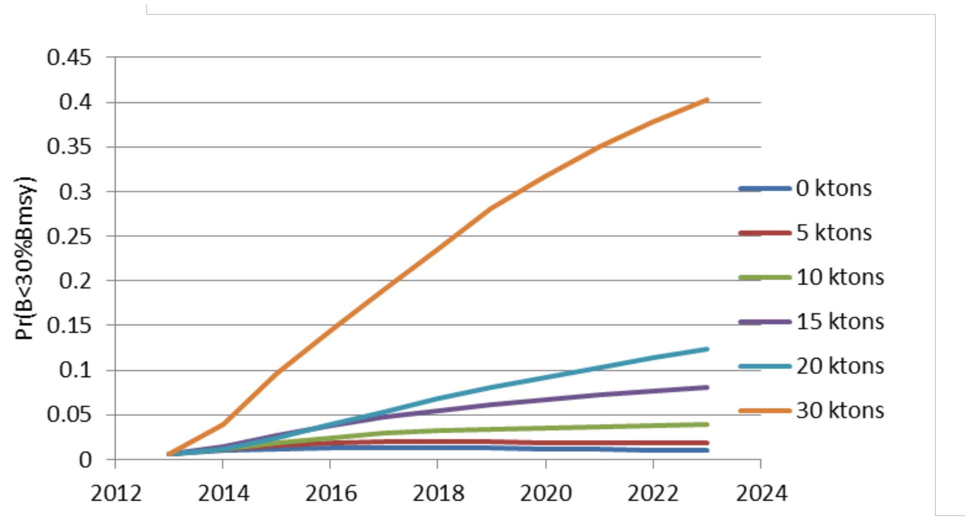


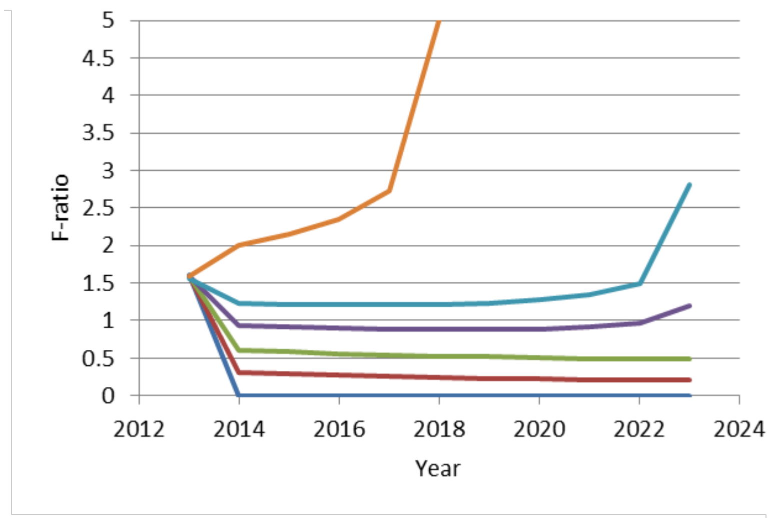
Yield 2014-2023 at diff. F options

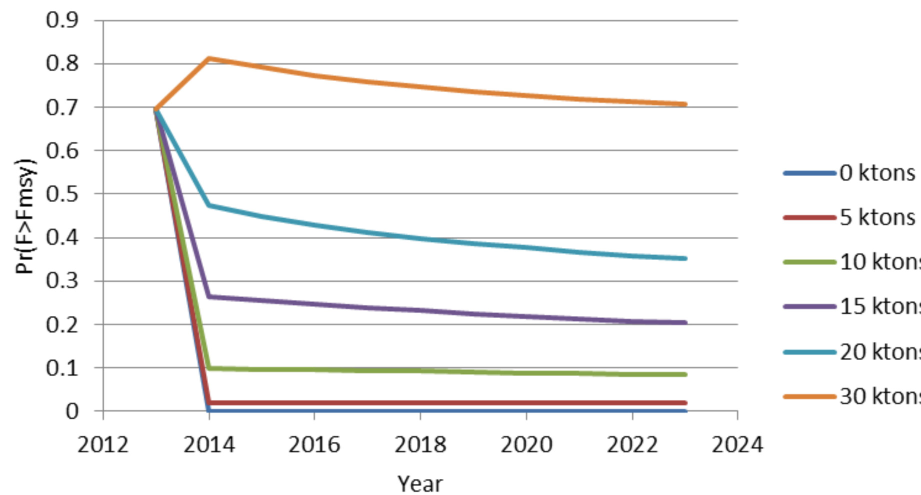


Projections



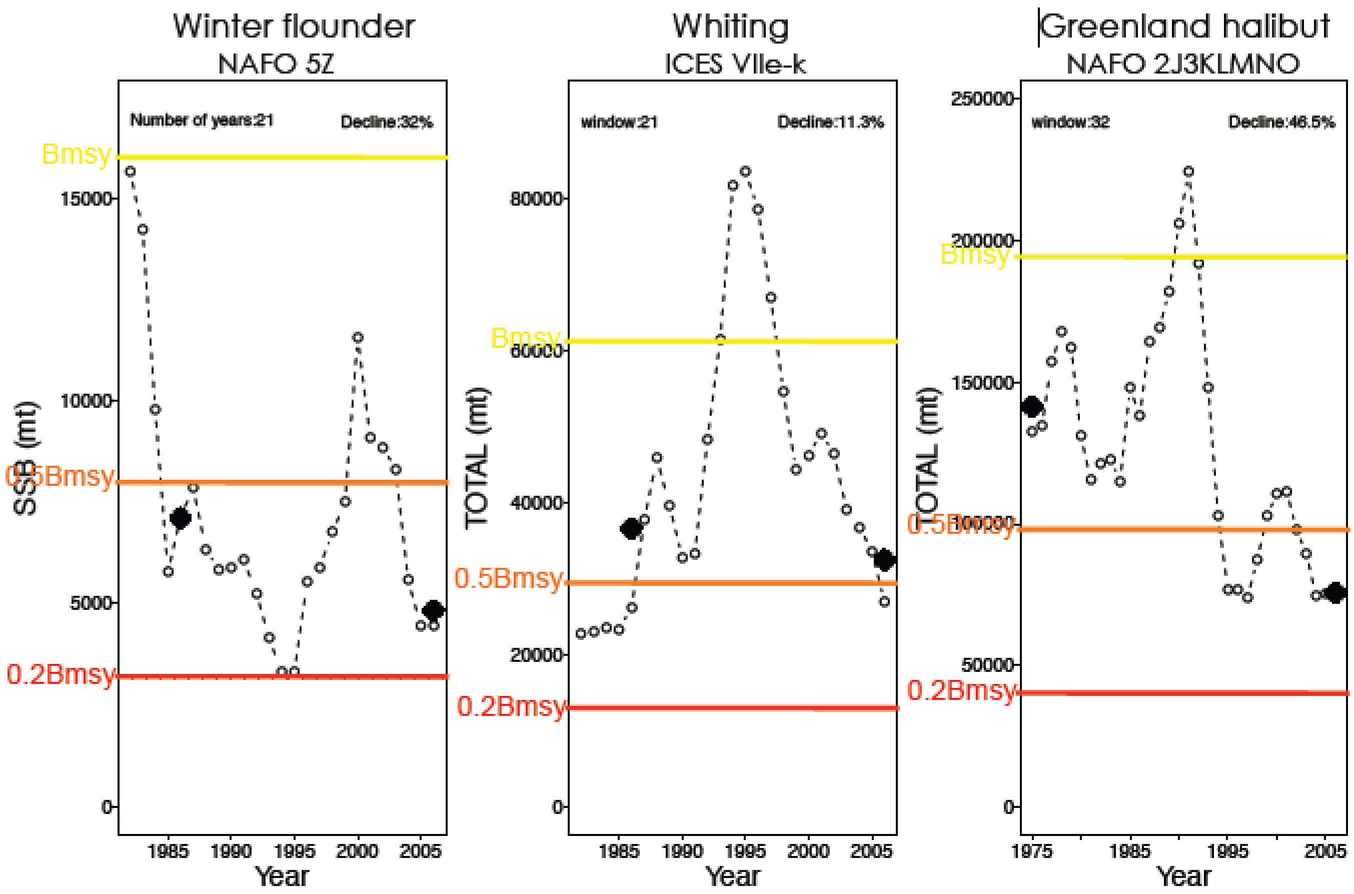






Conservation Perspective vs. Fisheries Perspectives on "Collapse"

Misses



A note on the growth based on tag-recapture experiments on Greenland Halibut (*Reinhardtius hippoglossoides*) in Subarea Va.

Bjarki Þór Elvarsson

Fisheries Advisory Section
Marine Research Institute, Reykjavík, Iceland
(bthe@hafro.is)

Do not cite without authors permission

November 28, 2013

1 Introduction

This document describes available data from tag-recapture experiments in the Va area. Analysis are conducted to estimate growth.

2 Methods

The dataset in this excercise consists of 983 recaptures of Greenland Halibut tagged in years between 1971 until 1978. Around 258 of the tagged individuals do not have sex assigned to them.

Growth was estimated using length based variant of the Von Bertanlanffy growth curve:

$$\Delta L_i = (L_\infty - L_i)(1 - \exp(-k\Delta t)) \tag{1}$$

where L_i is the size of fish i when tagged, ΔL_i is the difference between the tagged length and recaptured length, L_∞ is maximum size, k is the growth rate and Δt is the time that has elapsed between tagging and recapture.

A modification of the recaptured length is needed as greenland halibut has been observed to shrink over time. A scaling factor using same year recoveries is used here as the fish are expected to have grown substantially during that time. It was estimated using a linear model of tagged length regressed to recaptured length where the constant term is fixed to zero.

3 Results

The scaling factor was estimated to be 1.014 ($\sigma_\beta = 0.007214$). Changes in length by year can be seen in figure 1. The estimated values for k and L_∞ is shown in table 1. Contrasted to the growth assessments obtained from Norwegian age reading the parameter values are not significantly different.

