WORKSHOP ON THE EVALUATION OF ASSESSMENTS AND MANAGEMENT PLANS FOR LING, TUSK, PLAICE AND ATLANTIC WOLFFISH IN ICELANDIC WATERS (WKICEMP)

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Contents

i Executive summary

The Workshop on evaluation of the adopted harvest control rules for ling, tusk, plaice and Atlantic wolffish in Icelandic waters (WKICEMP) was tasked with providing the technical basis needed by ICES to respond to the request from Iceland on evaluation of a set of proposed harvest control rules for ling, tusk, plaice and Atlantic wolffish. The workshop addressed all its terms of reference, with the following main outcomes:

For the four stocks a review of the stock structure and identity was carried out. Based on genetic studies, tagging data and other evidence it was concluded that the interchange of the four stocks with other stocks of the same species was low enough to be treated as isolated populations. Life-history data, fishery-dependent and fishery-independent data was analysed to identify the best available data to feed into the stock assessment model. Ecosystem drivers and multi-species and mixed fisheries interactions were also considered but were not included directly in the assessment framework.

For the four stocks the data and settings to fit a SAM assessment model were agreed. For ling and tusk the general trends obtained with the new model were similar to the trends obtained with the previously used model but the model performance was better. Plaice and Atlantic wolffish were not previously assessed by ICES.

Precautionary Approach and MSY reference points were calculated. The harvest control rules proposed were based on ICES MSY advice rule. For the four stocks the proposed fishing mortality corresponded to a yield at or very close to the maximum sustainable yield, while resulting in less than 5% probability of SSB being below B_{lim}. The rule with the proposed reference points can, therefore, be considered to be precautionary and in conformity with the MSY approach.

ii Expert group information

Expert group name	Workshop on the evaluation of assessments and management plans for ling, tusk, plaice and Atlantic wolffish in Icelandic waters (WKICEMP)
Expert group cycle	Annual
Year cycle started	2022
Reporting year in cycle	1/1
Chair	Dorleta Garcia, Spain
Invited experts	Elisabeth Van Beveren, Canada
	Olav Nikolai Breivik, Norway
	Alexander Kempf, Germany (preliminary meeting)
	Jonathan White, Ireland (preliminary meeting)
Meeting venue and dates	4–8 April 2022, virtual meeting, 9 participants

1 Introduction

The Workshop on the evaluation of assessments and management plans for ling, tusk, plaice and Atlantic wolffish in Icelandic waters (WKICEMP), was convened to prepare the technical basis needed by ICES to respond to the request from Iceland on evaluation of a set of proposed harvest control rules for those stocks. The request, listed in Annex 1 of this report, also included a review of input data and assessment methodology for ling and tusk, plaice and Atlantic wolffish. The workshop was given the following Terms of Reference:

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 (where applicable):
   i. Stock identity and migration issues;
   ii. Life-history data;
   iii. Fishery-dependent and fishery-independent data;
   iv. Further inclusion of environmental drivers, multi-species 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 about environmental drivers, including multispecies interactions, and ecosystem impacts should be integrated in the methodology;

c) Re-examine and update (if necessary) MSY and PA reference points according to ICES guidelines (see Technical document on reference points);

d) Evaluate the proposed Harvest Control Rule(s) for the management plans for the stocks and develop conclusions on whether the proposed HCR(s) can be considered as consistent with the precautionary approach and in conformity with the ICES MSY framework and can therefore be used as the basis for ICES fishing opportunity advice for the stock.

The proposed HCR is based on the ICES advice rule (ICES, 2021a) which applies a target fishing mortality (F) at or below F_{MGT}. The target F is decreased linearly to zero according to the ratio of SSB to MGT $B_{trigger}$ when SSB is lower than MGT $B_{trigger}$. F_{MGT} should be defined in such a way that the SSB when fishing at F_{MGT} has a probability lower than 5% of being below MGT $B_{trigger}$. MGT $B_{trigger}$ should not be lower than MSY $B_{trigger}$ and F_{MGT} no higher than F_{msy}.

In April, ICES received additional correspondence from Iceland, specifying the particular form of the harvest control rules that should be evaluated for each stock. See Annex 1 of this report for details of the request.

The workshop was successful in addressing all its Terms of Reference.

This report is organised as follows:

Section 2 covers the work and conclusions on tusk, including data revision, stock assessment, reference points and harvest control rule evaluation. Section 3, section 4 and section 5 follows the same structure for ling, plaice and Atlantic wolffish. Section 6 covers the reviewers' report for the four stocks. The annexes at the end of the report include a list of participants (Annex 1), the request letter from Iceland to ICES (Annex 2), the WKICEMP resolution (Annex 3), and the working documents submitted to the workshop (Annex 4).

2 Tusk in 5.a and 14

Tusk in 5.a and 14 is being re-assessed here as the previously benchmarked Gadget model has begun to show greater instability in retrospective patterns in recent years (see WD03). The new assessment model is SAM (Nielsen and Berg (2014), Albertsen and Trijoulet (2020)), a statistical state-space catch at age model. This implementation of the models is based on commercial catch at age and landings data from 1979 onwards, the Icelandic spring groundfish survey that started in 1985, data from the autumn groundfish survey in Iceland from 2000, and data from a gillnet survey conducted in spring. The maximum age of the model is 10, which is considered a plus group. The assessment model estimates showed that spawning stock biomass has been relatively constant over the entire portion of the time series supported by the most reliable data (since 2019), but that the most recent years have shown a minimum (2019). This minimum appears to be the result of extremely low recruitment estimates during 2011–2012 (age 1). However, recruitment levels have since recovered to a relatively high level. Fishing mortality levels were relatively high from roughly 1995–2015, but have shown a relatively steep decrease after this period.

During the workshop, and in the exchanges between the Icelandic scientists and the reviewers leading to it, most of the discussion surrounded model convergence, the best model configuration for this stock and which recruitment estimates to consider as likely to occur in the future. Tusk otolith reading is especially difficult at higher ages, and data differed in quality through time. To aid in model convergence, it was decided not to extend the age structure older than 10, and to use total catch data instead of catch-at-age data in the initial historical period. For the observation model, it was decided to split the residual variance for survey and catch at age for some of the youngest and oldest age groups. Afterwards, those variance parameters that had similar estimates were grouped. It was further decided that survey residuals would be treated as auto-correlated with age within only the autumn survey, as their inclusion in the spring survey prevented model convergence in some cases and in others did not visually improve residual patterns to a large degree. Auto-correlated residuals were, however, not applied to the commercial catch series as it was considered inappropriate as sampling from commercial catches should be independent by design.

The proposed assessment model developed for the workshop assumed a value for natural mortality, M, of 0.15. A wide range of estimates for natural mortality were tested and none showed a significant improvement in terms of model fit. It was therefore decided to use an M of 0.15.

It was decided at the meeting to use the whole time series when estimating a stock-recruitment relationship to use in projections. As estimated spawning stock biomass has not varied to a great degree and the lowest levels correspond with some of the highest recruitment estimates, it was decided that the minimum spawning stock biomass more likely reflects B_{pa} rather than B_{lim}. The absolute minimum was not used because it was observed in a recent year and uncertainty is higher in those estimates.

Reference points were calculated for the stock. This resulted in B_{pa} of 4800 t, based on the lowest estimate of SSB observed (2016), and $B_{lim} = B_{pa}e^{-1.645\sigma_B}$ of 3400 t, with σ_B being set to the ICES default of 0.2. The fishing pressure reference points, defined in terms of fishing mortality applied to ages from 7 to 10, were estimated in accordance with the ICES guidelines (ICES, 2021b). This resulted in an estimate of F_{lim} of 0.44, F_{PA} of 0.23 and F_{msy} of 0.23. The MSY $B_{trigger}$ was set as B_{pa}.

A Management Strategy Evaluation (MSE) was conducted for Tusk in 5.a. The operating model, which generates the "true" future populations in the simulations, was based on equilibrium simulations (eqsim). Selection, maturity and stock weights were based on the resampling of estimates by age from previous 10 years. Recruitment was projected using a mean value equal to the mean of estimated recruits in the whole time series and a multiplicative log-normal error based on the CV and autocorrelations estimated by the assessment model. The recruitment had a break point in B_{lim} from which it decreased linearly to zero. Advice error in the simulations was implemented as auto-correlated log-normal variations in F, with a CV of 0.212 and ρ of 0.423.

The proposed HCR for the Icelandic Tusk fishery, which sets a TAC for the fishing year y/y+1 (1 September of year y to 31 August of year y+1) based on a fishing mortality F_{mgt} of 0.23 applied to ages 7 to 10 modified by the ratio SSB_y /MGT $B_{trigger}$ when SSB_y < MGT $B_{trigger}$, maintains a high yield while being precautionary as it results in lower than 5% probability of SSB < B_{lim} in the medium and long term.

3 Plaice in 5.a

As plaice in 5.a is new to ICES, an assessment method for plaice was established during this benchmark (see WD01). Plaice became part of the ICES assessment process after an MoU between Iceland and ICES was signed on 1 December 2019. The new assessment model is SAM (Nielsen and Berg (2014), Albertsen and Trijoulet (2020)), a statistical state-space catch at age model based on commercial catch at age from 1980 onwards and the Icelandic spring groundfish survey that started in 1985. The maximum age of the model is 12, which is considered a plus group. The assessment showed that the number of recruits to the stock reduced substantially after 1990.

During the workshop, and in the exchanges between the Icelandic scientists and the reviewers of the workshop, the discussion fell mainly into three categories: treatment of observation residuals, natural morality and the reasons for the shift in the number of recruits observed after 1990. For the observation model, it was decided that the residual variance for the survey and catch at age should be split by age. Those variance parameters that had similar estimates were then grouped. It was further decided that survey residuals would be treated as auto-correlated with age. This was, however, not applied to the commercial catch series as it was considered inappropriate because sampling from commercial catches should be independent by design.

The proposed assessment model developed for the workshop assumed a value for natural mortality, M, of 0.15. A wide range of estimates for natural mortality obtained from literature were tested and none showed a significant improvement in terms of model fit. It was therefore decided to use an M of 0.15.

The assessment model detected a shift in recruitment level occurred in 1990 (1993 at age 3). After this shift the estimated recruitment remained nearly constant at a low level. The exact reason for this level shift is unknown. This is not the only species in Icelandic waters for which a change in recruitment has been observed in recent years and it has been related to higher temperatures. One potential explanation could be increased mortality and poorer condition of a part of the stock due high rates of ichtyophonus infections observed in the Faxaflói bay area from 1995. No information is however available on the prevalence of this infection prior to 1995 and in other areas.

Reference points were calculated for the stock. This resulted in B_{lim} of 10 100 t, based on the lowest estimate of SSB where high recruitment had been observed, and $B_{pa} = B_{lim}e^{1.645\sigma_B}$ of 12 400 t. The fishing pressure estimates, defined in terms of fishing mortality applied to ages between 5 and 10, were estimated in accordance to the ICES guidelines (ICES, 2021b). This resulted in an estimate of F_{lim} of 0.57, F_{PA} of 0.46 and F_{msy} of 0.41. The MSY $B_{trigger}$ was set as B_{pa}.

A Management Strategy Evaluation (MSE) was conducted for plaice in 5.a. The operating model, which generates the "true" future populations in the simulations, was based on equilibrium simulations (eqsim). Selection, maturity and stock weights were based on the resampling of estimates by age from previous 10 years. Recruitment was projected using a mean value equal to the mean of estimated recruitment values since 1990 and multiplicative a log-normal error based on the CV and autocorrelations estimated by the assessment model. The recruitment had a break point in B_{lim}, from which it decreased linearly to 0. Advice error in the simulations was implemented as auto-correlated log-normal variations in F, with a CV of 0.212 and ρ of 0.412.

The proposed HCR for the Icelandic plaice fishery, which sets a TAC for the fishing year y/y+1 (1 September of year y to 31 August of year y+1) based on a fishing mortality of 0.3 applied to ages 5 to 10 modified by the ratio SSB/MGT $B_{trigger}$ when SSB < MGT $B_{trigger}$, is considered to be precautionary as it results in lower than 5% probability of SSB < B_{lim} in the medium and long term.

4 Atlantic Wolffish in 5.a

As Atlantic wolffish in 5.a is new to ICES, an assessment method for Atlantic wolffish was established during this benchmark (see WD02). Atlantic wolffish became part of the ICES assessment process after an MoU between Iceland and ICES was signed on 1 December 2019. The new assessment model is SAM (Nielsen and Berg (2014), Albertsen and Trijoulet (2020)), a statistical state-space catch at age model based on commercial catch at age and landings data from 1979 onwards, the Icelandic spring groundfish survey that started in 1985, and data from the autumn groundfish survey in Iceland from 2000. The maximum age of the model is 16, which is considered a plus group. The assessment showed that SSB has been rather stable over the time period, while fishing mortality has gradually decreased, and recruitment has slightly decreased after 2001 but remained stable.

During the workshop, and in the exchanges between the Icelandic scientists and the reviewers leading to it, most of the discussion surrounded the maturation and growth processes, and geographical variation in them. It was decided that calculating catch at age and summing over these to form a total catch at age appears to be enough treatment to account for this variation. Maturation data are sparse so a single ogive applied to annual length distributions was used. For the observation model, it was decided that the residual variance for survey and catch at age would be split for some of the youngest and oldest age groups, although those variance parameters that had similar estimates were grouped. It was further decided that survey residuals would be treated as auto-correlated with age. This was, however, not applied to the commercial catch series as it was considered inappropriate as sampling from commercial catches should be independent by design. Finally, although power relationships in catchability of the oldest ages marginally improved fits to the data, these were removed due to a lack of knowledge regarding the biological basis.

The proposed assessment model developed for the workshop assumed a value for natural mortality, M, of 0.15.A wide range of estimates for natural mortality were tested and none showed a significant improvement in terms of model fit. It was therefore decided to use an M of 0.15.

The assessment model assesses that a shift in estimated recruitment level occurred after 2001 (at age 4). After this shift the estimated recruitment has remained fairly constant at this low level. The reason for this level shift is unknown but this is not the only species in Icelandic waters that changes in recruitment have been observed in recent years. It has been speculated for many shifts that they are related to higher temperatures, but may be related to other habitat changes also. If the shift observed after 2001 is temporary, it may be the result of autocorrelation with a very long lag, but interpreting it as such without a longer time series may not be precautionary.

Reference points were calculated for the stock. This resulted in B_{pa} of 21 000 t, based on the lowest estimate of SSB observed after the 2001 shift in recruitment had been observed (2002), and $B_{lim} = B_{pa}e^{-1.645\sigma_B}$ of 18 500 t, with σ_B being set to the ICES default of 0.2. The fishing pressure estimates, defined in terms of fishing mortality applied to ages from 10 to 15, were estimated in accordance to the ICES guidelines (ICES, 2021b). This resulted in an estimate of F_{lim} of 0.33, F_{PA} of 0.20 and F_{msy} of 0.20. The MSY $B_{trigger}$ was set as Bpa.

A Management Strategy Evaluation (MSE) was conducted for Atlantic wolffish in 5.a. The operating model, which generates the "true" future populations in the simulations, was based on equilibrium simulations (eqsim). Selection, maturity and stock weights were based on the resampling of estimates by age from previous 10 years. Recruitment was projected using a mean value equal to the mean of the estimated recruitment after 2001 and a multiplicative log-normal error based on the CV and autocorrelations estimated by the assessment model. The recruitment had a break point in $Blim$, from which it decreased linearly to 0. Advice error in the simulations was implemented as auto-correlated log-normal variations in F, with a CV of 0.212 and ρ of 0.423.

The proposed HCR for the Icelandic Atlantic wolffish fishery, which sets a TAC for the fishing year y/y+1 (1 September of year y to 31 August of year y+1) based on a fishing mortality $Fmgt$ of 0.20 applied to ages 10 to 15 modified by the ratio SSB_y /MGT $B_{trigger}$ when SSB_y < MGT $B_{trigger}$, maintains a high yield while being precautionary as it results in lower than 5% probability of SSB < B_{lim} in the medium and long term.

5 Ling in 5.a

Ling in 5.a is being re-assessed here as the previously benchmarked Gadget model showed greater retrospective patterns in recent years (see WD04). The new assessment model is SAM (Nielsen and Berg (2014), Albertsen and Trijoulet (2020)), a statistical state-space catch at age model based on commercial catch at age and landings data from 1979 onwards, the Icelandic spring groundfish survey that started in 1985, data from the autumn groundfish survey in Iceland from 2000, and data from a gillnet survey conducted in spring. The maximum age of the model is 12, which is considered a plus group. The assessment showed that there was a peak in spawning stock biomass around 2013–2017 due to a spike in recruitment (age 2) around 2005–2010 that appears to have passed as recent recruitment levels more closely resembled estimates prior to this period. Fishing mortality slowly decreased over time.

During the workshop, and in the exchanges between the Icelandic scientists and the reviewers leading to it, most of the discussion surrounded the best model configuration for this stock and which recruitment estimates to consider as likely to occur in the model. For the observation model, it was decided that the residual variance for survey and catch at age would be split for some of the youngest and oldest age groups. Afterwards, those variance parameters that had similar estimates were grouped. It was further decided that survey residuals would be treated as auto-correlated with age within all surveys. This was, however, not applied to the commercial catch series as it was considered inappropriate as sampling from commercial catches should be independent by design. Finally, although power relationships in catchability of the youngest ages marginally improved fits to the data, these were removed due to a lack of knowledge regarding a biological basis.

The proposed assessment model developed for the workshop assumed a value for natural mortality, M, of 0.15. A wide range of estimates for natural mortality were tested and none showed a significant improvement in terms of model fit. It was therefore decided to use an M of 0.15.

It was decided at the meeting to remove the highest values of recruitment from the time series when estimating a stock-recruitment relationship to use in projections. The reason for the level shift is unknown but this is not the only species in Icelandic waters that changes in recruitment have been observed in recent years. It has been speculated for many shifts that they are related to higher temperatures, but may be related to other habitat changes also. The shift appears to have been temporary, so it was not included in future projections in order to be precautionary.

Reference points were calculated for the stock. This resulted in B_{lim} of 9000 t, based on the lowest estimate of SSB observed (1993), and $B_{pa} = B_{lim}e^{1.645\sigma_B}$ of 11 100 t, with σ_B being set to the ICES default of 0.2. The fishing pressure estimates, defined in terms of fishing mortality applied to ages from 8 to 11, were estimated in accordance to the ICES guidelines (ICES, 2021b). This resulted in an estimate of F_{lim} of 0.95, F_{PA} of 0.62 and F_{msy} of 0.30. The MSY $B_{trigger}$ was set as B_{pa}.

A Management Strategy Evaluation (MSE) was conducted for Ling in 5.a. The operating model, which generates the "true" future populations in the simulations, was based on equilibrium simulations (eqsim). Selection, maturity and stock weights were based on the resampling of estimates by age from previous 10 years. Recruitment was projected using a mean value equal to the mean of the estimated recruitment excluding those in years 2004 to 2010 and a multiplicative log-normal error based on the CV and autocorrelations estimated by the assessment model. The recruitment had a break point in B_{lim} from which it decreased linearly to zero. Advice error in the simulations was implemented as auto-correlated log-normal variations in F, with a CV of 0.212 and ρ of 0.423.

The proposed HCR for the Icelandic Ling fishery, which sets a TAC for the fishing year y/y+1 (1 September of year y to 31 August of year y+1) based on a fishing mortality F_{mgt} of 0.30 applied to ages 8 to 11 modified by the ratio SSB_y /MGT $B_{trigger}$ when SSB_y < MGT $B_{trigger}$, maintains a high yield while being precautionary as it results in lower than 5% probability of SSB < B_{lim} in the medium and long term.

6 Reviewers' comments

The development of a data-rich stock assessment and management plan for ling, tusk, plaice and Atlantic wolffish in Icelandic waters represents a substantial piece of work that will provide managers with good quality advice needed for decision making. The reviewers commend the group for their thoroughly executed and well-prepared work.

General comments:

The meeting was postponed a month and held as an online meeting because of the Russian invasion of Ukraine. Because of the postponement, only two of three reviewers could participate at the Benchmark. However, all three reviewers were involved in pre-meetings before the benchmark. The Icelandic scientists were very organized and presented their work systematically and in a similar format for all the four species.

Input data and assumptions

The definition of the stocks as units was justified at the start of the meeting and relevant biological information was provided. The Icelandic researchers presented all model input data and answered all comments and questions by the reviewers. The overall quality of the assessment benefits greatly from the existence of two to three large-scale fisheries-independent survey indices that overall displayed agreeing patterns. The calculation of age proportions in the catch and survey data are reliant on the availability of sufficient otolith readings across relevant strata; uncertainties in these were stated transparently and were perceived as acceptable. All input data was calculated based on common methods.

Assessment model

The assessment model SAM was proposed for all four species. It is the first time SAM is applied for these species, and a large number of configurations was therefore investigated. The Icelandic researchers searched through the parameter space in SAM with a good and standard procedure. AIC was applied for a first search for optimal model configurations, further were residual and retro plots investigated and applied as guidance to modify the configurations. After several iterations with the reviewers, the Islandic researchers ended up with final configurations. Jitter analysis was performed to confirm that the selected models were not sensitive to starting values.

The Icelandic researchers investigated all assessment model configurations comments by the reviewers. It was apparent that although there is always some subjectivity in model configuration, this would not lead to meaningfully different results.

Reference points

Reference points were explored using eqsim and following standard ICES procedure. Estimated recruitment was used to select stock types in reference point estimation, this was done in alignment with "ICES Technical Guidelines, section "16.4.3.1: ICES fisheries management reference points for category 1 and 2 stocks" to select the reference points B_lim and B_pa. Further was EqSim applied to estimate F_lim, F_pa, F_05 and F_MSY.

Conclusion

The Precautionary Approach and MSY reference points have been calculated in line with ICES guidelines. We state that the contribution of knowledge in this report is of sufficient quality and relevance to form the basis of the advice.

7 References

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Annex 1: List of participants

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Annex 2: Request from Iceland to ICES

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Reykjavík 13. október 2021
Tilv.: ANR21100105/15.09.00

Re-evaluation of the management plan for ling and tusk evaluation of management plans for plaice and Atlantic wolffish in Icelandic waters.

The Government of Iceland is in the process of re-evaluating the management plans for ling and tusk in Icelandic waters. The management strategy for these stocks is to maintain the exploitation rate at the rate which is consistent with the precautionary approach and that generates maximum sustainable yield (MSY) in the long term.

Part of the management plans is the adoption of harvest control rule (HCR) for setting annual total allowable catch (TAC). The HCR adopted should be precautionary and in accordance with the ICES MSY approach. The current management plans for ling and tusk were first evaluated by ICES before the 2017/2018 fishing year and were found to be consistent with the precautionary approach and in conformity with the ICES MSY-framework.

As stipulated in the MoU between Iceland and ICES, plaice and Atlantic wolffish are stocks in which Iceland expects advice on from ICES. As with the above-mentioned stocks the management strategy for plaice and Atlantic wolfish is to maintain the exploitation rate at the rate which is consistent with the precautionary approach and that generates maximum sustainable yield (MSY) in the long term in part with the adoption of a management plan.

Technical documentation of the proposed HCRs will be produced by national experts at the Marine and Freshwater Research Institute and made available to ICES before the 15th of February 2022. A more detailed request will be sent to ICES, stipulating the exact form of the HCRs to be evaluated before the 15th of February.

The Government of Iceland requests ICES to evaluate whether the proposed harvest control rules are in accordance with its objectives, given current ICES definition of reference points or any re-evaluation of those points that may occur in the process. Additionally, the evaluation should also include review of input data and the applied assessment methodology. It is expected that the ICES advice for the 2022/2023 fishing year for ling, tusk, plaice and Atlantic wolffish be based on the above-mentioned HCRs.

Fyrir hönd sjávarútvegs- og landbúnaðarráðherra

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Tilv.: MAR22020279/12.09.05

Efni: Subject: Evaluation of the management plans for plaice, wolffish, ling and tusk in Icelandic waters, input data and stock assessment.

In a letter (ANR21100105/15.09.00) from 13th of October 2021 the Icelandic Ministry of Industries and Innovation requested ICES to evaluate the performance of the management plans for plaice, wolffish, ling and tusk against their general aim of maintaining the exploitation rate at the rate which is consistent with the precautionary approach and generates maximum sustainable yield (MSY) in the long-term. ICES was also asked to evaluate the assessment methods and estimated reference points.

As stipulated in the MoU between Iceland and ICES these four stocks are among the stocks in which Iceland expects advice from ICES.

Based on further consultations with national scientists, the Ministry of Food, Agriculture and Fisheries requests ICES to explore the consequences of applying the HCRs listed below and to evaluate if they are consistent with the precautionary approach and in conformity with the ICES MSY framework. In doing so, ICES is also requested to evaluate the basis of assessment framework for plaice and wolffish and re-evaluate the basis of assessment for tusk and ling.

Plaice: The HCR is applied to calculate the annual total allowable catch (TAC) based on a forecast from the assessment model with a target fishing mortality, calculated as the mean over ages 5 to 10, F_{MGT}, set to 0.30. The TAC for the fishing year *y* /*y* +1 (September 1 of year *y* to August 31 of year *y* +1) is then calculated from the projected catch for the upcoming fishing year.

If the spawning stock biomass (SSB) falls below 12 400 tonnes (MGT $B_{trigger}$), the harvest control rule dictates that F_{MGT} shall be reduced linearly to zero based on the ratio between the SSB estimated and MGT $B_{trigger}$.

Wolffish: The HCR is applied to calculate the annual total allowable catch (TAC) based on a forecast from the assessment model with a target fishing mortality, calculated as the mean over ages 10 to 15, F_{MGT}, set to 0.20. The TAC for the fishing year *y* /*y* +1 (September 1 of year *y* to August 31 of year *y* +1) is then calculated from the projected catch for the upcoming fishing year.

If the spawning stock biomass (SSB) falls below 21 000 tonnes (MGT $B_{trigger}$), the harvest control rule dictates that F_{MGT} shall be reduced linearly to zero based on the ratio between the SSB estimated and MGT $B_{trigger}$.

Ling: The HCR is applied to calculate the annual total allowable catch (TAC) based on a forecast from the assessment model with a target fishing mortality on the ages 8 to 11, F_{MGT}, set as 0.30. The TAC for the fishing year y /y +1 (September 1 of year y to August 31 of year y +1) is then calculated from the catch projection for the fishing year.

If the spawning stock biomass (SSB) falls below 11 100 tonnes (MGT $B_{trigger}$), the harvest control rule dictates that F_{MGT} shall be reduced linearly to zero based on the ratio between the SSB estimated and MGT $B_{trigger}$.

Tusk: The HCR is applied to calculate the annual total allowable catch (TAC) based on a forecast from the assessment model with a target fishing mortality on the ages 7 to 10, F_{MGT}, set as 0.23. The TAC for the fishing year y /y +1 (September 1 of year y to August 31 of year y +1) is then calculated from the projected catch for the upcoming fishing year.

If the spawning stock biomass (SSB) falls below 4 800 tonnes (MGT $B_{trigger}$), the harvest control rule dictates that F_{MGT} shall be reduced linearly to zero based on the ratio between the SSB estimated and MGT $B_{trigger}$.

On behalf of the Minister of Food; Agriculture and Fisheries

Kristján Freyr Helgason

Áslaug Eir Hólmgeirsdóttir

Annex 3: Resolutions

WKICEMP Workshop on the evaluation of assessments and management plans for ling, tusk, plaice and Atlantic wolffish in Icelandic waters

2022/2/FRSG30 The workshop on the evaluation of assessments and management plans for ling, tusk, plaice and Atlantic wolffish in Icelandic waters (WKICEMP), chaired by Alexander Kempf (Germany), and attended by three invited external experts Jonathan White (Ireland), Elisabeth Van Beveren (Canada) and Olav Nikolai Breivik (Norway) will be established and meet online and in Iceland (hybrid format), 4–8 April 2022, to update (if required) operational assessment models and reference points and evaluate management plan HCRs for ling (lin.27.5a), tusk (usk.27.5a14), plaice (ple.27.5a) and Atlantic wolfish (caa.27.5a) in Icelandic waters. The work will be 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 (where applicable):
    i. Stock identity and migration issues;
    ii. Life-history data;
    iii. Fishery-dependent and fishery-independent data;
    iv. Further inclusion of environmental drivers, multi-species 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 about environmental drivers, including multispecies interactions, and ecosystem impacts should be integrated in the methodology;
c) Re-examine and update (if necessary) MSY and PA reference points according to ICES guidelines (see Technical document on reference points);
d) Evaluate the proposed Harvest Control Rule(s) for the management plans for the stocks and develop conclusions on whether the proposed HCR(s) can be considered as consistent with the precautionary approach and in conformity with the ICES MSY framework and can therefore be used as the basis for ICES fishing opportunity advice for the stock.

WKICEMP will report by 20 April 2022 for the attention of the Advisory Committee.

Stock	Stock code	Stock leader
Ling (*Molva molva*) in Division 5.a (Iceland grounds)	lin.27.5a	Anika Sonjudottir
Plaice (*Pleuronectes platessa*) in Division 5.a (Iceland grounds)	ple.27.5a	Elzbieta Baranowska
Tusk (*Brosme brosme*) in Subarea 14 and Division 5.a (East Greenland, and Iceland grounds)	usk.27.5a14	Pamela Woods
Atlantic wolffish (*Anarhichas lupus*) in Division 5.a (Iceland grounds)	caa.27.5a	Pamela Woods

Supporting Information

Priority:	High
Scientific justification and relation to action plan:	The Ministry of Industries and Innovation in Iceland require an independent review of the proposed HCRs in advance of the 2022/23 fishing season.
Resource requirements:	Work to be conducted by national experts in Iceland.
Participants:	National experts from Iceland and interested NWWG and WGDEEP members
Secretariat facilities:	SharePoint site and online meeting facilities.
Financial:	Part of Iceland-ICES MOU.
Linkages to advisory committees:	Reports to ACOM
Linkages to other committees or groups:	NWWG, WGDEEP
Linkages to other organizations:	-

Annex 4: Working Documents

List of working documents

Plaice in 5a

Contents

1 Stock ID and sub-stock structure

Plaice is found on the continental shelf around Iceland with the highest abundance occurring southwest and west of the island. It is mainly found on sandy or muddy substrate, occurring at depths ranging from shallow coastal areas down to 200 meters, sometimes even deeper. Genetic studies [8], [6] suggest that plaice found on the Icelandic and Faroese shelf areas are genetically different from plaice found elsewhere.

Information from historical tagging experiments suggest that plaice in Icelandic waters are mainly contained within the shallow waters of the continental shelf. Of the 3849 recorded recaptures of plaice tagged in Iceland, only 8 were recorded outside of the Icelandic EEZ. Furthermore, none of the recaptures in Icelandic waters originated from other areas. This indicates high site fidelity of the stock and low connectivity with plaice found in the adjacent Faroese waters.

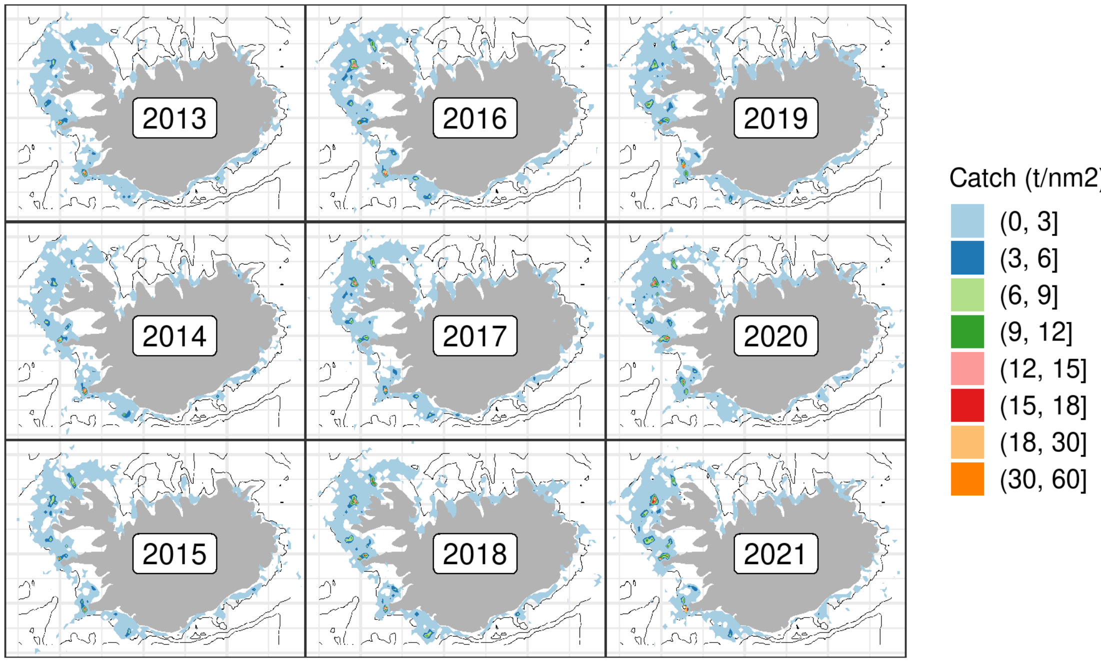

Figure 1: Plaice in 5a. Spatial distribution of catches by all gears.

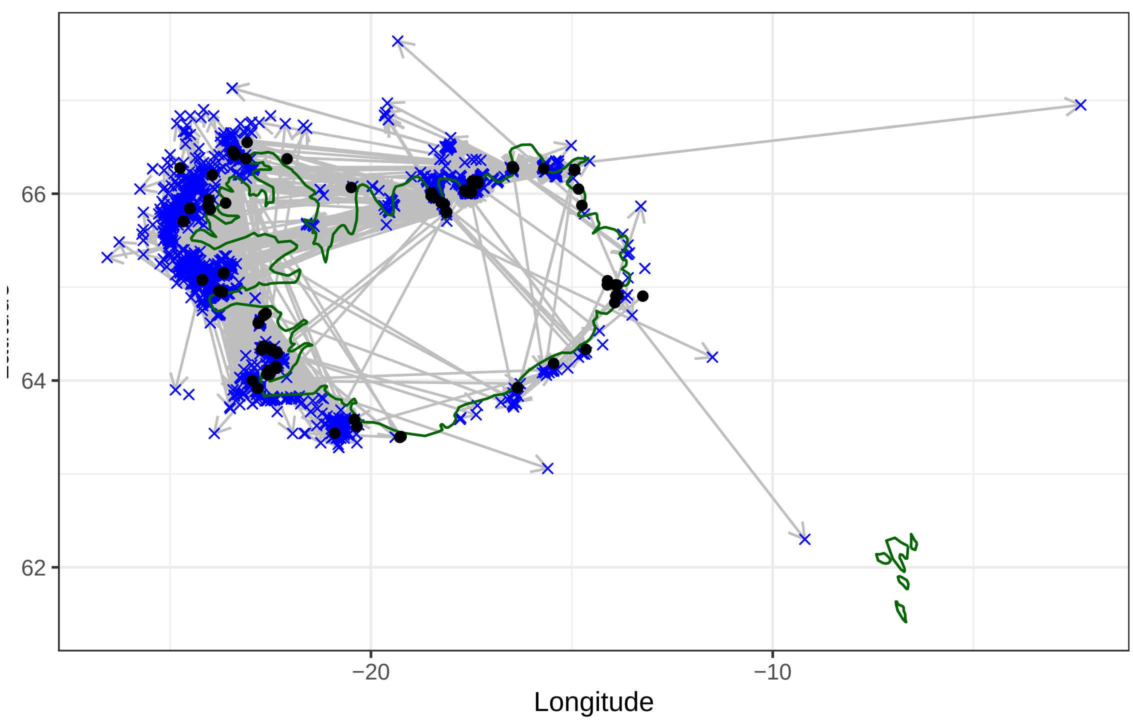

Figure 2: Plaice in 5a. Overview of mark-recaptures from tagging experiments in Icelandic waters

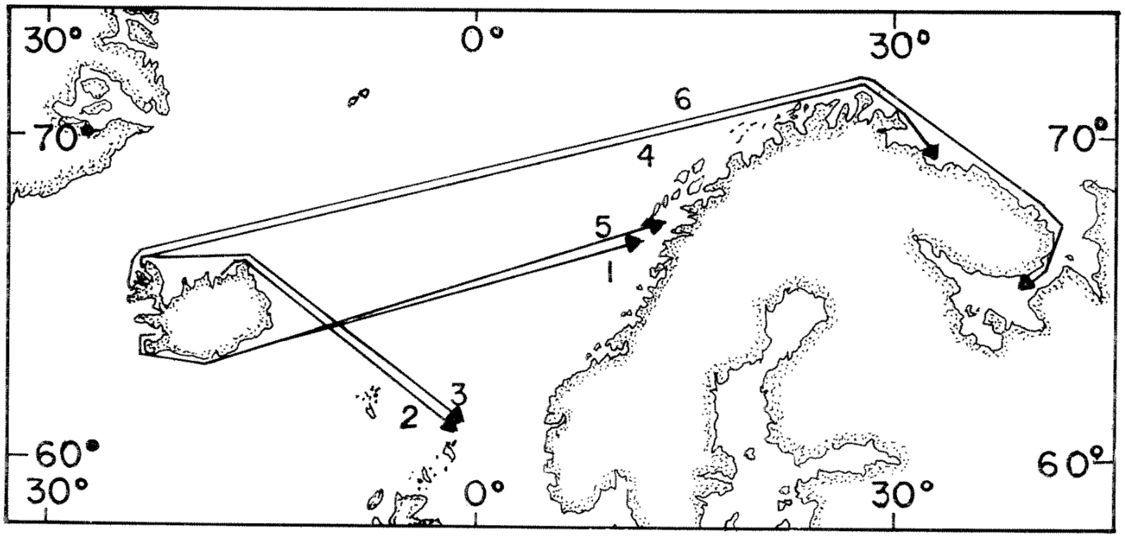

Figure 3: Plaice in 5a. Historical recaptures from tagging experiments in Icelandic waters to adjacent waters. See text for further details.

Sigurdsson [17] observed long distance migrations to the Barents sea. Similar migrations were not observed in recent tagging studies in Icelandic waters [20] and the validity of these older observations are considered questionable (Sigurdsson pers. comm). Furthermore, the older observations are in conflict with the results from Le Moan, Bekkevold, and Hemmer-Hansen [8].

Tagging data suggests considerable movement within Icelandic waters, this is in accordance with the observed distributional shifts between the spring and autumn surveys, and suggests that sub-stock structure for plaice in Icelandic waters is negligible.

2 Issue list

In a letter dated at October 18, 2021, the government of Iceland requested that ICES evaluate the performance of the harvest control rules for tusk, ling, plaice and Atlantic wolffish, and update/develop new assessments as appropriate.

3 Scorecard on data quality

Scorecard on data quality was not used.

4 Multispecies and mixed fisheries issues

The plaice fishery in 5.a has been entirely Icelandic since the expansion of the EEZ. Icelandic plaice is mainly caught in mixed seine fisheries where the target species are predominantly flatfish species, plaice in particular.

The plaice fishery in 5.a has changed substantially in the last two decades with the number of seiners landing plaice decreasing from 122 in 2000 to 35 in 2021. The number of trawlers decreased by half and was 61 vessels in 2021. Danish seine and bottom otter trawl are the main fishing gears, with seine accounting for approximately 65% of all plaice landings and trawl accounting for approximately 30%. This ratio has stayed consistent for the last two decades. Plaice landings were at a historical high in the mid-1980s with over 14 thous. tonnes landed in 1985 and 1988. Landings remained over 10 thous. tonnes until 1997. Subsequently, plaice landings in 5.a have remained stable at 5-8 thous. tonnes. The main fishing grounds for plaice according to logbook data are west and north-west of Iceland. The catch from these fishing grounds accounts for 75% of all reported catch. The majority of plaice catch is taken at 20-100 m depth.

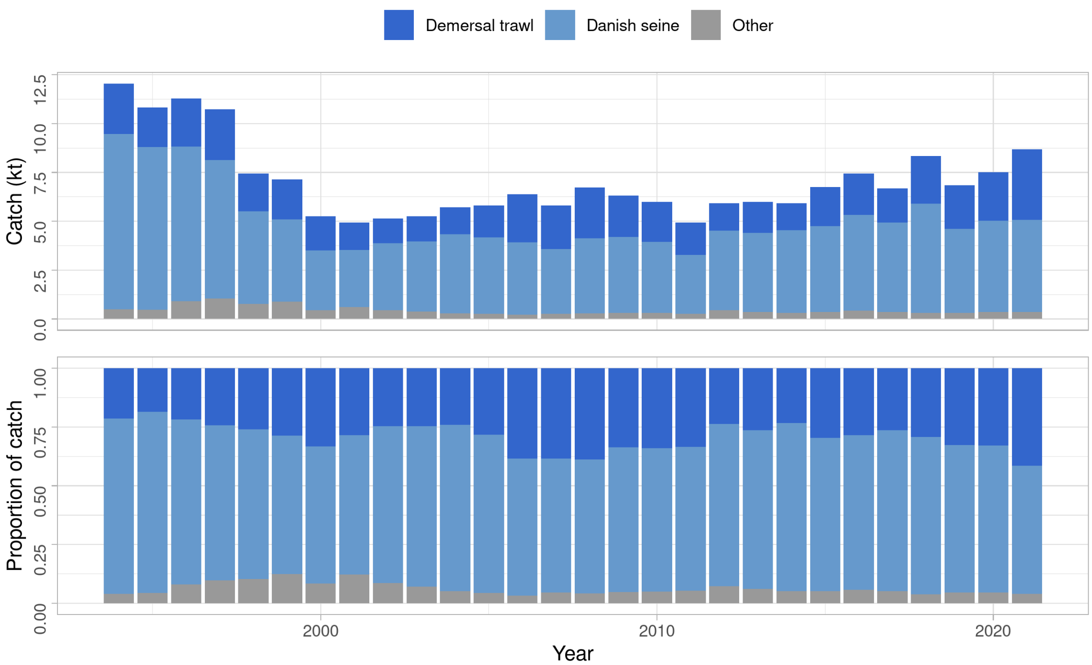

Figure 4: Plaice in 5a. Landings by year

5 Ecosystem drivers

Adult plaice are distributed on the continental shelf and slope, and are most common in the waters west and north-west of Iceland. Plaice prefer muddy and sandy substrates and the optimal depth range for adult fish is 10-200 m, whilst juveniles are generally found in intertidal areas down to 10 m depth. The main spawning grounds are situated in the warmer waters south and west of Iceland, although spawning components can be found along the entire Icelandic coast. The plaice population in the southern and western parts of the Icelandic shelf has high fidelity to both its spawning and feeding areas ("Skarkolamerkingar við Ísland" [18], Solmundsson, Palsson, and Karlsson [20]).

In the south and south-west spawning grounds, the spawning period ranges from the end of February to early June, peaking in March and April (Gunnarsson, Jonasson, and McAdam [4]; "Skarkolamerkingar við Ísland" [18]; Solmundsson, Karlsson, and Palsson [19]; Sæmundsson [16]). In the colder waters in the north, the spawning season is later, commencing towards the end of March and finishing before mid-July, with peaks in May and June (Gunnarsson, Jonasson, and McAdam [4]). Spawning takes place at approximately 50-100 m depth and the pelagic eggs disperse clockwise around Iceland following the Atlantic water currents from the south and the coastal current which originates south of Iceland and flows clockwise around the country (see in Gunnarsson, Jonasson, and McAdam [4]). Female plaice are serial spawners that produce quite large eggs in the beginning of the spawning season, and thus large larvae. Post-hatch larvae stay in the water column for approximately 53-61 days, with the pelagic phase lasting longer in the north of Iceland (Gunnarsson, Jonasson, and McAdam [4]). After the onset of metamorphosis, larvae seek the bottom and settle in intertidal waters, this period starts in the second half of May (Hjorleifsson and Palsson [5]).

Sexual dimorphism in growth is inherent in plaice in 5.a as females grow faster and reach larger size than males.

Considerable changes have been observed in plaice habitats, both in terms of changes in fishing pressure

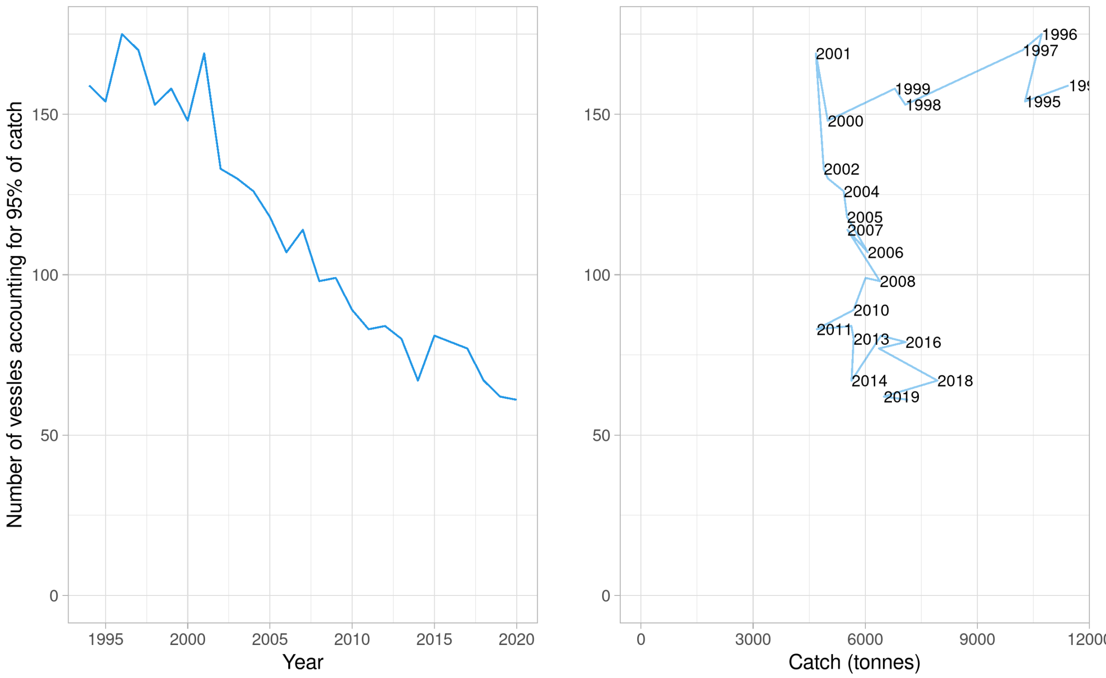

Figure 5: Plaice in 5a. Landings by year

and the ecosystem. Jónsdóttir, Bakka, and Elvarsson [7] noted that species diversity in the fjords in the western and northern part of the country shifted dramatically at the turn of the century. These changes were attributed mainly to increases in the abundance of juvenile gadoids such as cod, haddock and whiting. These changes coincided with increased temperature, generally lower fishing pressure, and shifts in the distributions of species. Examples of these distributional shifts include the Icelandic haddock stock which has produced a noticeable northern shift in distribution [11], the minke whale population [21] with shifts possibly driven by shifts in forage fish species and influx of the mackerel to the North Western Atlantic [12]. Projected effects of climate change are also expected to affect species differently depending on their thermal tolerances and habitat affinities (e.g., depth). Some warm-water species such as tusk and ling shifting northward gaining suitable habitat available to them (e.g,. haddock, tusk, and ling) while others lose ground due to depth constraints (e.g. plaice) and most cold-water species lose (e.g., Atlantic wolffish, Mason et al. [10], Campana et al. [2]).

In addition to shifts in the environment, a high rate of *Ichtyophonus* infections were observed in the late 90's in Faxaflói bay southwest of Iceland [13], which may have had adverse effects on the stock. The infection rate reached its peak in the years 1997 and 1998 and affected all age classes. In the following years, infection rates were reduced. Prior to the infection rate peak, the limited available data suggests that the infection rates were low from 1980 to 1995, and high in the mid 70's (Fig. 6). The infection rate has not been measured since 2013.

6 Stock Assessment

6.1 Catch – quality, misreporting, discards

Annual estimates of landings of plaice from Icelandic waters are available since 1905 (Figure 7. The historical information are largely derived from the Statistical Bulletin, with an unknown degree of accuracy, and retrieved from Statlant. For the period between 1966 to 1993, landings of Icelandic vessels were recorded by Fiskifélagið (a precursor to the Directorate of Fisheries). The more recent landings (from 1993 onwards) are

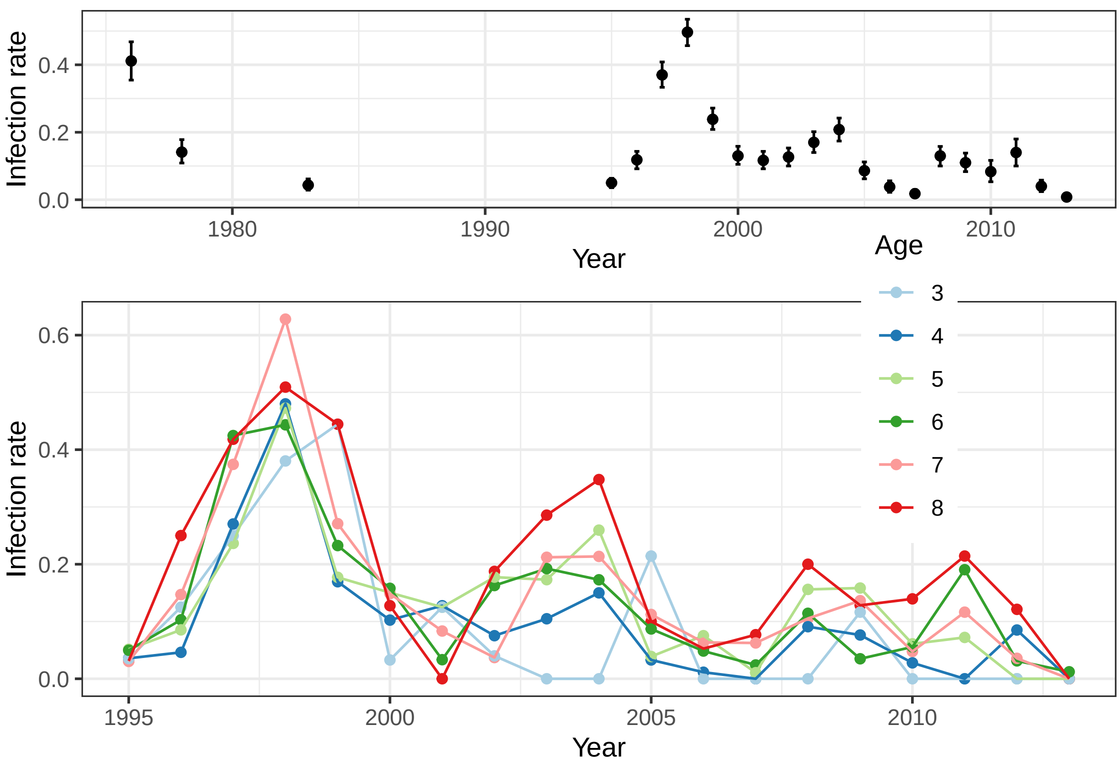

Figure 6: Plaice in 5a. Observed infection rates of *Ichtyophonus* in plaice by year (top panel) and, year and age (bottom panel) from a survey of Faxaflói bay. In the top panel points indicate median rate of infection from all samples and the bars 95% confidence ranges. The bottom panel shows the infection rate by age.

from the Directorate of Fisheries which are reported to ICES annually. After 2013, all landings in 5a are recorded by the Directorate, both foreign and domestic vessels.

The Directorate of Fisheries also collects logbook records from all vessels operating in Icelandic waters. This database started as a voluntary industry collaboration with the MFRI. In 1993, it became mandatory for all large vessels to report all catches, and in 1999 it became mandatory for all vessels.

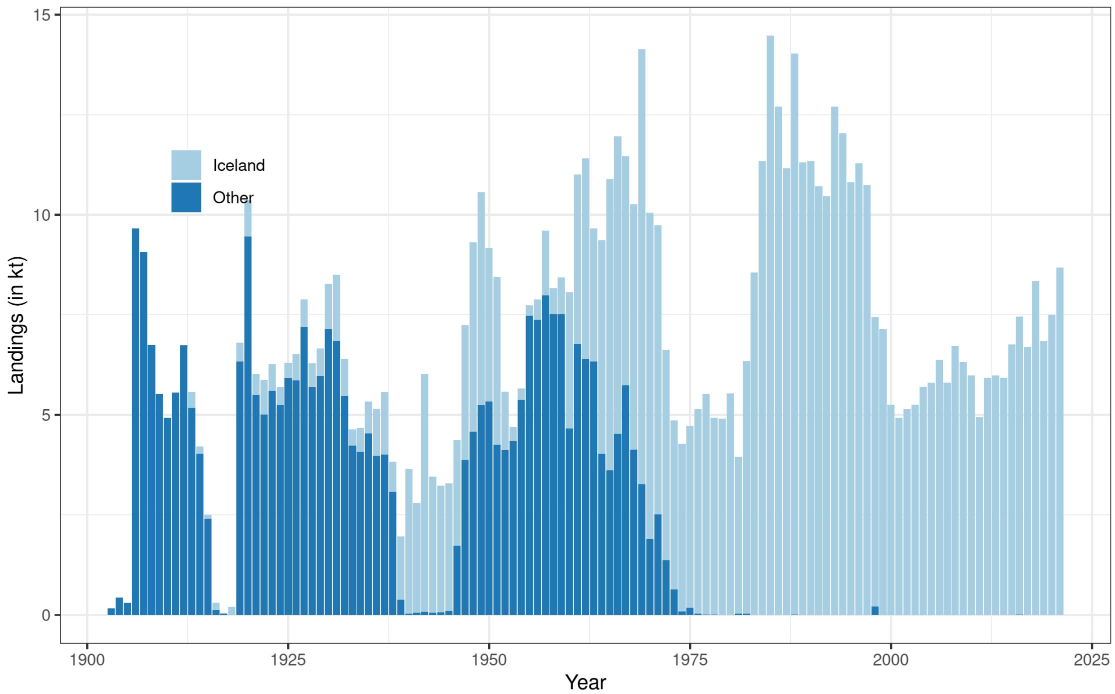

Figure 7: Plaice in 5a. Time series of historical landings.

The estimates by the Directorate of Fisheries are based on a full census by weighing fish at the dock when landed or in fish processing factories prior to processing. Information on the landings of each trip are stored in a centralised database to which the Marine and Freshwater Research Institutes (MFRI) employees have full access. Captains are required to keep up-to-date logbooks that contain information about timing (day and time), location (latitude and longitude), fishing gear and the amount of each species in each fishing operation. The Directorate of Fisheries and the Coast Guard can, during each fishing trip, check if the amount of fish stored aboard the vessel matches what has been recorded in the logbooks. In part, this acts as a deterrent for potential illegal and unrecorded landings.

Nearly all plaice are landed, gutted, and converted to ungutted using the conversion factor 0.92. The real gutting factor can vary year to year so the amount of ungutted plaice landed may be different than the estimated value. All the bookkeeping of catch is in terms of gutted fish and the reference to ungutted catch is just gutted divided by 0.92 so this does not matter in the assessment.

Discards are illegal in Icelandic waters but are assumed to take place to some degree. A discard monitoring program of the MFRI, designed to estimate highgrading of cod and haddock, has been in place since 2001. According to Pálsson et al. [14] the discard rate for plaice caught in demersal seine was high, 7.11% of the landed catch and involved mainly fish under 40 cm length. However, following discards measurements show no discards of plaice caught in danish seine (Pálsson et al. [15]). Discards are therefore assumed to be negligible, or at least consistent between years.

The commercial catch at age is shown in Fig. 11. It is estimated based on disaggregated ALKs by gear (bottom trawl and demersal seine) and semiannually. For the years between 1980 and 1993 the ALKs are grouped together across years as the number of available age-readings were lower (Fig. 8). An upwards trend in mean length at age can be observed in the catches (Fig. 9). This coincides with an observed shift in the length distribution in the catches (Fig. 10.

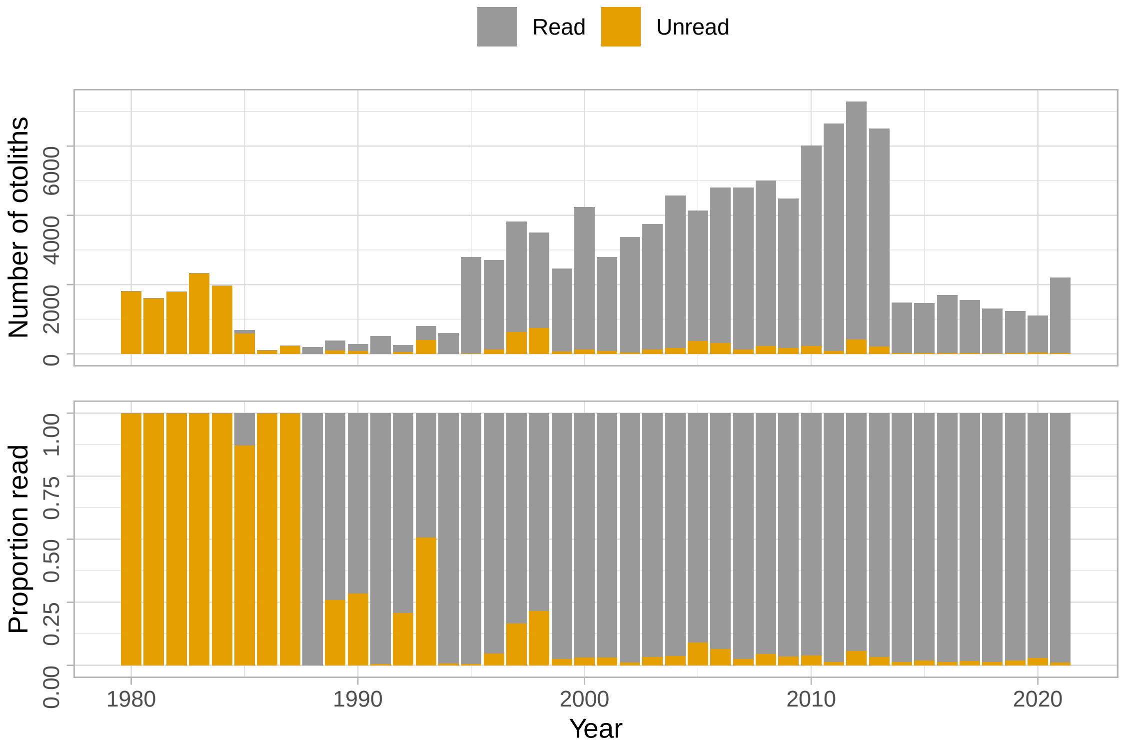

Figure 8: Plaice in 5a. Amount of available otoliths from commercial catches (both from on-board observers and port sampling).

6.2 Surveys

6.2.1 Research cruises

Information on abundance and biological parameters from plaice in 5a is available from three surveys, the Icelandic groundfish survey in the spring, the Icelandic autumn survey and the Icelandic coastal survey.

The Icelandic groundfish survey has been conducted annually since 1985.The survey covers the most important distribution area of the fishable biomass. The autumn survey commenced in 1996 and expanded in 2000 to include deep water stations. It provides additional information on the development of the stock. The autumn survey has been conducted annually with the exception of 2011 when a full autumn survey could not be conducted due to a fisherman strike. Although both surveys were originally designed to monitor the Icelandic cod stock, the surveys are considered to give a fairly good indication of the plaice fishable stock but limited information for the juvenile population. A detailed description of the Icelandic spring and autumn groundfish surveys is given in Marine and Freshwater Research Institute [9]. Fig. 13 shows both a recruitment index and the trends in various biomass indices. Changes in spatial distribution observed in the spring survey are shown in Fig. 14. The figure shows that a larger proportion of the observed biomass now resides in the west and northwest (areas W and NW).

Survey abundance at age from the spring survey is shown in Fig. 15. The autumn survey at age is not available as otoliths from the survey have not been processed. Fig. 16 shows the consistency in the survey index between ages. Correlation between adjacent year classes is considered satisfactory.

To address the lack of information on recruitment and the juvenile population in the spring and autumn surveys, a coastal beam trawl survey was started in 2016 and its design evolved to its current design in 2018.

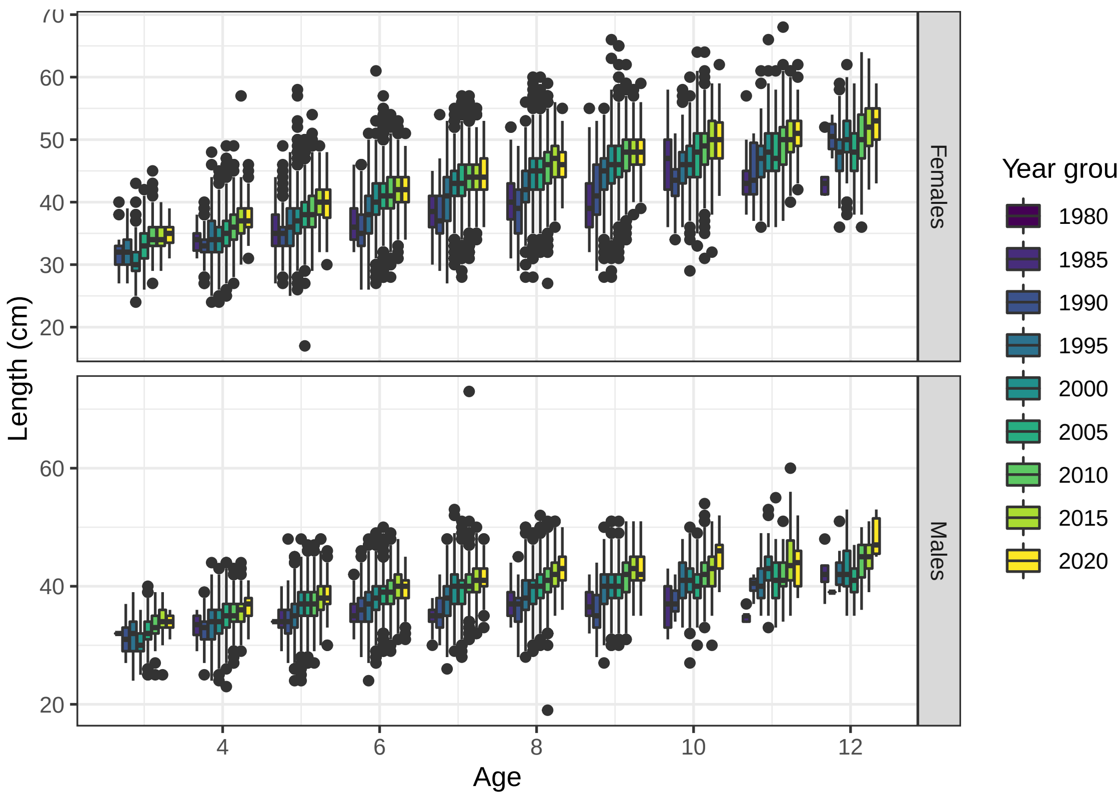

Figure 9: Plaice in 5a. Boxplot of lengths as function age, by year (5 year blocks) and sex.

This survey was specially designed to target young plaice and dab in Icelandic coastal waters. Four criteria were used to define the sampling stations: tows need to be within 50 m depth range, close to the shore (within 5 nm), have a sandy bottom according to ship´s sonar, and are close (10 nm) to the areas where demersal seine fisherman previously marked feasible to find juvenile plaice or/and dab. Approximately 74 stations along the Icelandic coast have been sampled each year in late-August since 2018. In 2018, all the stations around Iceland were found and sampled for the first time, therefore the plots below are produced with the starting point set in that year. In 2019, there was a shift in the timing of the survey due to a shiptime conflict with other assignments, this resulted in the survey moving back into July. The impact of this shift in timing are clearly seen in the 2019 survey data as the length distribution is missing the smallest length groups from the catch.

Information from this survey is expected to provide valuable information in the coming years, but at present it will not be included in the assessment because the time-series is considered too short.

6.3 Catch and effort series

Logbook catch per unit of effort data (Fig. 18) shows similar trends in stock development as the surveys. They indicate that the stock reached its lowest levels around the turn of the century and has has been steadily increasing since.

6.4 Weights, maturities, growth

6.4.1 Growth

Mean weight at age in the stock and catch weight is shown in Fig. 19. Those data are obtained from the groundfish survey in March and commercial catches respectively. Stock weights are also used as mean weight

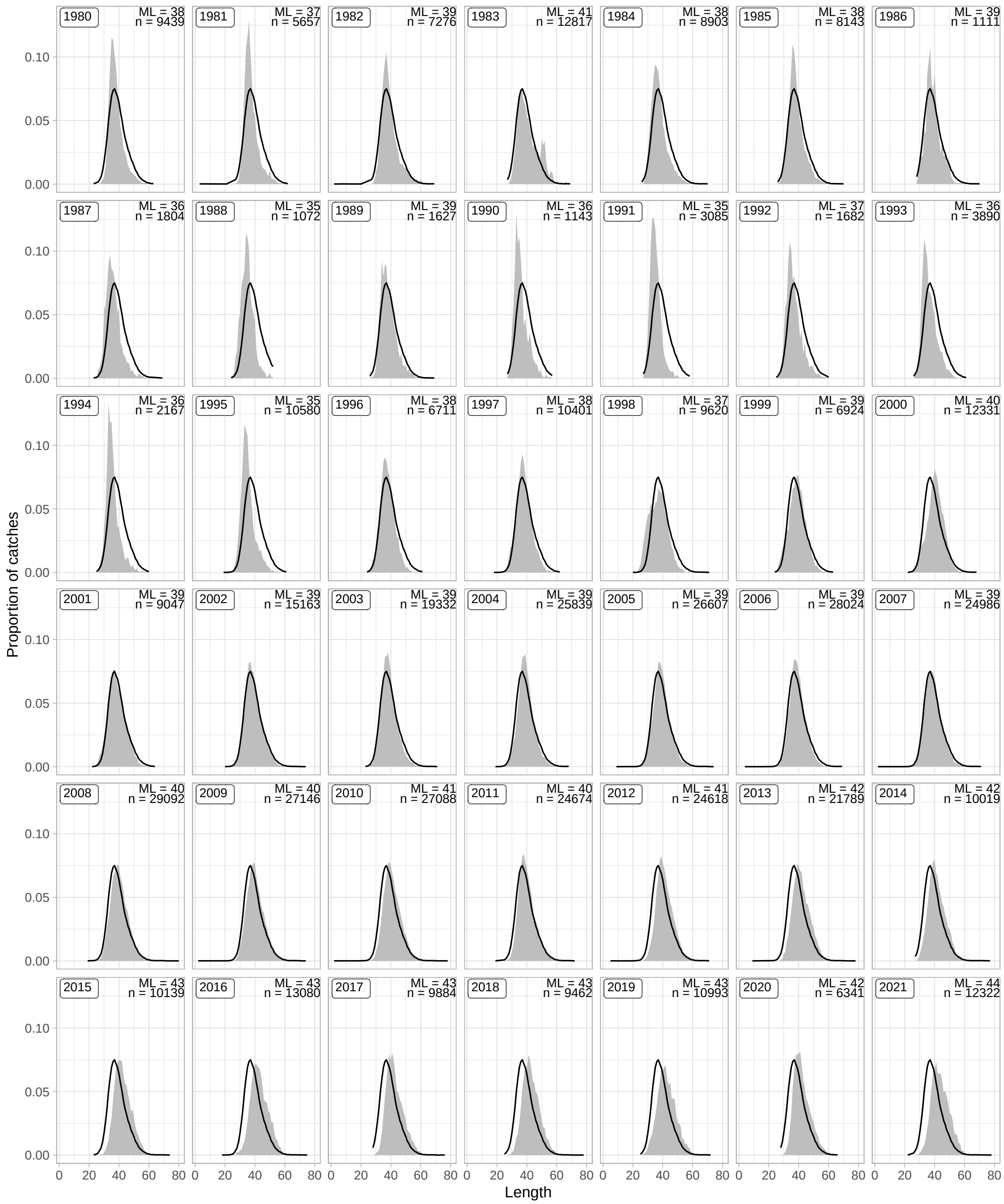

Figure 10: Plaice in 5a. Length distribution from commercial catches, both from port sampling and onboard monitoring programs. Shaded region show the proportion of fish by year and solid black line the average proportion from 1979. Mean length and number of length measurements are shown in the top right corner.

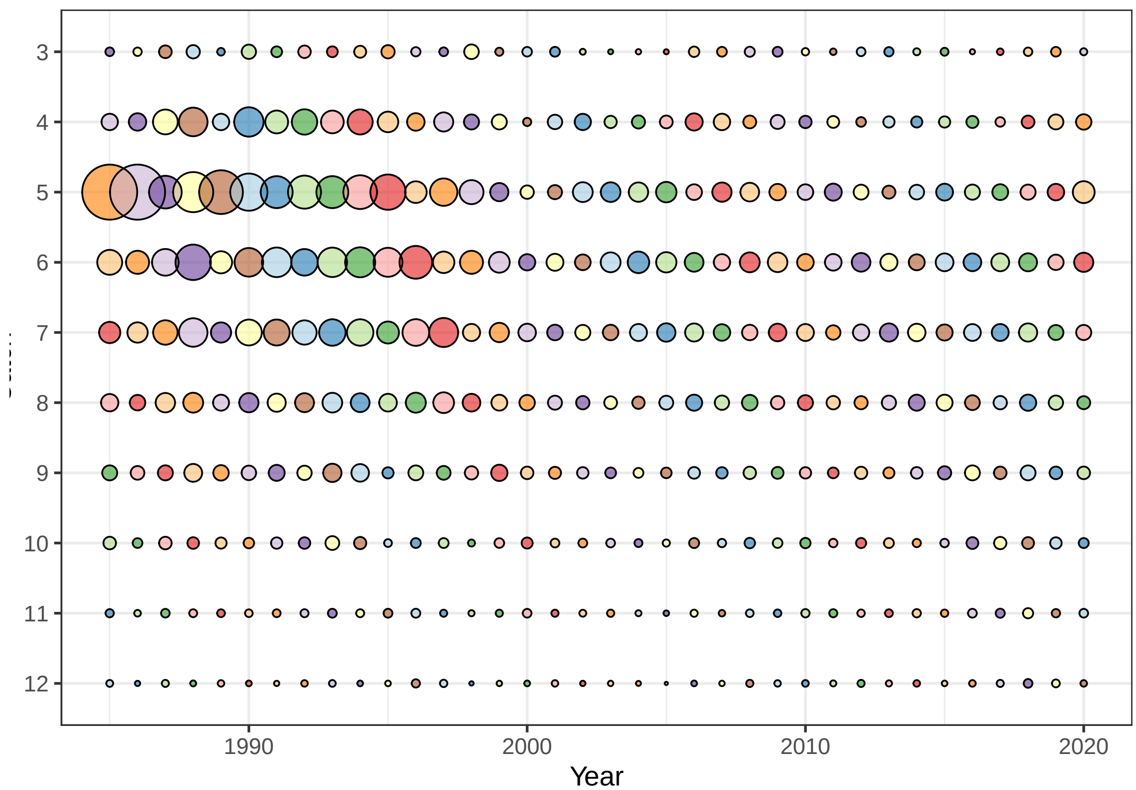

Figure 11: Plaice in 5a. Catch at age, point sizes indicate the numbers by age. Points are colored by year class.

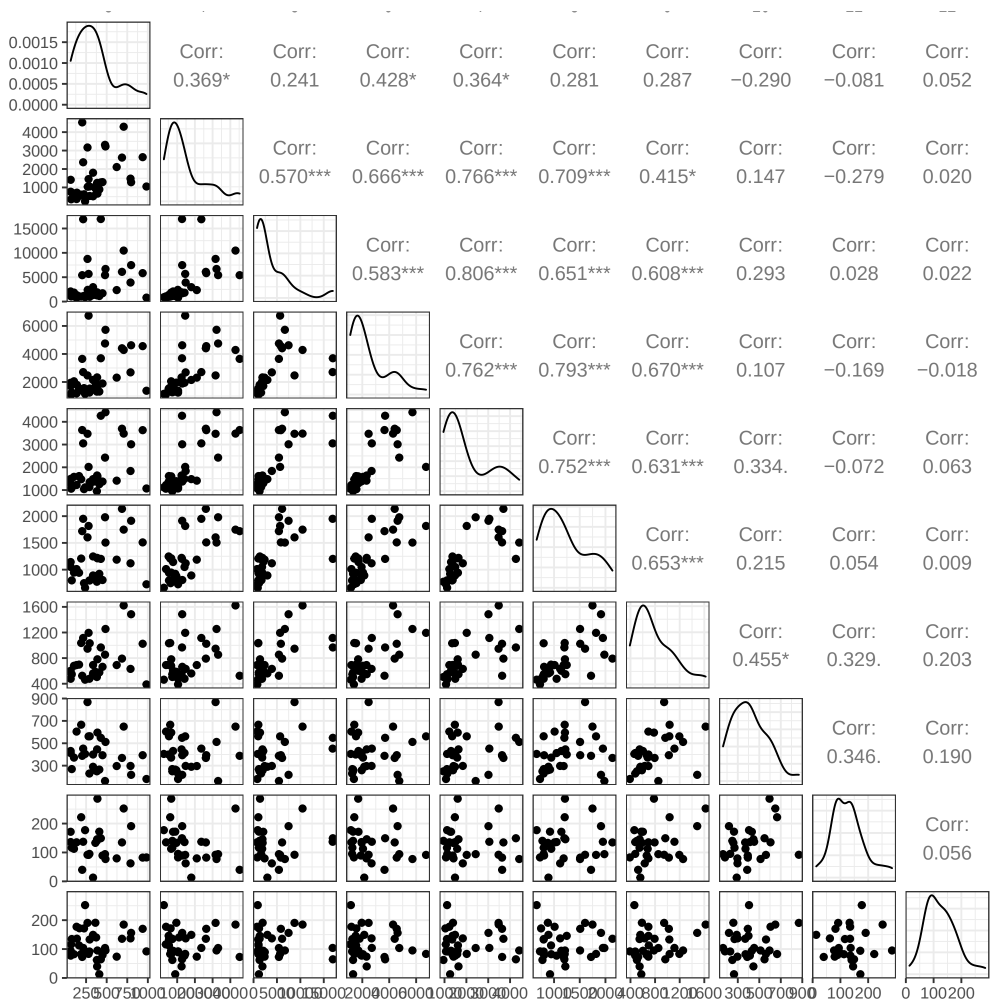

Figure 12: Placie in 5a. Internal consistency of the catch at age matrix. The panels illustrate the correlations between age groups, upper triangle panels show the estimated correlation while the lower show the relationship between the indices.

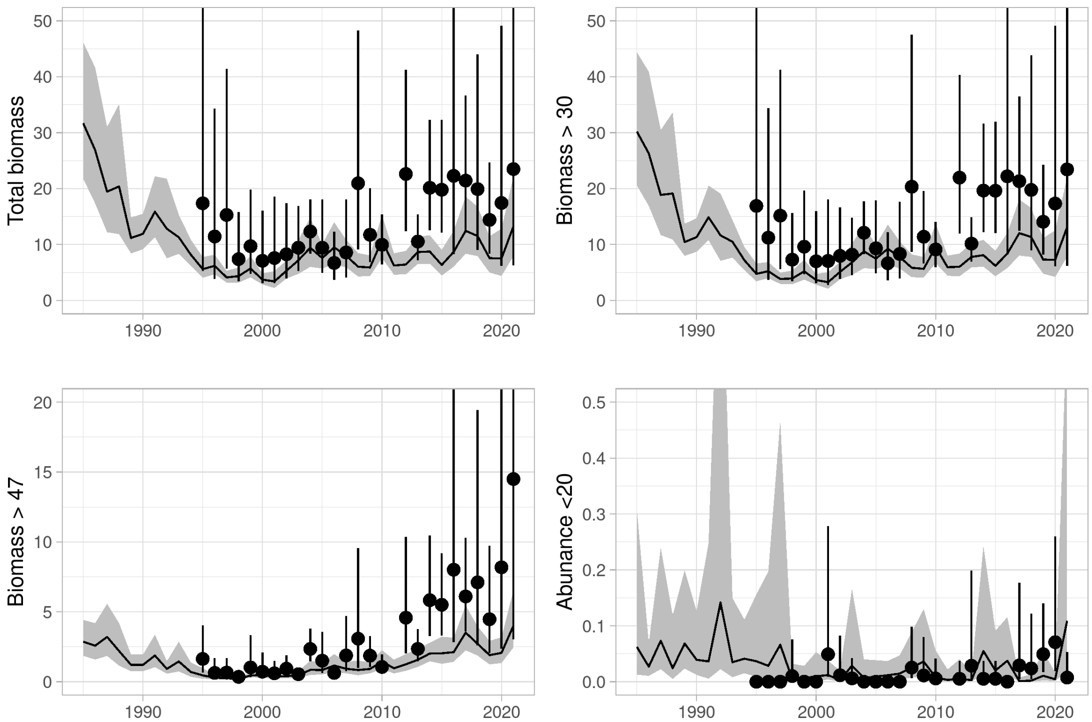

Figure 13: Plaice in 5a. Biomass trajectories from the spring and autumn surveys.

at age in the spawning stock. The weights are approximated from lengths. For stock weights for age 9 are smoothed using a running 3 year average. Prior to 1985 the stock weights are assumed fixed at 1985 levels.

6.4.2 Maturities

Maturity-at-age data are given in Fig. 20. Those data are obtained from the groundfish survey in March. Based on guidelines from PGCCDBS it was decided to use mature females as the basis for maturity at age. Prior to 1985 the proportion mature is assumed fixed at 1985 levels. Maturity at age is estimated from yearly maturity at length ogives estimated using logistic regression treating individuals as fixed effects. Maturity at age was smoothed with a 3 year running average.

6.4.3 Natural mortality

Natural mortality was set as 0.15 in the models presented here. Alternative formulations are been considered in the results section.

6.5 Assessment model

The assessment model used is the State space Assessment Model (SAM) described in Albertsen and Trijoulet [1]. The model runs from 1980 onwards and ages 3 to 12 are tracked by the model, treating age 12 as a plus group. Observations in SAM are assumed to arise from a multivariate normal process with an expected value derived from the model. SAM allows for the investigation of how to treat patterns in the residuals by defining different parameters by age for observation residual variances and correlations for all data sets. Furthermroe, the user can define age groups for survey catchabilities, and related power relationships, and process variances for the $\log(N)$ and $\log(F)$ residuals.

For plaice in 5a a number of combinations of parameter settings were initially investigated:

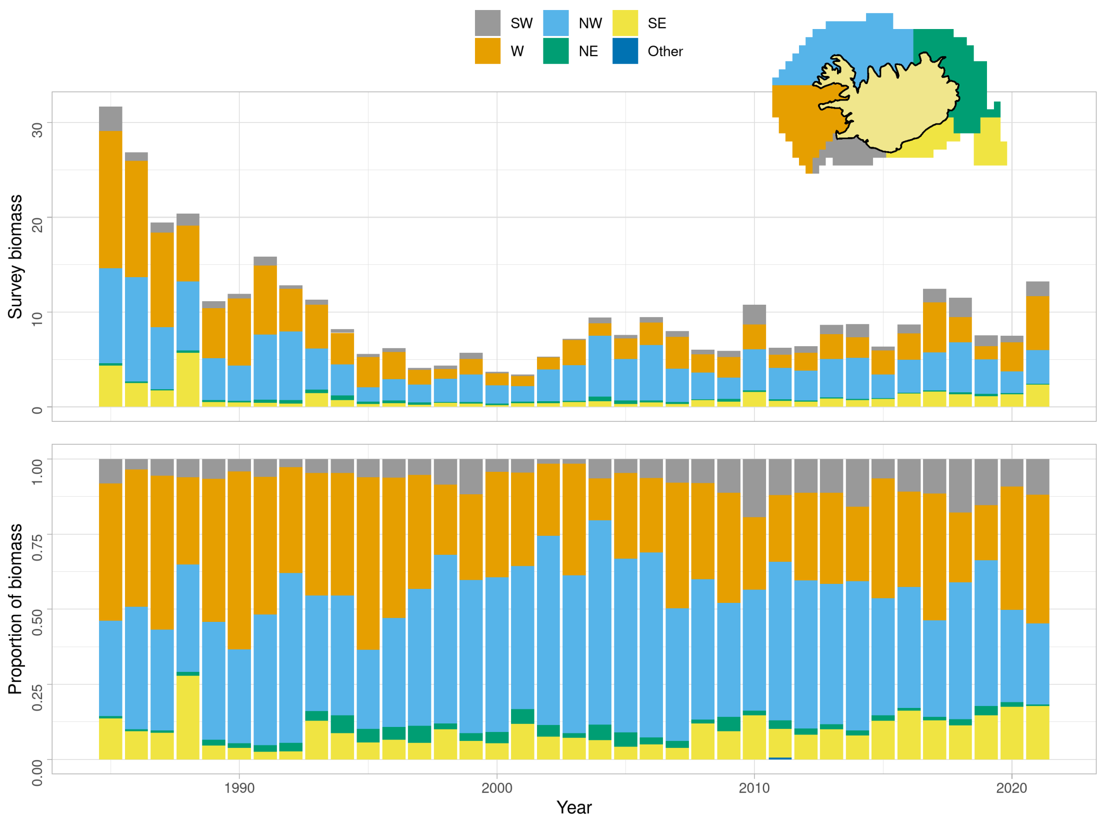

Figure 14: Plaice in 5a. Biomass by area from the spring suvrey.

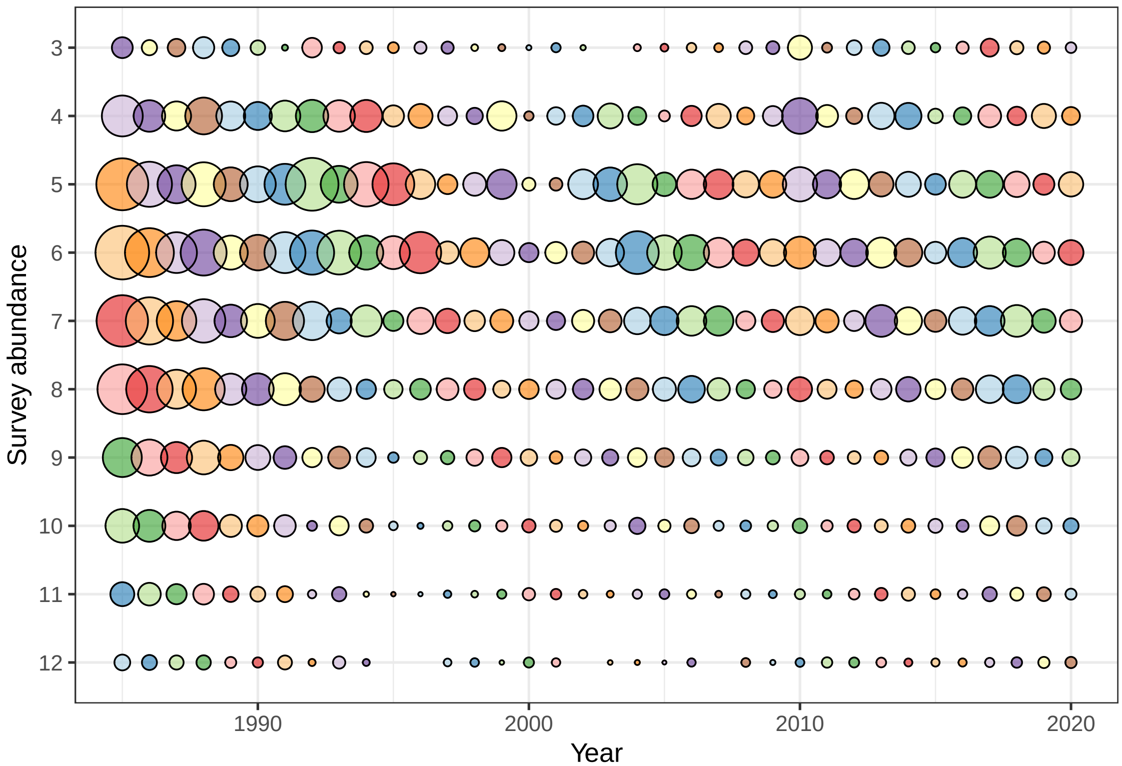

Figure 15: Plaice in 5a. Survey numbers at age from the spring survey, point sizes indicate the estimated swept area abundance by age. Points are colored by year class.

- Observation variances for both catch and survey data were split by age, into two year groups.
- Adjacent age groups residuals were treated as they were correlated, again split into groups of two.
- A break in the recruitment was estimated to have occurred in 1993 (at age 3)
- $\log(N)$ variance split at age 3 and older ages vs not splitting.

The results of this exercise can be seen in the following table:

log(L)	#par	AIC	Obs. var	Obs. AR	Rec. break	N var.	M
-534.2246	15	1098.4492	Fixed	-	-	1st year	0.15
-448.7464	23	943.4928	2 yr blocks	-	-	1st year	0.15
-345.5819	23	737.1639	Fixed	2 yr blocks	-	1st year	0.15
-319.9399	31	701.8798	2 yr blocks	2 yr blocks	-	1st year	0.15
-527.0604	17	1088.1207	Fixed	-	1993	1st year	0.15
-439.1976	25	928.3952	2 yr blocks	-	1993	1st year	0.15
-311.1941	33	688.3882	2 yr blocks	2 yr blocks	1993	1st year	0.15
-315.5654	31	693.1309	2 yr blocks	2x Comm, surv. 2yr	1993	1st year	0.15
-330.9008	27	715.8016	2 yr blocks	Fixed	1993	1st year	0.15
-318.4425	30	696.8850	2 yr blocks	2x Comm, surv. 2yr	1993	Single parameter	0.15

In general treating observation residuals as they were correlated AR(1) processes had the greatest effect on lowering the negative log likelihood, and in combination with splitting the observation variances to 2 year groups the overall AIC was lowered by nearly 350. An additional reduction in AIC occurred when the recruitment process was split into two periods, before and after 1993.