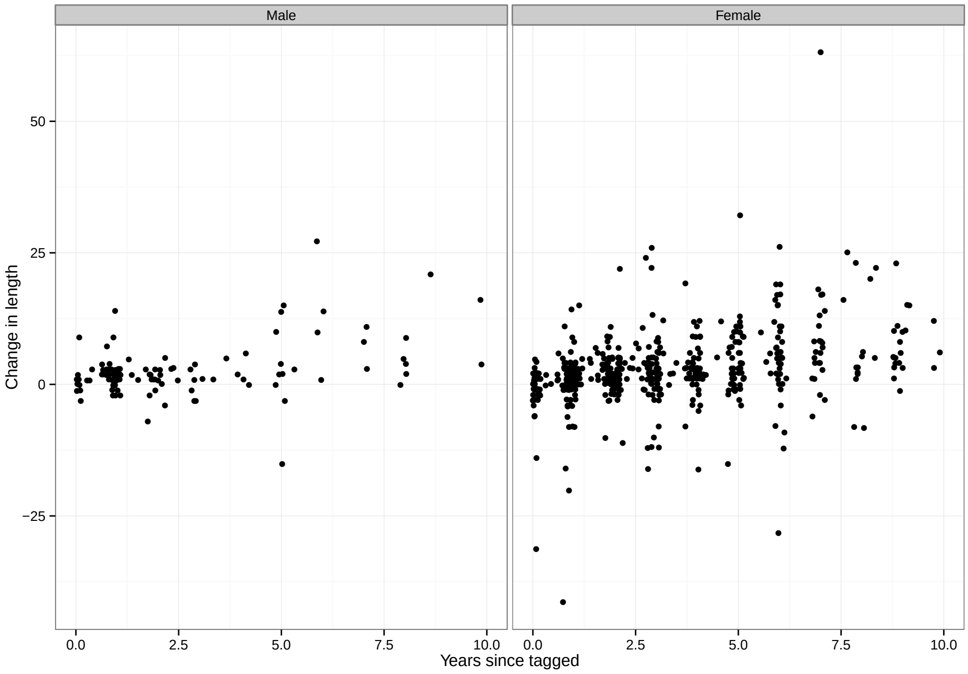


Figure 1: Change in length over time by sex.

	L_∞	Std. err	k	Std. err
Males	68.93610	1.30649	0.18432	0.03896
Females	79.88409	0.86059	0.12621	0.01108

Table 1: Point estimates of the length based von Bertalanffy equation (see equation 1) for males and females.

	L_∞	Std. err	k	Std. err	t_0	std.err
Males	66.0697	5.2249	0.1124	0.0356	-3.4802	1.6443
Females	77.03083	4.09396	0.10995	0.02563	1.81721	1.22634

Table 2: Point estimates of obtained from the Norwegian length and age data for males and females

3 Results

4 Discussion

This analysis supports the data available on growth from the Norwegian catches. However issues such as tag loss and/or fleet selectivity are not accounted for as data on tag loss is not currently available.

Biomass indices of Greenland halibut (*Reinhardtius hippoglossoides*) in Faroese waters

Petur Steingrund, Faroe Marine Research Institute

Abstract

Four biomass indices of Greenland halibut are presented: the bottom survey in (1) March and (2) August, (3) the research vessel Greenland halibut trip in May-June, and (4) the commercial trawler CPUEs. There was a strong correlation between 2, 3 and 4, but these series did not extend into the 1980s when the biomass of Greenland halibut was quite high at Iceland. However, the March survey started to 1983 and a regression with the commercial trawlers was performed, so that the latter series could be extended back to 1983. There was an overall agreement between the extended trawler CPUE series at the Faroes and the Icelandic trawler CPUE. Interestingly, the ratio between the Faroese/Icelandic CPUEs was correlated with the subpolar gyre index, indicating that either hydrographic factors or other factors (e.g. the amount of forage fish such as blue whiting) may shift the distribution of Greenland halibut in an east-west fashion. Probably, a biomass index might be developed, which is some weighted average of many indices for Greenland halibut in the east Greenland/Iceland/Faroe area.