The best fitting model from this exercise was investigated further by systematically loosening up the model parameters. These explorations focused on three avenues:

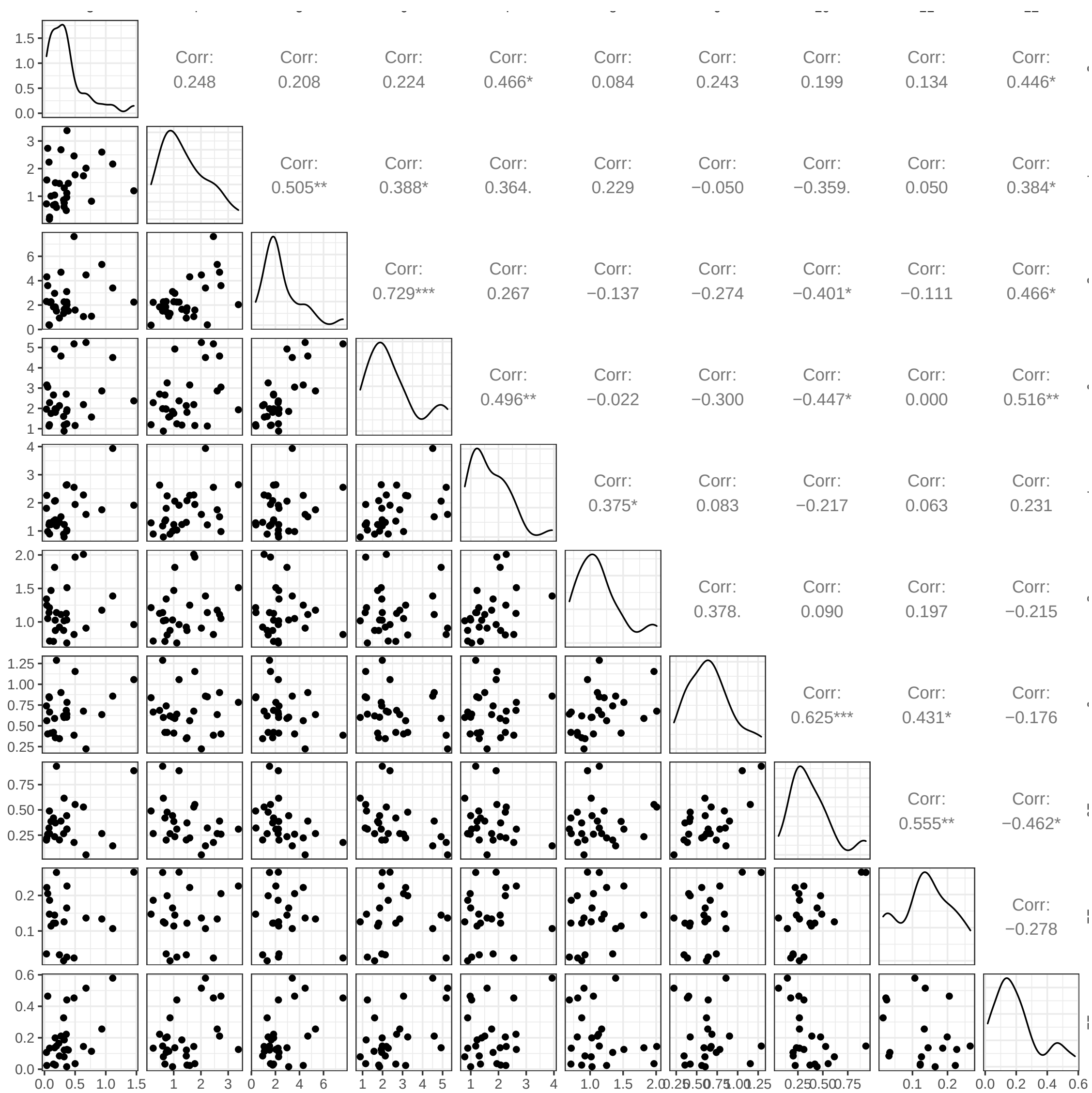

Figure 16: Plaice in 5a. Internal consistency between age based survey indices from the spring survey. The panels illustrate the correlations between age groups, upper triangle panels show the estimated correlation while the lower show the relationship between the indices.

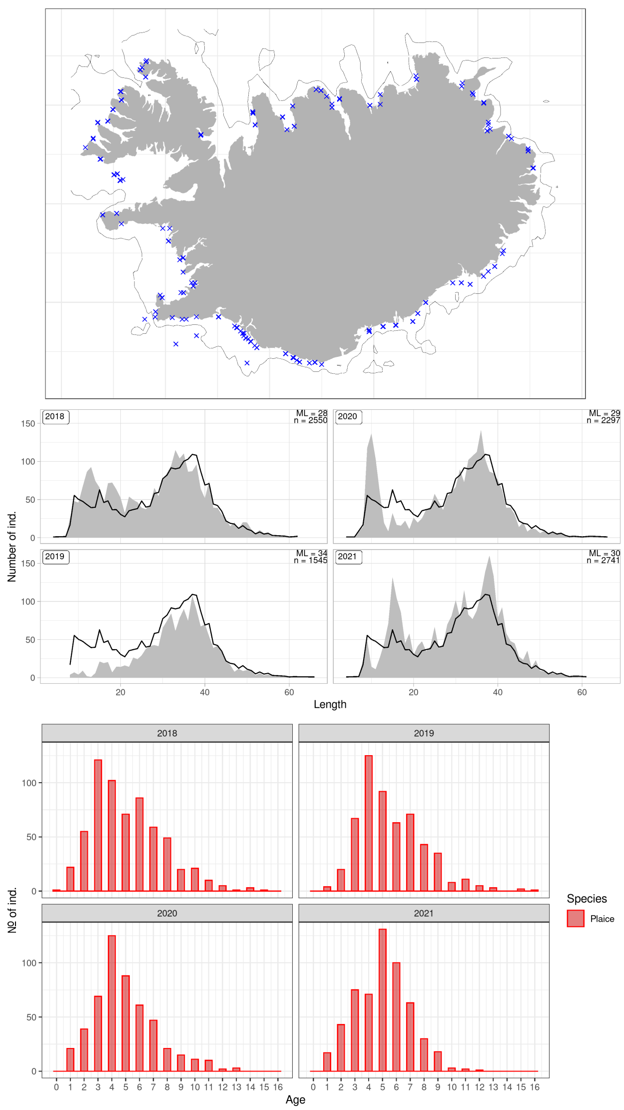

Figure 17: Plaice in 5a. Illustration of preliminary results from the beam trawl survey. Top left figure shows the survey stations, top right the observed length distribution and the bottom figure the age distribution.

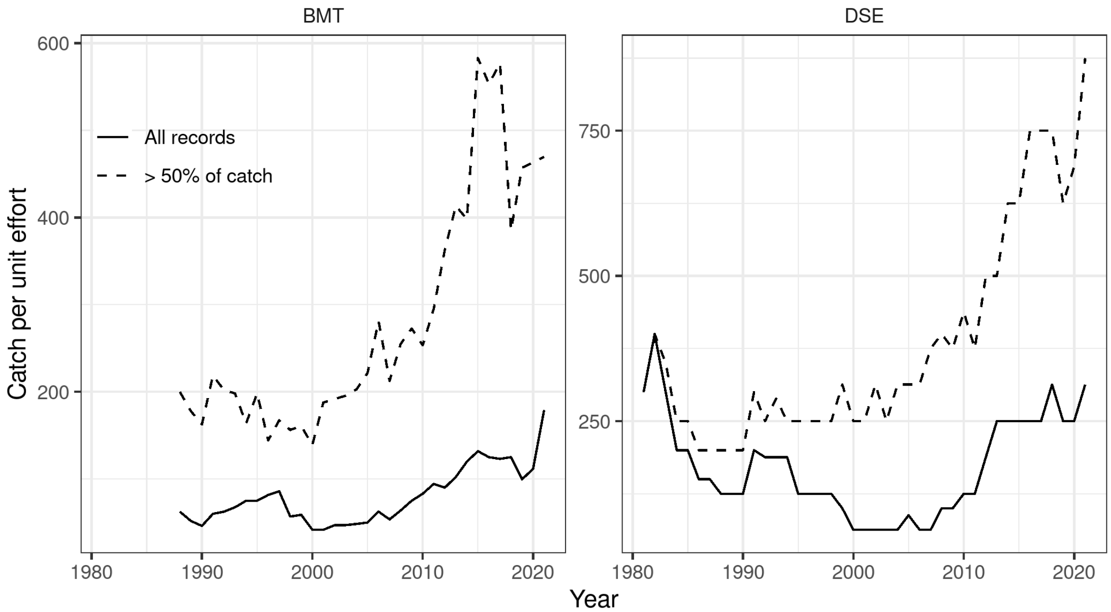

Figure 18: Plaice in 5a. Catch per unit effort from demersal seine and bottom trawl estimated base on commercial logbook data.

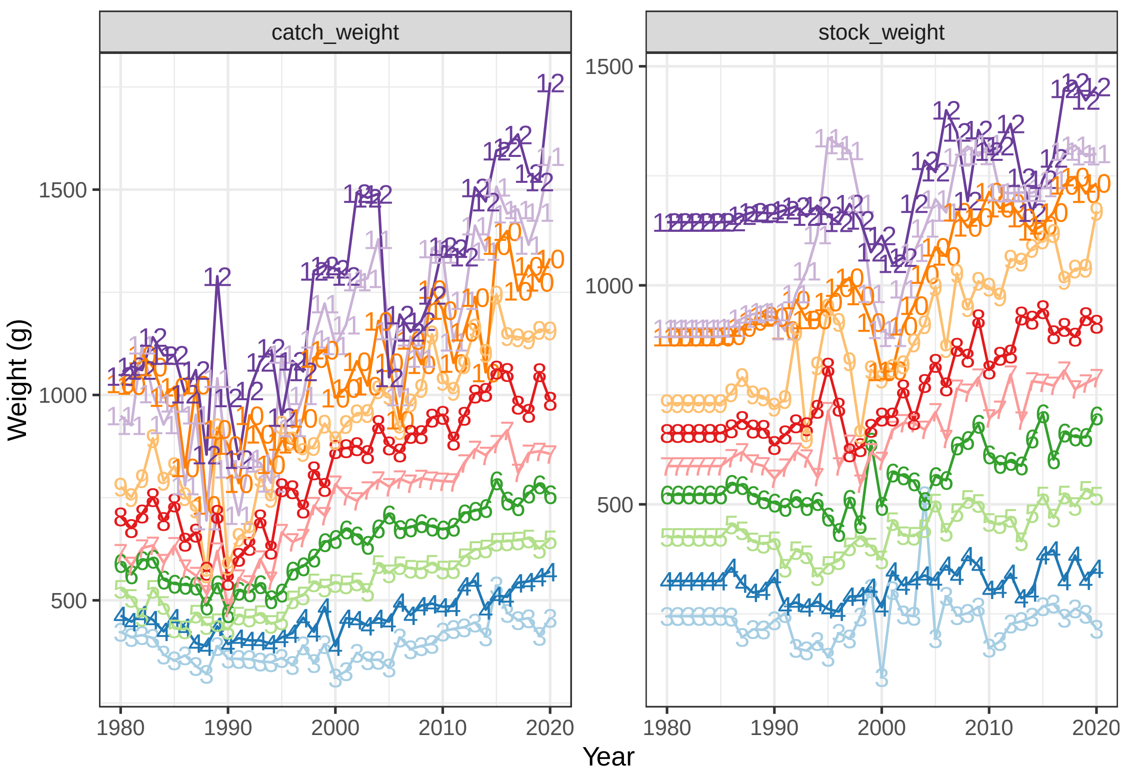

Figure 19: Plaice in 5a. Weight at age observed in the spring survey and from the commercial catches.

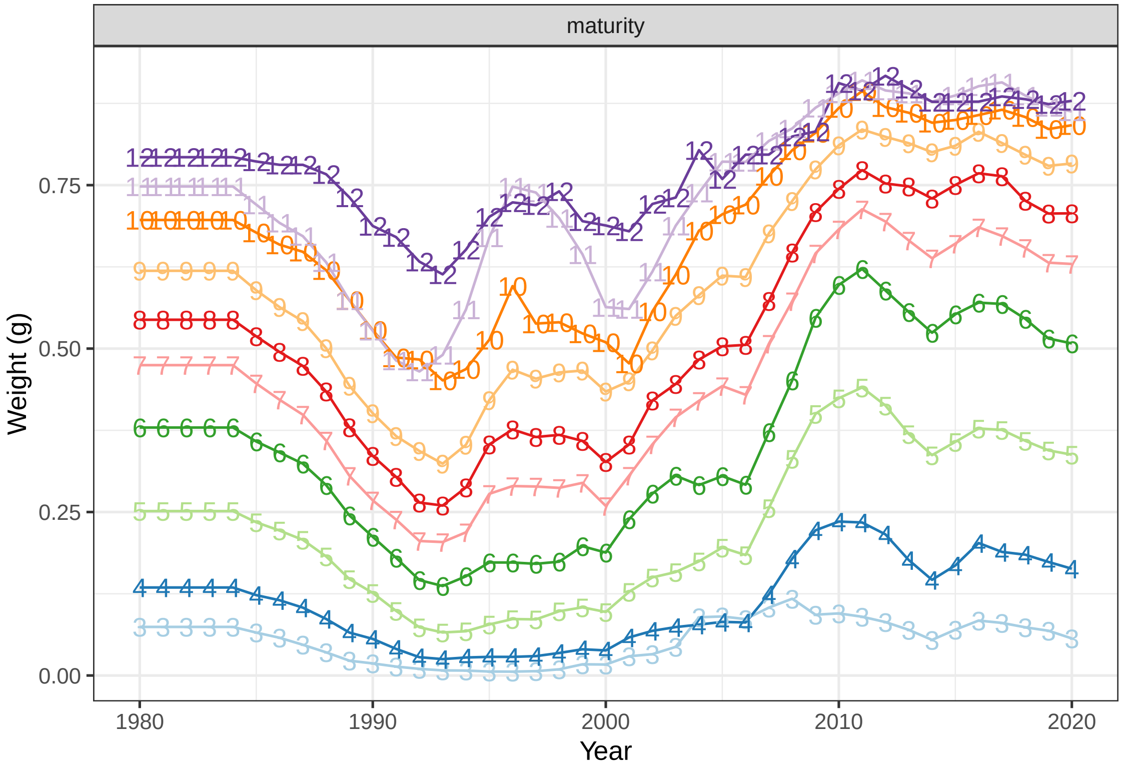

Figure 20: Plaice in 5a. Proportion mature at age from the spring survey.

- Observation variance was split into 1 yr age groups, one data set at a time,
- Correlation between residuals similarly broken into 1 year chunks.
- Survey catchability parameters

In these explorations, adjacent parameters with similar values were joined together based on visual inspection. This resulted in a model that considerably reduced the AIC:

log(L)	#par	AIC	Rec. break	Obs. AR
-268.4884	27	590.9768	1993	Both
-285.1900	25	620.3800	1993	Survey only
-278.7159	25	607.4319		Both
-295.4948	23	636.9896		Survey only

The fit to data is illustrated in Fig. 21 where no concerning residual patterns were revealed. The process residuals for $\log(N)$ and $\log(F)$, shown in Fig. 22, also reveal no pattern.

Fig. 23 shows the estimated model parameters. Observation variances are lowest for the spring survey and commercial catches for ages 5 to 8 and 7 to 8 respectively, with the highest variances at either ends of the age range. Survey variances are in general higher than that of the the commercial catches. Strong positive correlations were estimated between ages for the commercial catches, less for survey catches. Process variances were fixed across all ages for both $\log(N)$ and $\log(F)$, with populations variances estimated at 0.06.

Survey catchabilty showed an increasing trend with age, peaking at the age of 10, while slightly lower at 11 and 12.

6.6 Stock overview

Population dynamics of plaice estimated by this model (Fig. 26) show a clear reduction in the level of recruitment (at age 3) in 1993, and subsequently we see an increase in fishing mortality and reduction in

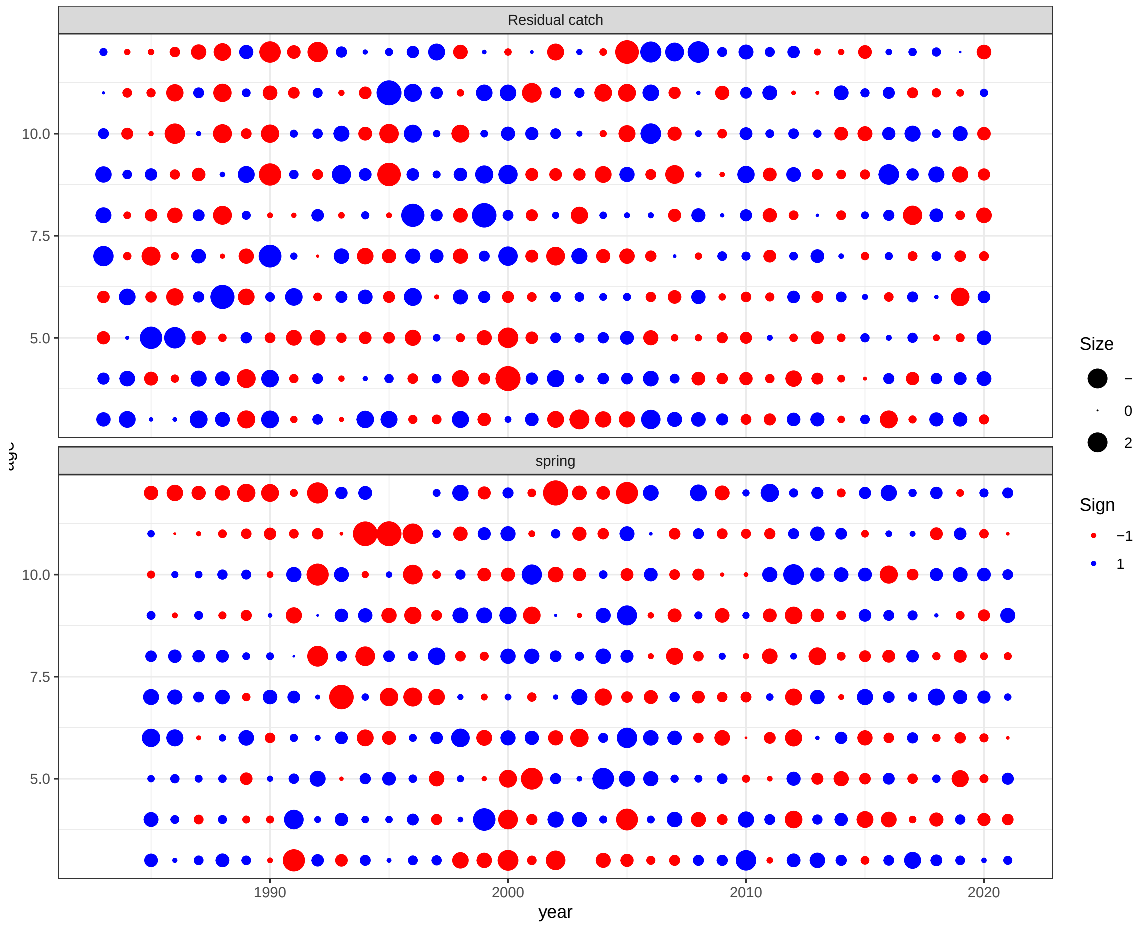

Figure 21: Plaice in 5a. Model residuals from the assessment model. Red circles indicate where the model estimates are higher than the observed while blue indicate models estimates lower than observed.

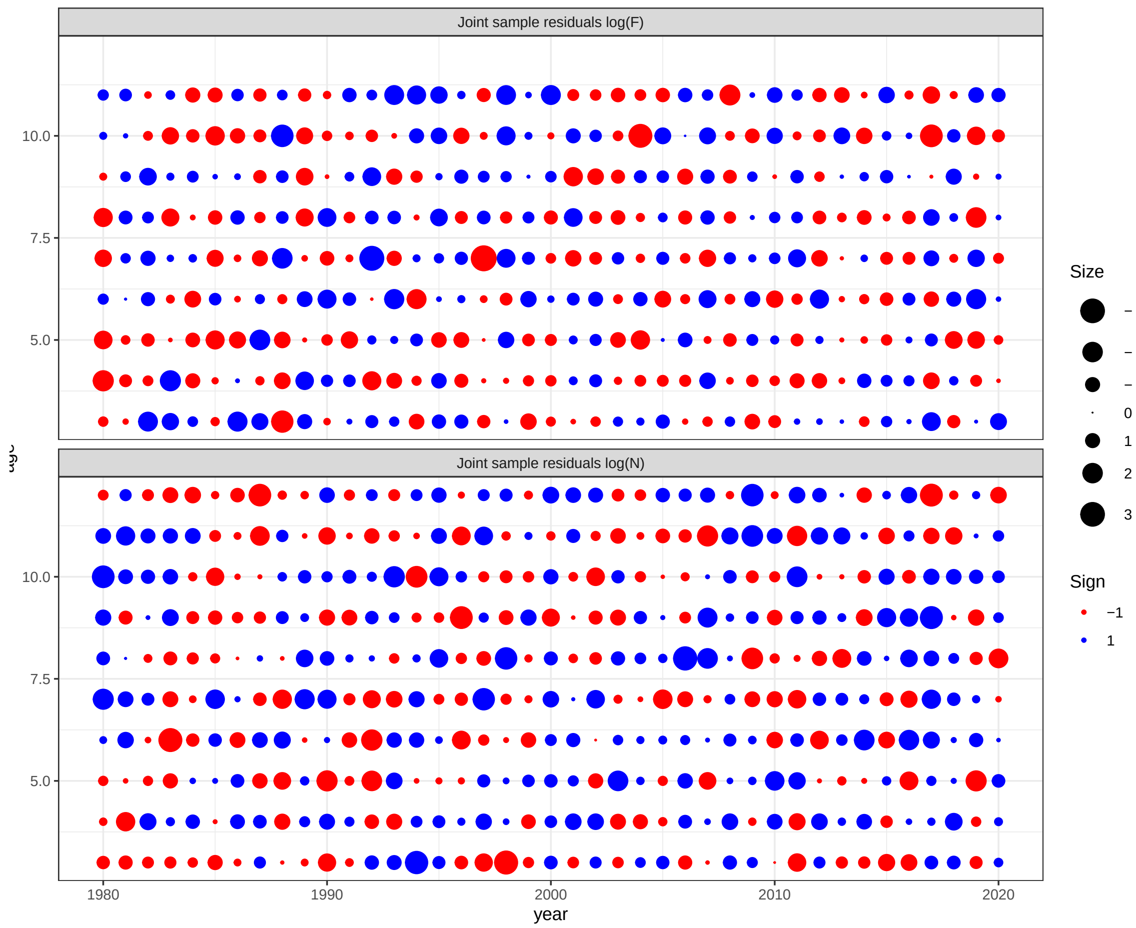

Figure 22: Plaice in 5a. Process residuals from the assessment model.

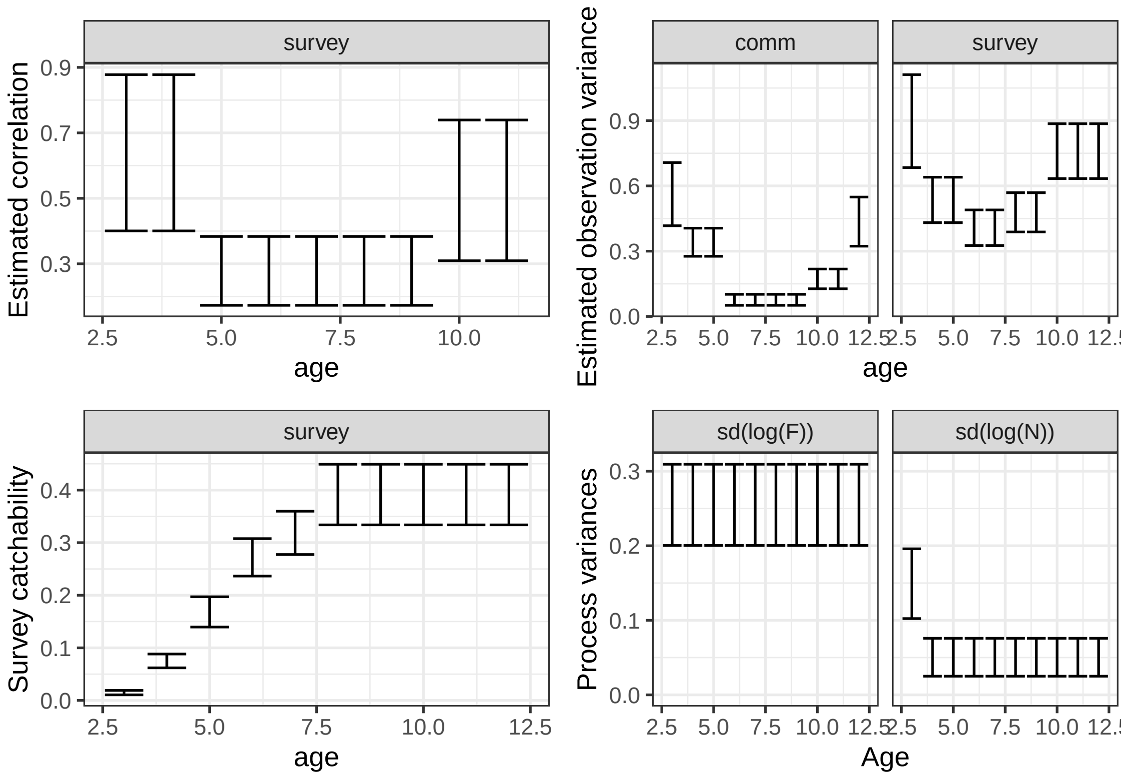

Figure 23: Plaice in 5a. Illustration of estimated model parameters.

total catches. Spawning stock biomass (SSB) was at its lowest value at the turn of the century. In recent years recruitment is seen to be stable at the post 1993 levels whereas fishing mortality has been reduced and SSB increased. Catches have remained stable, slightly increasing.

6.7 Analytical retrospective

The proposed model had low Mohn's ρ statistic values for spawning stock biomass, fishing mortality, and recruitment. Analytical retrospective plots do not indicate any substantial deviations in assessment (Fig. 27). These Mohn's ρ values are well within the range recommended by Carvalho et al. [3].

6.8 Leave-out analysis

Fig. 28 shows the results comparing the full model estimates with estimates where the survey time series has been omitted from the observation likelihood. The results show good agreement between model estimates with and with out the survey suggesting high influence of the catch data to the final model.

6.8.1 Ranges of natural mortality

A range of M's were investigated (see Fig. 29) along with size dependent M using both the Gislason and Chernov method. The profile likelihood is minimized when M is set as 0.24 with a 95% confidence range of 0.13 to 0.34. The assumption of natural mortality as 0.15 for all ages appears to be within the confidence range suggested by the profile likelihood.

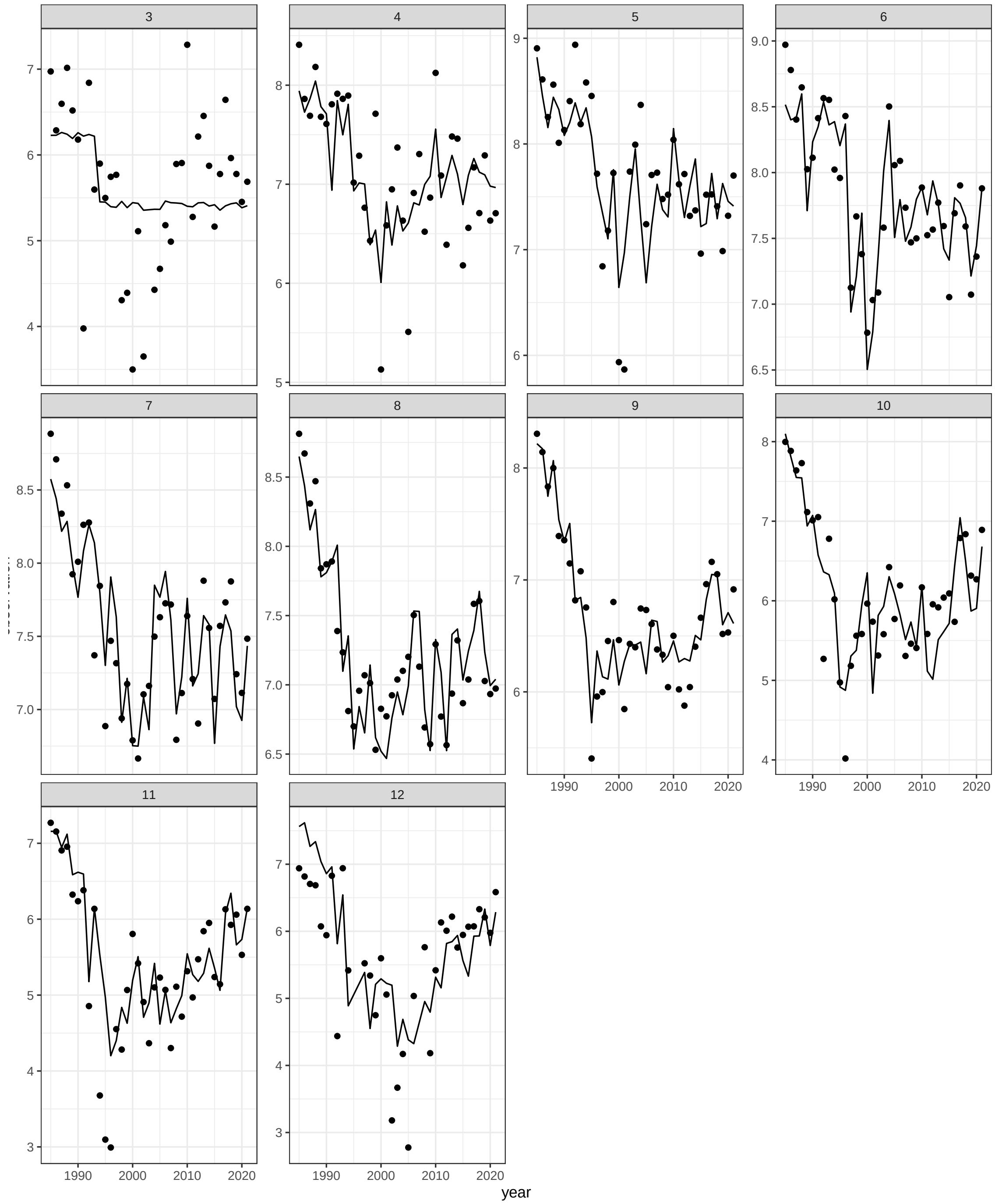

Figure 24: Plaice in 5a. Illustration of the model fit to the survey data by age. Points indicate the log observations while the solid lines the model fit.

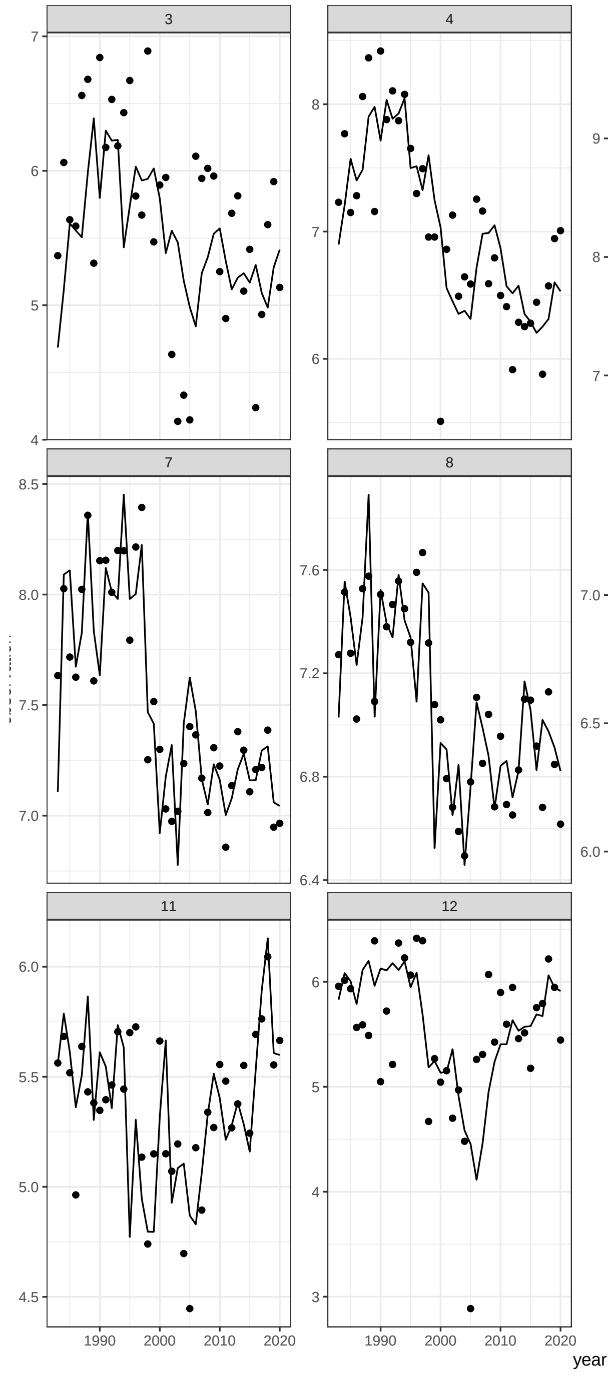

Figure 25: Plaice in 5a. Illustration of the model fit to the commercial catch in age. Points indicate the log observations while the solid lines the model fit.

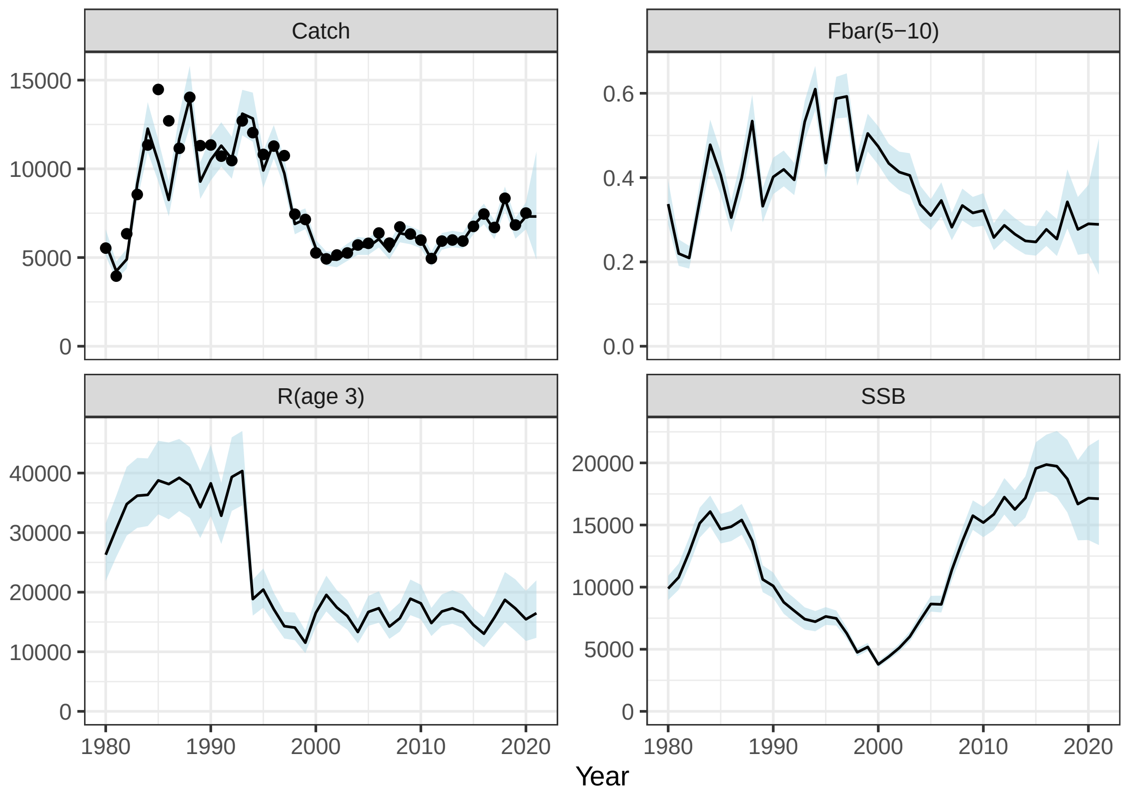

Figure 26: Plaice in 5a. Estimates of spawning stock biomass, fishing mortality (weighted average of ages 5 to 10), recruitment and landings from the best model. Black line represents the point estimates and blue ribbon the 90% confidence intervals.

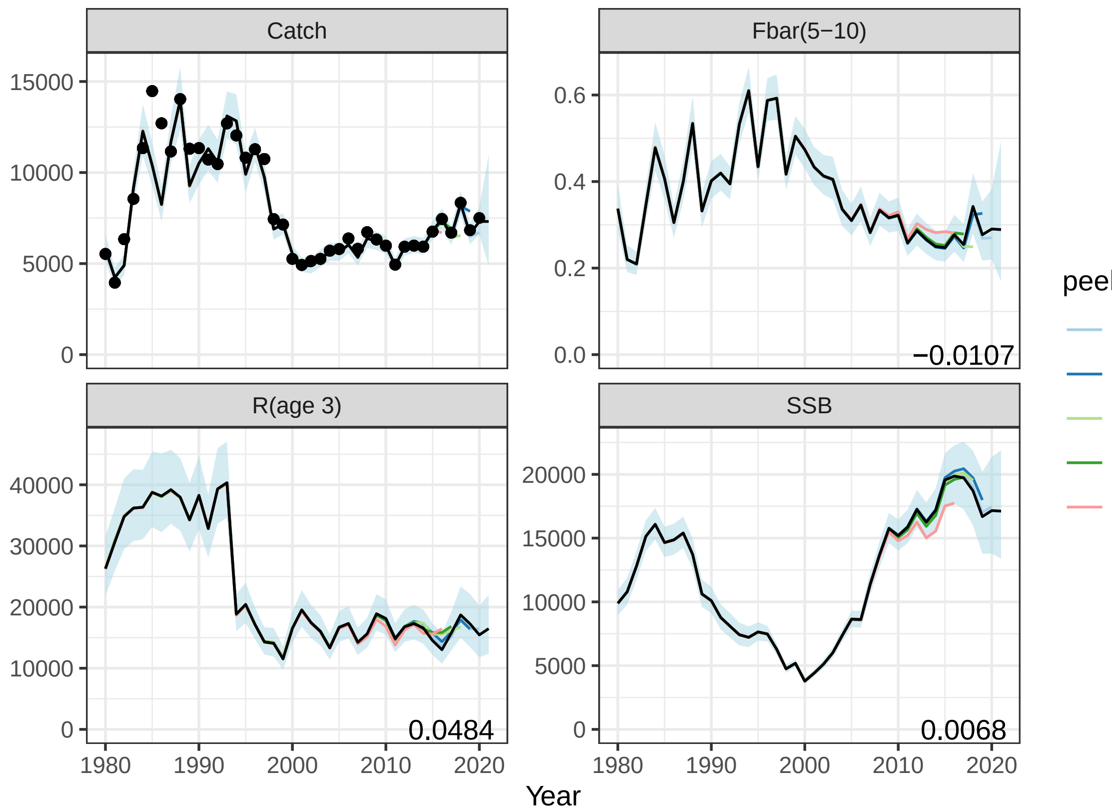

Figure 27: Plaice in 5a. Analytical retrospective estimates of SSB, catch, F and recruitment. Mohns rho is indicated in the bottom right corner.

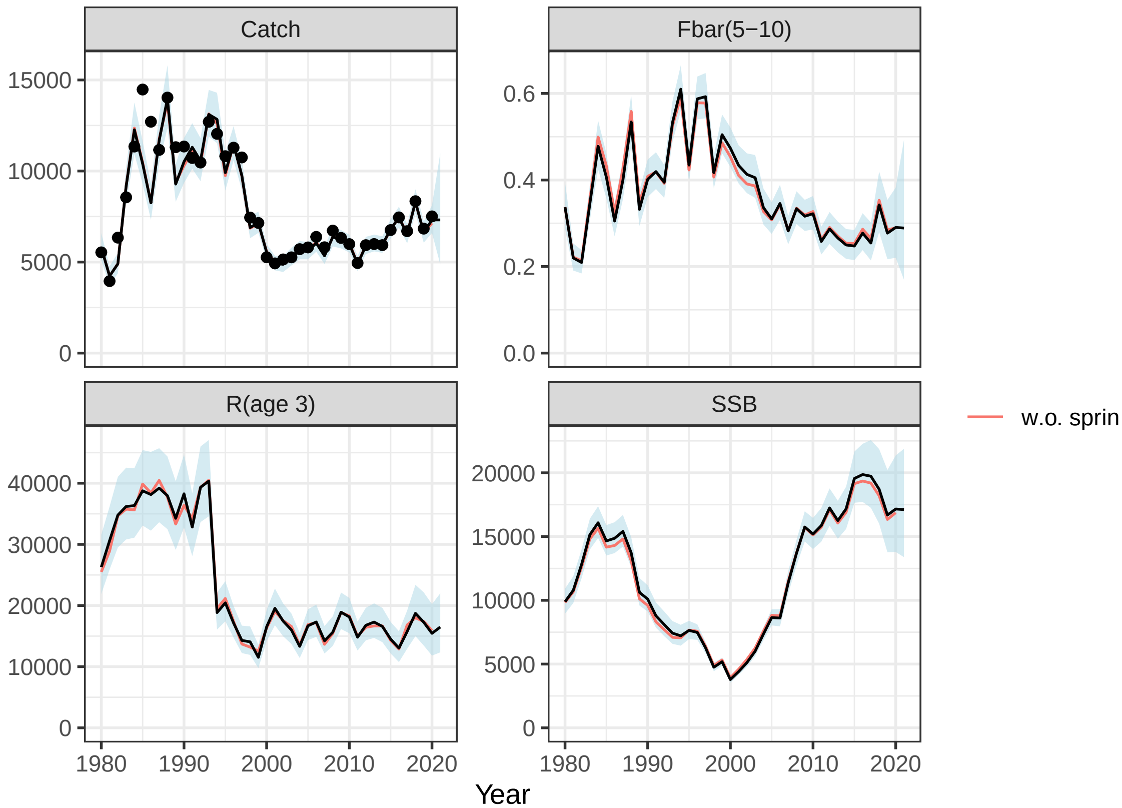

Figure 28: Plaice in 5a. Leave-out estimates of SSB, catch, F and recruitment.

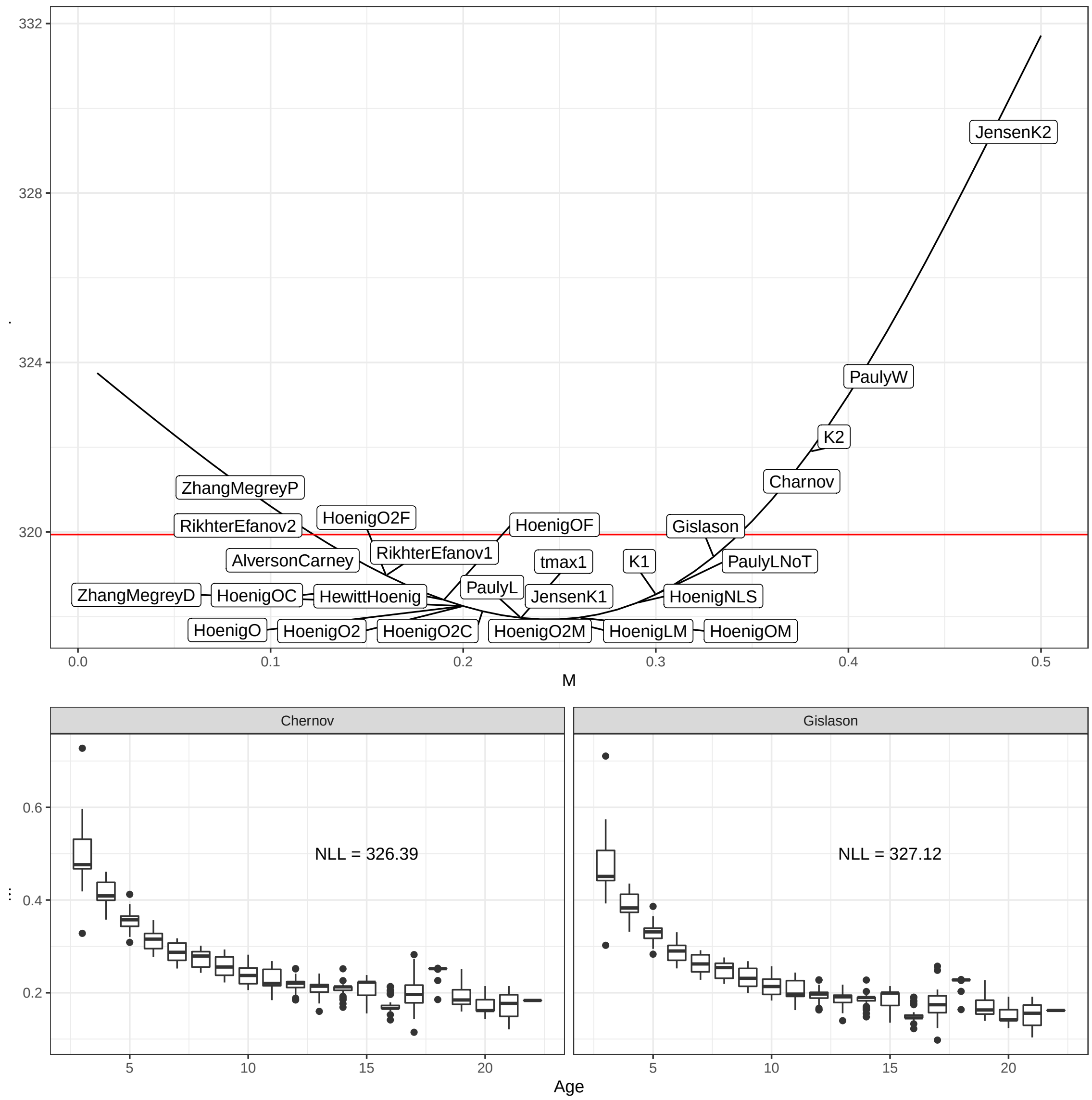

Figure 29: Plaice in 5a. Left panel shows a profile likelihood plot (negative log likelihood) for different values of fixed M. Results from different M derivations based on life-history parameters are overlayed. Red line indicates 95% confidence regions. Bottom panels show boxplots of size based M values along with the negative log-likelihood values from the fitted SAM model.

7 Short term projections

Short term projections are performed using the standard procedure in SAM using the `forecast` function. Three year averages are used for stock and catch weights, and maturity. From this projection the advice is derived. The advice is based on the Icelandic fishing year starting in September each year. This causes a mismatch between the assessment model, which is based on the calendar year. So in order to provide advice for the fishing year, the standard projection procedure in SAM will need to be adapted to accommodate these differences. So given the assessment in year y the interim year catches are based on the following fishing mortality:

$$F_y = \left(\frac{8}{12}F_{sq} + \frac{4}{12}F_{mgt}\right)$$

and therefore the total catches for year y will be:

$$C_y = \frac{F_y}{F_y + M}\left(1 - e^{-(F_y+M)}\right)B_y$$

and the part of the catch in the fishing year y-1/y will be

$$\frac{\frac{8}{12}F_{sq}}{\left(\frac{8}{12}F_{sq} + \frac{4}{12}F_{mgt}\right)}C_y$$

and the catch in fishing year y/y+1 will be:

$$C_{y/y+1} = \frac{\frac{4}{12}F_{mgt}}{\left(\frac{8}{12}F_{sq} + \frac{4}{12}F_{mgt}\right)}C_y + \frac{8}{12}C_{y+1}$$

where

$$C_{y+1} = \frac{F_{mgt}}{F_{mgt} + M}\left(1 - e^{-(F_{mgt}+M)}\right)B_y$$

8 Appropriate Reference Points (MSY)

According ICES technical guidelines, two types of reference points are referred to when giving advice for category 1 stocks: *precautionary approach* (PA) reference points and *maximum sustainable yield* (MSY) reference points. The PA reference points are used when assessing the state of stocks and their exploitation rate relative to the precautionary approach objectives. The MSY reference points are used in the advice rule applied by ICES to give advice consistent with the objective of achieving MSY.

Generally ICES derives these reference points based on the level of the spawning stock biomass and fishing mortality. The following sections describe the derivation of the management reference points in terms of fishing mortality (F) and SSB (B). It further describes the model for stock–recruitment, weight and maturity at age, and assessment error is used to project the stock in order to derive the PA and MSY reference points.

8.0.1 Setting B_{lim} and B_{pa}

B_{lim} was considered from examination of the SSB–Recruitment (at age 3) scatterplot based on the estimates from the stock assessment, as illustrated in fig. 30. The figure shows that the recruitment is fairly independent of the size of SSB with a strong shift in level after 1990. Given the strong auto correlation in the number of independent estimates of the number of recruits is low. In this situation there is no clear guidance from the ICES technical guidelines, however given this strong correlation one could treat this SSB-recruitment relationship as type 1 (Spasmodic stock). In that scenario B_{lim} is derived from the lowest observed SSB with period when large recruitment is observed (i.e. B_{loss} = SSB(1990) = 10100 t).

In line with ICES technical guidelines B_{pa} is then calculated based on multiplying B_{lim} with $e^{1.645\sigma_{SSB}}$, where σ is the CV in the assessment year of SSB or 0.12, used for calculating B_{pa} from B_{lim}. This is considered to reflective of the true assessment error of the SSB as the assessment is seen to be stable and input data are internally consistent. Therefore B_{pa} should be set at $B_{lim}e^{1.645*\sigma_{SSB}} = 12400$ t.

8.0.2 Stock recruitment relationship

A variety of approaches are common when estimating a stock–recruitment relationship. In the absense of a stock-recruitment signal from the available historical data (Fig. 30, the ICES guidelines suggest that the “hockey-stick’ ’ recruitment function is used, i.e.

$$R_y = \bar{R}_y \min(1, S_y/B_{break})$$

where R_y is annual recruitment, S_y the spawning stock biomass, B_{break} the break point in hockey stick function and $\bar{R}_y$ is the recruitment when not impaired due to low levels of SSB. Here $\bar{R}_y$ is considered to be drawn from an auto–correlated log–normal distribution with a mean, CV and ρ estimated based on the estimated recruits after 1990. This is done to account for possible auto-correlation in the recruitment time–series and possible shifts in productivity of the stock. An example of the simulated relationship is shown in fig. 31.

8.0.3 Stock– and catchweights

Prediction of weight at age in the stock, selectivity and the maturity at age follow the traditional process from the ICES guidelines, that is the average of the last 10 years of values for weight, selectivity and maturity at age used in the projections. These values are illustrated in figures 32 to 34.

8.0.4 Management procedure in forward projections

Illegal landings and discards by Icelandic fishing vessels are considered to be negligible (as noted above). Current knowledge of plaice in 5.a, discussed above, suggests that it should be assessed as a single stock unit. As this is the first time the stock is assessed by ICES the appropriated assessment error is simulated in terms of fishing mortality by assuming F in the projections is a log-normal AR(1) process with the default values for CV as 0.212 and autocorrelation of 0.423.

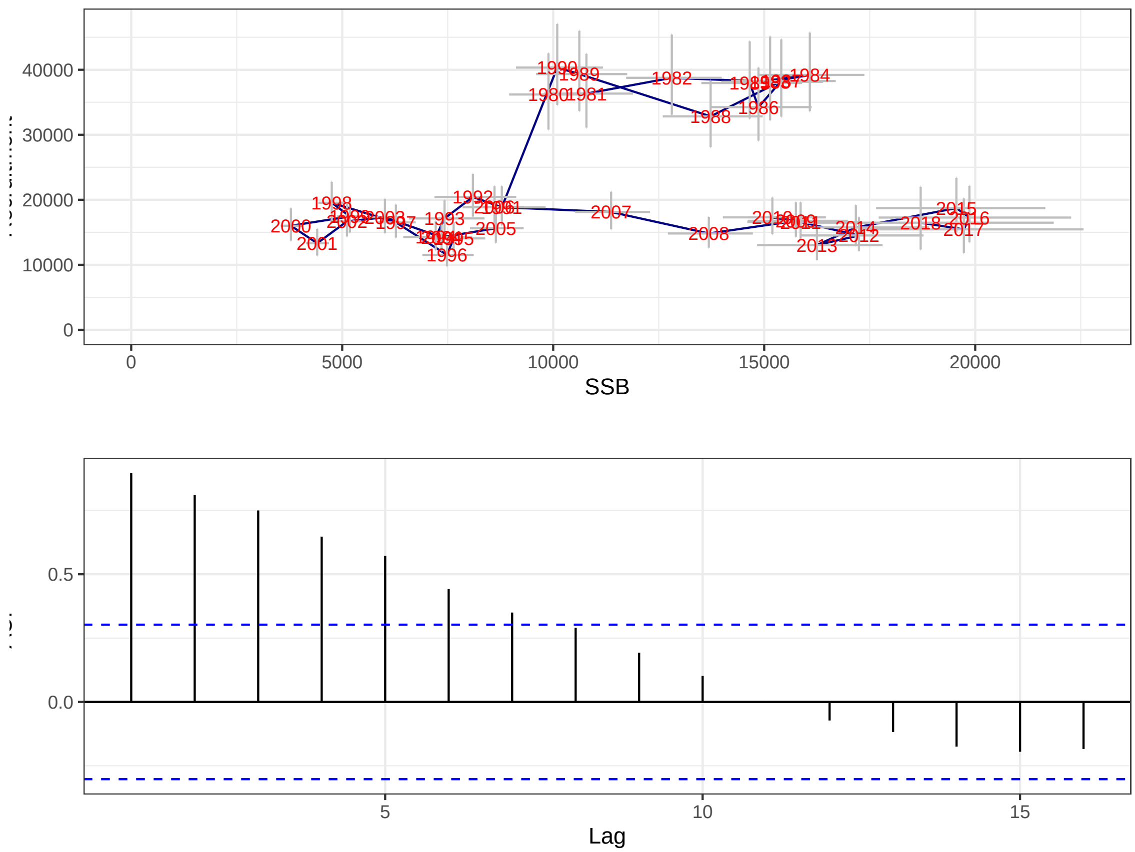

Figure 30: Plaice in 5a. Upper panel shows the stimated stock recruitment plot. Grey crossed indicate uncertainty, red text point estimate with the associated year and black lines show the progression of the stock recruitment relationship. The lower panel show the estimated autocorrelation of the recruitment time-series.

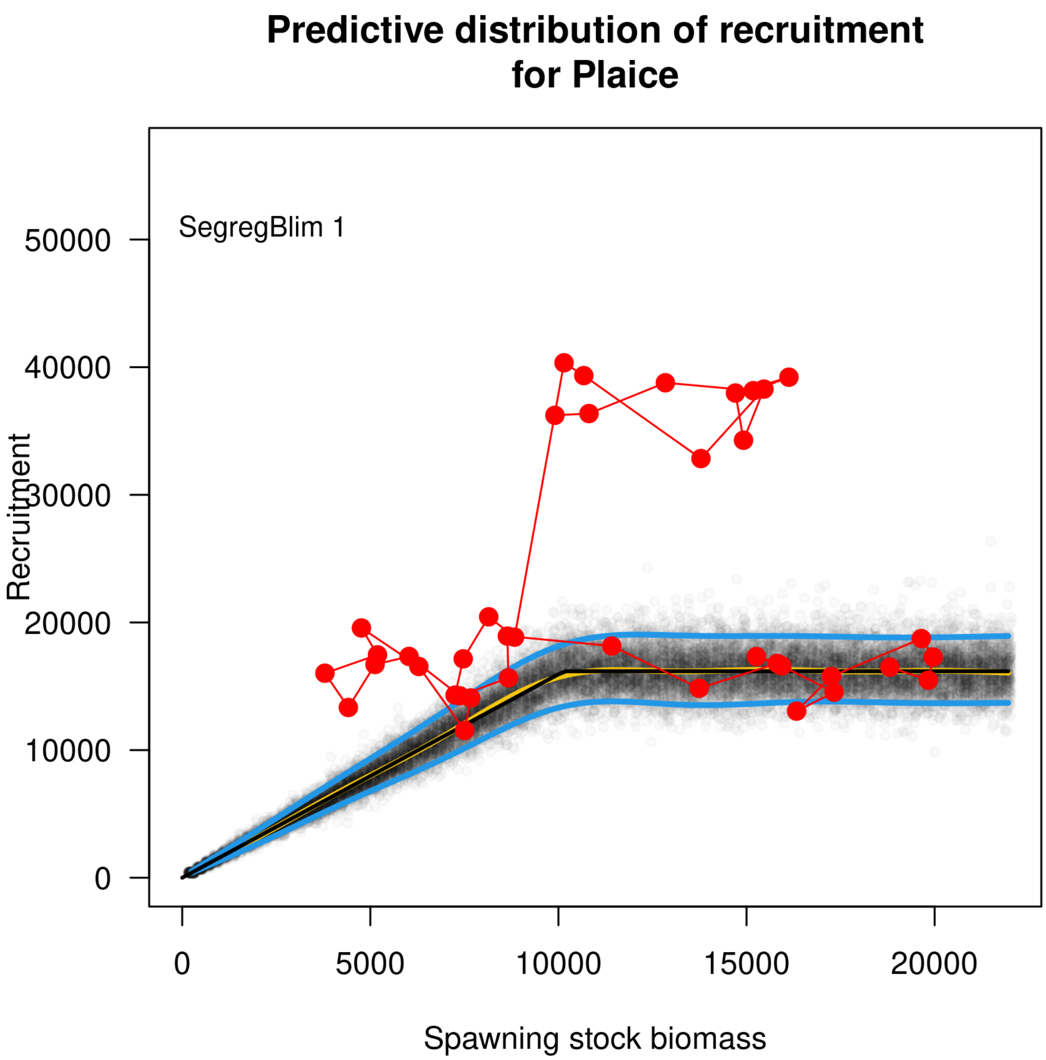

Figure 31: Plaice in 5a. Estimated stock recruitment function used in the projections. Red points and lines show the model estimates, grey points show the simulated recruitment and blue lines the 95th quantiles.

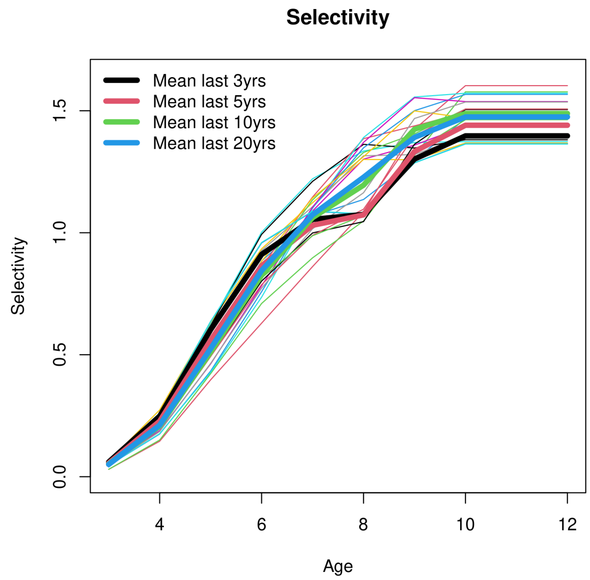

Figure 32: Plaice in 5a. Settings for the projections. Estimated selectivity at age by year (narrow coloured lines) illustrated with 3, 5, 10 and 20 year averages (thick lines).

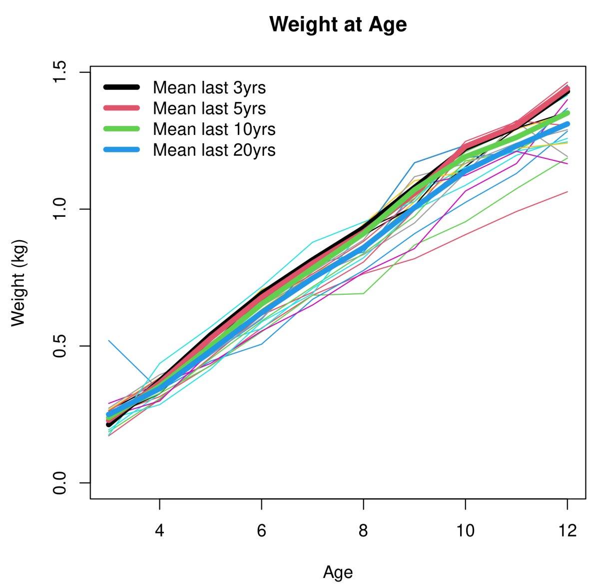

Figure 33: Plaice in 5a. Settings for the projections. Estimated weight at age by year (narrow coloured lines) illustrated with 3, 5, 10 and 20 year averages (thick lines)

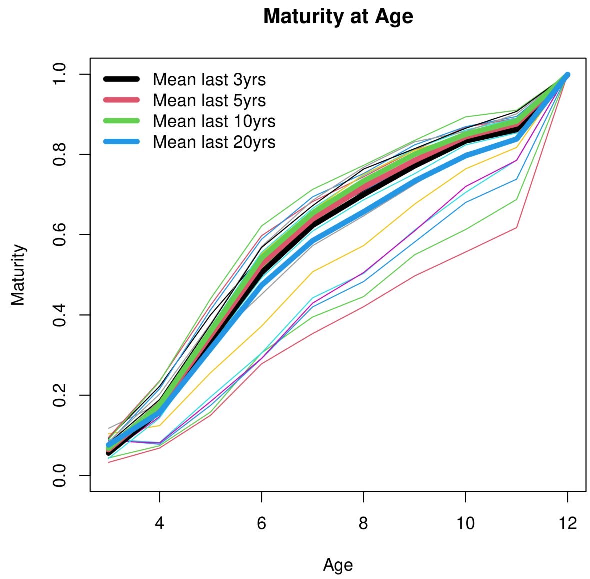

Figure 34: Plaice in 5a. ettings for the projections. Estimated maturity at age by year (narrow coloured lines) illustrated with 3, 5, 10 and 20 year averages (thick lines)

8.0.5 Setting F_{lim} and F_{pa}

According to the ICES guidelines, the precautionary reference points are set by simulating the stock using the stock-recruitment, growth and maturity relationship described above, based on a wide range of fishing mortalities, ranging from 0 to 1 and setting F_{lim} as the F that, in equilibrium, gives a 50% probability of SSB $> B_{lim}$ without assessment error.

For each replicate the stock status was projected forward 50 years as simulations, and average of those projected values used to estimate the MSY reference points. The results from the steady state simulations estimate the value of F, F_{lim}, resulting in 50% long–term probability of SSB $> B_{lim}$ to be at 0.57.

8.0.6 MSY reference points

As an additional simulation experiment where, in addition to recruitment and growth variations, assessment error was added. The harvest rate that would lead to the maximum sustainable yield, F_{msy}, was then estimated. Average annual landings and 90% quantiles were used to determine the yield by F. Fig. 36 shows the evolution of catches, SSB and fishing mortality for select values of F. The equilibrium yield curve is shown in fig. 35, where the maximum average yield, under the recruitment assumptions, is 6.8 thousand tons.

In line with ICES technical guidelines, the MSY $B_{trigger}$ is set as B_{pa} as this is the first time the reference points are evaluated. Maximum yield is estimated to be obtained at a F of 0.41. F_{p05}, i.e. the maximum F that has less than 5% chance of going below B_{lim} when the advice rule is applied, is 0.46, thus not limiting the estimate of F_{msy}. The evolution of the spawning stock biomass is shown in figure 36 and equilibrium spawning stock biomass is shown in figure 35.

When the ICES AR rule is implemented is it appears that the probability of going below B_{pa} exceeds 0.2, suggesting that on average the effective fishing mortality is lower than the target F_{msy} of 0.4 suggesting that catch levels could fluctuate more than the fishable biomass level. So a lower fishing mortality could have similar yields while being more stable.

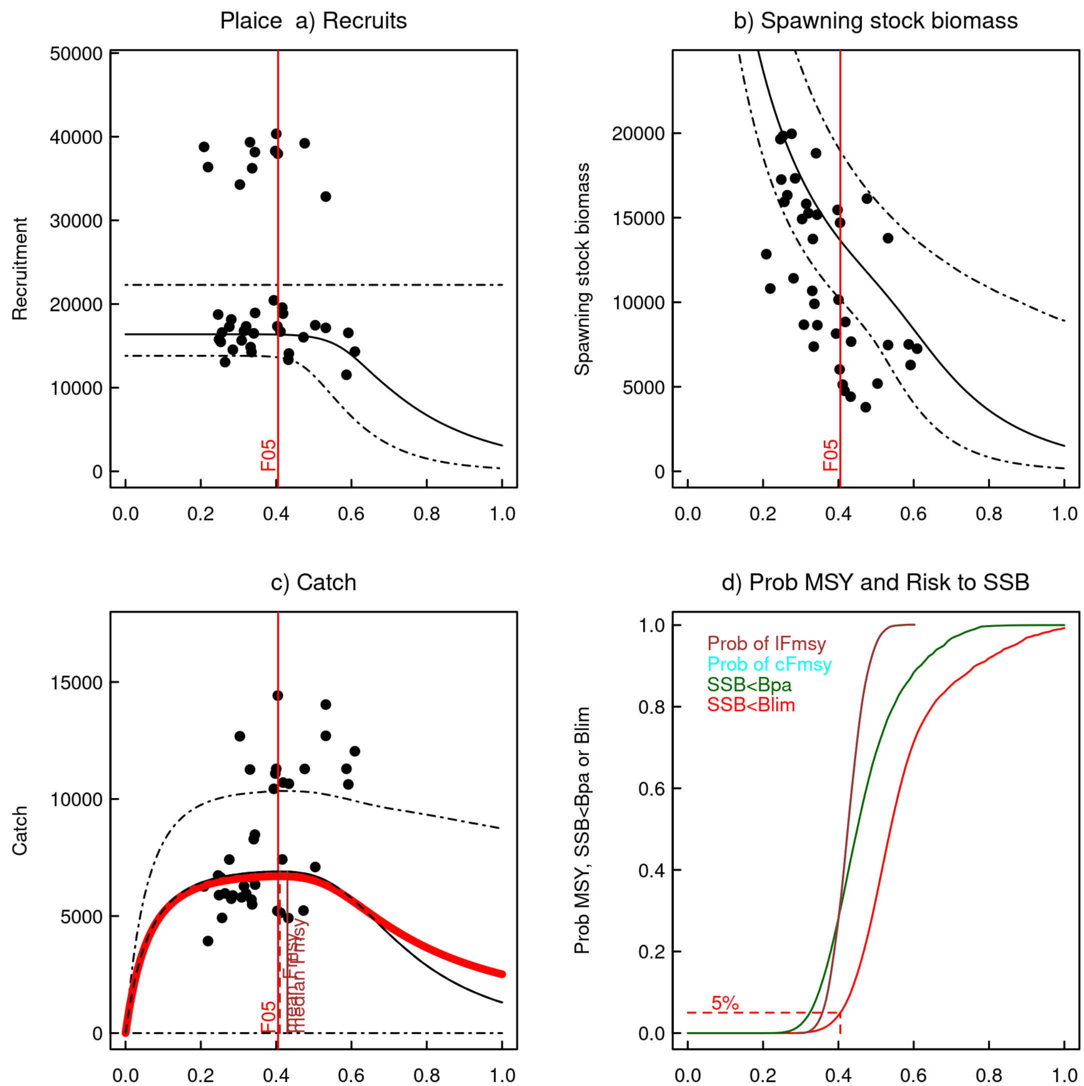

Figure 35: Plaice in 5a. Equilibrium catch, recruitment, SSB and risk from forward projections. No trigger values used.

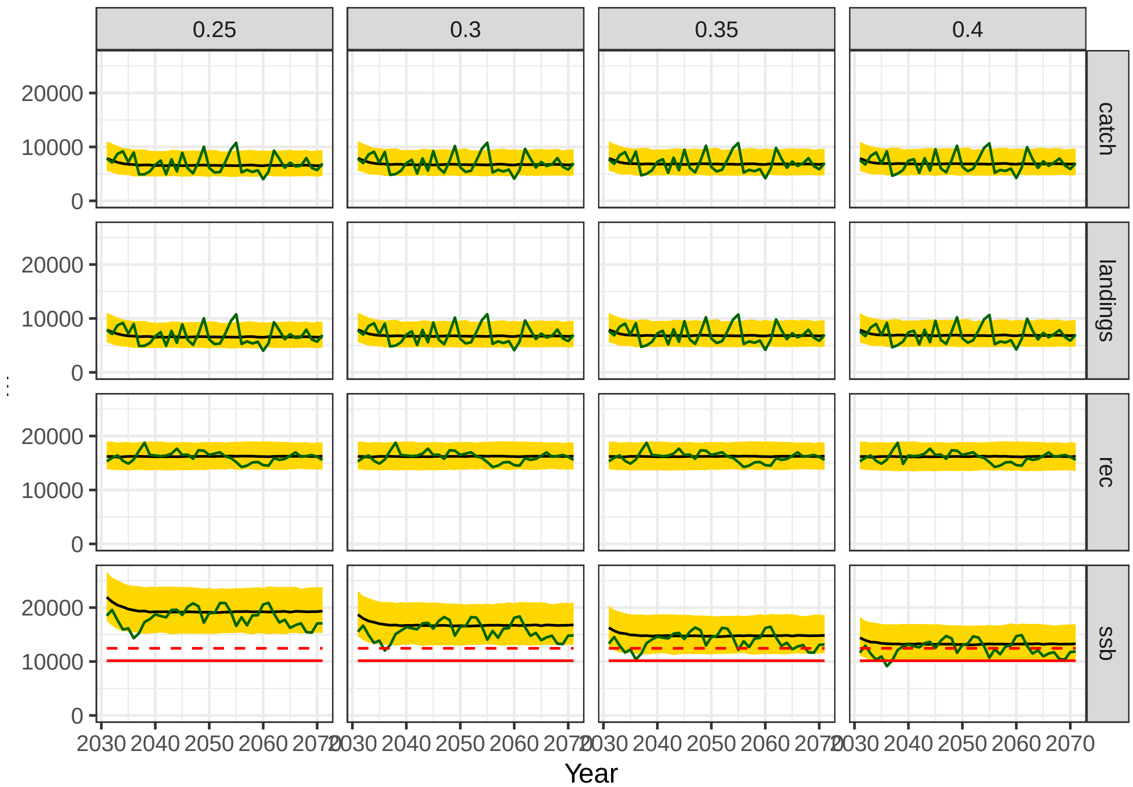

Figure 36: Plaice in 5a. Results from the projections for select fishing mortalities. Black solid line shows the mdiian projection, yellow ribbon the 5 and 95 percentiles and the dashed and solid red lines Bpa and Blim respectively. Green line show on realisation from the projections.

Plaice in 5a. Overview of estimated reference points

Reference point	Value	Basis
MSYBtrigger	12400	Bpa
5thPerc_SSBmsy	11300	5th quantile of SSB when fishing at Fmsy
Bpa	12400	Blim x exp(1.645 sigma_SSB)
Blim	10100	Lowest SSB (1990) when large recruitment was observed (Type 1)
Flim	0.57	F leading to P(SSB < Blim) = 0.5
Fp05	0.46	F, when ICES AR is applied, leading to P(SSB > Blim) = 0.05
Fmsy_unconstr	0.41	Unconstrained F leading to MSY
Fmsy	0.41	F leading to MSY

9 Model configuration

```
## # Configuration saved: Wed Apr 13 15:27:05 2022
## #
## # Where a matrix is specified rows corresponds to fleets and columns to ages.
## # Same number indicates same parameter used
## # Numbers (integers) starts from zero and must be consecutive
## # Negative numbers indicate that the parameter is not included in the model
## #
## $minAge
## # The minimium age class in the assessment
##  3
##
## $maxAge
## # The maximum age class in the assessment
##  12
##
## $maxAgePlusGroup
## # Is last age group considered a plus group for each fleet (1 yes, or 0 no).
##  1 1
##
## $keyLogFsta
## # Coupling of the fishing mortality states processes for each age (normally only
## # the first row (= fleet) is used).
## # Sequential numbers indicate that the fishing mortality is estimated individually
## # for those ages; if the same number is used for two or more ages, F is bound for
## # those ages (assumed to be the same). Binding fully selected ages will result in a
## # flat selection pattern for those ages.
##    0   1   2   3   4   5   6   7   8   8
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##
## $corFlag
## # Correlation of fishing mortality across ages (0 independent, 1 compound symmetry,
## # 2 AR(1), 3 separable AR(1).
## # 0: independent means there is no correlation between F across age
## # 1: compound symmetry means that all ages are equally correlated;
## # 2: AR(1) first order autoregressive - similar ages are more highly correlated than
## # ages that are further apart, so similar ages have similar F patterns over time.
## # if the estimated correlation is high, then the F pattern over time for each age
## # varies in a similar way. E.g if almost one, then they are parallel (like a
## # separable model) and if almost zero then they are independent.
```

```
## # 3: Separable AR - Included for historic reasons . . .  more later
##  2
##
## $keyLogFpar
## # Coupling of the survey catchability parameters (nomally first row is
## # not used, as that is covered by fishing mortality).
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##    0   1   2   3   4   5   5   5   5   5
##
## $keyQpow
## # Density dependent catchability power parameters (if any).
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##
## $keyVarF
## # Coupling of process variance parameters for log(F)-process (Fishing mortality
## # normally applies to the first (fishing) fleet; therefore only first row is used)
##    0   0   0   0   0   0   0   0   0   0
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##
## $keyVarLogN
## # Coupling of the recruitment and survival process variance parameters for the
## # log(N)-process at the different ages. It is advisable to have at least the first age
## # class (recruitment) separate, because recruitment is a different process than
## # survival.
##  0 1 1 1 1 1 1 1 1 1
##
## $keyVarObs
## # Coupling of the variance parameters for the observations.
## # First row refers to the coupling of the variance parameters for the catch data
## # observations by age
## # Second and further rows refers to coupling of the variance parameters for the
## # index data observations by age
##    0   1   1   2   2   2   2   3   3   4
##    5   6   6   7   7   8   8   9   9   9
##
## $obsCorStruct
## # Covariance structure for each fleet ("ID" independent, "AR" AR(1), or "US" for unstructured). | Pos
##  "ID" "AR"
##
## $keyCorObs
## # Coupling of correlation parameters can only be specified if the AR(1) structure is chosen above.
## # NA's indicate where correlation parameters can be specified (-1 where they cannot).
## #3-4 4-5 5-6 6-7 7-8 8-9 9-10 10-11 11-12
##   NA  NA  NA  NA  NA  NA  NA  NA  NA
##    0   0   1   1   1   1   1   2   2
##
## $stockRecruitmentModelCode
## # Stock recruitment code (0 for plain random walk, 1 for Ricker, 2 for Beverton-Holt, 3 piece-wise co
##  3
##
## $noScaledYears
## # Number of years where catch scaling is applied.
##  0
```

```
##
## $keyScaledYears
## # A vector of the years where catch scaling is applied.
##
##
## $keyParScaledYA
## # A matrix specifying the couplings of scale parameters (nrow = no scaled years, ncols = no ages).
##
## $fbarRange
## # lowest and higest age included in Fbar
##  5 10
##
## $keyBiomassTreat
## # To be defined only if a biomass survey is used (0 SSB index, 1 catch index, 2 FSB index, 3 total ca
##  -1 -1
##
## $obsLikelihoodFlag
## # Option for observational likelihood | Possible values are: "LN" "ALN"
##  "LN" "LN"
##
## $fixVarToWeight
## # If weight attribute is supplied for observations this option sets the treatment (0 relative weight
##  0
##
## $fracMixF
## # The fraction of t(3) distribution used in logF increment distribution
##  0
##
## $fracMixN
## # The fraction of t(3) distribution used in logN increment distribution (for each age group)
##  0 0 0 0 0 0 0 0 0 0
##
## $fracMixObs
## # A vector with same length as number of fleets, where each element is the fraction of t(3) distribut
##  0 0
##
## $constRecBreaks
## # Vector of break years between which recruitment is at constant level. The break year is included in
##  1993
##
## $predVarObsLink
## # Coupling of parameters used in a prediction-variance link for observations.
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##
## $hockeyStickCurve
## #
##  20
##
## $stockWeightModel
## # Integer code describing the treatment of stock weights in the model (0 use as known, 1 use as obser
##  0
##
## $keyStockWeightMean
```

```
## # Coupling of stock-weight process mean parameters (not used if stockWeightModel==0)
##  NA NA NA NA NA NA NA NA NA NA
##
## $keyStockWeightObsVar
## # Coupling of stock-weight observation variance parameters (not used if stockWeightModel==0)
##  NA NA NA NA NA NA NA NA NA NA
##
## $catchWeightModel
## # Integer code describing the treatment of catch weights in the model (0 use as known, 1 use as obse
##  0
##
## $keyCatchWeightMean
## # Coupling of catch-weight process mean parameters (not used if catchWeightModel==0)
##  NA NA NA NA NA NA NA NA NA NA
##
## $keyCatchWeightObsVar
## # Coupling of catch-weight observation variance parameters (not used if catchWeightModel==0)
##  NA NA NA NA NA NA NA NA NA NA
##
## $matureModel
## # Integer code describing the treatment of proportion mature in the model (0 use as known, 1 use as o
##  0
##
## $keyMatureMean
## # Coupling of mature process mean parameters (not used if matureModel==0)
##  NA NA NA NA NA NA NA NA NA NA
##
## $mortalityModel
## # Integer code describing the treatment of natural mortality in the model (0 use as known, 1 use as o
##  0
##
## $keyMortalityMean
## #
##  NA NA NA NA NA NA NA NA NA NA
##
## $keyMortalityObsVar
## # Coupling of natural mortality observation variance parameters (not used if mortalityModel==0)
##  NA NA NA NA NA NA NA NA NA NA
##
## $keyXtraSd
## # An integer matrix with 4 columns (fleet year age coupling), which allows additional uncertainty to
```

10 Input data

10.1 Survey at age

year	3	4	5	6	7	8	9	10	11	12
1985	1.068	4.484	7.367	7.873	7.216	6.719	4.047	2.972	1.437	1.032
1986	0.537	2.595	5.490	6.499	6.059	5.827	3.437	2.653	1.280	0.913
1987	0.732	2.189	3.846	4.460	4.180	4.062	2.524	2.076	0.998	0.817
1988	1.113	3.584	5.225	5.695	5.075	4.770	2.981	2.276	1.048	0.801
1989	0.677	2.166	3.013	3.058	2.764	2.543	1.623	1.230	0.558	0.434
1990	0.482	2.016	3.401	3.337	3.010	2.618	1.564	1.109	0.511	0.381
1991	0.053	2.458	4.471	4.507	3.875	2.672	1.271	1.155	0.591	0.923
1992	0.935	2.735	7.620	5.248	3.935	1.617	0.914	0.194	0.128	0.085
1993	0.269	2.598	3.596	5.179	1.588	1.387	1.185	0.880	0.462	1.033
1994	0.365	2.684	5.332	3.049	2.552	0.907	0.857	0.411	0.040	0.225
1995	0.244	1.115	4.694	2.861	0.979	0.812	0.222	0.145	0.022	0.000
1996	0.313	1.462	2.249	4.580	1.754	1.051	0.387	0.056	0.020	0.000
1997	0.320	0.865	0.937	1.243	1.505	1.175	0.402	0.178	0.095	0.250
1998	0.074	0.620	1.313	2.136	1.032	1.111	0.635	0.260	0.072	0.209
1999	0.081	2.235	2.265	1.604	1.306	0.686	0.900	0.266	0.159	0.115
2000	0.033	0.169	0.378	0.883	0.888	0.922	0.641	0.389	0.332	0.270
2001	0.166	0.724	0.353	1.131	0.785	0.874	0.346	0.310	0.226	0.157
2002	0.038	1.041	2.295	1.198	1.217	1.017	0.620	0.203	0.135	0.024
2003	0.000	1.589	2.961	1.962	1.289	1.139	0.601	0.265	0.079	0.039
2004	0.084	0.759	4.314	4.925	1.805	1.213	0.849	0.616	0.164	0.065
2005	0.107	0.247	1.395	3.154	2.060	1.342	0.838	0.321	0.187	0.016
2006	0.178	1.004	2.223	3.257	2.266	1.815	0.739	0.489	0.159	0.154
2007	0.147	1.487	2.272	2.283	2.247	1.250	0.589	0.202	0.074	0.000
2008	0.363	0.679	1.771	1.754	0.892	0.806	0.562	0.235	0.166	0.318
2009	0.367	0.958	1.845	1.808	1.227	0.714	0.421	0.223	0.112	0.066
2010	1.457	3.376	3.103	2.661	2.078	1.470	0.666	0.478	0.203	0.226
2011	0.196	1.197	2.036	1.852	1.350	0.872	0.412	0.266	0.144	0.460
2012	0.500	0.595	2.243	1.933	0.997	0.710	0.357	0.386	0.238	0.407
2013	0.636	1.776	1.510	2.371	2.644	1.029	0.421	0.371	0.344	0.502
2014	0.355	1.738	1.590	1.985	1.915	1.512	0.604	0.420	0.384	0.317
2015	0.175	0.483	1.056	1.157	1.179	0.961	0.782	0.443	0.188	0.382
2016	0.323	0.706	1.845	2.189	1.942	1.139	1.056	0.310	0.171	0.432
2017	0.767	1.300	1.850	2.703	2.280	1.968	1.288	0.888	0.460	0.434
2018	0.389	0.819	1.652	1.980	2.631	2.009	1.154	0.932	0.374	0.561
2019	0.323	1.467	1.082	1.179	1.396	1.127	0.677	0.553	0.428	0.497
2020	0.233	0.760	1.511	1.574	1.229	1.026	0.686	0.528	0.252	0.394

10.2 Catch at age

year	3	4	5	6	7	8	9	10	11	12
1980	149.464	1011.724	2313.322	1721.170	1462.218	976.026	543.774	394.753	159.957	154.703
1981	133.418	855.559	1828.709	1286.899	1074.207	690.653	380.974	259.030	101.657	97.429
1982	104.514	703.172	6059.500	1338.675	1139.525	750.688	442.428	330.722	145.754	172.175
1983	214.604	1380.088	3138.486	2392.451	2065.797	1439.435	944.384	687.368	260.525	386.296
1984	429.162	2364.203	5030.711	3855.830	3060.957	1833.229	1243.144	764.878	293.849	409.058
1985	280.380	1273.484	16897.186	3197.222	2246.920	1447.222	1039.025	696.898	249.197	377.554
1986	267.337	1453.166	16941.584	2706.355	2051.383	1122.287	845.317	372.821	143.057	261.110
1987	706.600	3166.958	5674.394	3693.805	3051.964	1857.994	1041.201	693.826	280.688	267.658
1988	796.671	4292.369	8750.633	6736.498	4266.306	1950.403	1543.612	576.747	228.480	241.829
1989	202.934	1283.524	10465.968	2468.544	2017.070	1201.015	1114.653	528.849	217.284	595.667
1990	937.043	4527.305	7479.353	4286.009	3473.647	1816.800	966.195	452.162	210.076	155.756
1991	480.058	2642.317	5416.250	4621.931	3481.364	1603.407	1194.582	548.623	220.437	305.228
1992	686.065	3310.922	5836.762	3649.142	3011.850	1747.791	947.026	561.678	235.767	183.560
1993	485.578	2619.422	5425.570	4559.009	3637.666	1913.348	1621.855	868.022	300.256	583.448
1994	621.623	3222.212	6098.504	4747.619	3633.090	1719.480	1484.897	648.928	231.391	506.484
1995	789.611	2106.091	6688.935	4407.072	2425.534	1509.580	524.550	217.970	299.018	429.861
1996	334.362	1478.089	2355.922	5725.358	3695.950	1979.012	1023.998	387.696	306.946	610.401
1997	290.271	1796.997	3908.315	2310.683	4420.376	2136.310	853.548	393.519	169.835	596.331
1998	983.065	1050.167	2955.030	2687.421	1412.174	1505.965	792.211	162.782	114.456	106.623
1999	237.777	1050.314	1606.892	2145.948	1837.061	1186.621	1254.949	368.795	172.377	193.958
2000	362.922	246.922	807.189	1243.442	1480.189	1118.773	691.571	511.778	287.881	155.045
2001	383.965	953.691	896.080	1375.731	1130.457	891.227	631.741	296.409	172.462	172.909
2002	102.976	1247.676	1943.359	1151.153	1068.912	797.619	560.448	297.341	159.322	109.960
2003	62.599	659.729	1899.611	1954.956	1118.552	726.502	477.460	289.954	180.317	143.801
2004	76.060	768.136	1844.511	2327.803	1387.916	661.144	389.698	229.550	109.594	88.267
2005	63.277	726.028	2075.946	2051.103	1640.541	879.928	463.178	180.662	85.358	17.938
2006	449.584	1414.534	1145.476	1714.942	1580.338	1220.224	585.977	404.569	177.282	192.523
2007	381.156	1288.193	1816.521	1262.443	1299.180	945.451	548.769	258.656	133.525	201.797
2008	410.767	727.972	1701.883	1945.806	1112.139	1142.590	679.949	445.483	208.309	432.230
2009	387.969	891.751	1280.093	1890.858	1491.133	799.165	602.232	371.719	194.294	227.030
2010	190.619	663.766	1141.448	1312.357	1372.675	1049.885	547.572	430.872	258.648	363.989
2011	134.505	607.839	1381.456	1315.838	950.905	806.250	477.347	269.309	239.900	269.288
2012	294.124	370.570	1028.338	1693.170	1256.163	774.335	664.128	412.368	194.047	382.021
2013	334.867	537.722	744.728	1405.642	1603.313	921.511	504.876	393.109	216.327	234.690
2014	164.878	519.500	988.755	1192.678	1474.527	1212.162	576.435	249.362	257.660	248.021
2015	224.962	533.696	1343.131	1532.318	1221.560	1207.294	781.586	264.721	189.404	176.894
2016	69.284	629.148	1065.302	1506.862	1350.788	1010.803	1036.049	595.347	296.604	315.233
2017	138.607	357.562	1171.949	1542.502	1364.068	797.511	691.535	665.552	318.303	327.902
2018	270.307	715.372	1057.047	1562.064	1614.574	1246.502	1031.826	604.466	422.079	501.238
2019	372.327	1037.502	1295.546	1103.950	1040.780	941.615	692.473	562.471	258.256	382.342
2020	169.479	1104.453	2402.198	1794.118	1059.391	747.496	698.198	399.585	288.525	231.545

10.3 Catch weights

year	3	4	5	6	7	8	9	10	11	12
1980	423	463	528	590	616	704	777	1028	950	1046
1981	410	448	506	563	585	676	751	1024	926	1070
1982	415	465	460	597	627	711	797	1098	1122	1060
1983	408	453	528	601	634	751	894	1069	1003	1141
1984	368	424	489	550	592	693	791	994	928	1097
1985	354	458	432	540	633	738	826	1020	981	1097
1986	366	434	429	538	578	643	754	823	779	1003
1987	340	396	468	536	560	665	724	1025	952	1061
1988	321	388	440	487	516	572	566	732	694	855
1989	389	437	447	539	620	711	921	917	1041	1289
1990	358	393	429	469	482	548	585	878	820	994
1991	357	408	463	523	554	606	654	785	707	844
1992	357	402	458	520	540	633	671	951	846	1011
1993	351	402	467	539	601	700	799	905	835	1080
1994	349	394	443	503	549	623	749	831	786	1115
1995	360	410	451	519	665	775	928	888	1100	946
1996	343	420	503	572	642	771	889	881	921	1083
1997	390	458	512	583	653	724	862	944	999	1057
1998	347	423	544	604	731	817	876	1090	1137	1302
1999	394	484	532	642	706	776	930	1110	1223	1315
2000	312	389	543	650	783	868	890	993	1121	1307
2001	328	457	539	673	755	871	930	1017	1171	1290
2002	372	453	546	658	742	876	955	1082	1276	1492
2003	354	438	521	635	769	856	956	1023	1284	1480
2004	355	456	589	675	793	930	1014	1181	1379	1490
2005	337	448	566	709	777	878	1000	1080	1157	1043
2006	410	496	586	674	796	860	915	940	996	1196
2007	381	464	578	678	786	906	982	1134	1142	1154
2008	389	487	576	688	797	905	1018	1075	1090	1180
2009	394	492	590	680	793	945	1148	1258	1357	1244
2010	424	484	576	673	790	952	1035	1207	1344	1363
2011	430	486	577	680	789	890	1011	1078	1130	1358
2012	434	536	606	712	835	950	1075	1154	1231	1337
2013	446	547	623	718	868	1004	1164	1239	1412	1506
2014	413	477	627	725	853	1008	1103	1055	1351	1471
2015	537	512	643	793	882	1062	1245	1365	1507	1595
2016	470	508	644	743	914	1056	1144	1399	1442	1604
2017	452	543	646	730	812	977	1141	1254	1452	1635
2018	457	546	651	760	859	957	1136	1315	1366	1541
2019	414	558	626	783	863	1056	1159	1276	1446	1520
2020	458	570	649	759	857	986	1157	1333	1582	1761