Introduction

In the NWWG report, only the research vessel Greenland halibut trip (series 3) and the commercial trawlers (series 4) are used as biomass indices of Greenland halibut at the Faroes. Here, I introduce the results from the two bottom trawls also, the March survey (series 1) and the August survey (series 2). An attempt is made to combine two of the series (March survey and trawlers) to obtain an index extending back into the 1980s.

Materials and Methods

The biomass indices of the commercial trawlers and the research vessel Greenland halibut trip are obtained from Working Document 13 in this benchmark and described in NWWG 2013. The bottom trawl surveys (in March and August), conducted with the research vessel “Magnus Heinason” are described in the NWWG 2013 report. In short, the bottom trawl survey in March cover 100 fixed stations (1 hour duration) on the Faroe Plateau, whereas 200 fixed stations are occupied in August. The depth ranges from 65 to 520 metres.

Results

Series 2-4 were highly correlated, but there was a curvelinear relationship between the August survey and the Greenland halibut trip and the trawlers. The reason is likely that the bottom survey only covers the shallow part of the Greenland halibut distribution at the Faroes. These three series showed that the biomass was high in the mid 1990s and after 2007. The spring survey (series 1) caught few Greenland halibut in general since 1993, but much larger catch in the 1980s.

An attempt was made to extend the biomass series as much as possible. A weak correlation was obtained between the March survey and the trawlers for 1991-2001 (Figure 2), and this relationship was used to extend the trawler series back to 1983 (Figure 3). Overall, there was a close relationship between the extended Faroe trawler index and the Icelandic trawler index (Figure 4).

Although speculative, it can be seen that the Faroese index rises in the later part of the series, whereas the Icelandic series does not so to any great extent (and the index in east Greenland actually decreases, not shown here). Knowing the fact that temperatures have risen in the North Atlantic in recent years, as for example, expressed by the index of the subpolar gyre. Taking the ratio between the Faroese and the Icelandic index as a rough measure of and east-west shift in distribution and relating it to the subpolar gyre index (Figure 5) gives the impression that there might be some relationship.

Discussion

The correlation between the three of the four Faroese biomass indices indicates that all capture the overall stock development in Faroese waters. The extension of the trawler series seemed to capture the high stock size in the 1980s, which corresponded well with the Icelandic trawlers. It can be seen that the medium high values in the Icelandic index 1999-2002 were not observed in the Faroese series. Such an upward jump is not expected for a long-lived species like Greenland halibut, and may be related to other factors than the stock size of Greenland halibut.

One such factor may be the hydrography (temperature or the subpolar gyre index, see Hátún *et al.*, 2005) or related effects, such as the amount of forage fish, such as blue whiting (Hátún *et al.*, 2009). The east-west shift in Greenland halibut distribution, as expressed as the ratio between the Faroese and Icelandic biomass indices, indicates that the distribution shifts to the west when it is cold, and to the east when it is warm (Figure 5). The mechanism might be that during warm years (retracted subpolar gyre) the recruitment of blue whiting and subsequent biomass increases considerably (Hátún *et al.*, 2009), probably causing Greenland halibut to migrate to the eastern area of its distribution to feed on these fish. There is, of course, a need to investigate this issue in more detail, since there is a large uncertainty associated when taking the ratio between two already shaky series.

The take-home message is that there might not be any need to agonize too much about the disagreement between the biomass series of Greenland halibut in the east Greenland/Icelandic/Faroese area because it might simply reflect a shift in the distribution, but not necessarily that any of the series are wrong. Probably some weighted average of the available series could be used as a measure of the overall biomass of Greenland halibut in the east Greenland/Iceland/Faroese area.

Acknowledgements

Thanks to Hjálmar Hátún, Faroe Marine Research Institute, for allowing me to use the index of the subpolar gyre.

References

Hatun, H., Sando, A.B., Drange, H., Hansen, B., and Valdimarsson, H. 2005. Influence of the Atlantic subpolar gyre on the thermohaline circulation. Science (Washington, D.C.), 309: 1841–1844.
doi:10.1126/science.1114777. PMID:16166513.

Hátún, H., Payne, M.R., and Jacobsen, J.A. 2009. The North Atlantic subpolar gyre regulates the spawning distribution of blue whiting (*Micromesistius poutassou*). Can. J. Fish. Aquat. Sci. 66: 759–770 (2009).

Figures

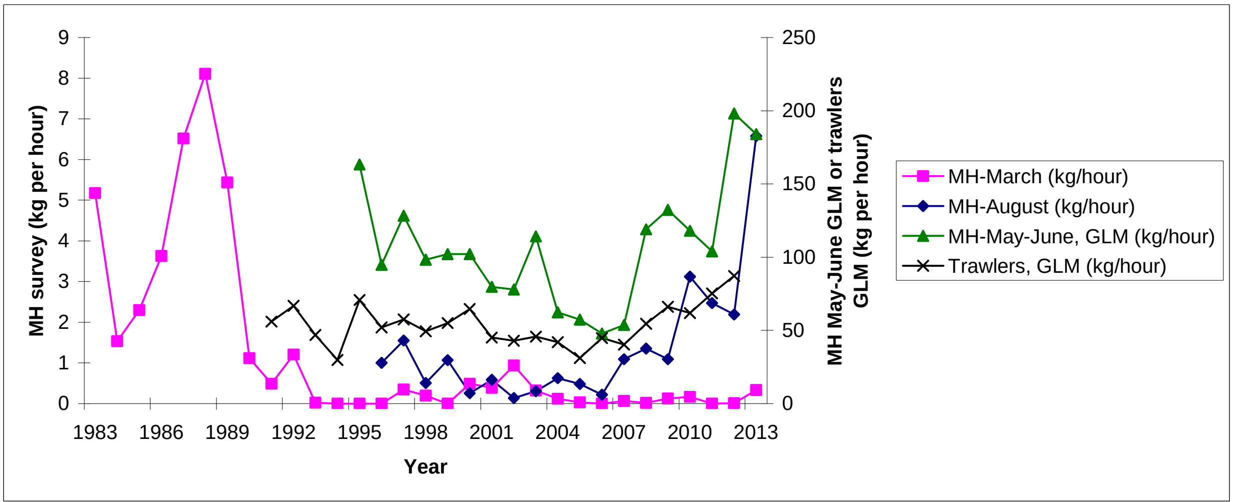


Figure 1. Greenland halibut at the Faroes. Biomass indices by the research vessel (Magnus Heinason – MH) and commercial single trawlers (series 4). The bottom surveys are performed in March (series 1) and August (series 2), whereas the research vessel performs a less standardized trip for Greenland halibut in May-June (series 3), which here is treated by a GLM.