10.4 Stock weights

year	3	4	5	6	7	8	9	10	11	12
1980	245	325	426	522	587	663	731	882	902	1144
1981	245	325	426	522	587	663	731	882	902	1144
1982	245	325	426	522	587	663	731	882	902	1144
1983	245	325	426	522	587	663	731	882	902	1144
1984	245	325	426	522	587	663	731	882	902	1144
1985	245	325	426	522	587	663	731	882	902	1144
1986	243	356	454	546	606	673	755	885	903	1145
1987	197	320	440	543	619	692	790	904	924	1159
1988	215	299	415	521	594	672	750	918	934	1167
1989	214	303	410	511	588	672	746	930	939	1165
1990	235	332	418	503	559	635	722	927	939	1164
1991	251	268	355	494	584	659	740	897	896	1172
1992	172	276	395	513	621	684	893	967	980	1180
1993	166	265	386	495	605	678	649	921	1033	1157
1994	187	277	336	507	563	717	816	921	1115	1182
1995	151	261	361	471	713	814	949	962	1336	1159
1996	206	255	372	436	587	722	916	995	1321	1143
1997	193	290	403	512	639	618	826	1018	1307	1186
1998	243	291	424	454	547	630	660	976	1187	1148
1999	308	310	403	642	619	674	807	915	981	1076
2000	105	265	374	496	600	700	786	803	899	1113
2001	303	347	461	572	670	700	810	805	881	1050
2002	248	315	429	566	686	764	819	907	991	1064
2003	245	327	428	552	686	691	869	954	1075	1187
2004	520	338	445	507	670	776	910	1025	1130	1284
2005	193	326	503	564	711	822	997	1087	1197	1258
2006	290	360	437	555	650	768	856	1066	1166	1400
2007	246	337	482	634	764	859	1027	1167	1292	1349
2008	251	382	512	646	755	834	949	1132	1317	1192
2009	266	360	502	683	790	924	1009	1155	1295	1355
2010	172	305	459	613	697	807	996	1213	1323	1305
2011	187	308	454	591	716	838	974	1176	1213	1318
2012	227	342	468	598	796	843	1060	1187	1210	1369
2013	233	286	415	588	691	930	1053	1154	1212	1246
2014	243	299	479	649	781	921	1085	1123	1211	1166
2015	267	384	520	707	778	945	1104	1137	1222	1241
2016	273	395	469	602	771	888	1119	1167	1241	1290
2017	240	325	522	663	806	905	1012	1229	1306	1449
2018	262	383	496	654	763	882	1038	1248	1319	1463
2019	249	326	533	653	776	929	1039	1210	1295	1422
2020	215	353	519	702	789	912	1169	1233	1300	1453

10.5 Maturity

year	3	4	5	6	7	8	9	10	11	12
1980	0.074	0.135	0.251	0.379	0.475	0.544	0.619	0.697	0.748	0.793
1981	0.074	0.135	0.251	0.379	0.475	0.544	0.619	0.697	0.748	0.793
1982	0.074	0.135	0.251	0.379	0.475	0.544	0.619	0.697	0.748	0.793
1983	0.074	0.135	0.251	0.379	0.475	0.544	0.619	0.697	0.748	0.793
1984	0.074	0.135	0.251	0.379	0.475	0.544	0.619	0.697	0.748	0.793
1985	0.066	0.123	0.234	0.358	0.447	0.519	0.589	0.677	0.720	0.786
1986	0.058	0.115	0.222	0.341	0.422	0.495	0.563	0.659	0.692	0.781
1987	0.047	0.104	0.207	0.324	0.399	0.473	0.542	0.648	0.672	0.781
1988	0.035	0.086	0.182	0.291	0.359	0.434	0.500	0.620	0.632	0.767
1989	0.023	0.066	0.147	0.245	0.305	0.379	0.443	0.574	0.574	0.731
1990	0.018	0.056	0.126	0.212	0.268	0.336	0.401	0.528	0.527	0.688
1991	0.014	0.041	0.099	0.180	0.238	0.304	0.366	0.486	0.482	0.671
1992	0.010	0.028	0.074	0.146	0.206	0.265	0.343	0.483	0.465	0.633
1993	0.008	0.025	0.066	0.137	0.204	0.260	0.324	0.451	0.490	0.614
1994	0.008	0.028	0.068	0.152	0.219	0.288	0.353	0.469	0.560	0.651
1995	0.006	0.028	0.078	0.173	0.278	0.353	0.421	0.514	0.670	0.701
1996	0.006	0.028	0.086	0.173	0.290	0.376	0.468	0.596	0.748	0.724
1997	0.007	0.030	0.086	0.171	0.289	0.365	0.454	0.538	0.739	0.719
1998	0.009	0.034	0.098	0.174	0.287	0.368	0.464	0.540	0.700	0.741
1999	0.017	0.040	0.104	0.198	0.295	0.359	0.466	0.523	0.644	0.695
2000	0.017	0.038	0.097	0.188	0.259	0.327	0.434	0.510	0.563	0.688
2001	0.029	0.058	0.128	0.239	0.306	0.353	0.450	0.477	0.561	0.679
2002	0.033	0.068	0.150	0.278	0.354	0.421	0.497	0.557	0.618	0.721
2003	0.044	0.074	0.158	0.305	0.395	0.446	0.550	0.613	0.688	0.731
2004	0.089	0.078	0.175	0.291	0.420	0.483	0.582	0.680	0.739	0.804
2005	0.090	0.082	0.196	0.305	0.443	0.504	0.612	0.705	0.786	0.759
2006	0.086	0.081	0.184	0.292	0.429	0.506	0.609	0.720	0.785	0.797
2007	0.104	0.124	0.256	0.372	0.507	0.573	0.676	0.764	0.818	0.797
2008	0.117	0.179	0.332	0.451	0.573	0.647	0.726	0.803	0.837	0.824
2009	0.093	0.222	0.400	0.547	0.646	0.709	0.774	0.830	0.868	0.832
2010	0.095	0.235	0.424	0.597	0.682	0.744	0.811	0.868	0.891	0.906
2011	0.090	0.234	0.441	0.622	0.713	0.773	0.835	0.894	0.910	0.895
2012	0.082	0.216	0.413	0.589	0.694	0.753	0.824	0.869	0.895	0.917
2013	0.070	0.177	0.369	0.556	0.665	0.748	0.814	0.861	0.890	0.898
2014	0.054	0.146	0.337	0.524	0.638	0.730	0.800	0.845	0.878	0.877
2015	0.070	0.168	0.357	0.552	0.661	0.750	0.810	0.850	0.887	0.877
2016	0.084	0.203	0.378	0.570	0.685	0.768	0.832	0.857	0.901	0.878
2017	0.080	0.189	0.376	0.568	0.672	0.764	0.814	0.865	0.907	0.886
2018	0.074	0.185	0.359	0.546	0.654	0.726	0.797	0.854	0.887	0.881
2019	0.068	0.174	0.344	0.515	0.631	0.707	0.780	0.836	0.870	0.874
2020	0.057	0.163	0.338	0.508	0.629	0.707	0.783	0.842	0.863	0.879

10.6 Landings

Year	Landings
1980	5530
1981	3951
1982	6340
1983	8553
1984	11342
1985	14473
1986	12705
1987	11157
1988	14032
1989	11307
1990	11343
1991	10713
1992	10464
1993	12702
1994	12040
1995	10813
1996	11281
1997	10743
1998	7443
1999	7145
2000	5259
2001	4925
2002	5143
2003	5258
2004	5707
2005	5802
2006	6382
2007	5810
2008	6725
2009	6323
2010	5984
2011	4943
2012	5927
2013	5988
2014	5927
2015	6754
2016	7451
2017	6694
2018	8341
2019	6835
2020	7506

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Atlantic wolffish (*Anarhichas lupus*) in ICES division 5.a

Contents

1 Introduction

The Atlantic wolffish *Anarhichas lupus* (Anharhichadidae) is a long eel-like(~1 m max) fish found in colder northern regions of the Atlantic Ocean. Its striped appearances distinguishes from the similar spotted and northern wolffishes (*Anarhichas minor* and *Anarhichas denticulatus*). It has a thick skull and strong jaws, as it specializes on hard-shelled mollusks, crabs, lobsters, sea urchins and other echinoderms. It is a hardy species known for being difficult to handle as it can survive several hours out of water on deck and still be lively enough to bite. For this reason they probably have good survival if discarded.

In general, Atlantic wolffish are sedentary and solitary, and found mostly rocky bottoms, and over sand and mud. They are found on continental shelf and slope around Iceland, and mostly caught around 0 to 180 m depth (Fig. 1).

Atlantic wolffish abundance has declined drastically during recent years, especially in the north-west Atlantic Ocean where it was listed by the Canadian Species at Risk Act (SARA) as a species of 'special concern' (Kulka and Simpson [11]). The recent Red List assessments for European marine fish in the north-eastern Atlantic (Nieto et al. [16]) listed Atlantic wolffish as Data Deficient.

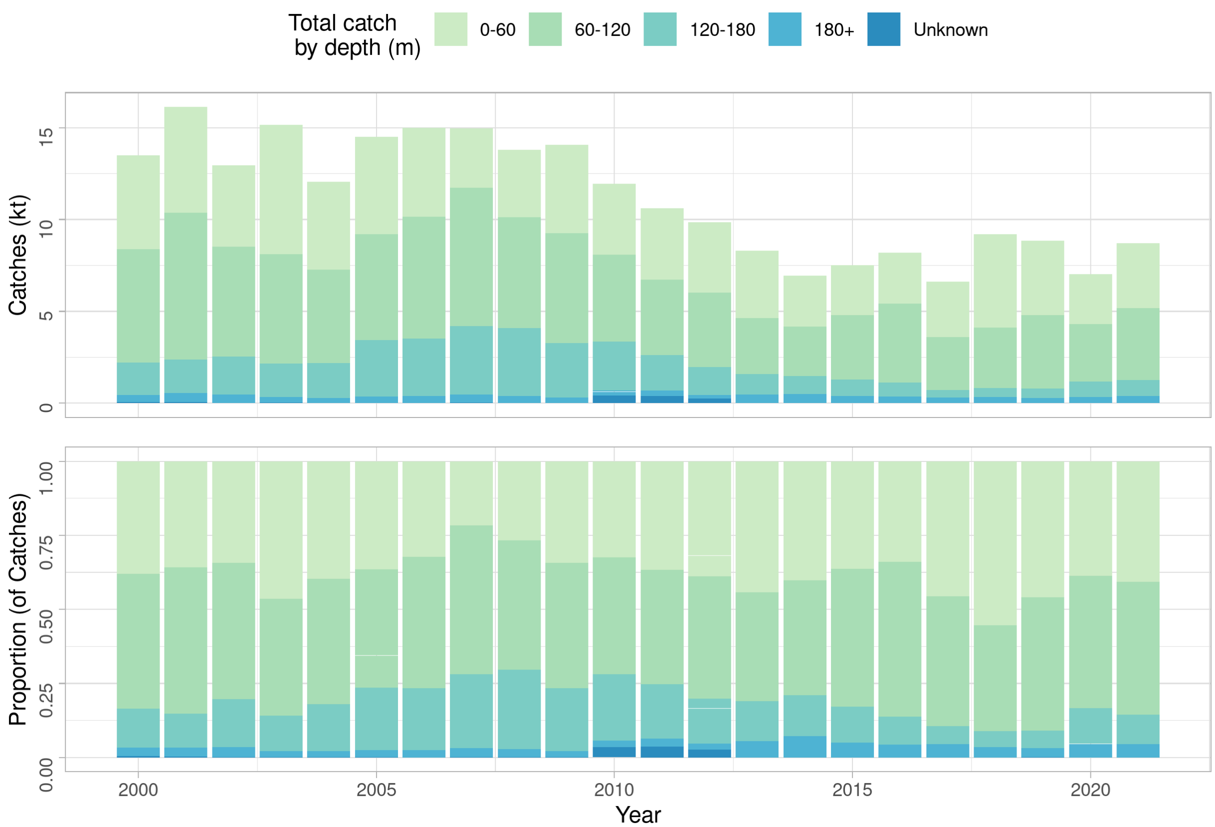

Figure 1: Atlantic wolffish in 5.a. Catch reported in logbooks by depth and gear, in terms of biomass (top panels) and proportion (bottom panels).

2 Stock ID and sub-stock structure

The main distribution Atlantic wolffish in east North Atlantic is from southern Barents Sea south to English Channel in the North Sea. It is also in the Western part of Baltic Sea, Kattegat and Skagerrak. Atlantic wolffish is common in the Shetland and Faroe Islands, Iceland and Greenland. In Greenland it is found from

Tasiilaq on the east coast to Disco Bay at the west coast. In the west North Atlantic the distribution ranges from Hudson Bay to Cape Cod. Around Iceland, the main spawning grounds are in the northwest off the westfjords of Iceland (also where main fishing grounds are, Fig. 2), but smaller areas exist in the northeast. Spawning season begins in early fall. During this and egg incubation times, which lasts 4 – 5 months, a 1000 km^2 area in the main fishing grounds is closed (15th of September - 1st of May). Several feeding grounds are in the north. Little is known regarding connectivity of different Atlantic wolffish populations across the Atlantic. Although several other Icelandic species exhibit connectivity for example with populations in Greenlandic waters, for example, no clear trends in cohort movements can be seen between samples taken from the spring survey in Iceland and the Greenlandic survey. Length distributions indicate a greater size range in Iceland (Fig. 3), but this may be the result of warmer waters and faster growth (see section on **Ecosystem drivers**). Timing and/or depth appears to be more important factor in determining the shape of the Icelandic spring survey length distributions, as the autumn survey shows a very similar shape during a similar sampling period (Fig. 3).

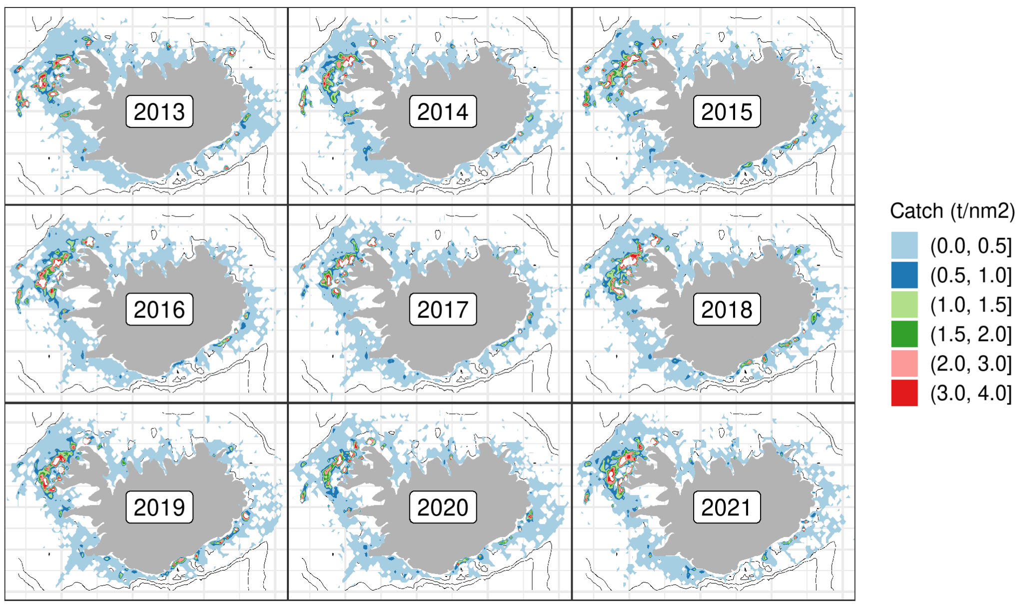

Figure 2: Atlantic wolffish in 5.a. Spatial distribution of Atlantic wolffish catch density according to logbooks.

Atlantic wolffish is distributed all around Iceland, but its population density is most northwest of Iceland (MFRI [13]). A study using neutral markers did not find any genetic structure between Icelandic components including the main spawning ground ('Látragrunn') and feeding grounds as far as F4 (see Fig. 2 in Pampoulie et al. [19]). Differences in life-history traits have been noticed between Atlantic wolffish east and west of Iceland (Gunnarsson et al. [4], Gunnarsson et al. [6]). Homing behavior and migration patterns between several feeding and spawning areas have also been observed using tagging data. However, these areas appear shared among individuals, so no strong patterns suggesting population partitioning based on migration behavior were found in usage of these areas (Gunnarsson et al. [5]).

The Atlantic wolffish's sedentary behavior, its lack of data indications of connectivity with populations outside Iceland, and the lack of evidence for population partitioning within Iceland, leads this benchmark to conclude that Atlantic wolffish within 5.a should be considered its own ICES stock unit for the purposes of stock assessment.

3 Current advisory process

The Marine and Freshwater Research Institute (MFRI) of Iceland has given advice based on maximum sustainable yield (MSY) since 2001 but fishing activities exceeded the advised catch for several years. However, since 2013, catches have agreed with the total allowable catches (TAC) recommended by the MFRI. Concurrently, the fishable stock and the spawning stock have been stable and even increased slightly despite the relatively low recruitment.

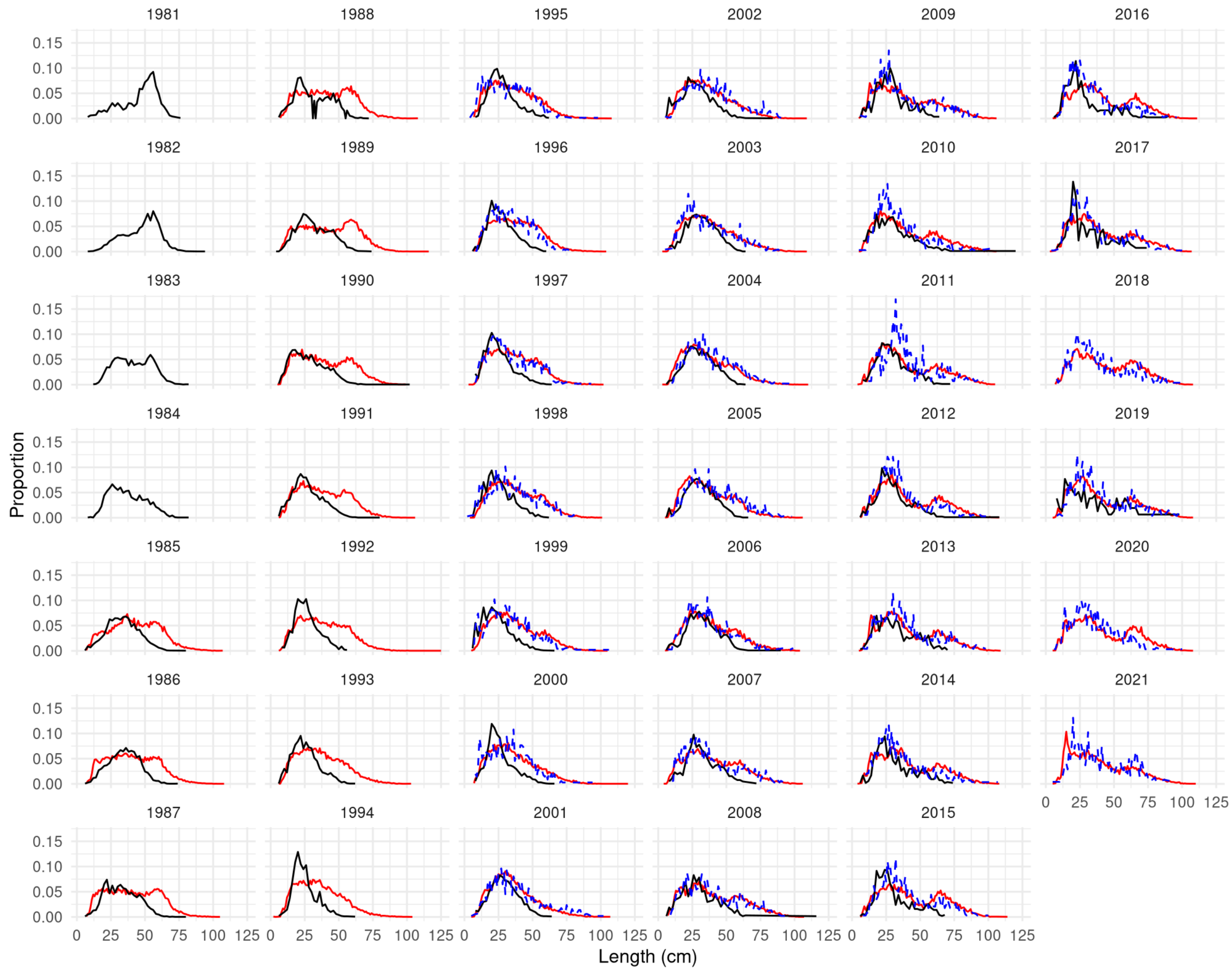

Figure 3: Atlantic wolffish in 5.a. Red lines indicate length distributions observed during the Icelandic groundfish survey conducted in spring (March). Blue dashed lines indicate length distributions observed during the Icelandic groundfish survey conducted in spring (September - October). The black lines are length distributions observed in the Greenlandic survey conducted in ICES area 14 in September - December.

To provide advice, stock assessments of the Atlantic wolffish in the past have been based on an age- and length-structured Gadget model that was fit to spring survey indices in four length ranges, length distribution data from the spring survey, and length-at-age keys. Catch were implemented as direct removals from the population (no error). Only harvestable biomass is tracked (no maturation or spawning stock biomass). The model was reasonably stable and gave a decent fit to the data, with the exception of the bimodal shape in length distribution data (described under 'Issue list', and noticeable in the red lines in Fig. 3)) and a survey index that corresponded with this length range (MFRI [13], ICES [9]). The model was then projected for 1 year with an assumption of recruitment equaling the mean of the previous three years, the current fishing year's quota being filled according to fishing rates observed during the last two fishing quarters in the previous year, and a target fishing mortality. The target $F_{target} = 0.3$ was based on an F_{max} from a yield-per-recruit analysis. In 2021 a chapter for Atlantic wolffish was included in WGDEEP report in preparation for this benchmark (ICES [9]). see here

All around the north Atlantic, Atlantic wolffish abundance has declined drastically during recent years, especially in the northwest Atlantic Ocean where it was listed by the Canadian Species at Risk Act (SARA) as a species of 'special concern' (Kulka and Simpson [11]). The recent Red List assessments for European marine fish in the north-eastern Atlantic, Nieto et al., 2015 listed Atlantic wolffish as Data Deficient. In Icelandic waters, recruitment was good from 1993 to 1999 but since then it decreased to a historical low level in 2011. Concurrently with the enlargement of preserved area at Látragrunn, the downward trend in the recruitment ceased and recruitment has since 2011 been rather stable and increased a little. Currently ICES does not assess any other Atlantic wolffish stock.

4 Issue list

In a letter dated at October 18, 2021, the government of Iceland requested that ICES evaluate the performance of the harvest control rules for Atlantic wolffish and update/develop new assessments as appropriate. In response, Atlantic wolffish assessment will be provided annually by the ICES Working Group on Deepwater Species (ICES [9]). As this addition has been anticipated in previous years, presentations on Atlantic wolffish biology have been given in previous annual meetings.

In the current assessment, several issues should be noted. First, length-based survey indices of different length ranges are in disagreement with each other. That is, if the assessment is to fit the index of the smallest length range of Atlantic wolffish, then it will have to disregard patterns in the largest length range, and vice versa.

Second, this disagreement in length indices is also apparent in length distribution data. Observed length distributions are difficult to fit because of a higher-than expected number of individuals observed close to 65 cm versus a lower-than-expected number of individuals observed in the 45 - 55 cm range. This peak around 65 cm varies in strength across years but does not appear to correspond with individual cohorts (Fig. 4).

Third, length distributions are randomly sampled, and although age distribution sampling is designed to be random, samples are actually biased toward sampling slightly more large Atlantic wolffish than expected. This can be seen, for example, when comparing distributions of Atlantic wolffish sampled with only length data, and those sampled with both length and age data.

Finally, growth appears to differ by region, but length-at-age data are highly variable and little is known regarding how reliable current ageing methods are (see section on **Ecosystem drivers** for more information on variable life history).

5 Scorecard on data quality

Scorecard on data quality was not used

6 Multispecies and mixed fisheries issues

Atlantic wolffish is a targeted species, but because its distribution is diffuse in relation to more valuable species (e.g., cod *Gadus morhua* and haddock *Melanogrammus aeglefinus*), it's catch usually comprises a smaller proportion of hauls in the mixed fishery that also target these species (add table). Denser aggregations of Atlantic wolffish can be found in feeding areas and in spawning areas (Gunnarsson et al. [6], Gunnarsson et al. [5]). For this reason, areas have been closed to fishing in the northwest of Iceland off the westfjords ('Látragrunn') during 15th of September - 1st of May. Nonetheless this area is the still the main fishing grounds for Atlantic wolffish outside the closure period (Table 1, Fig. 6, Fig. 2).

7 Ecosystem drivers

Considerable changes have been observed in the area, both in terms of changes in fishing pressure and the ecosystem. Jónsdóttir et. al. (2019) [10] noted that species diversity in the fjords in the western and northern part of the country shifted dramatically at the turn of the century. These changes were attributed

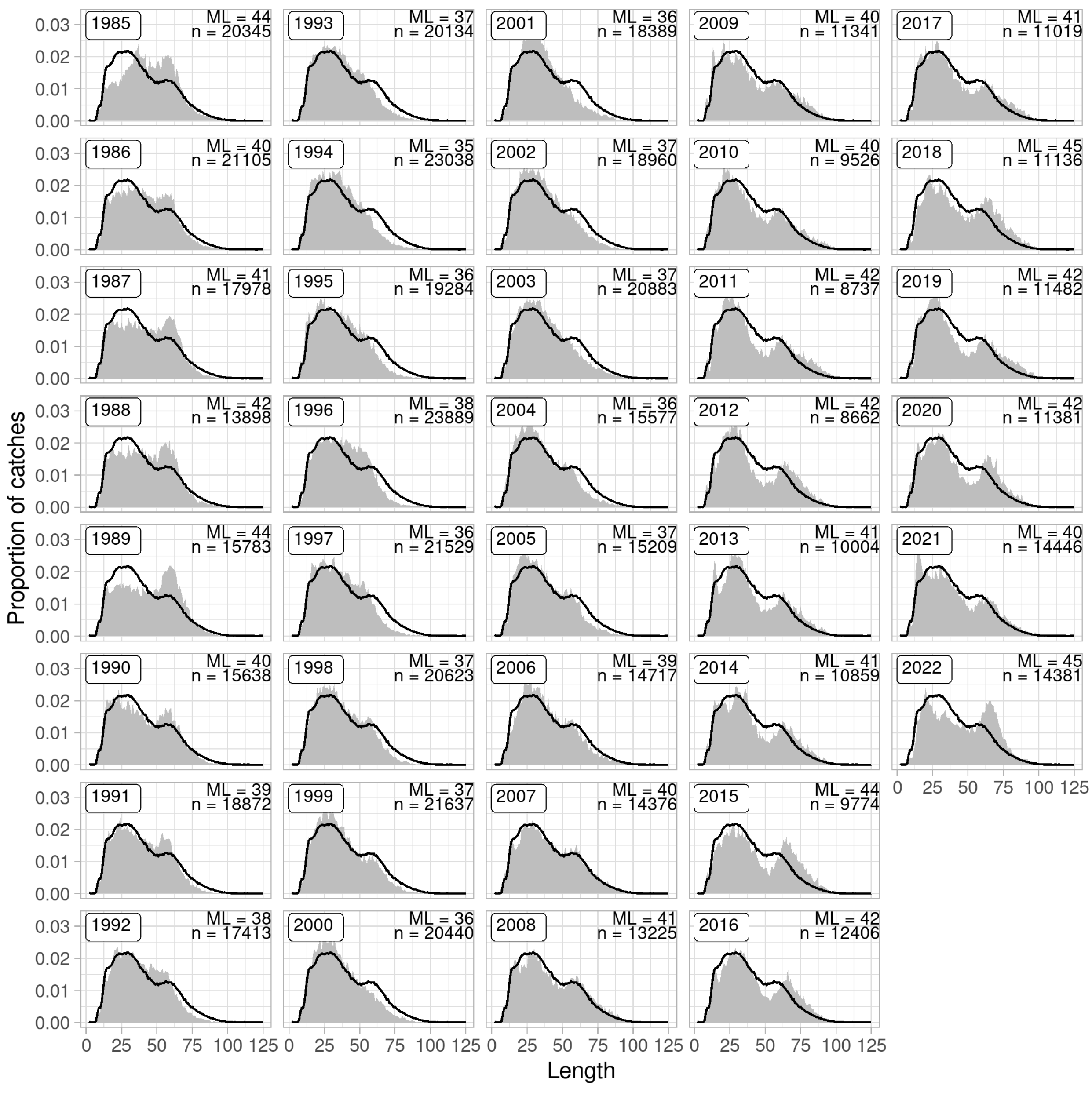

Figure 4: Atlantic wolffish in 5.a. Length distributions observed from the spring Icelandic groundfish survey. Mean lengths (ML) and sample sizes (n) are shown. The mean distribution over all years is represented by the black line.

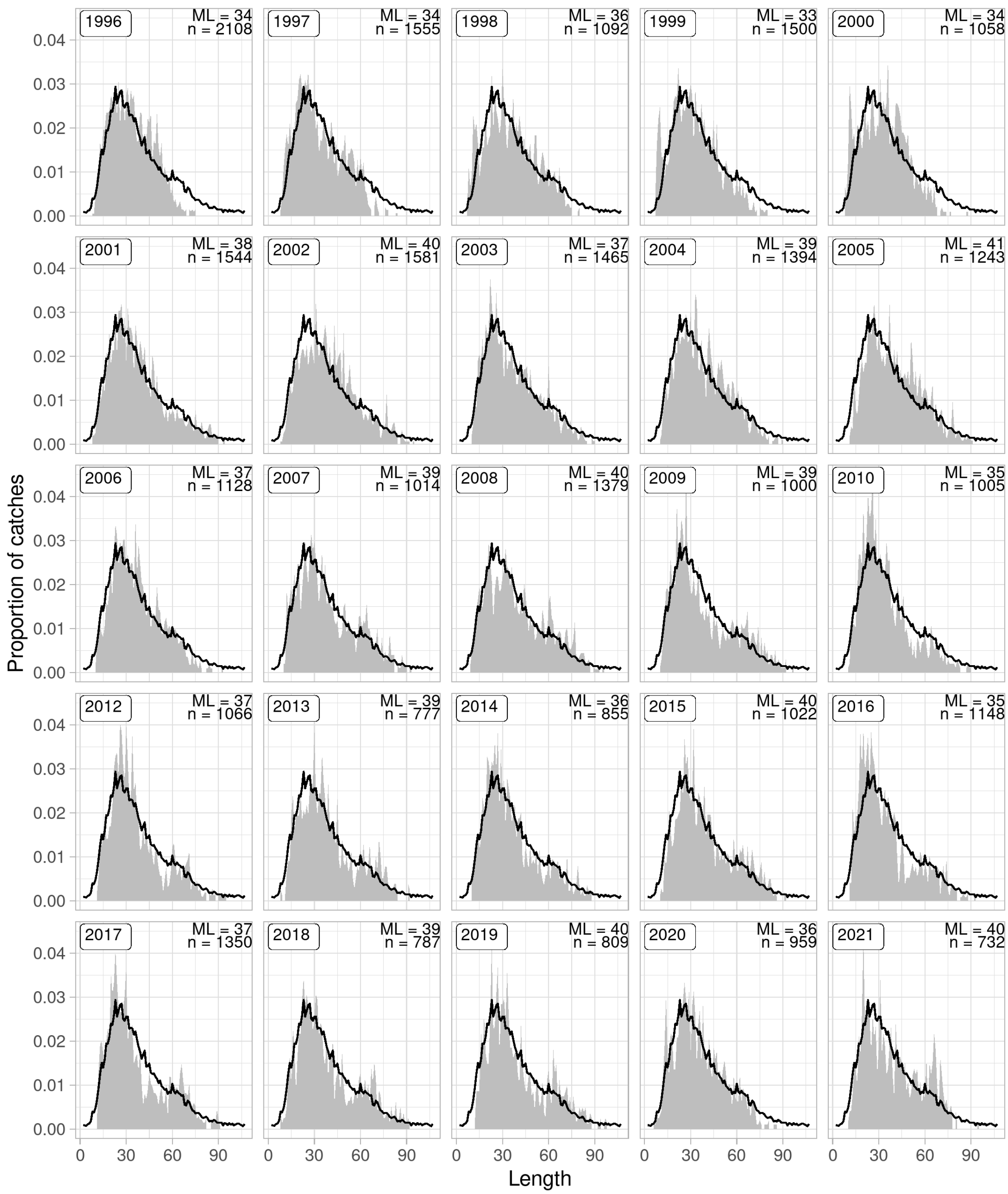

Figure 5: Atlantic wolffish in 5.a. Length distributions observed from the autumn Icelandic groundfish survey. Mean lengths (ML) and sample sizes (n) are shown. The mean distribution over all years is represented by the black line.

Table 1: Atlantic wolffish in 5.a. Distribution of landings among gears and time periods.

Year	Months	Long- and hand-lines	Other	Seines	Trawls
2018	Jan-June	5011	28	1431	1076
2018	July-Dec	693	4	754	698
2019	Jan-June	4516	41	1575	1233
2019	July-Dec	715	5	579	551
2020	Jan-June	2448	9	1461	1146
2020	July-Dec	553	6	686	1031
2021	Jan-June	3561	17	1333	1832
2021	July-Dec	418	8	680	1214
2022	Jan-June	1148	3	196	1790

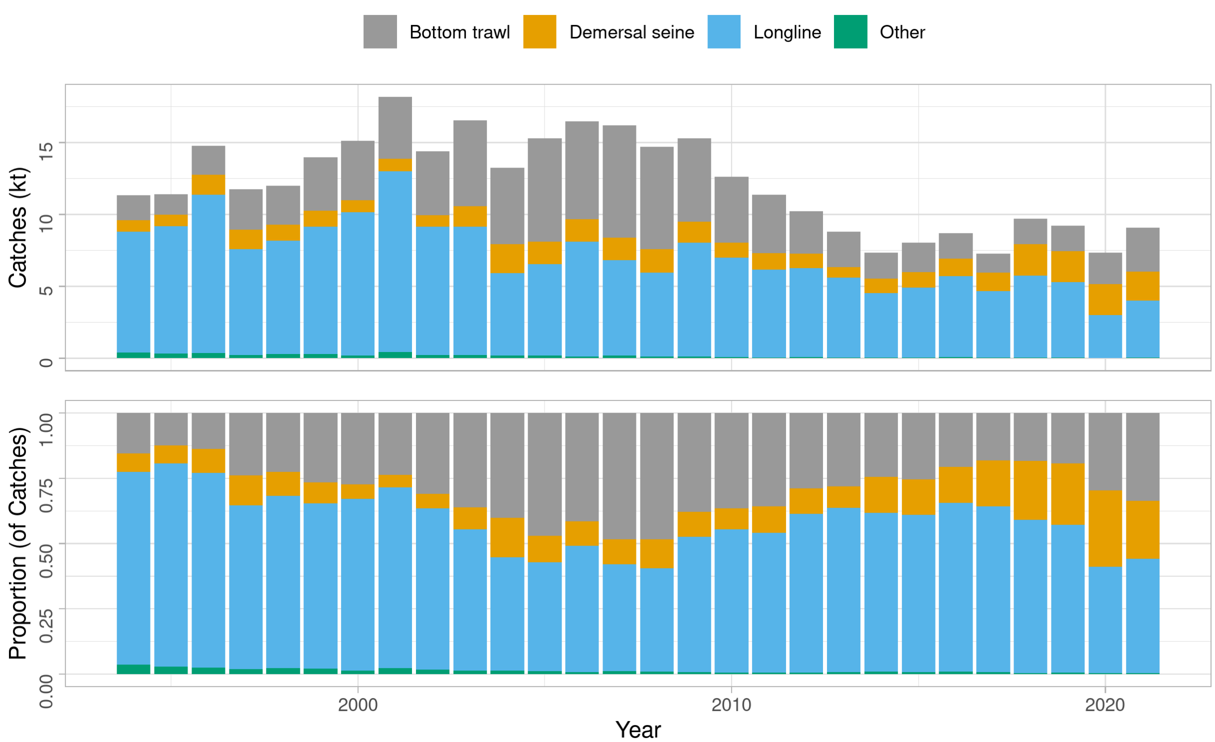

Figure 6: Atlantic wolffish in 5.a. Spatial distribution of catches by all gears.

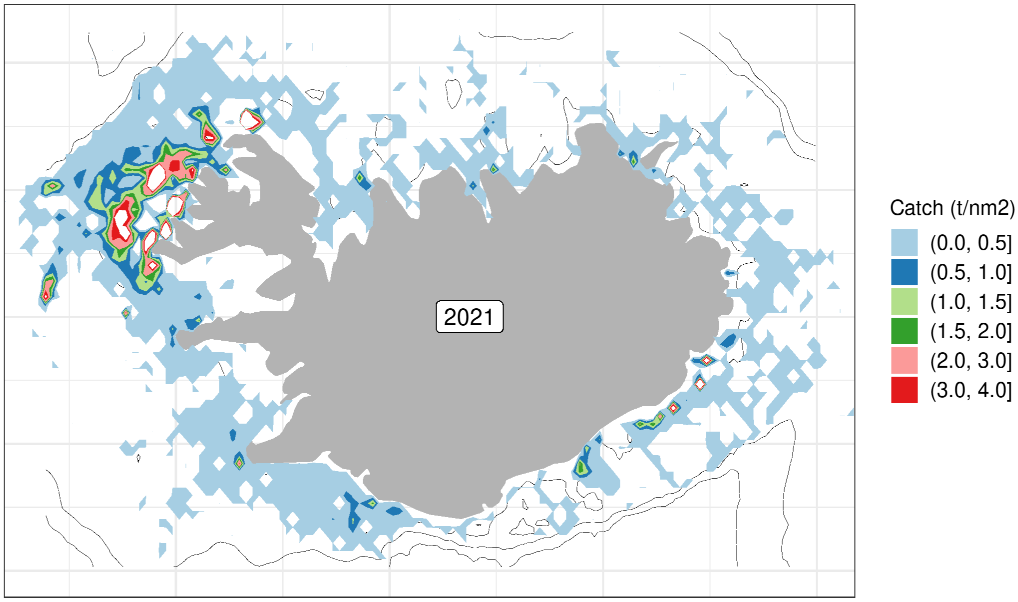

Figure 7: Atlantic wolffish in 5.a. Spatial distribution of catches in 2021 by all gears according to logbooks.

mainly to increases in the abundance of juvenile gadodids such as cod, ling and whiting. These changes coincided with increased temperature, generally lower fishing pressure towards and shifts in distribution of species. An example of these shifts range from the Icelandic haddock stock, with a noticeable northern shift in distribution [13], the minke whale population [22] possibly due to shifts in forage fish species and influx of the mackerel to the North Western Atlantic [18]. Projected effects of climate change are also expected to affect species differently depending on their thermal tolerances and habitat affinities (e.g., depth). Some warm-water species such as tusk and ling shifting northward gaining suitable habitat available to them (e.g,. ling, tusk, and haddock) while others lose ground due to depth constraints (e.g., plaice) and most cold-water species lose (e.g., Atlantic wolffish, Mason et al. [12], Campana et al. [2]).

In the Atlantic wolffish, growth has been studied in Iceland (Jónsson, 1982), the White Sea (Barsukov, 1959; Pavlov and Novikov, 1993), north Norway (Hansen, 1992), Skagerak (Gjøsæter et al., 1990), the North Sea (Liao and Lucas, 2000) and Canada (Nelson and Ross, 1992). These studies suggested that the growth rate of common wolffish increased with higher temperature. This variation in growth corresponds with a gradient of warm water originating from the Gulf Stream in the southwest corner of Iceland that cools as it travels north and east around Iceland in both directions. Water is the coolest in the northeast. However, it is unclear whether differences in growth are the direct result of temperature differences, ecosystem differences as the food availability is also likely to change with a temperature gradient, or unknown size-dependent migration patterns.

According to studies on maturity of Atlantic wolffish at Canada, North Norway and White Sea, the fish matured earlier in colder sea than warmer, which is in contradiction of the study of Gunnarsson et al., 2006 (Hansen, 1992; Pavlov and Novikov, 1993; Templeman, 1986). Study on growth and maturity of Atlantic wolffish at its main spawning- and fishing grounds W and NW of Iceland revealed temporal difference in growth and maturity and relationship between fast growth and earlier maturation (Gunnarsson, 2014). This study also showed a negative relationship between growth and temperature, which might indicate that the seabed temperature W and NW of Iceland has due to global warming rise above optimal temperature for Atlantic wolffish growth. Since 1995, the seabed temperature off Iceland has been constantly increasing (Valdimarsson et al., 2012). Although there is a large fluctuation in seabed temperature by season and location around Iceland (Valdimarsson et al., 2012), the temperature in the study area and season in the study of Gunnarsson, 2014 was presumed to reflect the annual difference in fluctuation in seabed temperature.

This close association of the Atlantic wolffish with the sea floor and its ability to move large distances when migrating indicate that it is likely in response to changes in temperature or ecosystem dynamics. For example, the southern limits of the distribution Atlantic wolffish North Sea have been moving north in recent years, possible due to global warming (Bluemel et al., 2022). Changes in location around Iceland and/or depth may create a more optimal environment. However, because Atlantic wolffish inhabit a rocky substrate and shallower depth range, this ability to adjust is limited. In addition, because males are constrained to guard nests for several months out of the year, large distributional changes on a seasonal basis are unlikely.

7.0.1 Variability in biological relationships

As mentioned earlier, life history parametersof Atlantic wolffish appears to vary around Iceland. Exploratory plots were created to visualize whether variation in biological relationships (maturity at length, length at age, and weight at length), could be detected among sampling types (spring survey, autumn survey, or commercial) or regions around Iceland, between sexes, or over time. Regions were defined according to Bormicon divisions that have been modified slightly to be more easily applicable in Gadget (Stefánsson and Pálsson [21], MRI [14], Fig. 8). Full results are not shown, but the main results included:

- As described above, growth curves and maturity ogives appear to vary by region and time, but not by sex (Figs. 9, 10). Sparse data has led to the use of a maturity ogive fixed over time in stock assessment models.
- Weight at lengths appear stable across time, space and sexes
- Commercial samples exhibit faster growth than average and curvature toward a lower L_∞, indicating a different susceptibility of individuals with a certain life history to fishing. This pattern may be a byproduct of the main fishing grounds overlapping the main spawning grounds, but also may be the result of differences in behaviour of faster-growing individuals (e.g., possibly greater aggression).

Also note that differences in length-at-ages become particularly strong around age 9 – 11, around 40 - 70 cm (Figure 11). These differences can partially be explained by regional differences in growth. However, there is also spatial overlap in some areas of fast- and slow-growing individuals, indicating that annual migration may occur at roughly this age or there are other local / behavioral factors leading to bimodality in lengths at these ages.

This mixture of growth rates is likely to explain a regular 'hump' visible in annual length distributions from spring survey data where the numbers at 50 - 60 cm are less frequent and fish lengths 60 – 70 cm more frequent than would be expected normally (Figure 11), and that cannot otherwise be explained by the movement of cohorts through the length distributions. Although Atlantic wolffish in Greenlandic surveys show a similar 'hump' around 50 cm, it is not nearly as pronounced as in Icelandic data (Figure 3).

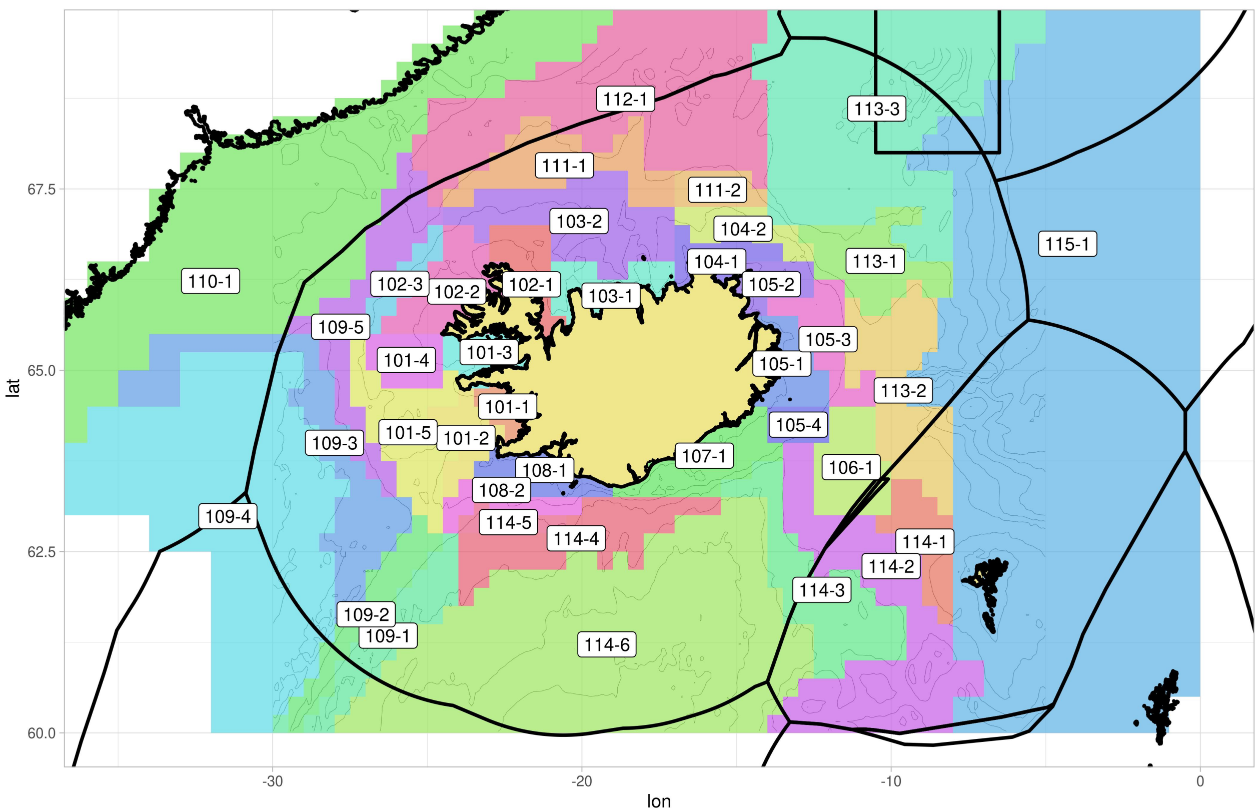

Figure 8: Atlantic wolffish in 5.a. Illustration of Gadget divisions, originally based on Bormicon divisions, used to analyse regional variation. The first three numbers (generally 101-116) indicate division number labels that correspond with plots showing regional variation in life history.

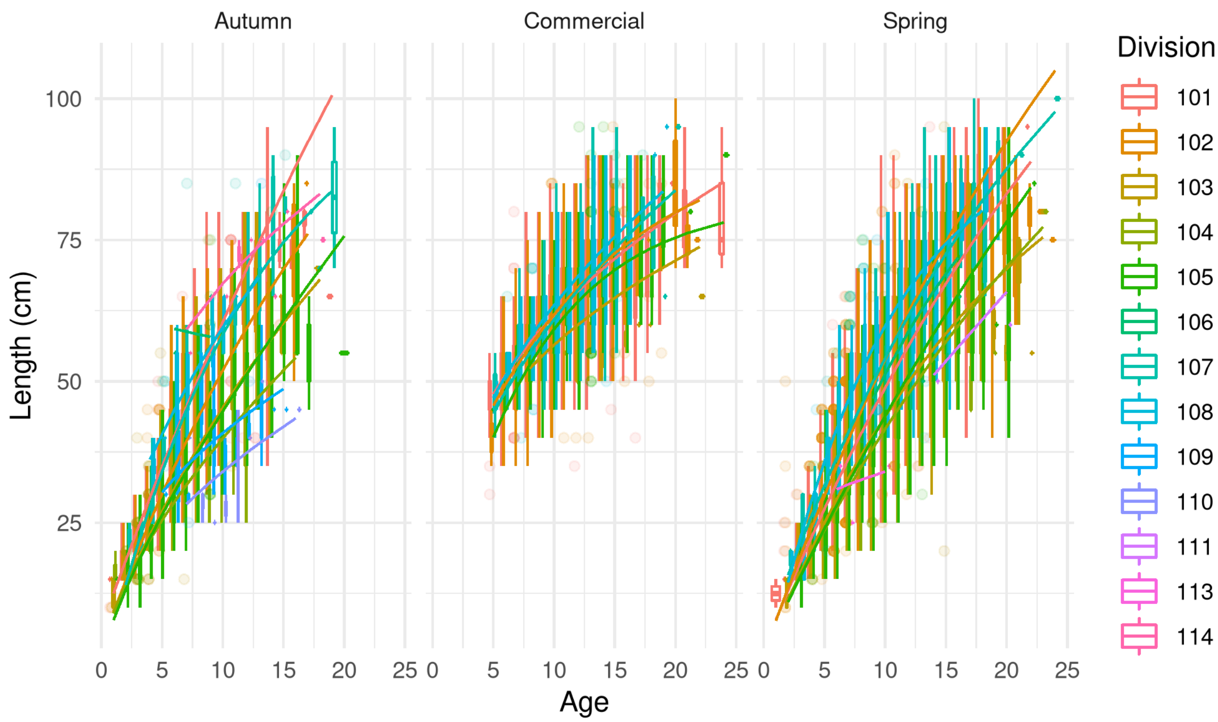

Figure 9: Atlantic wolffish in 5.a. Length at ages of females by region, plotted as boxplots with Von Bertalanffy growth curves overlaid where model fits were possible.

Figure 10: Atlantic wolffish in 5.a. Length at ages of females by region, plotted as boxplots with Von Bertalanffy growth curves overlaid where model fits were possible.

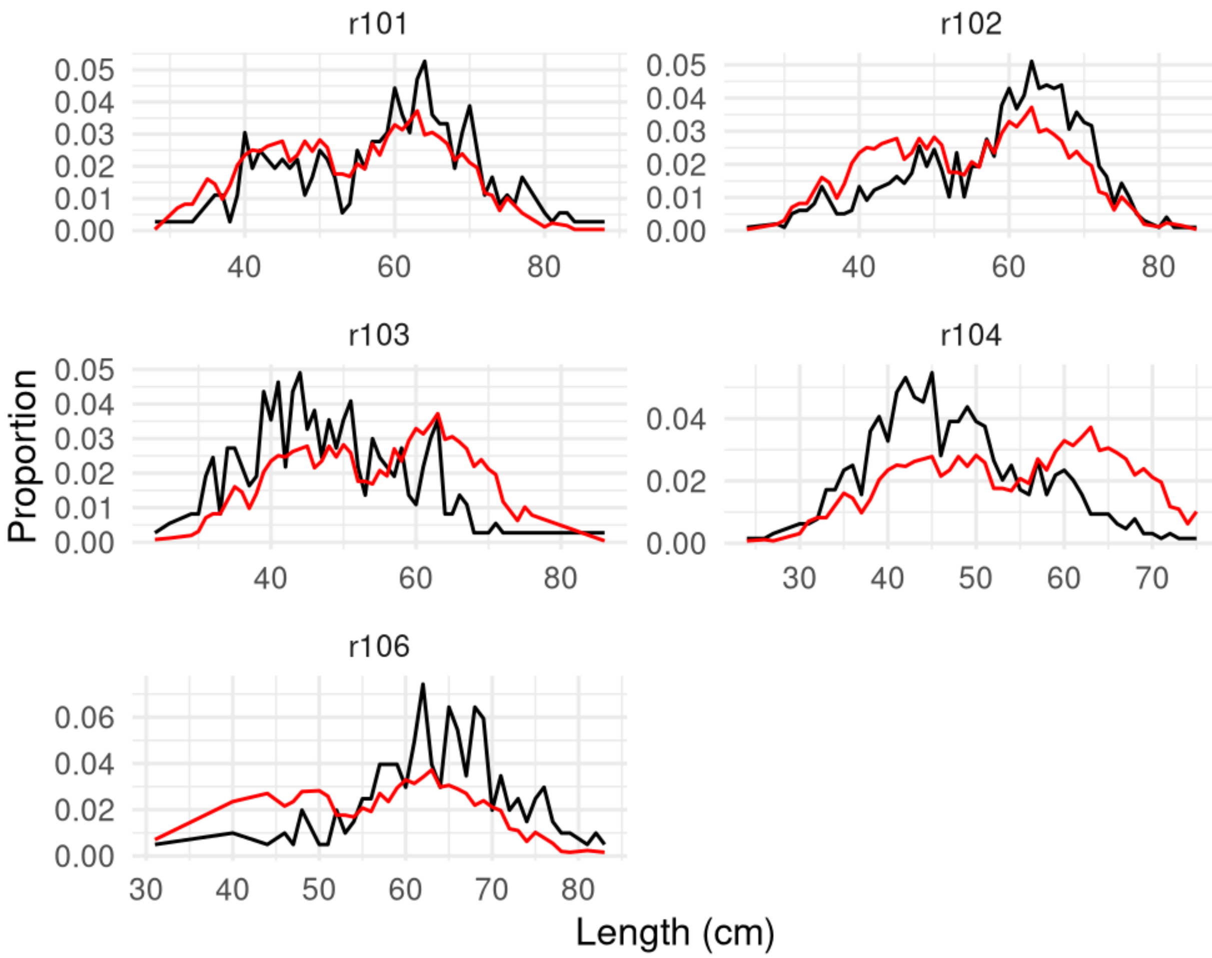

Figure 11: Atlantic wolffish in 5.a. Individuals aged 9 – 11 show especially strong bimodality in growht, which differs by region (panel). Black lines indicate region-specific frequencies of lengths observed; red lines indicate the same but with all data combined.

8 Stock Assessment

8.1 Catch – quality, misreporting, discards

Annual estimates of landings of Atlantic wolffish from Icelandic waters are available since 1905 and in recent decades, recorded by gear (Figure 12, 14). The historical information are largely derived from the Statistical Bulletin, with unknown degree of accuracy, and retrieved from Statlant. For the period between 1980 to 1993, landings of Icelandic vessels were recorded by Fiskifélagið (a precursor to the Directorate of Fisheries). Despite being generally accurate, there have been anecdotal instances of intentional misreporting of cod as Atlantic wolffish (by covering landed cod with a layer of Atlantic wolffish), so it is expected that this period of landings may be slightly less accurate than more recent records. The more recent landings (from 1993 onwards) are from the Directorate of Fisheries as annually reported to ICES. After 2013, all landings in 5.a. are recorded by the Directorate, while foreign vessel landings were obtained from Statlant.

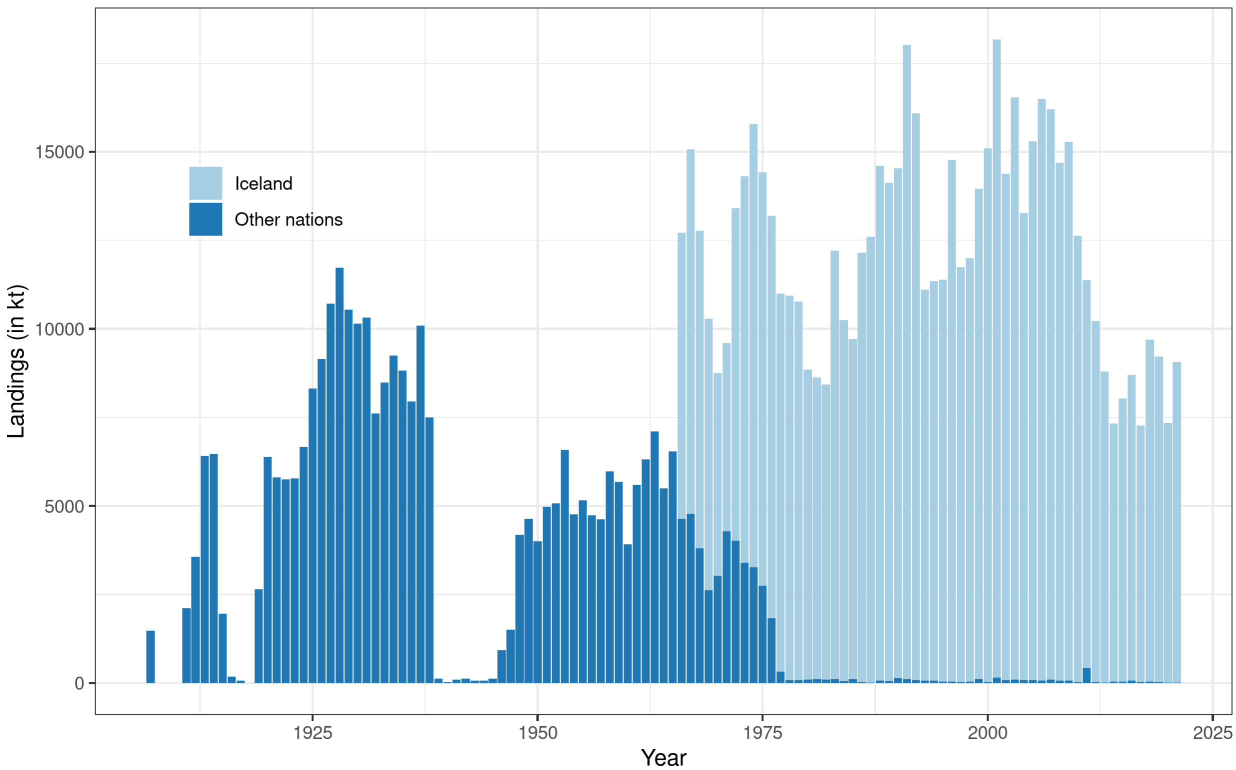

Figure 12: Atlantic wolffish in 5.a. Landings in 5.a.

The estimates by the Directorate of Fisheries are based on a full census by weighing fish at the dock when landed or in fish processing factories prior to processing. Information on the landings of each trip are stored in a centralised database of which the Marine and Freshwater Research Institutes (MFRI) employees have full access. Captains are required to keep up-to-date logbooks that contain information about timing (day and time), location (latitude and longitude), fishing gear and amount of each species in each fishing operation. Logbooks are especially useful for providing information on catch location and monitoring its change over time (13). The Directorate of Fisheries and the Coast Guard can, during each fishing trip, check if amount of fish stored aboard the vessel matches what has been recorded in the logbooks, in part to act as a deterrent for potential illegal and unrecorded landings.

Nearly all Atlantic wolffish is landed gutted and converted to ungutted using the conversion factor 1/0.90 (see the Directorate of Fisheries website here).

The real gutting factor can vary year to year so the amount of ungutted Atlantic wolffish landed may be different than the estimated value. All the bookkeeping of catch is in terms of gutted fish and any reference to ungutted catch is just ungutted divided by 0.90 so this does not matter in assessment.

Discards are illegal in Icelandic waters but are assumed to take place to some degree. A discard monitoring program of the MFRI, designed to estimate high-grading of cod and haddock, has been in place since 2001, but no estimates of discards exist for Atlantic wolffish in Icelandic waters.

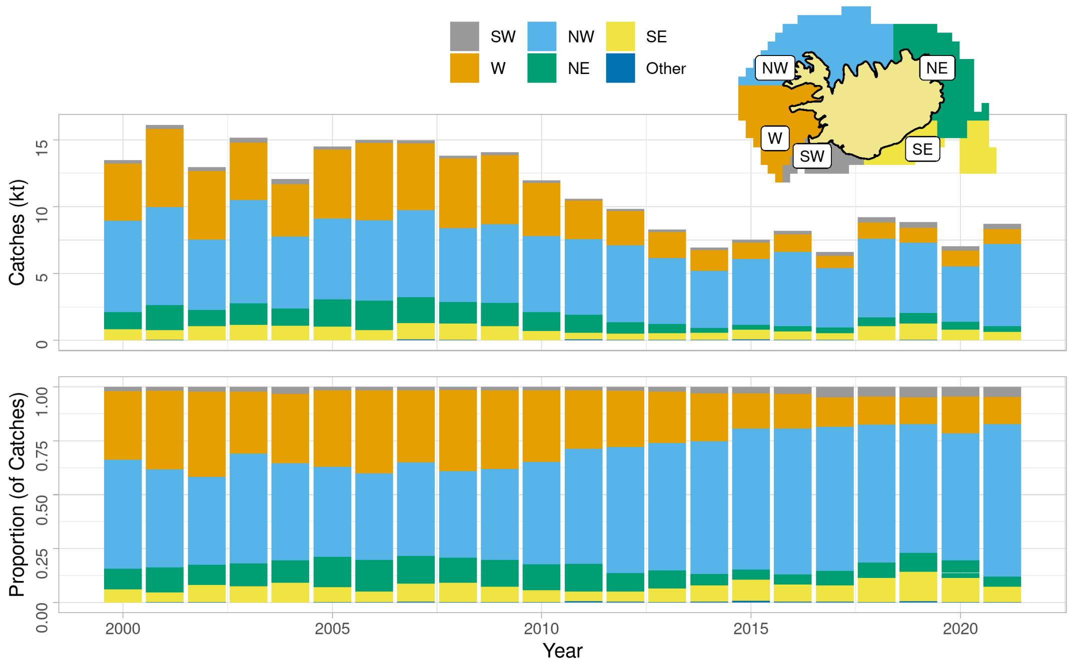

Figure 13: Atlantic wolffish in 5.a. Changes in spatial distribution of the Icelandic fishery as reported in logbooks. All gears combined.

8.2 Surveys

8.2.1 Research cruises

Information on abundance and biological parameters from Atlantic wolffish in 5.a is available from three surveys, the Icelandic groundfish survey in the spring (IGFS, referred to as the 'spring survey') and the Icelandic autumn survey (IAGS, referred to as the 'autumn survey'). Length distribution data are also available from the fisheries survey data from East Greenland, but no other biological data accompany these (see Fig. 3).

The Icelandic groundfish survey in the spring, which has been conducted annually since 1985, covers the most important distribution area of the fishable biomass. The autumn survey commenced in 1996 and expanded in 2000 to include deep water stations 15. It provides additional information on the development of the stock. The autumn survey has been conducted annually with the exception of 2011 when a full autumn survey could not be conducted due to a fisherman strike. Although both surveys were originally designed to monitor the Icelandic cod stock, the surveys are considered to give a fairly good indication of the fishable stock, the spring survey generally catches more Atlantic wolffish and showing more contrast between periods of high and low Atlantic wolffish density. A detailed description of the Icelandic spring and autumn groundfish surveys is given in Sólmundsson et al. [20]. Fig. 16 shows both a recruitment index and the trends in various biomass indices. In Icelandic waters, recruitment was good from 1993 to 1999 but since then it decreased to a historical low level in 2011. Concurrently with the enlargement of preserved area at Látragrunn the downward trend in the recruitment ceased and have since 2011 been rather stable and increased a little. Changes in spatial distribution observed in the spring and autumn survey are shown in Fig. 17. The figure

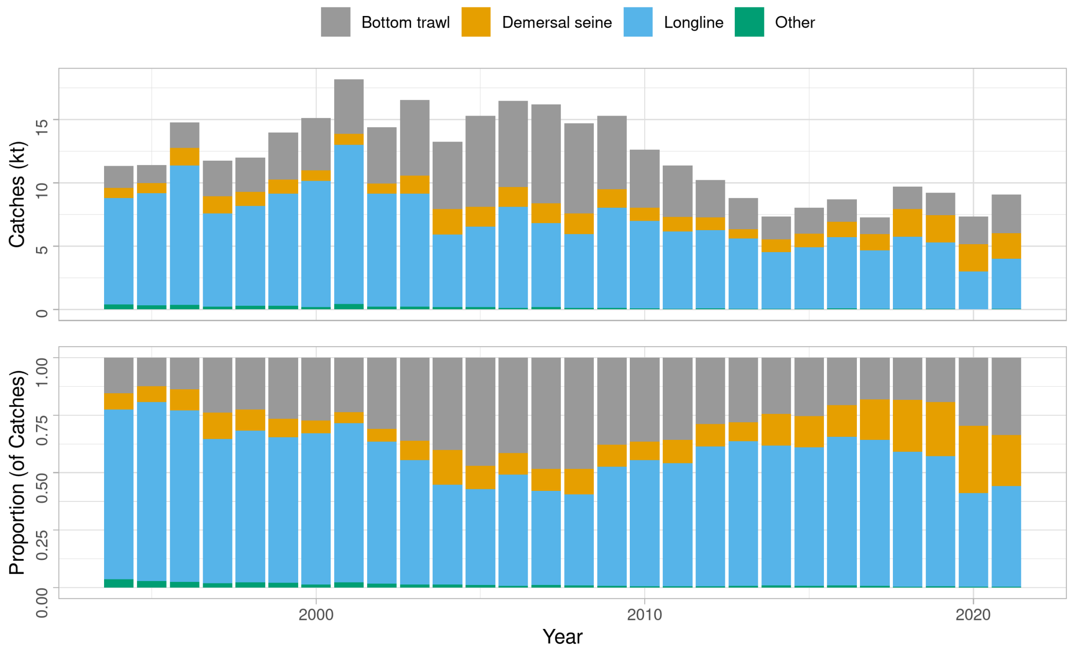

Figure 14: Atlantic wolffish in 5.a. Commercial landings by gear as registered in Icelandic logbooks.

shows that the largest proportion of the observed biomass resides in the northwest and west of Iceland, where the main fishing activities occur.

8.3 Weights, maturities, growth

Biological data from the commercial longline and trawl fleet catches are collected from landings by scientists and technicians of the Marine and Freshwater Research Institute (MFRI) in Iceland. The biological data collected are length (to the nearest cm), sex and maturity stage (if possible since most is landed gutted), and otoliths for age reading. Most of the fish that otoliths were collected from were also weighed (to the nearest gram).

Sampling from commercial catches of Atlantic wolffish is considered good; both in terms of spatial and temporal distribution of samples (Fig. 18).

8.3.1 Growth

Most Atlantic wolffish caught in the spring and autumn surveys have been aged to be 16 years of age or less, although it is not unusual to catch individuals through age 23. Rarely, individuals may attain ages up to 30, although it is unclear how reliable age reading is at ages over 20.

Studies on growth of female Atlantic wolffish at Iceland showed that in the warm sea NW of Iceland the average growth rate was about 5.5 cm year-1 for 1-10 years old fish, but in colder sea NE of Iceland the average growth rate was about 3.8 cm per year for same ages, in Jónsson study in 1982 the average growth rate was 5.8 cm per year for same age (Gunnarsson et al. [4]). The growth rate of female Atlantic wolffish in the warmer sea NW of Iceland seems to be like the growth rate of Atlantic wolffish at North Norway and in the colder sea NE of Iceland like growth rate of Atlantic wolffish in the White Sea.

Although Atlantic wolffish rarely attain sizes over 100 cm and 10 kg in the surveys and commercial catches, their growth does not appear to slow much at the largest sizes and is instead roughly linear. Fish caught in the commercial catches are substantially larger at age than those taken from surveys, indicating different selectivity. This is partially a result of commercial catches being mostly focused the northwest region

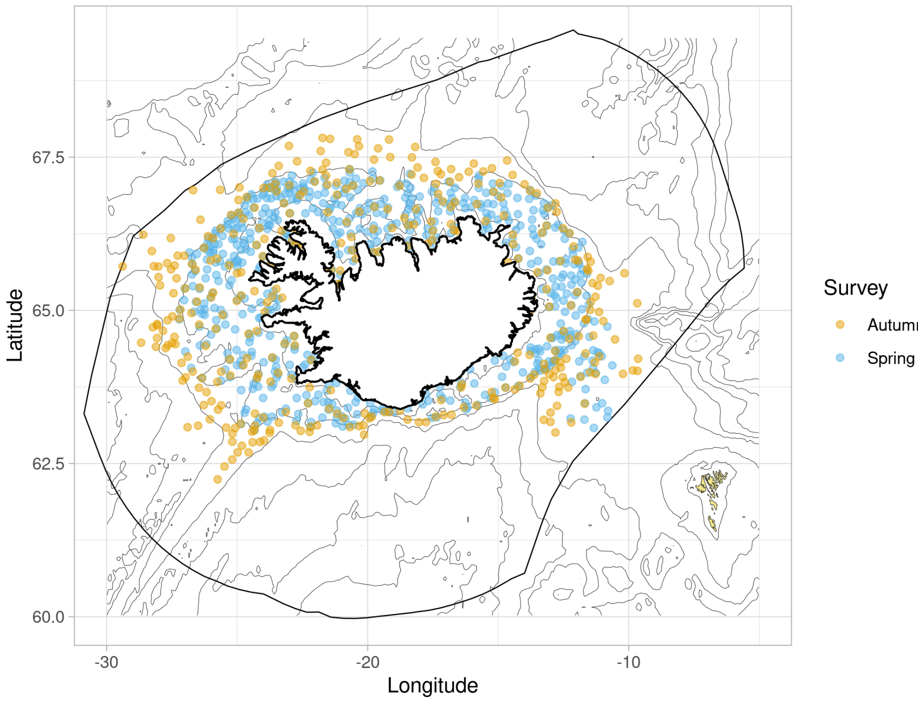

Figure 15: Atlantic wolffish in 5.a. Catch reported in logbooks by depth and gear, in terms of biomass (top panels) and proportion (bottom panels).

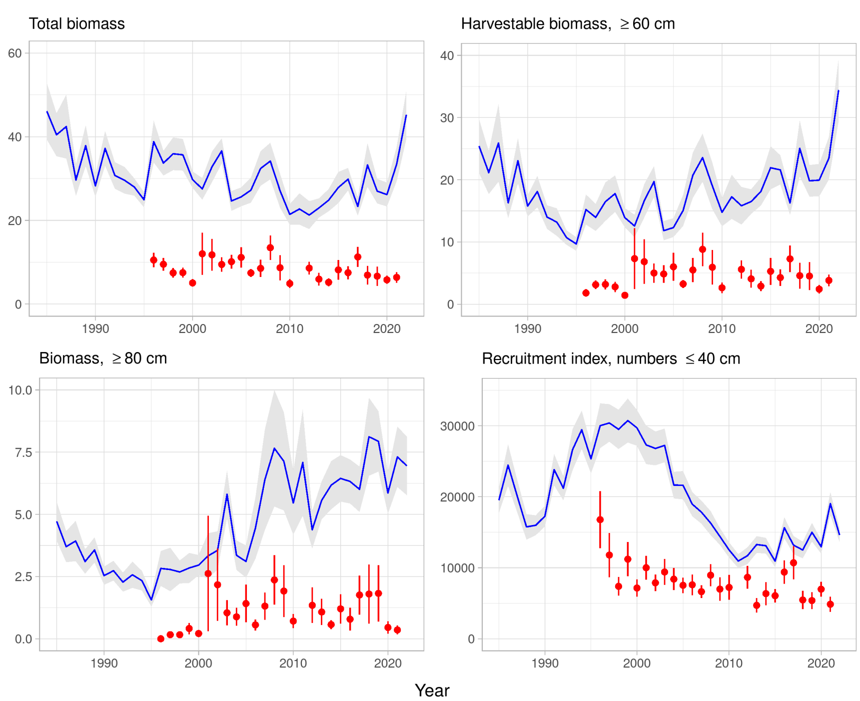

Figure 16: Atlantic wolffish in 5.a. Biomass trajectories from the spring and autumn surveys.

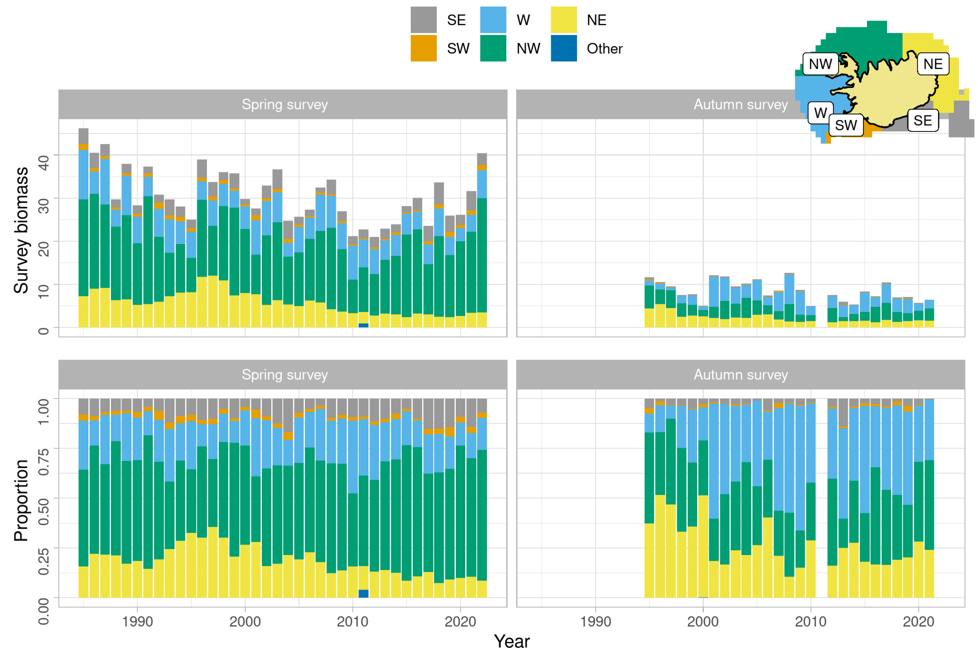

Figure 17: Atlantic wolffish in 5.a. Biomass by area from the spring and autumn survey.

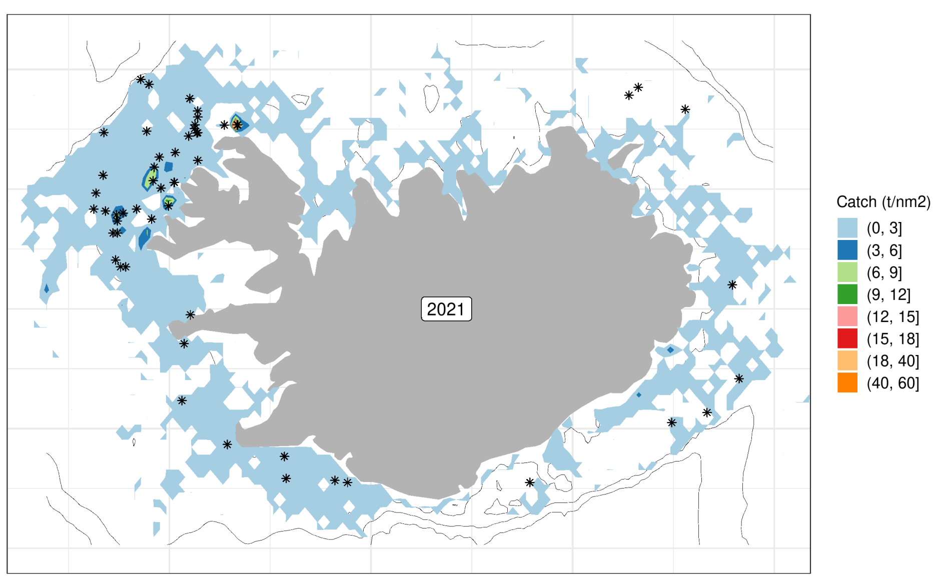

Figure 18: Atlantic wolffish in 5.a. Fishing grounds in 2021 as reported by catch in logbooks (tiles) and positions of samples taken from landings (asterisks) by longliners and trawlers.

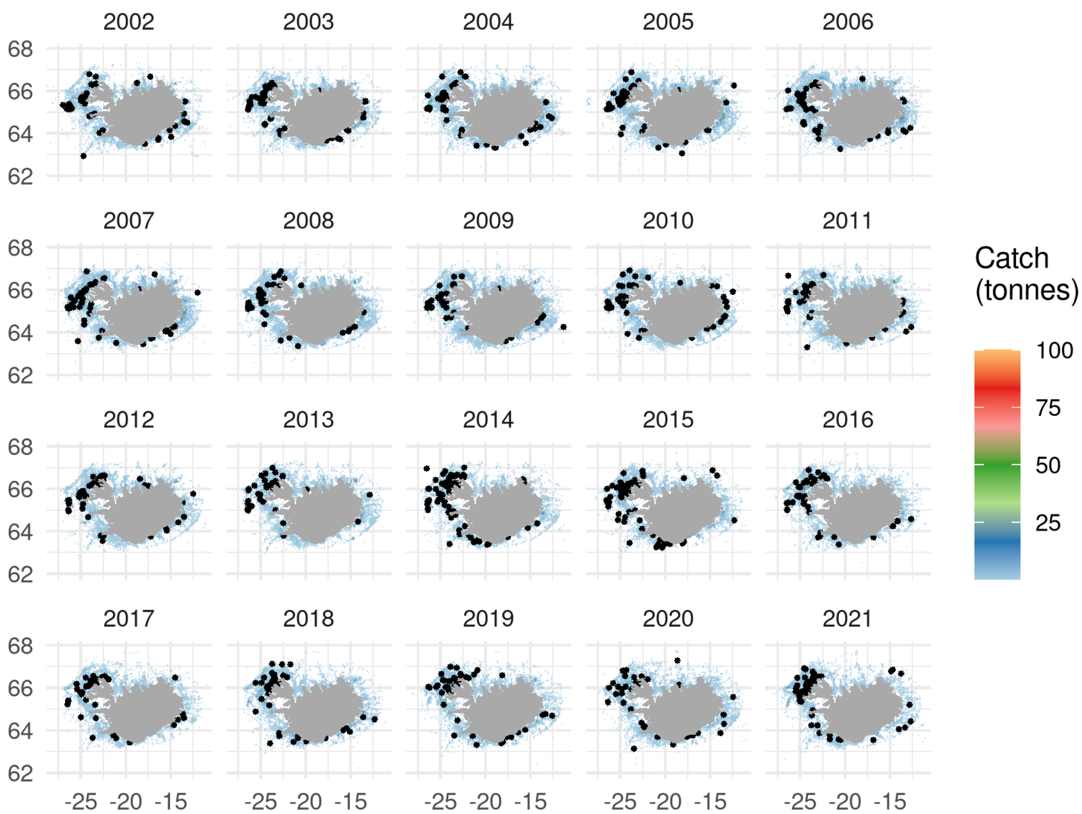

Figure 19: Atlantic wolffish in 5.a. Fishing grounds across years as reported by catch in logbooks (tiles) and positions of samples taken from landings (asterisks) by longliners and trawlers.

where faster growing Atlantic wolffish may be found, but may also be the result of behavior (see section on **Ecosystem drivers**). However, despite regional differences in growth, the length-weight relationship is highly stable, so there is likely little variation in condition.

Fish weights at length are available from both surveys and commercial data (Figs. 20 and 21). Stock weights were calculated as the mean weight at age taken from the spring survey in March, after converting lengths to weights using an estimated power relationship from fish with both length and weight data collected in both survey and commercial samples. Weights are calculated as the mean weight expected from the length distribution observed for that year. Before 1985, survey data were replaced with catch weight data, which are available from 1980. Where weight at a certain age were missing which occurred only in very rare cases, data from the other data sources were used to fill the gap. To reduce variation among years, stock weights were calculated as a moving average of the current and previous two years.

Figure 20: Atlantic wolffish in 5.a. Weight at age observed in the spring survey and from the commercial catches over years.

8.3.2 Maturities

Before spawning for the first time Atlantic wolffish is generally on the maturity stages cortical alveolus for several years (Barsukov, 1959; Gunnarsson et al. [4]). Fast growth and early maturation or slow grow and delay maturing seems to be the characteristic of Atlantic wolffish at Iceland. The fast-growing fish in NW of Iceland matured at the average about 63.5 cm long then 10.6 years old where this number for the slower growing fish in NE of Iceland were 72.6 cm and 13.8 years old (Gunnarsson et al. [4]).

Data are used from the autumn survey to correspond roughly with spawn timing, as well as commercial data from July - December for 2003 onwards. Maturation is difficult to detect in general and only read from females. Before spawning for the first time Atlantic wolffish is generally on the maturity stages cortical alveolus (CA) for several years. Such a prolonged CA stage is unknown for other species of teleosts in the

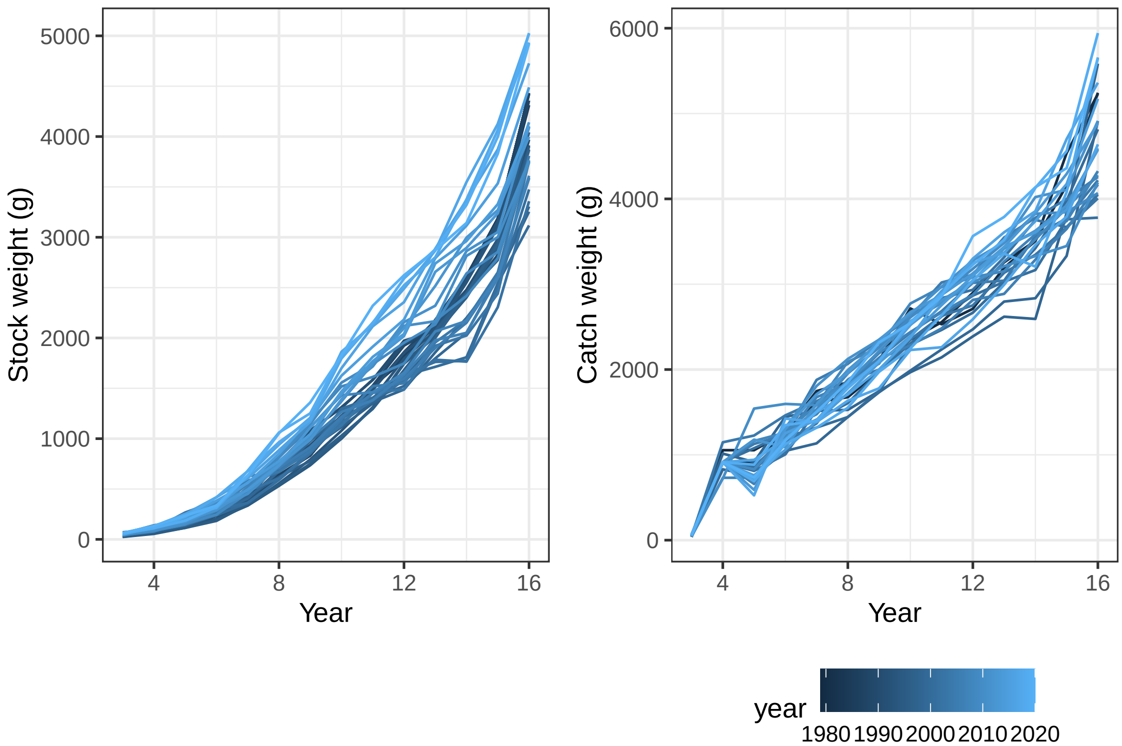

Figure 21: Atlantic wolffish in 5.a. Weight at age observed in the spring survey and from the commercial catches over age.

North Atlantic except for Spotted wolffish and Greenland halibut (Barsukov, 1959; Á. Gunnarsson et al., 2006; Gunnarsson et al., 2008; Junquera et al., 2003; Rideout et al., 1999). Years with skipped spawning is also possible. The duration of vitellogenesis is 5–6 months with spawning taking place from late summer to early winter, depending on geographical area (Pavlov and Novikov, 1993; Templeman, 1986; Tveiten and Johnsen, 1999). At Látragrunn, the main spawning grounds for Atlantic wolffish in Icelnad off the westfjords, spawning begins in late September. Otherwise, spawning usually began in late August or beginning of September and is completed in end of October (Gunnarsson et al. [6]). Atlantic wolffish is a determinate spawner with the oocytes being fertilized internally (Johannessen et al., 1993). The female spawns a single batch of demersal eggs which are 4–7 mm in diameter. After spawning, the female coils around the eggs, creating an egg cluster which is guarded by the male (Keats et al., 1985; Ringø and Lorentsen, 1987). The incubation time is between 800 and 1000 °C-days (Pavlov and Moksness, 1995).

Maturity-at-age data are given in Figs. 22 and 23. Maturity data from the autumn survey and a July - December commercial data from 2003. A fixed length-based ogive is used over all years due to sparse data.Where no observations occurred for a specific length group (rare), predictions from a model including all years was used to fill the gap. Prior to 1985 the proportion mature is assumed fixed at 1985 levels. To reduce variation among years, stock weights were calculated as a moving average of the current and previous two years.

8.3.3 Natural mortality

Natural mortality M was set as 0.15 in models presented here. Alternative formulations have been considered, but none appeared to have any greater support (see Appendix I).

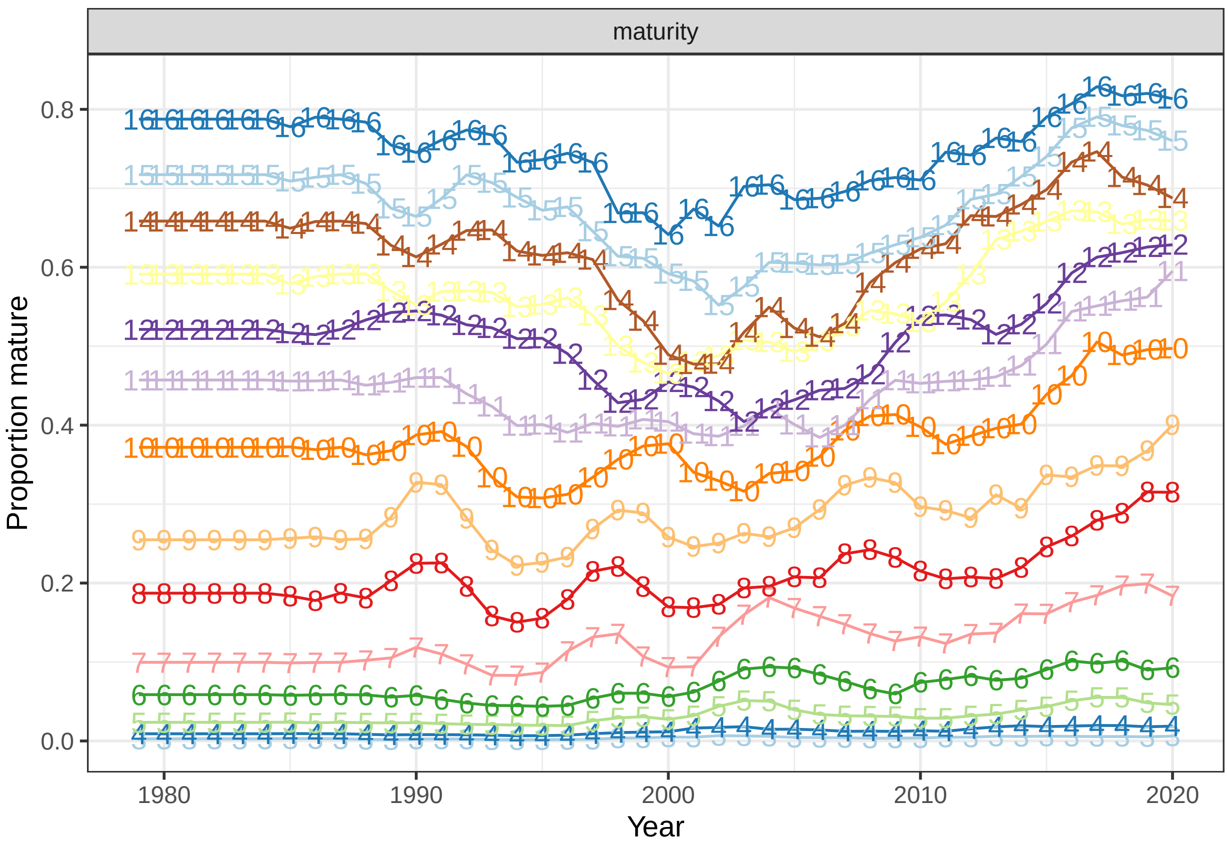

Figure 22: Atlantic wolffish in 5.a. Proportion mature at age from the autumn survey and commercial data over years.