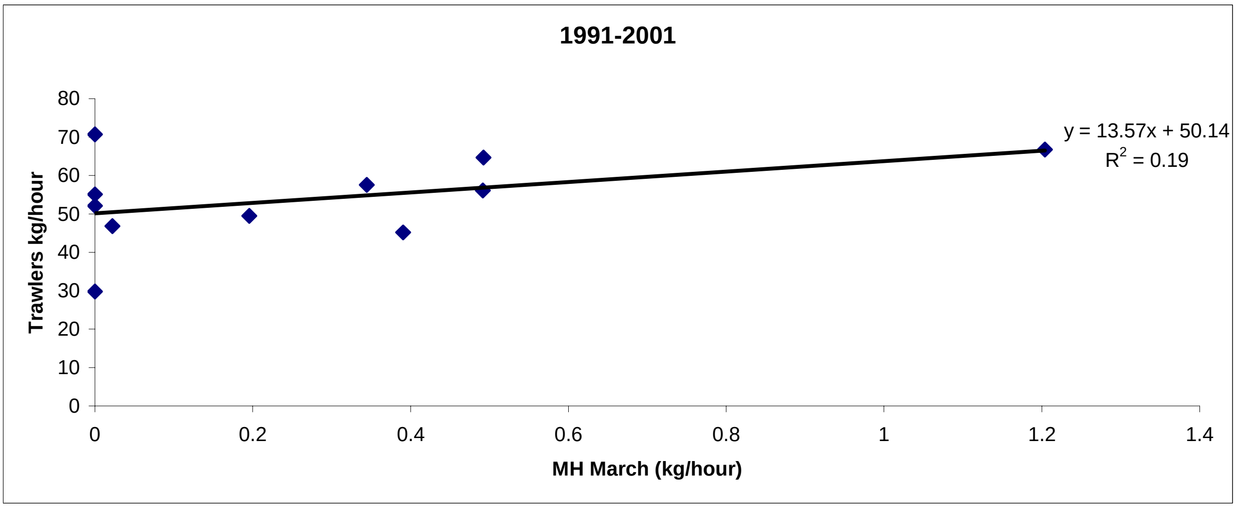


Figure 2. Greenland halibut at the Faroes. Regression between the March survey and the trawler survey.

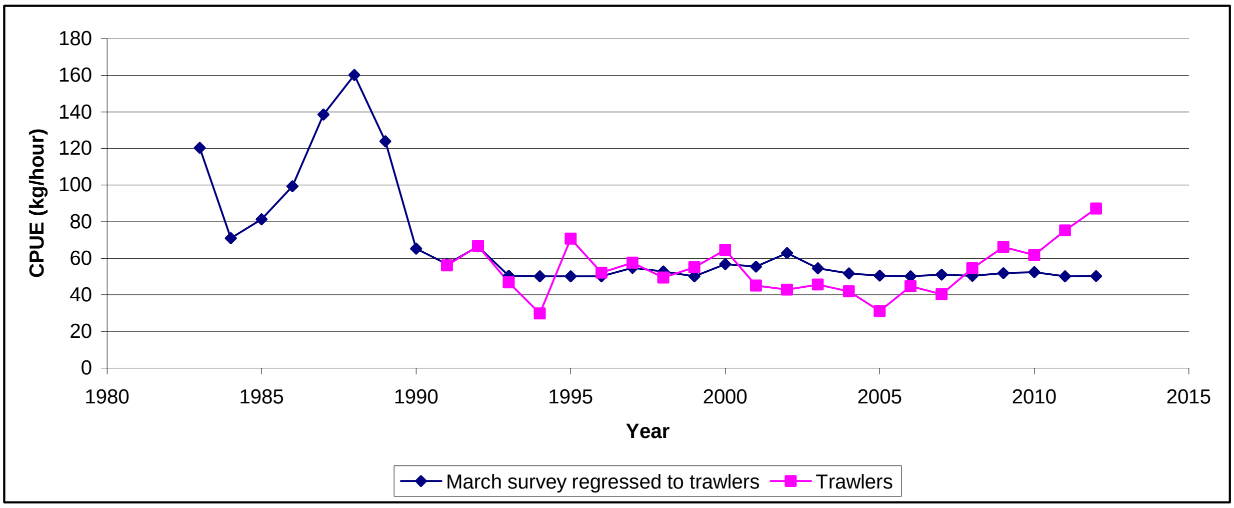


Figure 3. CPUE of Greenland halibut at the Faroes. March survey regressed to trawlers, compared with trawlers.

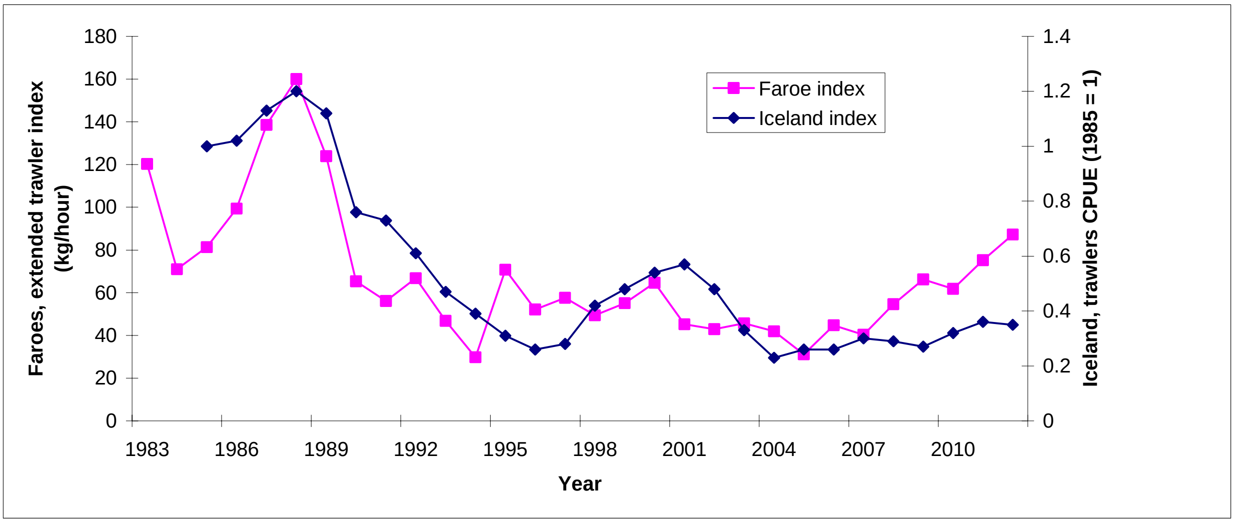
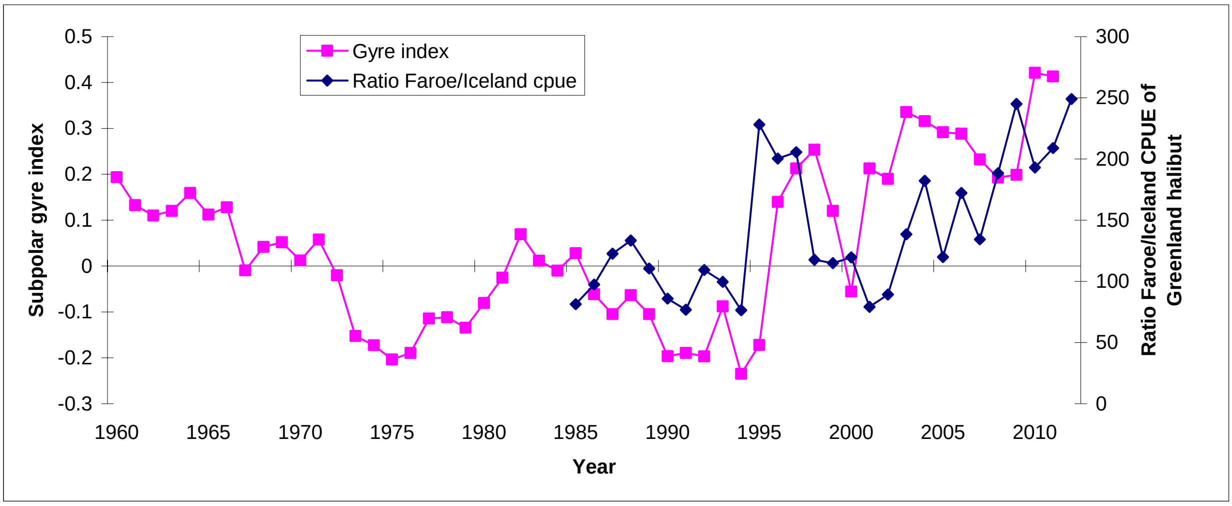


Figure 4. Greenland halibut: comparison of biomass indices for Faroes and Iceland.



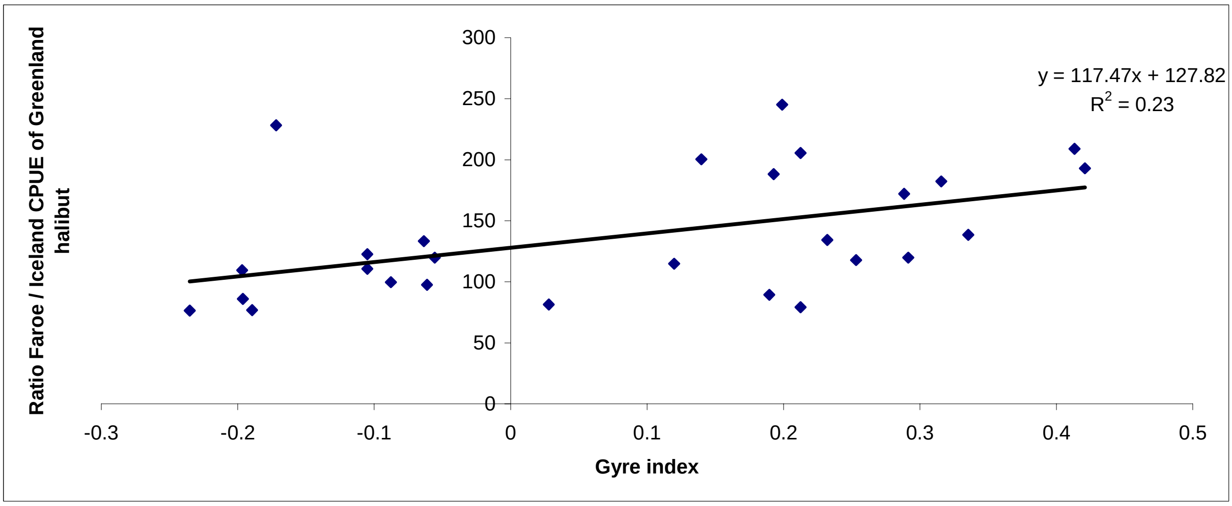


Figure 5. Comparison between the subpolar gyre index and the ratio between the Faroese and Icelandic CPUE series of Greenland halibut.

A note on the Greenland halibut (*Reinhardtius hippoglossoides*) CPUE estimates from Va

Gudmundur Thordarson

Fisheries Advisory Section
Marine Research Institute, Reykjavík, Iceland
(gudthor@hafro.is)

Do not cite without authors permission

November 28, 2013

Abstract

1 Introduction

The CPUE series from Va for Greenland halibut has in the past been used as part of the assessment of the stock and is currently the timeseries that is driving the Baysian stock production model. In this document the accurancy of this series is questioned.

2 The data used

The data used for the model comes from the Icelandic trawler fleet. The following filtration is done on the data.

Catch: Catch of Greenland halibut must be more than 100 kg

Proportion: Catch of Greenland halibut must be more then 50% of the total catch in the haul.

Area: The hauls used have to com from the statistical rectangles presented in figure 1

No hauls: To be included in the data a ship must have at least 20 valid Greenland halibut hauls.

No other screening of the data has been done before calculating the CPUE. Finally as the data-set is huge it is summarised over, years, months, rectangles and ships.

```
head(tmp.data)
      shipnr rectangle month year catch  towtime    lcatch  ltowtime
36774   1278       362     1 1985  1.70  2.50000 0.5306871 0.9162907
36565   1265       461     1 1985  8.00 13.83333 2.0794540 2.6270811
36724   1278       461     1 1985 13.30 18.25000 2.5877716 2.9041651
35705   1346       461     1 1985 13.92 17.91667 2.6333338 2.8857314
51927   1351       461     1 1985  6.30 18.00000 1.8405655 2.8903718
52284   1449       461     1 1985  7.15 20.75000 1.9671263 3.0325462
```

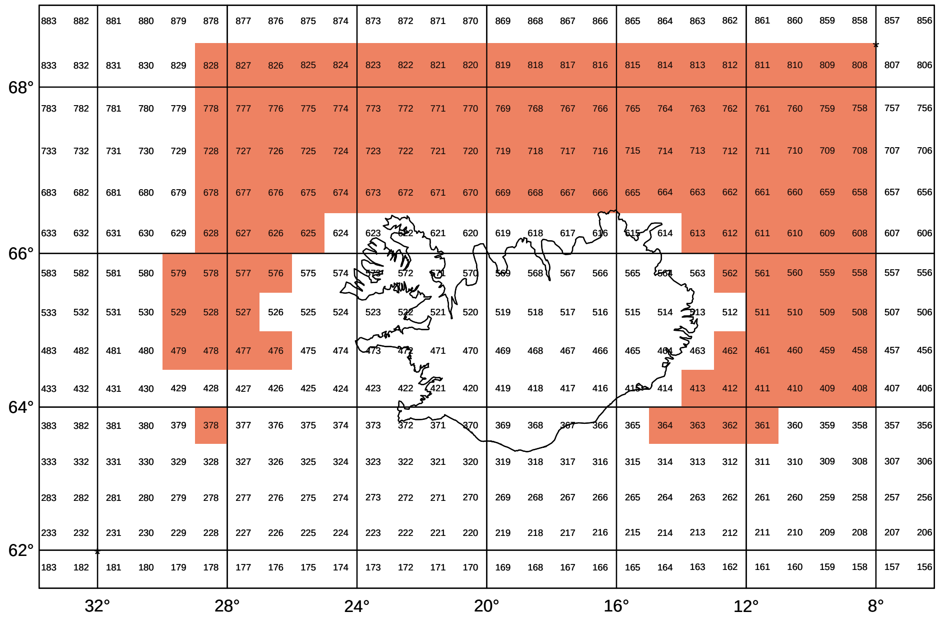


Figure 1: Rectangles used for calculation of Greenland halibut CPUE in Va

3 The model

The model used is a glm assuming a gaussian error structure, that is a normal linear model. The catch and the towtime are log transformed.

```
fit<-glm(lcatch ~ ltowtime+factor(year)+factor(month)+factor(shipnr)+
         factor(rectangle),
         data=tmp.data, family=gaussian())
```