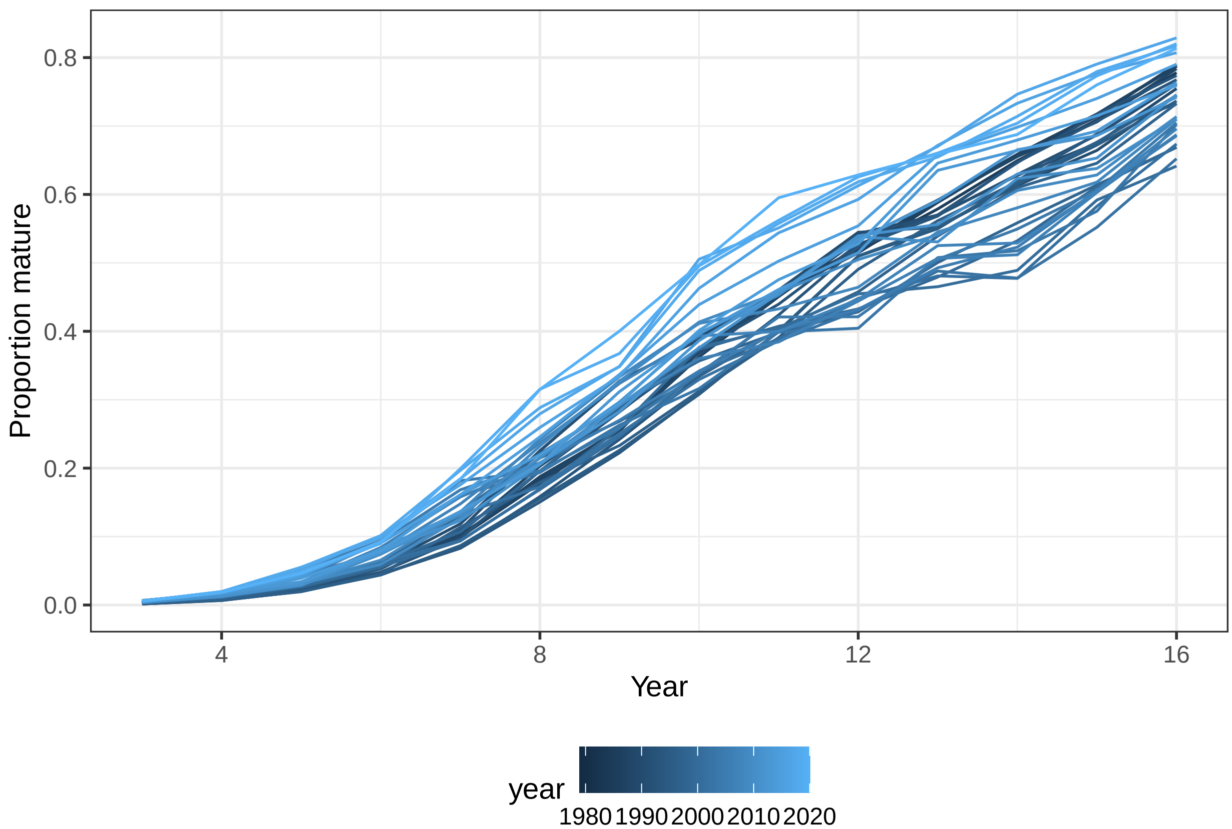

Figure 23: Atlantic wolffish in 5.a. Proportion mature at age from the autumn survey and commercial data over age.

9 Assessment model

Alternative age-structured and length- and age-structured models were explored, but because of the highly variable growth of Atlantic wolffish, it was decided that age-based models may give more stable results if differences in growth are accounted for by applying gear-, region- and time-specific age-length keys (ALKs) while generating total catch and survey data. Several structures of Gadget models, but none resolved the issues listed above with the original Gadget model. These were discontinued, as explorations indicated that accounting for this variation using a spatially explicit model could cause unstable results and assumptions regarding regular migration patterns, for which there is little data to inform.

Therefore, an age-based assessment was developed using SAM (Nielsen and Berg [15], Berg and Nielsen [1]). The model runs from 1979 onwards and ages 4 to 16 are tracked by the model, treating age 16 as a plus group. Observations in SAM are assumed to arise from a multivariate normal process with an expected value derived from the model. SAM allows for the investigation of how to treat patterns in the residuals by defining different parameters by age for observation residual variances and correlations for all data sets. Furthermore, the user can define age groups for survey catchabilities, and related power relationships, and process variances for the $\log(N)$ and $\log(F)$ residuals.

SAM model development began with ALK refinement and choice of model age structure that emphasized correlations among consecutive cohort observations within catch-at-age and survey index data. The youngest ages observed in the surveys were discarded due to low correlations with consecutive ages, so the model begins at the earliest age that Atlantic wolffish start appearing in the catch. Extensions of the maximum age up to 20 were explored but results did not change, so a maximum age of 16 was maintained.

Initial explorations were then used to find the most important configuration settings for stability in optimization and model fit. Model choice was based on minimizing AIC, while avoiding configurations for which there was little biological support. The set of models considered was created using an informed shotgun method for comparing several models with minor adjustments to configuration settings determined as those that had the greatest impact on AIC reduction. These settings included some combination of varying the pattern of linkages among ages of log observation error variances estimated, the pattern of power parameter in non-linear catchability relationships, the pattern of correlations among ages when AR(1) correlations were included in residuals, and the pattern of F variances estimated. Further parameter refinement was done through examination of residual patterns. Configurations with power relationships in catchability, correlations in catch residuals, and linkages of the recruitment process variance parameter with older ages were initially considered to marginally fit the data better, but excluded due to a lack of theoretical reasoning supporting such configurations. In general, the best model chosen had one of the lowest AIC values, but small increases in AIC were tolerated to reduce the number of parameters when differences between estimated parameter values were unlikely to be significant. Starting values were jittered to test for stability in model outcomes.

9.1 Input data

Spring survey length and age data ranged from 1985 through 2021, and spanned ages 4 - 16+ (Fig. 24). Age-length keys (ALKs) were created and applied within regions to account for regional growth differences. All ALKs were created using 5 cm length bins from 15 - 95 cm, with longer bins at lengths $0 - 15$ and 95+.Splitting data by region created some sparsity in the ALKs at large and small sizes depending on the region, so for length bins < 20 or > 70 cm, if no proportion were assigned to a given age, it was replaced with values observed in an ALK generated across all years (but within regions, times, and gear types). The same procedure was applied to ALKs from 106 specifically with a missing data < 40 cm (as wolffish are particularly fast-growing in this region) and to region 103 for wolffish > 50 cm (as wolffish are particularly slow-growing in this region). ALKs were rescaled to ensure sums to 1 within a length bin. Lagged correlations among adjacent ages in the spring survey indices indicate that the indices are highly informative for tracking cohorts (Fig. 25). Survey indices at age were generated from the spring survey data using standard stratification procedures ICES [8]). Younger ages than 4 were not included because correlations among survey indices adjacent in age were 0.5 or greater above age 4, but not as highly correlated below the age of 4 (Fig. 25).

Autumn survey indices at length and age were available from 2000 using a standard stratification procedure

(Fig. 26). Extensions to the survey were added in 2000 so 1996 - 1999 data were excluded. Most ages are not read from this survey, so ALKs from the spring survey are used, but adjusted to apply to the previous year and age group after preliminary analyses indicated better alignment with commercial age samples taken at the same time as the autumn survey was conducted. In the last year of autumn survey data, the same ALK as the previous year was used. Lagged correlations among adjacent ages in both the autumn indices indicate that the indices are informative, but not as informative as the spring survey (Figs. 27). These indices also have comparatively low contrast Fig. 16).

Catch at age and total landings are available from the 1970s, but only those from 1979 on are used due to available age data (Fig. 28). Annual ALKs were created from 1999 onwards to account for time-variable growth. These ALKs are region-, gear-, and time-specific, and applied to the approximate amount of catch from the corresponding sector. This was done to account for differences in growth patterns between sampling types and regions. Total catch-at-age over sectors is used in tuning. Lagged correlations among adjacent ages in the catch at age data indicate that they are highly informative for tracking cohorts (Fig. 29), but very few fish younger than 5 were found in the catch. Gear and timing were assigned based on landings data, but apportioning by region was done according to proportions observed in logbook data. Age readings before 1999 were possibly unreliable, so ALKs generated from this period were based on 1999 - 2000.

ALKs were generated by first grouping catch data by season (January - June versus July - December), region (according to Bormicon regions, see Fig. 8), and gear (all trawls versus long-lines and gillnets versus all seines), and binning lengths into 5 cm groups within the range 15 - 95, and extended bins of 0 - 15 and 95+ cm at each end of the range. After generating ALKs by partition as specifically as possible, the final ALKs used were a weighted sum of these and successively less partitioned ALKs to reduce the number of 0s. For example, an ALK generated from trawls in the first season and region 101 would be given a weight of 0.9 and summed with an ALK generated from trawls during all seasons in region 101 with a weight of 0.09, an ALK generated from trawls during all seasons and all regions with a weight of 1 - 0.09 - 0.009. This procedure was done within years or year group. Exploratory analysis indicated that ALKs changed very little with its inclusion, but was included to ensure that no data were lost (samples from length bins with no corresponding age data). In addition, because commercial samples are highly selective for middle length ranges, of Atlantic wolffish, proportions-at-age for length bins less than 50 cm over 75 cm were replaced with keys generated across all years 1999+ when no age data were available for the length bin. ALKs were rescaled to ensure sums to 1 within a length bin.

Catch at age data were generated by using gear-, region- and time-specific age-length keys to convert length distributions from the same gear, region and time combination in age distributions that reflect the same fishing segments. Catch at age by fishing segment was then calculated by applying a segment-specific ALK to the length distributions caught by that segment, scaled by their segment-specific catches. Segment-specific catch at ages were then summed across segments to generate a single catch at age per year. To calculate segment-specific catches, landings data were apportioned by season and gear assignments, as landings data are more likely to be more accurate and complete than logbook data. However, as no region is recorded in landings data, proportions among region were extrapolated from proportions among regions recorded in logbook data.

This procedure was applied for ALKs generated for each year beginning 1999 and later, but logbook region data were lacking for earlier data. For most of the earlier data (1981 - 1997), catch at age data were instead replaced with a series of total landings, so the gear-specific ALKs were only applied in 1979 - 1980 and 1998 - 1999. It was attempted to include catch at age data from 1990 - 1997, but they conflicted with later data and destabilized the model, so were removed. This total catch-at-age was used as input (Fig. 28. Lagged correlations among adjacent ages in the catch at age data indicate that they are highly informative for tracking cohorts (Fig. 29). Age readings from 2021 catch data were not complete at the time of analysis, so this year was excluded.

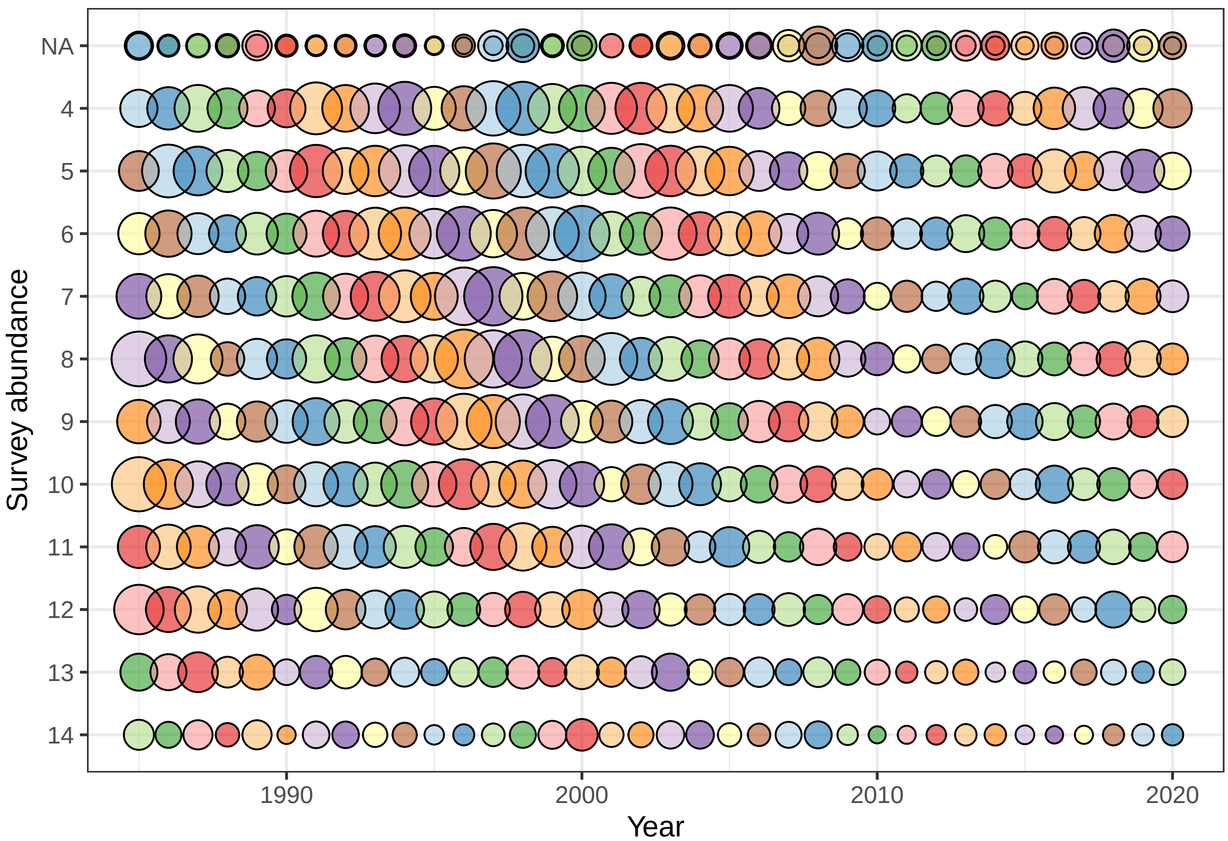

Figure 24: Atlantic wolffish in 5a. Survey numbers at age from the spring survey, point sizes indicate the estimated swept area abundance by age. Points are colored by year class.

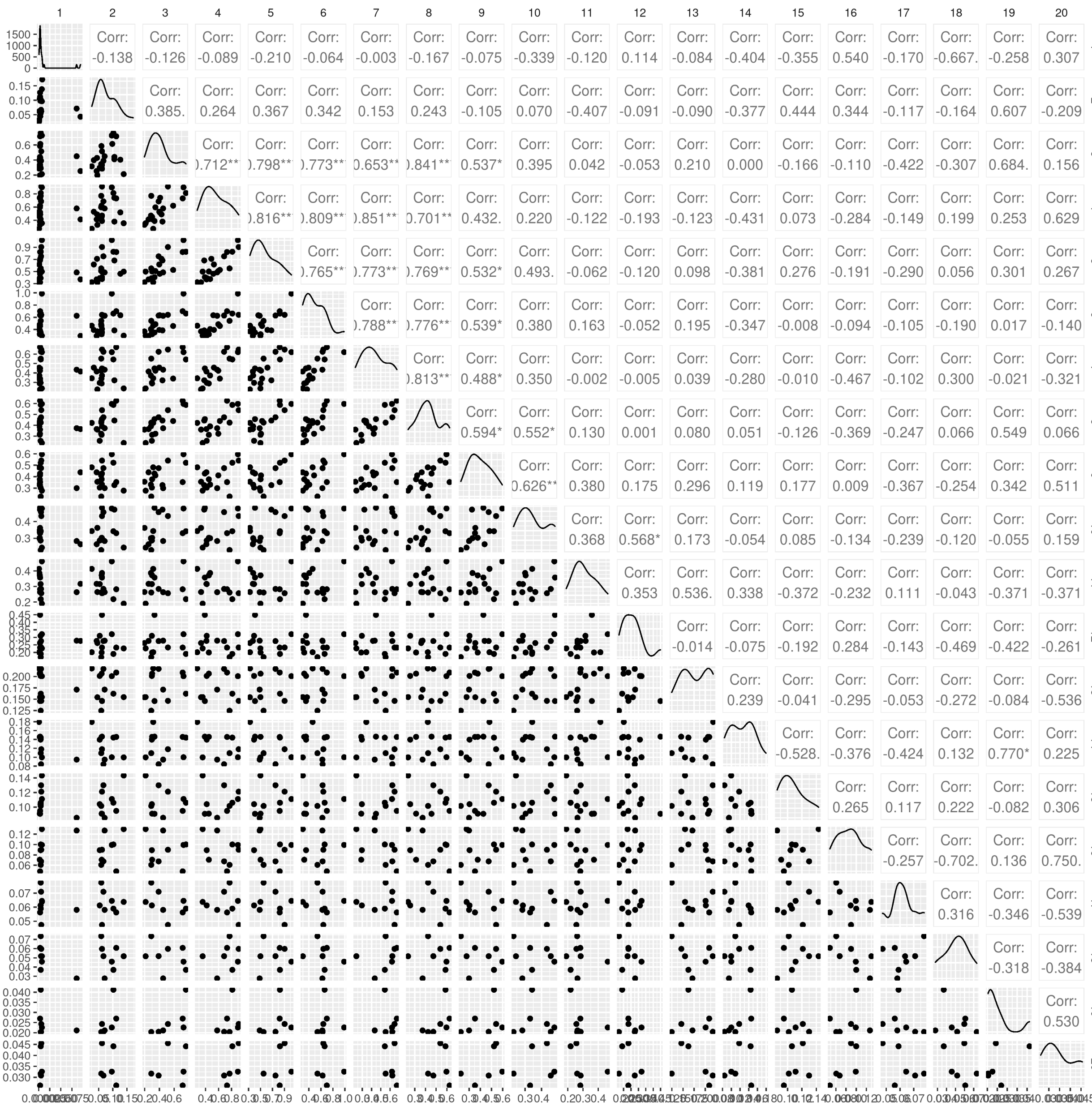

Figure 25: Atlantic wolffish in 5.a. Correlations among observations with a cohort observed at each age in spring survey indices.

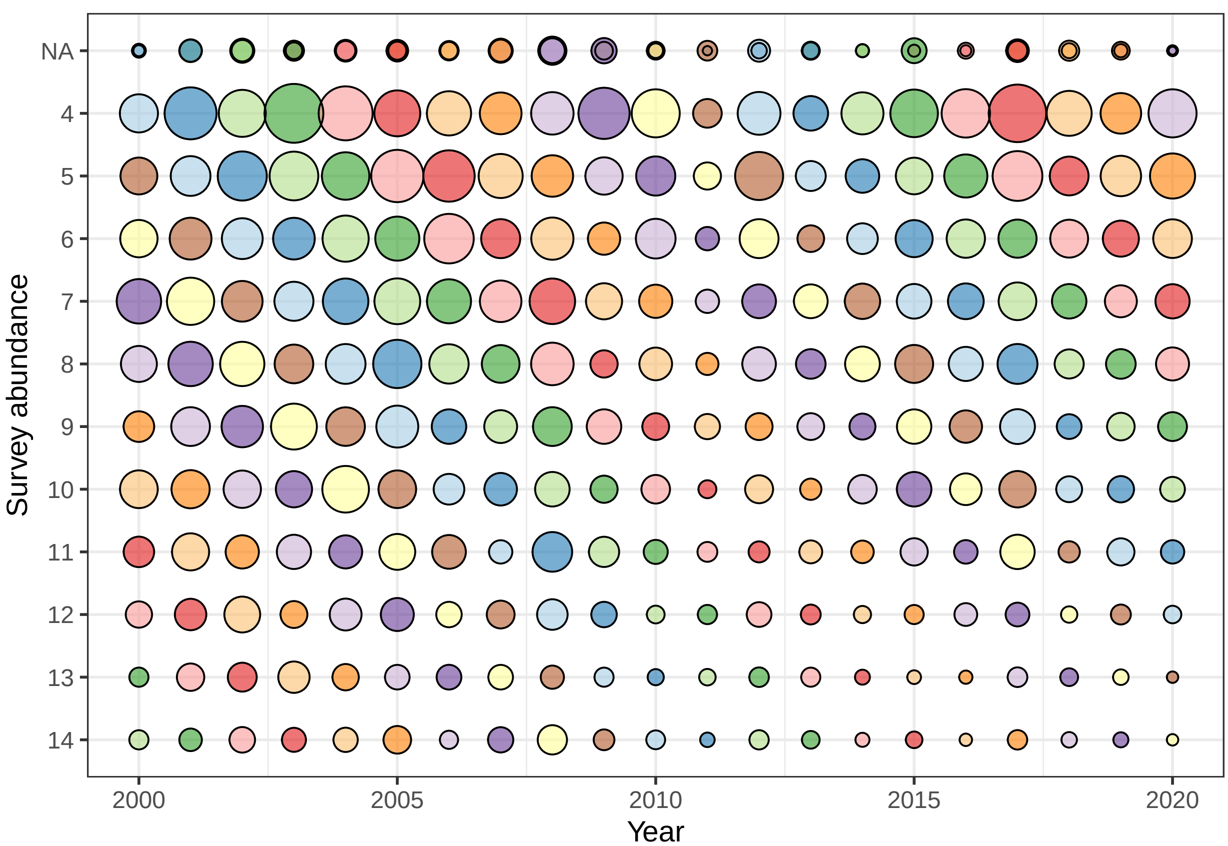

Figure 26: Atlantic wolffish in 5a. Survey numbers at age from the autumn survey, point sizes indicate the estimated swept area abundance by age. Points are colored by year class.

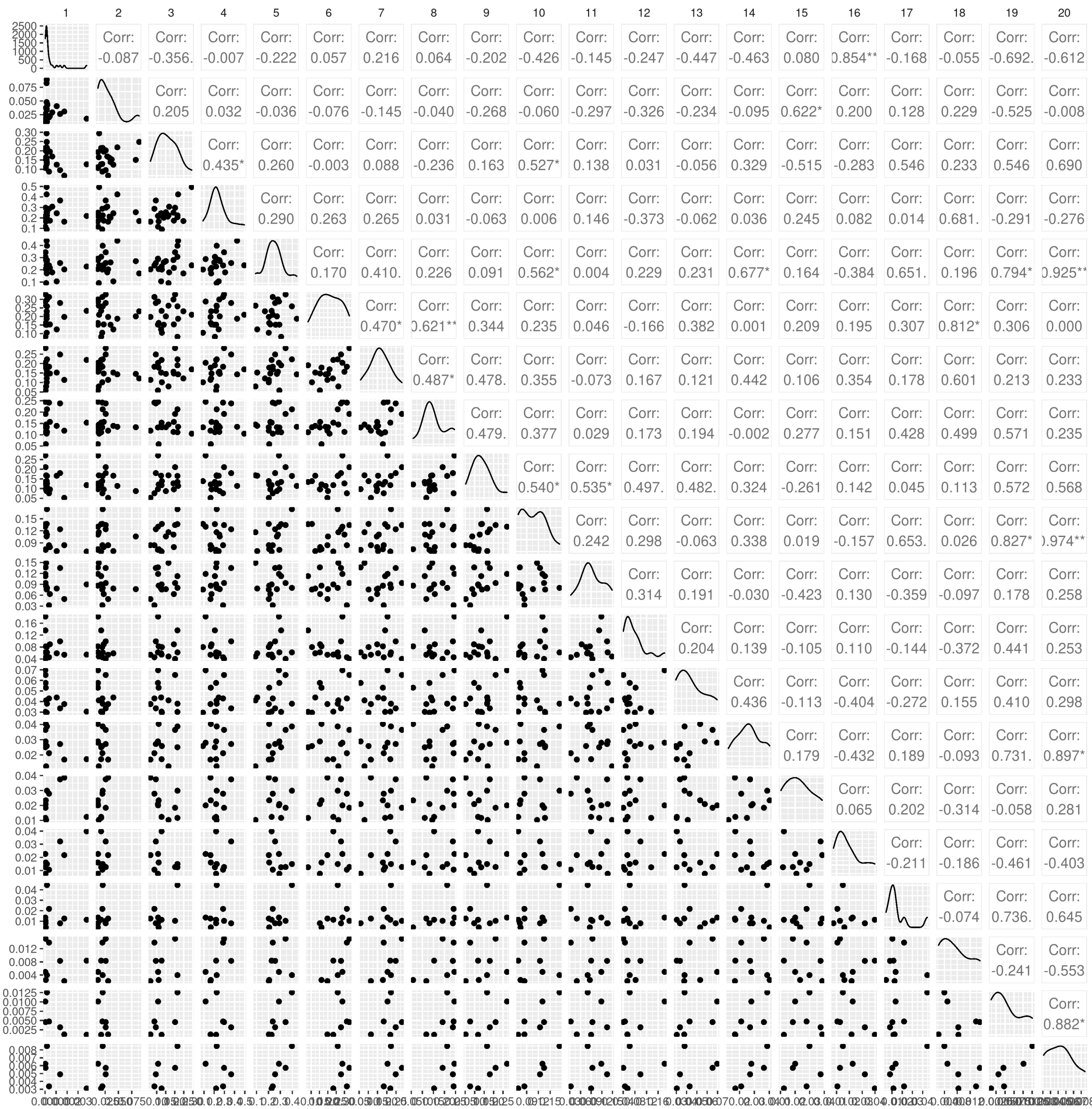

Figure 27: Atlantic wolffish in 5.a. Correlations among observations with a cohort observed at each age in autumn survey indices.

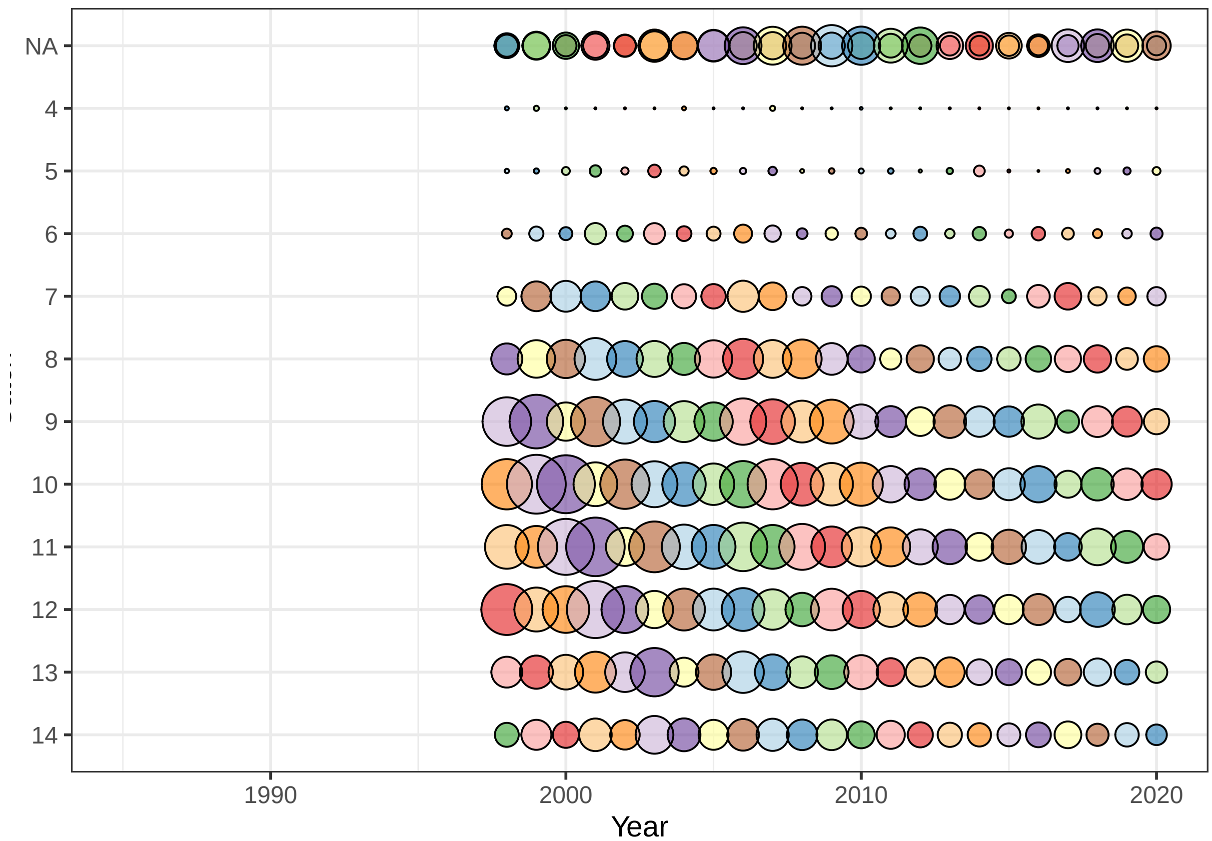

Figure 28: Atlantic wolffish in 5a. Catch at age, point sizes indicate the numbers by age. Points are colored by year class.

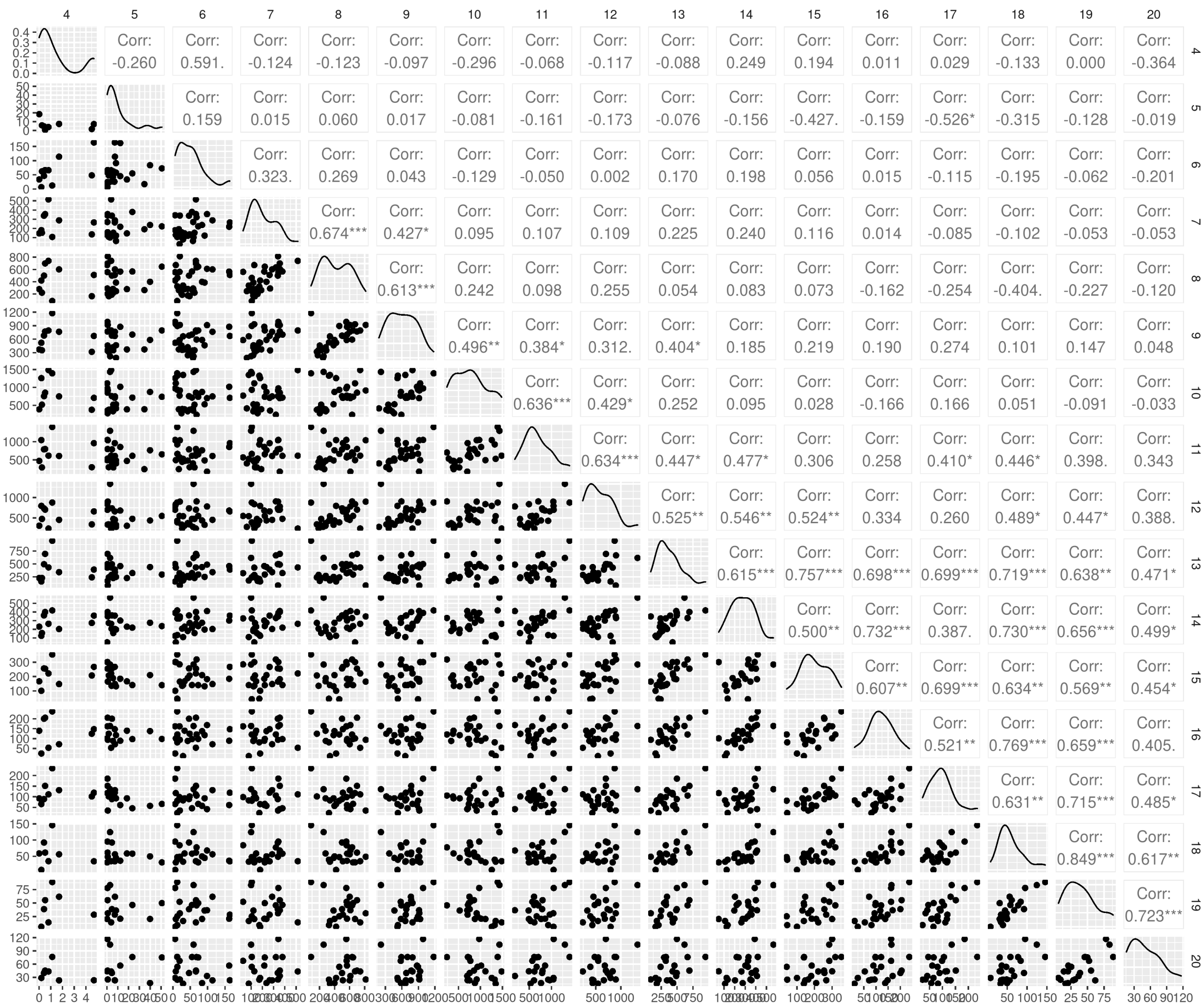

Figure 29: Atlantic wolffish in 5.a. Correlations among observations with a cohort observed at each age in catch at age data.

9.2 Results

9.2.1 Proposed model

The model ranged from 1979 to 2021 and included ages 4 - 16+, the last group including all ages over 16. The final model configuration included two AR(1) parameters estimating autocorrelation among ages in spring survey residuals. One parameter was estimated for the correlations that range 4/5–11/12, where '/' denotes the two ages being correlated, the other estimated for the range 12/13–15/16+. For the autumn survey, two autocorrelation parameters where estimated as corresponding with 4/5–9/10 and 10/11–15/16+ groupings. Observation variances were set for catch at age data to be a different parameter for ages 4 –8 versus 9 – 16+, for the spring and autumn surveys to have three parameters each estimated: for ages 4–9, 10–13, and 14–16+. All other parameters used default settings. Including power parameters in the catchability relationships was explored, and improved the fit to the data very slightly for ages 13 - 16+, but were in the end not included due to a lack of biological support for the parameterisation. Instead it was deemed better to maintain a simpler model structure, especially as the improvement to the model fit was very minimal. All other default settings were used.

9.2.2 Diagnostics

Fits to the catch-at-age data and survey numbers-at-age indices can be found in Fig. 30. The fit to total catch and landings data can be found in Figs. 31 and 32. Catch and spring survey data are followed the closest by the model, whereas fits to the autumn survey series are slightly more noisy but follow a similar pattern. Fits to landings data are quite variable, but more recent fits catch at age data are better.

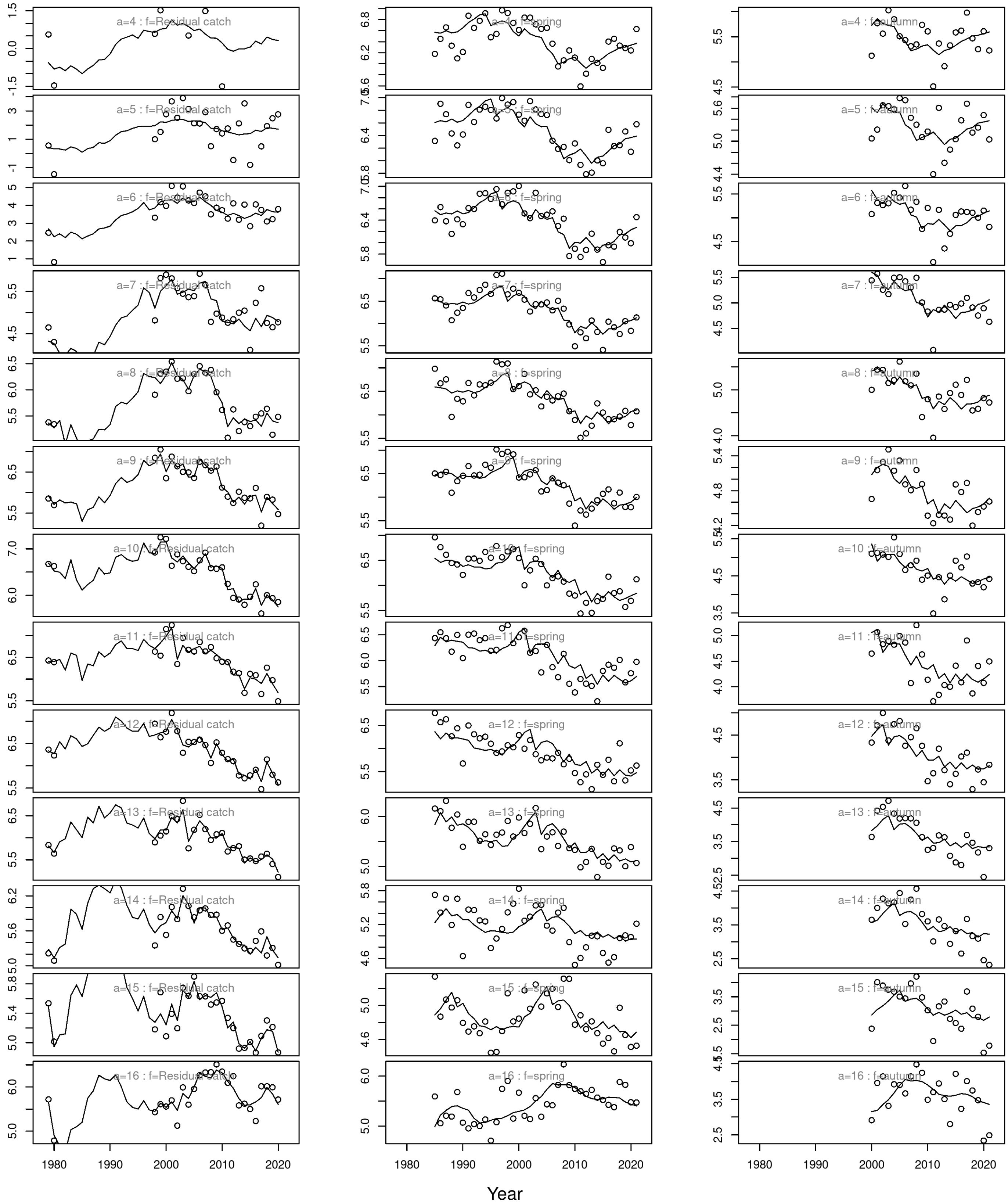

Figure 30: Atlantic wolffish in 5.a. Fit to the numbers at age input data to the proposed SAM model (columns left to right: catch, spring survey, and autumn survey.

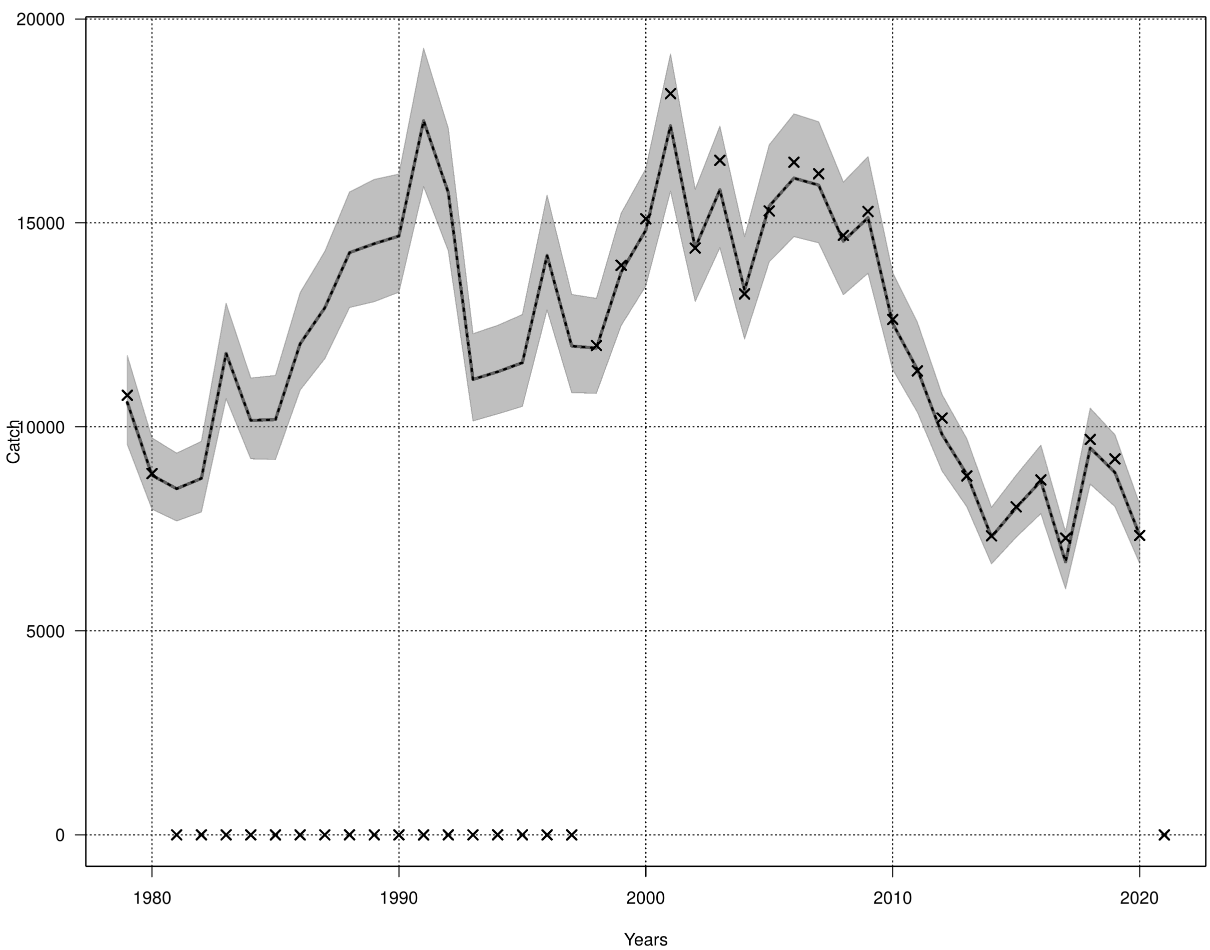

Figure 31: Atlantic wolffish in 5.a. Fit to the total catch in the proposed SAM model.

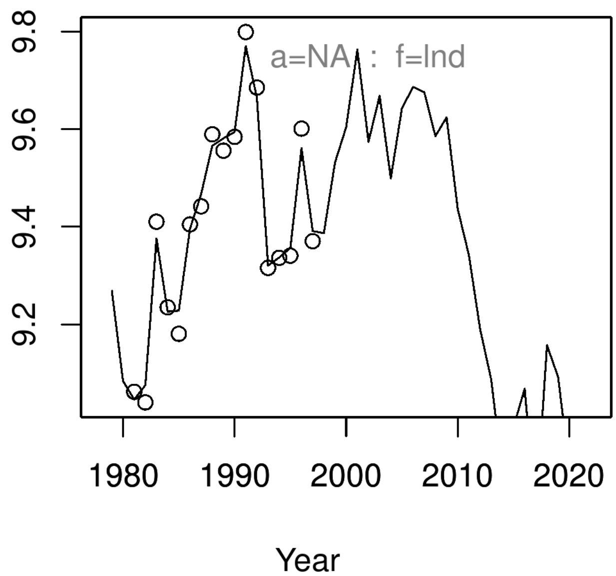

Figure 32: Atlantic wolffish in 5.a. Fit to the landings input data to the proposed SAM model.