The extraction of the CPUE is shown below. In short it is extracting the year factor from the model and the exponent of the year factor is taken as the CPUE value.

```
sum.fit <- summary(fit)
my.coefficients <- sum.fit$coefficients
tmp1 <-
my.coefficients[substring(unlist(dimnames(my.coefficients)[1]),1,12)
=='factor(year)',]

tmp1 <- as.data.frame(tmp1)
names(tmp1) <- c("log","stdError","tValue","p")
tmp1$year <- as.numeric(substring(unlist(dimnames(tmp1)[1]),13,17))
tmp1$Low <- exp(tmp1$log-tmp1$stdError*1.96)
```

```
tmp1$Mean <- exp(tmp1$log)
tmp1$High <- exp(tmp1$log+tmp1$stdError*1.96)
glim <- tmp1[,c("year","Low","Mean","High")]
rownames(glim) <- 1:nrow(glim)
```

The CPUE series generated is shown in figure 2.

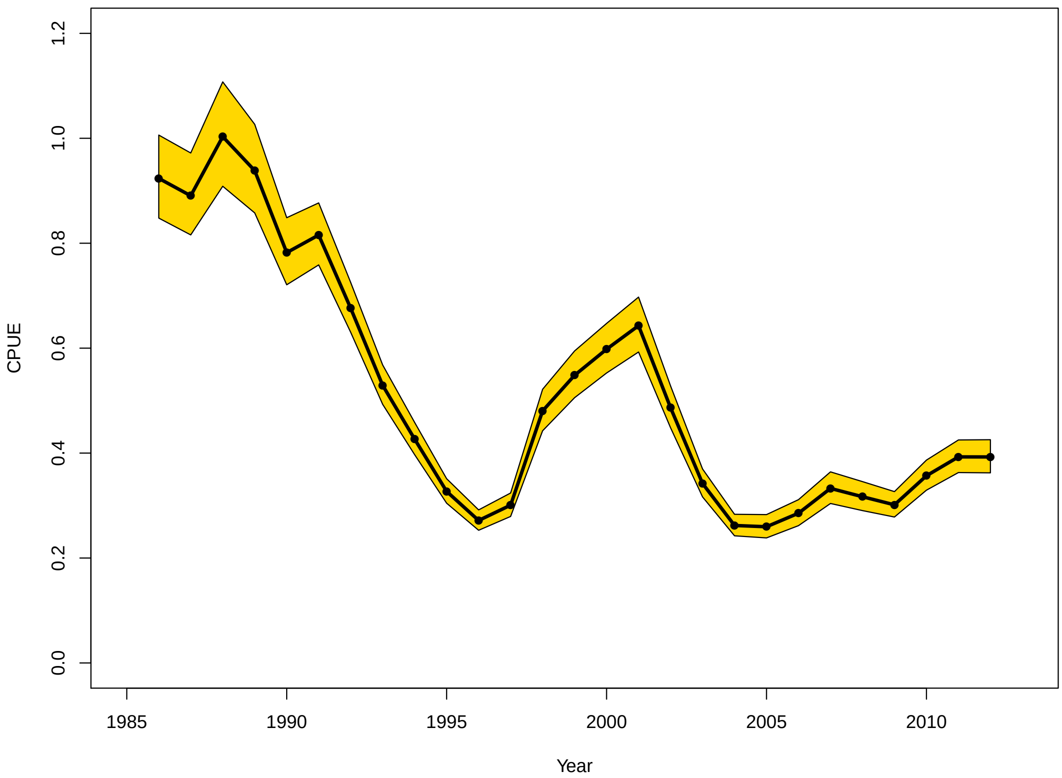


Figure 2: Current estimates of Greenland halibut CPUE in Va

4 Looking closer at the input data

In figure 3 it can be seen that in the periond between 1985 to 2001 there are distinctive seasonal peaks in catch rates. When using only the data from April to June and a loess-smother is fitted to the catch rates a very simiar trend is observed in figure 3 as from the year factor in the glm-model presented in figure 2. However if all the data is used a very different trend appears (blue line in figure 3).

The reason for these seasonal spikes according to Dr. Einar Hjörleifsson is what fisherman claimed to be fishing on spawning aggregations in the spring at fishing grounds known in Iceland as 'Hampiðjutorgið'. The trawlers would search for the edge of the Greenland current where the Greenland halibut would aggregate, then the trawlers would cue in line and then go over the spot one after another. Similar phenomen as seen in the Redfish fishery in the Irminger Sea. Catch rates were very high.

Because of the above it is interesting to look closer at the interaction between the rectangles and years in the model. If an interaction term of years and rectangle is included in the model, the interaction is significant. The AIC score for the original model is 34988.23 but for the model with the interaction the score is 33502.59. That is a difference in AIC-score of 1486.

```
> anova(fit2, test='F')
Analysis of Deviance Table

Model: gaussian, link: identity

Response: lcatch

Terms added sequentially (first to last)


                            Df Deviance Resid. Df Resid. Dev          F
NULL                                        20008      49641
ltowtime                     1    38005     20007      11636 1.2483e+05
factor(year)                27     2662     19980       8974 3.2388e+02
factor(month)               11      427     19969       8547 1.2749e+02
factor(shipnr)             112     1373     19857       7174 4.0263e+01
factor(rectangle)           72      591     19785       6583 2.6967e+01
factor(year):factor(month) 296      649     19489       5933 7.2042e+00
                              Pr(>F)
NULL
ltowtime                   < 2.2e-16 ***
factor(year)               < 2.2e-16 ***
factor(month)              < 2.2e-16 ***
factor(shipnr)             < 2.2e-16 ***
factor(rectangle)          < 2.2e-16 ***
factor(year):factor(month) < 2.2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

4 Looking closer at the input data

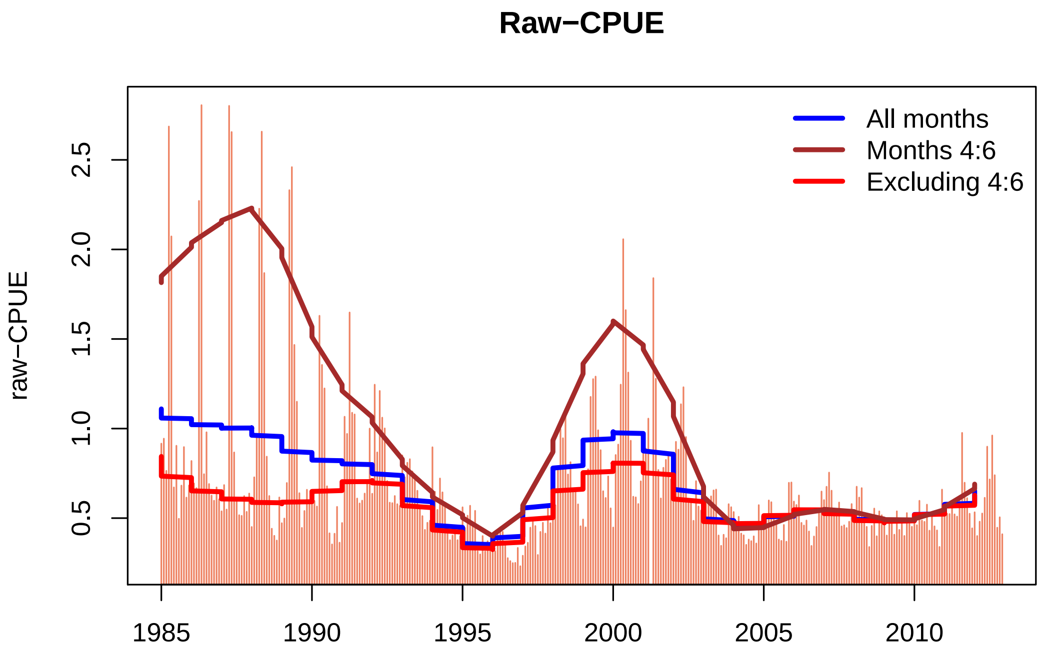


Figure 3: Average catch per haul in Va of Greenland halibut by month in 1985 to 2012 (bars), the lines are a loess smoother added on various subset of the data (See text for details).

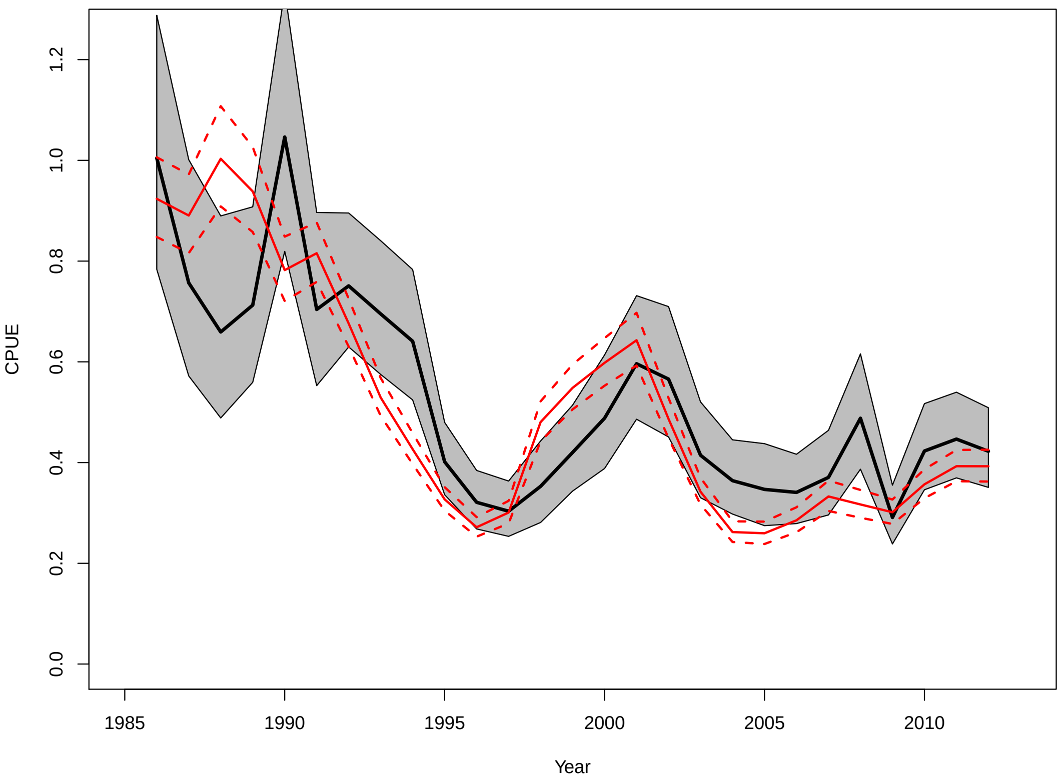


Figure 4: Estimates of Greenland halibut CPUE in Va when an interaction term of year and rectangles is included in the model (black lines and grey area), for comparison the original CPUE estimate is plotted in red.

4 Looking closer at the input data

5 Filtering out the 'Hampiðjutorgið'

In figure 5 the 'Hampiðjutorgið' is excluded and and only data from the blue rectangles is used for calculation of CPUE. The resulting 'raw' CPUE by month is shown as blue points in Figure 6. It can be seen that the rapid decrease in the 'raw' cpue dissapears from the beginnig of the time series.

The same glm model was then fitted to the trimmed data. Even though the Hampiðjutorgið has been removed from the data the interaction term between year and rectangle is significant.

```
> anova(fit.tr1, test='F')
Analysis of Deviance Table

Model: gaussian, link: identity

Response: lcatch

Terms added sequentially (first to last)


                            Df Deviance Resid. Df Resid. Dev          F
NULL                                         7760     9821.5
ltowtime                     1   4849.5      7759     4972.0 11106.2865
factor(year)                27    849.7      7732     4122.2    72.0770
factor(month)               11     59.6      7721     4062.6    12.4154
factor(shipnr)              87    305.3      7634     3757.3     8.0367
factor(rectangle)           62    281.4      7572     3475.9    10.3943
factor(year):factor(month) 294    298.0      7278     3177.9     2.3211
                              Pr(>F)
NULL
ltowtime                   < 2.2e-16 ***
factor(year)               < 2.2e-16 ***
factor(month)              < 2.2e-16 ***
factor(shipnr)             < 2.2e-16 ***
factor(rectangle)          < 2.2e-16 ***
factor(year):factor(month) < 2.2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

In terms of AIC scores the non interaction model had a AIC score of 18861.75 but when an interaction term was included the AIC score was 19172.83. So the later model has a lower AIC-score by 311. The resulting CPUE are shown in figure 7.

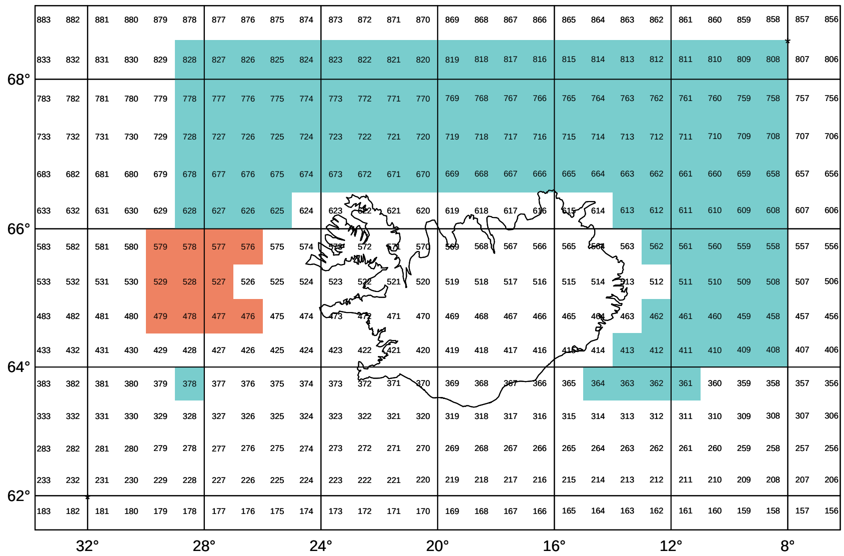


Figure 5: Rectangles used for calculation of Greenland halibut CPUE in Va

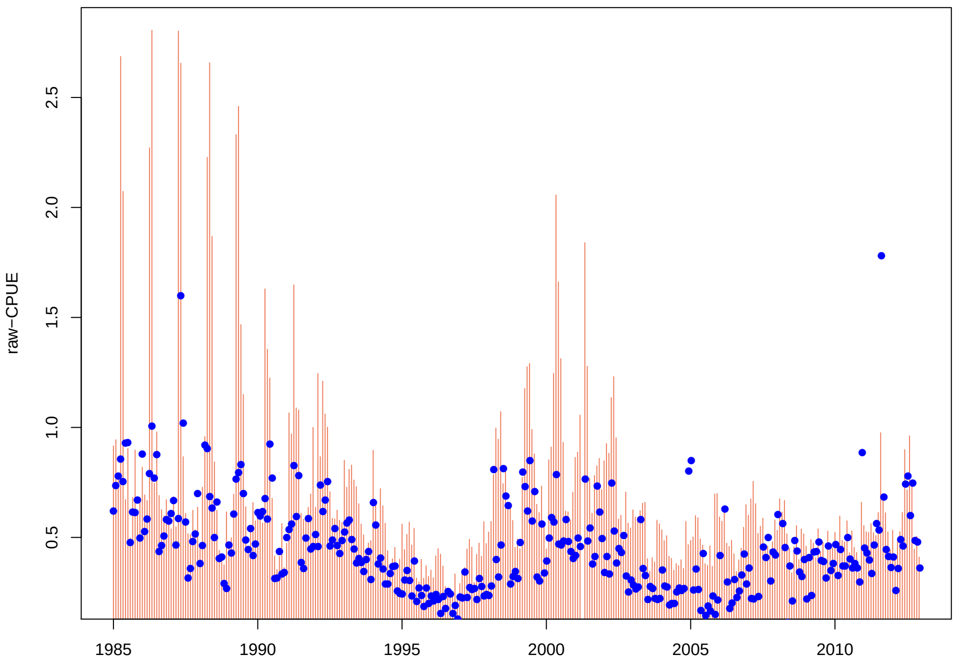


Figure 6: Average catch per haul in Va of Greenland halibut by month in 1985 to 2012 (bars), and blue points are when hauls from Hampiðjutorgið are excluded.

5 Filtering out the 'Hampiðjutorgið'

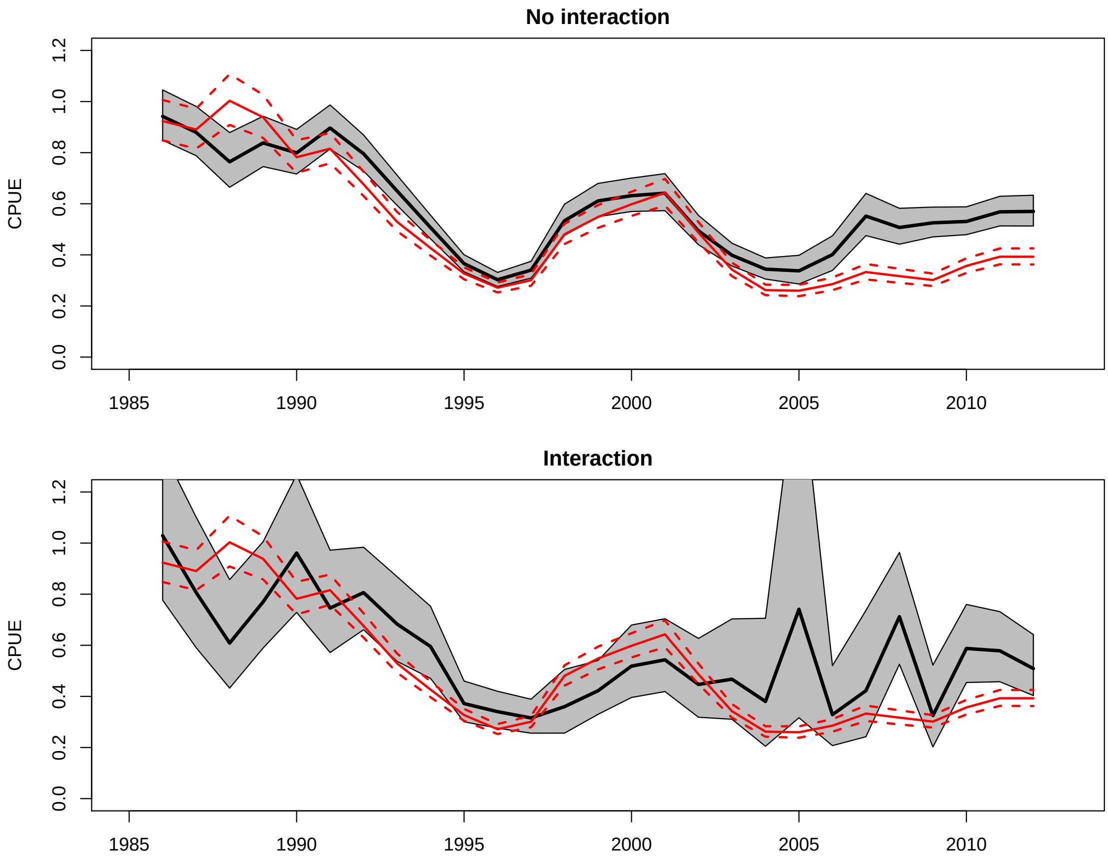


Figure 7: Estimates of Greenland halibut CPUE in Va when excluding hauls from the Hampiðjutorgið with or with out an interaction term of year and rectangles is included in the model (black lines and grey area), for comparison the original CPUE estimate is plotted in red.

5 Filtering out the 'Hampiðjutorgið'