Neither observation nor process residuals show obvious trends (Figs. 33 and 34).

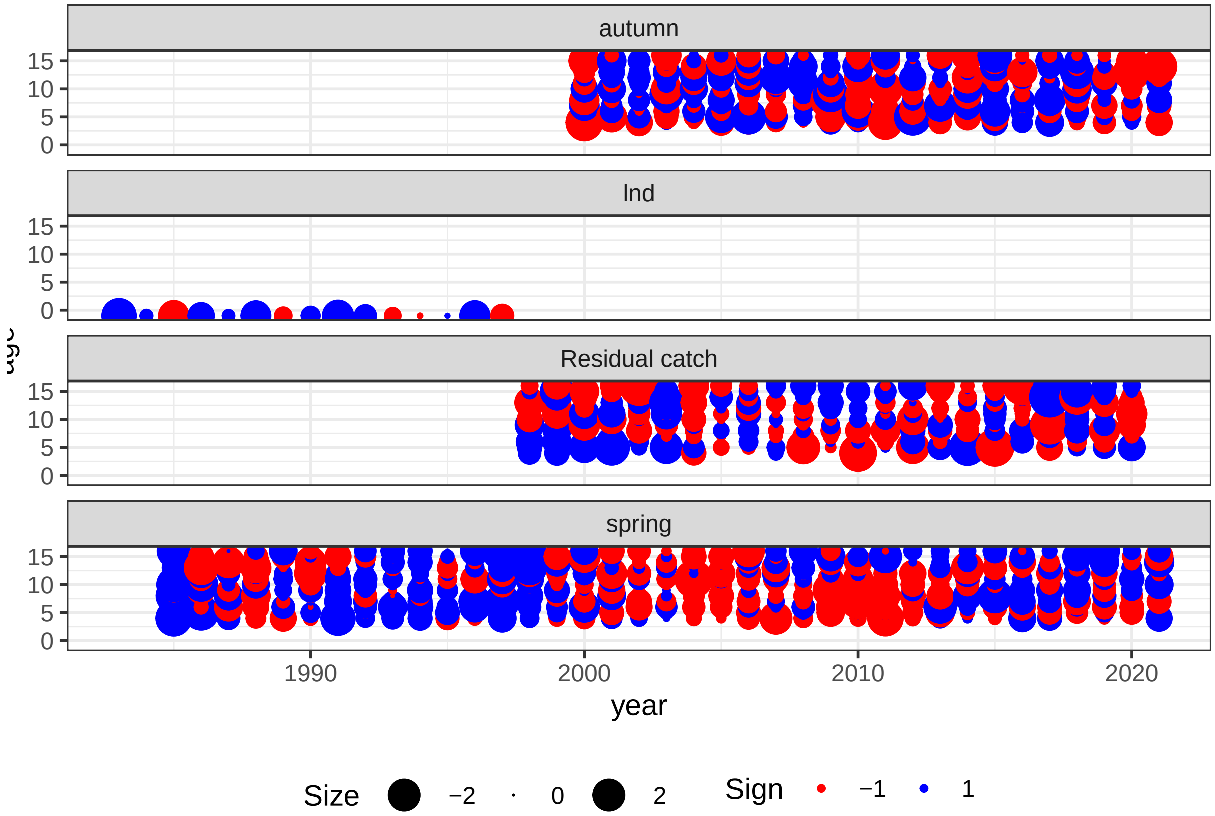

Figure 33: Atlantic wolffish in 5.a. Observation error residuals of the proposed SAM model.

An overview of model parameter estimates can be seen in Fig. 35. Parameters with similar values were joined across ages within data sources if estimates overlapped substantially; therefore those left show appreciable differentiation.

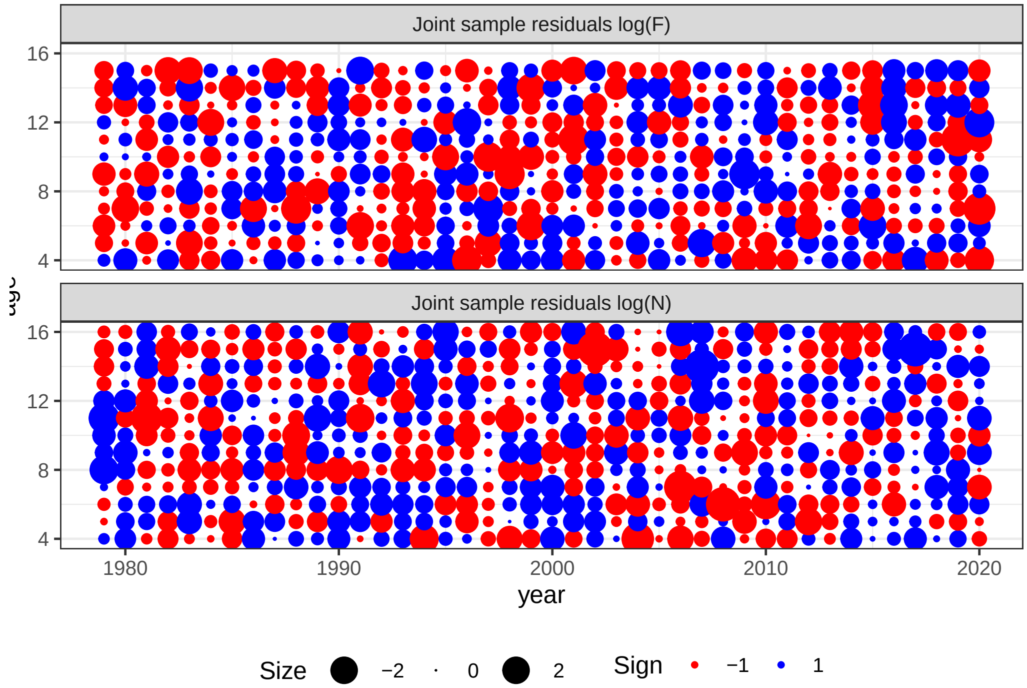

Figure 34: Atlantic wolffish in 5.a. Process error residuals of the proposed SAM model.

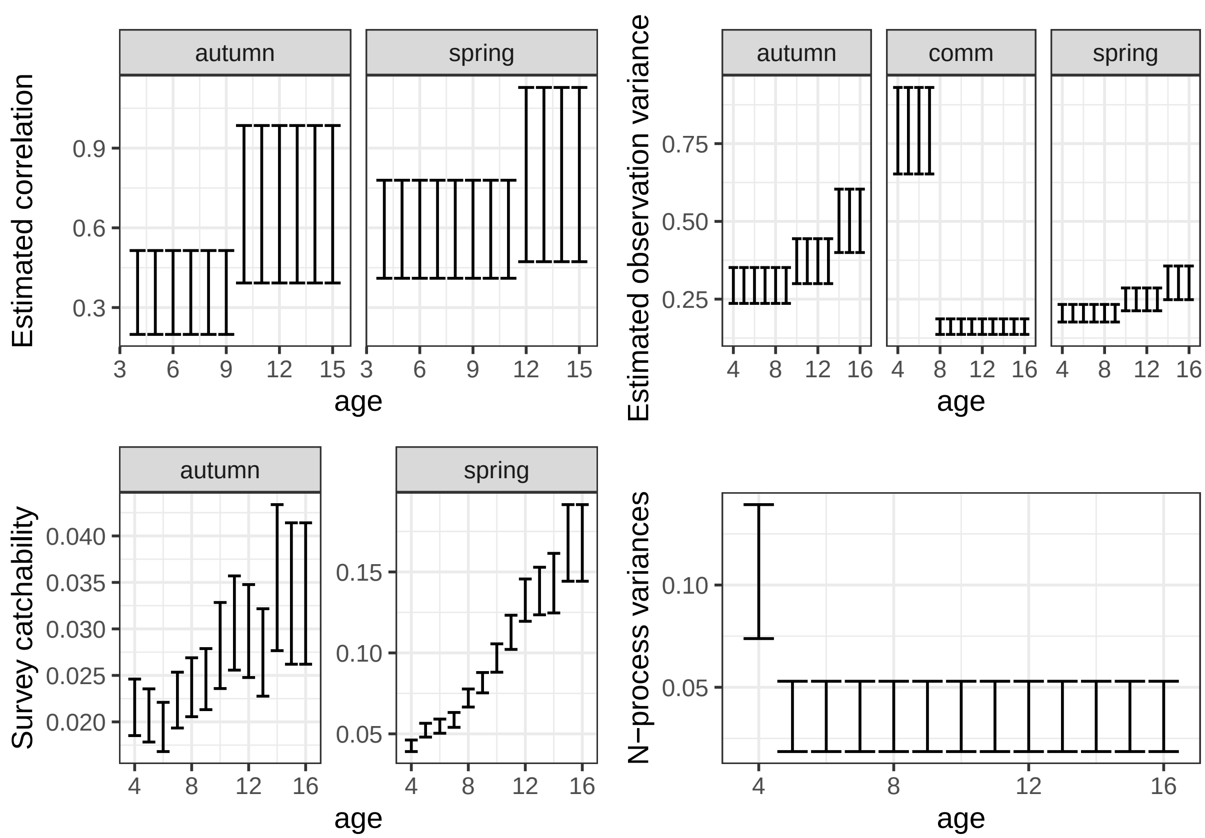

Figure 35: Atlantic wolffish in 5.a. Overview of the proposed SAM model parameter estimates.

Table 2: Atlantic wolffish in 5.a. Mohn's *ho* calculated from analytical retrospective analyses of the proposed model.

R(age 4)	SSB	Fbar(10-15)
0.034	-0.044	0.124

9.2.3 Stock overview

Population dynamics of the Atlantic wolffish estimated in this model show a clear trend of a high recruitment period from 1990 - 2000, corresponding with increased spawning stock biomass (SSB) and catches during the 1996 - 2010 period (Fig. 36). However, recruitment has decreased greatly from 1995 - 2008 and is relatively constant since then. Fishing mortality has declined slightly over this period, but is rather steady in recent years. The values for biomass are similar to the reference biomass used in the previously used Gadget stock assessment used within Iceland (not within ICES proceedings). Any trends prior to the spring survey data (1985) should be taken with caution due to a lack of data supporting the model during this period.

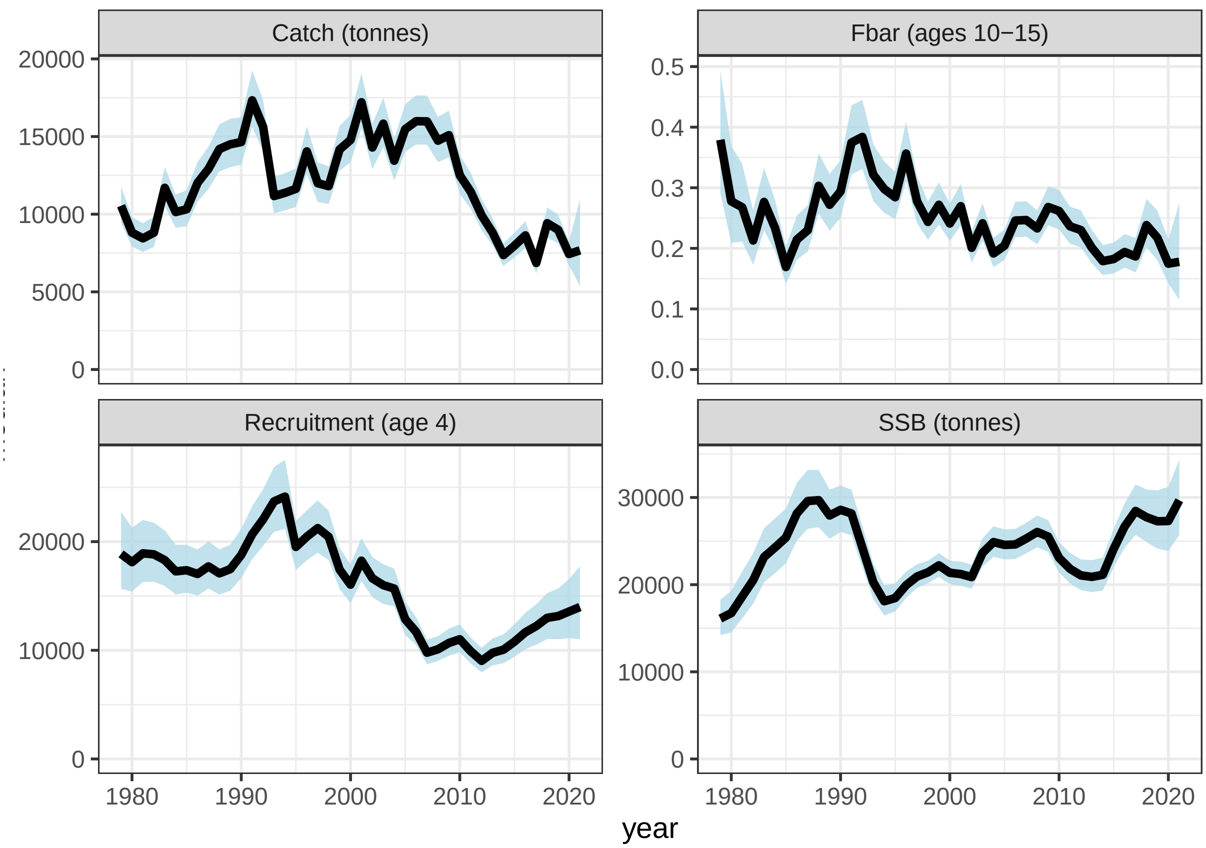

Figure 36: Atlantic wolffish in 5.a. Model results of population dynamics overview: estimated catch, average fishing mortality over ages 10 - 15 (Fbar), recruitment (age 4), and spawning stock biomass (SSB).

9.2.4 Retrospective analyses

The proposed model had relatively low Mohn's ρ statistic values for spawning stock biomass, fishing mortality, and recruitment (Table 2, Fig. 37). Higher Mohn's ρ values for recruitment are likely a result of high uncertainty due to low selectivity at the smallest age (4) detectable by the surveys. Mohn's ρ values are within the range recommended by Carvalho et al. [3] (< 0.2).

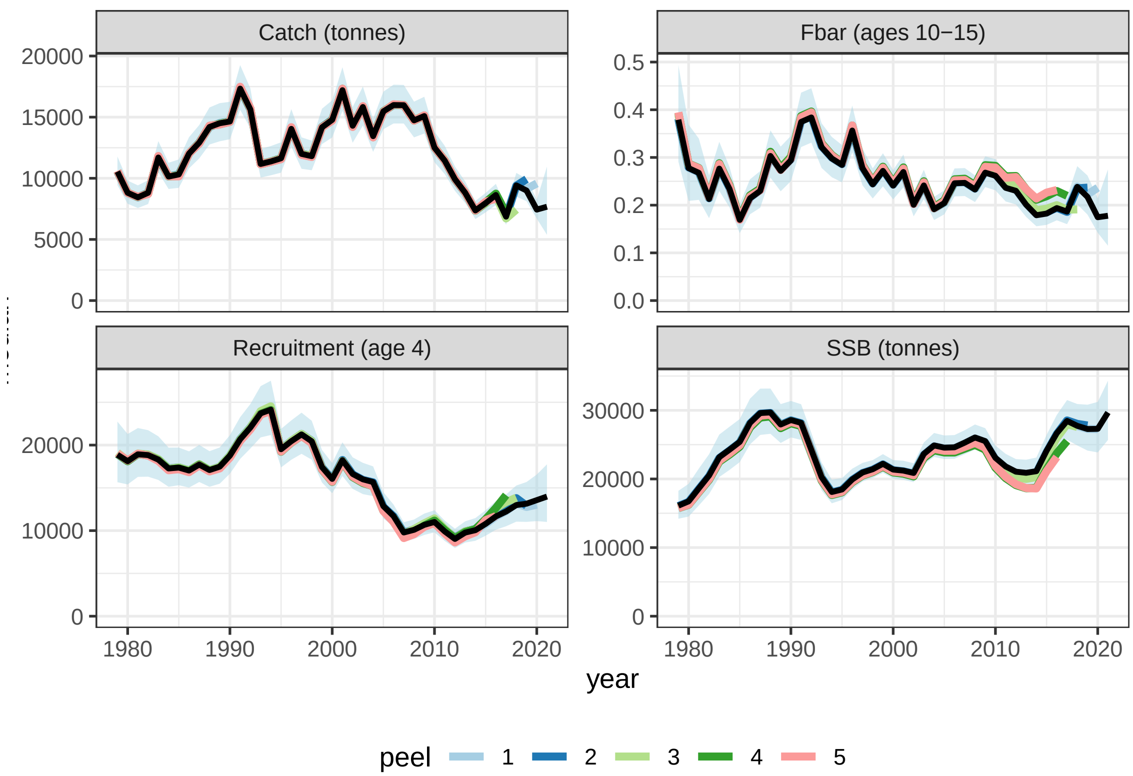

Figure 37: Atlantic wolffish in 5.a. Retrospective analyses: estimated catch, average fishing mortality over ages 10 - 15+ (Fbar), recruitment (age 4), and spawning stock biomass (SSB).

9.3 Leave-out analysis

Fig. 38 shows the results comparing the full model estimates with estimates where the survey time series has been omitted from the observation likelihood. The results show that both the spring and autumn survey data have a strong influence on model results in recent years, with spring survey data pulling biomass estimates up at the end of the time series and autumn survey data pulling biomass estimates down.

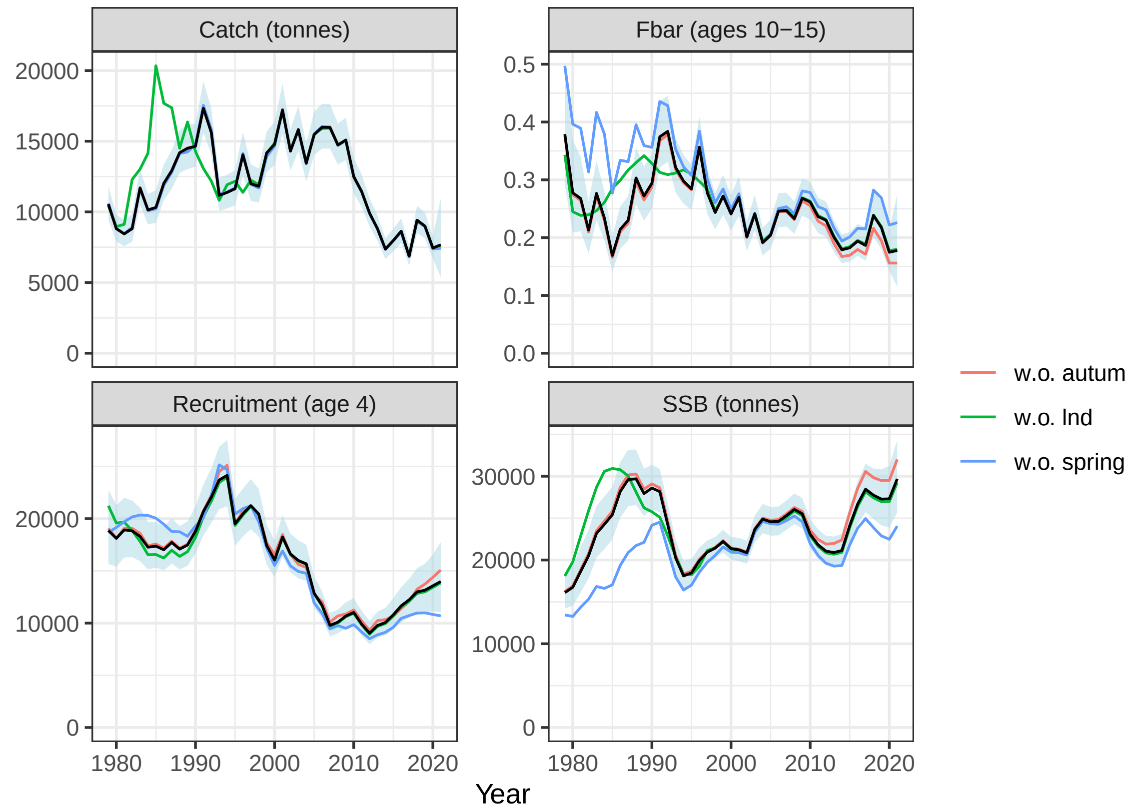

Figure 38: Atlantic wolffish in 5a. Leave-out estimates of SSB, catch, F and recruitment.

9.3.1 Ranges of natural mortality

A range of Ms was investigated (see Fig. 39) along with size dependent M using both the Gislason and Chernov method. The profile likelihood shows a minimum close to 0 and no other indicator based on life history attributes showed a clear indication of M. Therefore the assumption of natural mortality as 0.15 for all ages was maintained. As this is a rather long-lived species (commonly caught up to age 20 in Icelandic waters and rarely up to age 30), any difference from a true M would likely be downwards. See Appendix I for more detail.

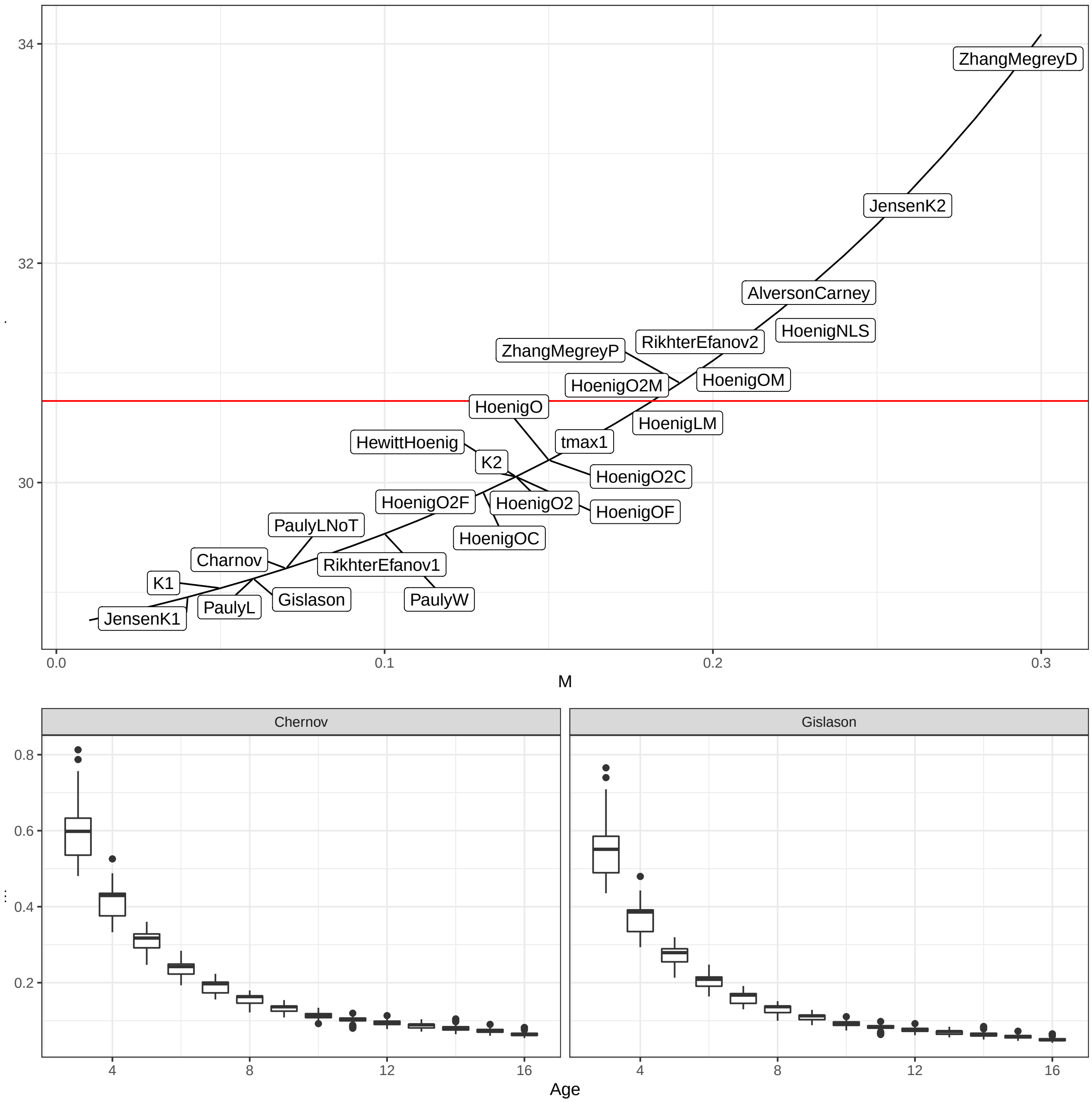

Figure 39: Atlantic wolffish in 5a. Left panel shows a profile likelihood plot (negative log likelihood) for different values of fixed M. Results from different M derivations based on life-history parameters are overlayed. Red line indicates 95% confidence regions. Bottom panels show boxplots of size based M values along with the negative log-likelihood values from the fitted SAM model.

10 Short term projections

Short term projections are performed using the standard procedure in SAM using the `forecast` function. Three year averages are used for stock and catch weights, and maturity. From this projection the advice is derived. The advice is based on the Icelandic fishing year starting in September each year. This causes a mismatch between the assessment model, which is based on the calendar year. So in order to provide advice for the fishing year, the standard projection procedure in SAM will need to be adapted to accommodate these differences. So given the assessment in year y the interim year catches are based on the following fishing mortality:

$$F_y = \left(\frac{8}{12}F_{sq} + \frac{4}{12}F_{mgt}\right)$$

and therefore the total catches for year y will be:

$$C_y = \frac{F_y}{F_y + M}\left(1 - e^{-(F_y+M)}\right)B_y$$

and the part of the catch in the fishing year y-1/y will be

$$\frac{\frac{8}{12}F_{sq}}{\left(\frac{8}{12}F_{sq} + \frac{4}{12}F_{mgt}\right)}C_y$$

and the catch in fishing year y/y+1 will be:

$$C_{y/y+1} = \frac{\frac{4}{12}F_{mgt}}{\left(\frac{8}{12}F_{sq} + \frac{4}{12}F_{mgt}\right)}C_y + \frac{8}{12}C_{y+1}$$

where

$$C_{y+1} = \frac{F_{mgt}}{F_{mgt} + M}\left(1 - e^{-(F_{mgt}+M)}\right)B_y$$

11 Appropriate Reference Points (MSY)

According ICES technical guidelines (ICES [7]), two types of reference points are referred to when giving advice for category 1 stocks:

precautionary approach (PA) reference points and *maximum sustainable yield* (MSY) reference points. The PA reference points are used when assessing the state of stocks and their exploitation rate relative to the precautionary approach objectives. The MSY reference points are used in the advice rule applied by ICES to give advice consistent with the objective of achieving MSY.

Generally ICES derives these reference points based on the level of the spawning stock biomass and fishing mortality. The following sections describe the derivation of the management reference points in terms of fishing mortality (F) and SSB (B). It further describes the model for stock–recruitment, weight and maturity at age, and assessment error which is used to project the stock stochastically in order to derive the PA and MSY reference points.

11.0.1 Setting B_{lim} and B_{pa}

B_{lim} was considered from examination of the SSB–Recruitment (at age 4) scatterplot based on the estimates from the stock assessment, as illustrated in Fig. 40. The figure shows that the recruitment is fairly independent of the size of SSB. However, recruitment appears to have shifted downwards after 2001 and remains stable at the lower level. The small dynamic range and lack of evidence for recruitment impairment suggests that this pattern could be considered to follow a Stock Category Type 6 pattern, especially if only considering the more recent productivity regime (only years after 2001). According to this pattern, B_{pa} is derived from the lowest observed SSB during that period (i.e. B_{loss} = SSB(2002) = 20868). In line with ICES technical guidelines B_{lim} is then calculated based on dividing B_{pa} by the standard factor, $e^{\sigma*1.645}$ where σ is the CV in the assessment year of SSB, used for calculating B_{pa} from B_{lim}. However the estimated σ is not considered to reflective of the true assessment error of the SSB due to various uncertainties and thus the CV used here to determine B_{lim} is 0.2, which is the default ICES value for assessment error. Therefore B_{lim} should be set at $B_{pa}e^{-1.645*0.2} = 20868t \div 1.4 = 18522t$. Fig. 41 shows the fit to a segmented regression setting B_{loss} to B_{lim} and only using the recruitment values observed after 2001.

If the assumption that recruitment is stable at this lower productivity level after 2001, rather than increasing to former levels again, is negated, then the stock should be re-evaluated as potentially being a Stock Category 5 stock. Reference points are unlikely to change much as the B_{lim} value calculated is already close to the minimum SSB value observed prior to 2001 (in 1994, ignoring the first two years of the model). However, higher mean recruitment will change long-term fishing dynamics and allow for higher values of fishing mortality. It is possible, for example, that current low recruitment levels are due to a very long lag in autocorrelation as Atlantic wolffish is a rather long-lived species. However, assuming this relationship was not considered precautionary given the length of the time series observed, so it was not assumed here.

11.0.2 Management procedure in forward projections

Illegal landings and discards by Icelandic fishing vessels are considered to be negligible (as noted above). Current knowledge of Atlantic wolffish in 5.a, discussed above, suggests that it should be assessed as a single stock unit. The currently proposed assessment model is more stable than historical assessments. In the projections described below the effect of assessment model is modeled as auto correlated log-normal variable with the mean as the true state of the stock. When deriving the assessment error CV based on the assessment (Table 3), the CV estimates are rather low, so default fishing mortality CV value of 0.212, and the default of 0.423 was kept for the correlation parameter ϕ to model assessment error. Default values were taken because estimates derived from the the model as listed in Table 2 are likely to be underestimates given various uncertainties regarding assessing this stock for the first time.

11.0.3 Stock recruitment relationship

A variety of approaches are common when estimating a stock–recruitment relationship. In the absence of a stock-recruitment signal from the available historical data (Fig. 40, the ICES guidelines suggest that the

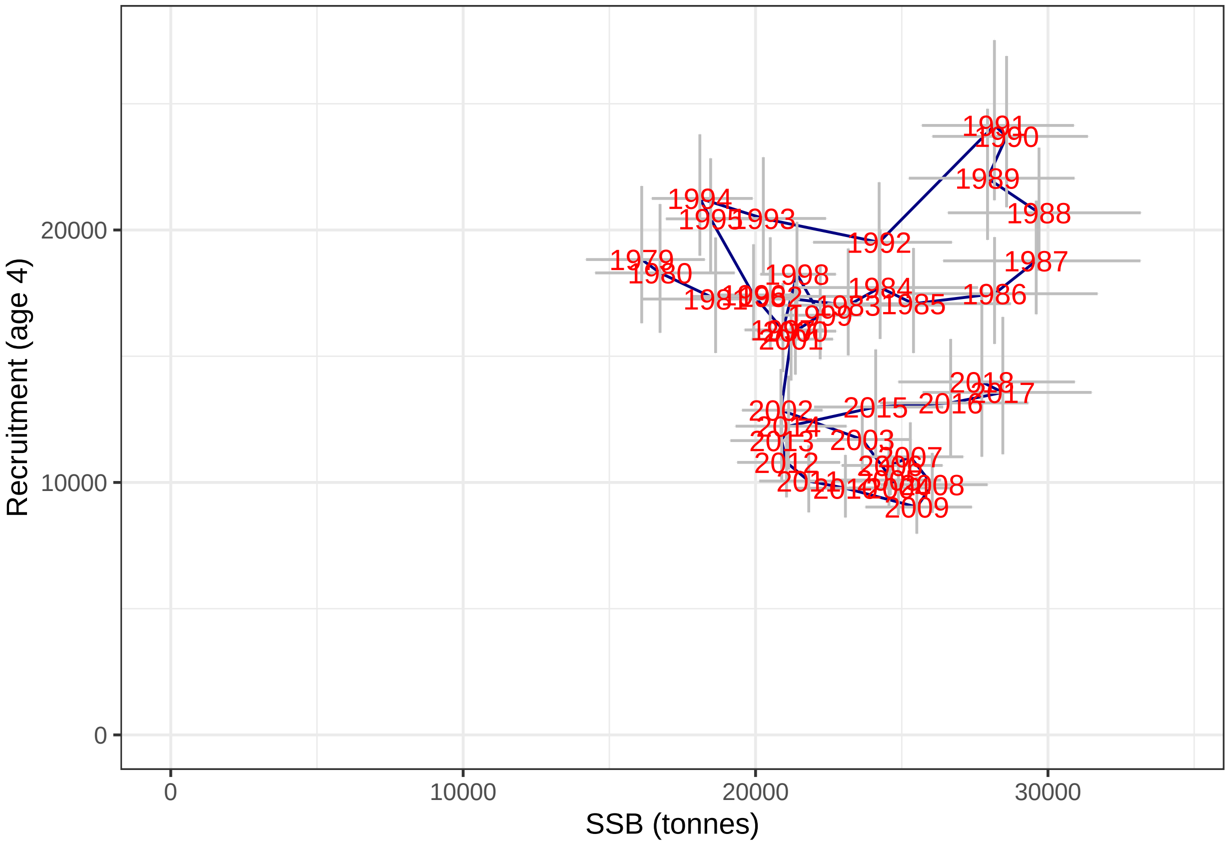

Figure 40: Atlantic wolffish in 5a. Estimated stock recruitment plot. Grey crossed indicate uncertainty, red text point estimate with the associated year and black lines show the progression of the stock recruitment relationship.

Table 3: Atlantic wolffish in 5a. Listing of the CV for key model outputs.

variable	cv
SSB (tonnes)	0.078
Fbar (ages 10-15)	0.114
Recruitment (age 4)	0.135
Catch (tonnes)	0.055

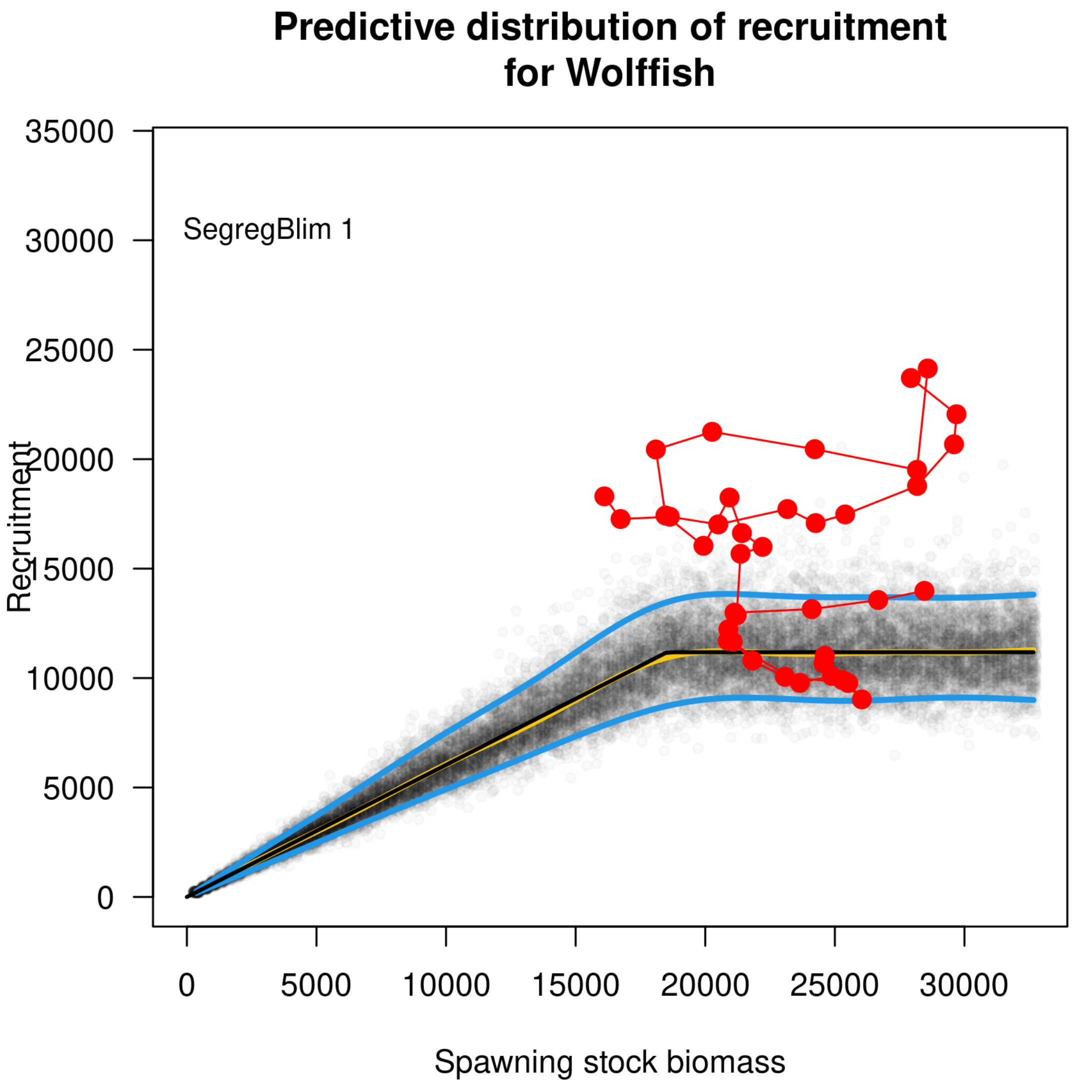

Figure 41: Atlantic wolffish in 5a. Segmented regression fitted to spawning stock biomass and recruitment (age 4).

"hockey-stick'' recruitment function is used, i.e.

$$R_y = \bar{R}_y \min(1, S_y/B_{break})$$

where R_y is annual recruitment, S_y the spawning stock biomass, B_{break} the break point in hockey stick function and $\bar{R}_y$ is the recruitment when not impaired due to low levels of SSB. Here $\bar{R}_y$ is considered to be drawn from an auto–correlated log–normal distribution with a mean, CV and ρ estimated based on the estimated recruits after 2001. This is done to account for possible auto-correlation in the recruitment time–series.

11.0.4 Stock– and catchweights

Prediction of weight at age in the stock, selectivity and the maturity at age follow the traditional process from the ICES guidelines, that is the average of the last 10 years of values for weight, selectivity and maturity at age used in the projections. These values are illustrated in Figures 42 to 44.

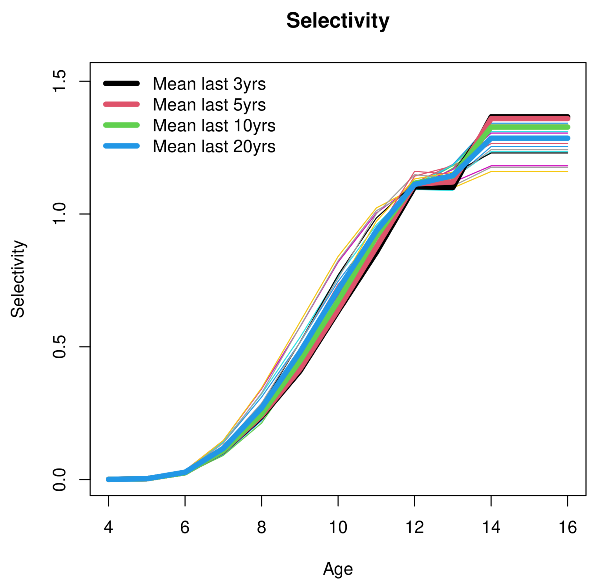

Figure 42: Atlantic Wolffish in 5a. Settings for the projections. Estimated selectivity at age by year (narrow coloured lines) illustrated with 3, 5, 10 and 20 year averages (thick lines).

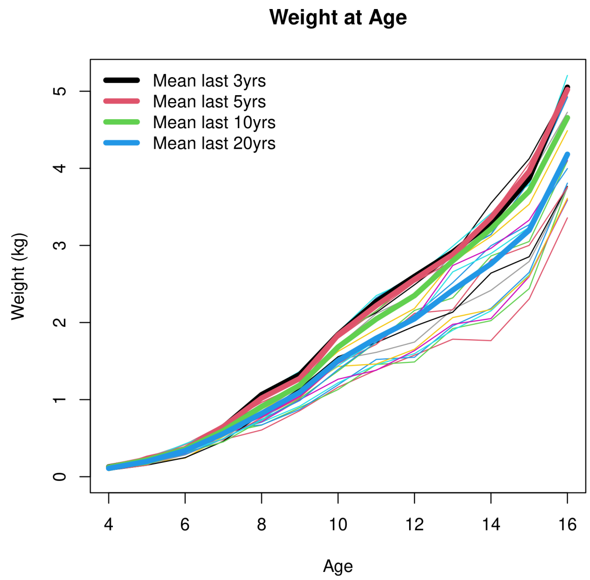

Figure 43: Atlantic Wolffish in 5a. Settings for the projections. Estimated weight at age by year (narrow coloured lines) illustrated with 3, 5, 10 and 20 year averages (thick lines)

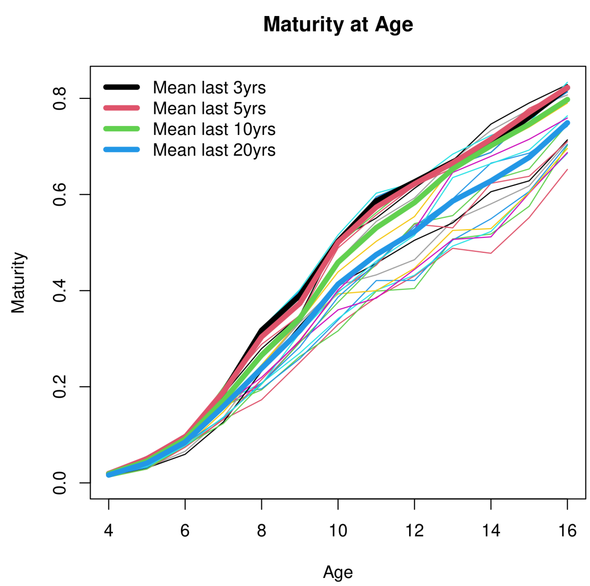

Figure 44: Atlantic Wolffish in 5a. Settings for the projections. Estimated maturity at age by year (narrow coloured lines) illustrated with 3, 5, 10 and 20 year averages (thick lines)

11.0.5 Setting $\mathbf{F}_{lim}$ and $\mathbf{F}_{pa}$

According to the ICES guidelines, the precautionary reference points are set by simulating the stock using the stock-recruitment, growth and maturity relationship described above, based on a wide range of harvest rates, ranging from 0 to 1 and setting F_{lim} as the F that, in equilibrium, gives a 50% probability of SSB $> B_{lim}$ without assessment error.

For each replicate the stock status was projected forward 50 years as simulations, and average of those projected values used to estimate the MSY reference points.

The results from the long–term simulations estimate the value of F, F_{lim}, resulting in 50% long–term probability of SSB $> B_{lim}$ to be at 0.33.

11.0.6 MSY reference points

As an additional simulation experiment where, in addition to recruitment and growth variations, assessment error was added. The harvest rate that would lead to the maximum sustainable yield, F_{msy}, was then estimated. Average annual landings and 90% quantiles were used to determine the yield by F. Fig. 47 shows the evolution of catches, SSB and fishing mortality for select values of F. The equilibrium yield curve is shown in Figs. 45, and with the $B_{trigger}$ implemented in an HCR in 46, where the maximum average yield, under the recruitment assumptions, is around 8 thousand tons, with very little reduction when F_{msy} is set using F_{p05}.

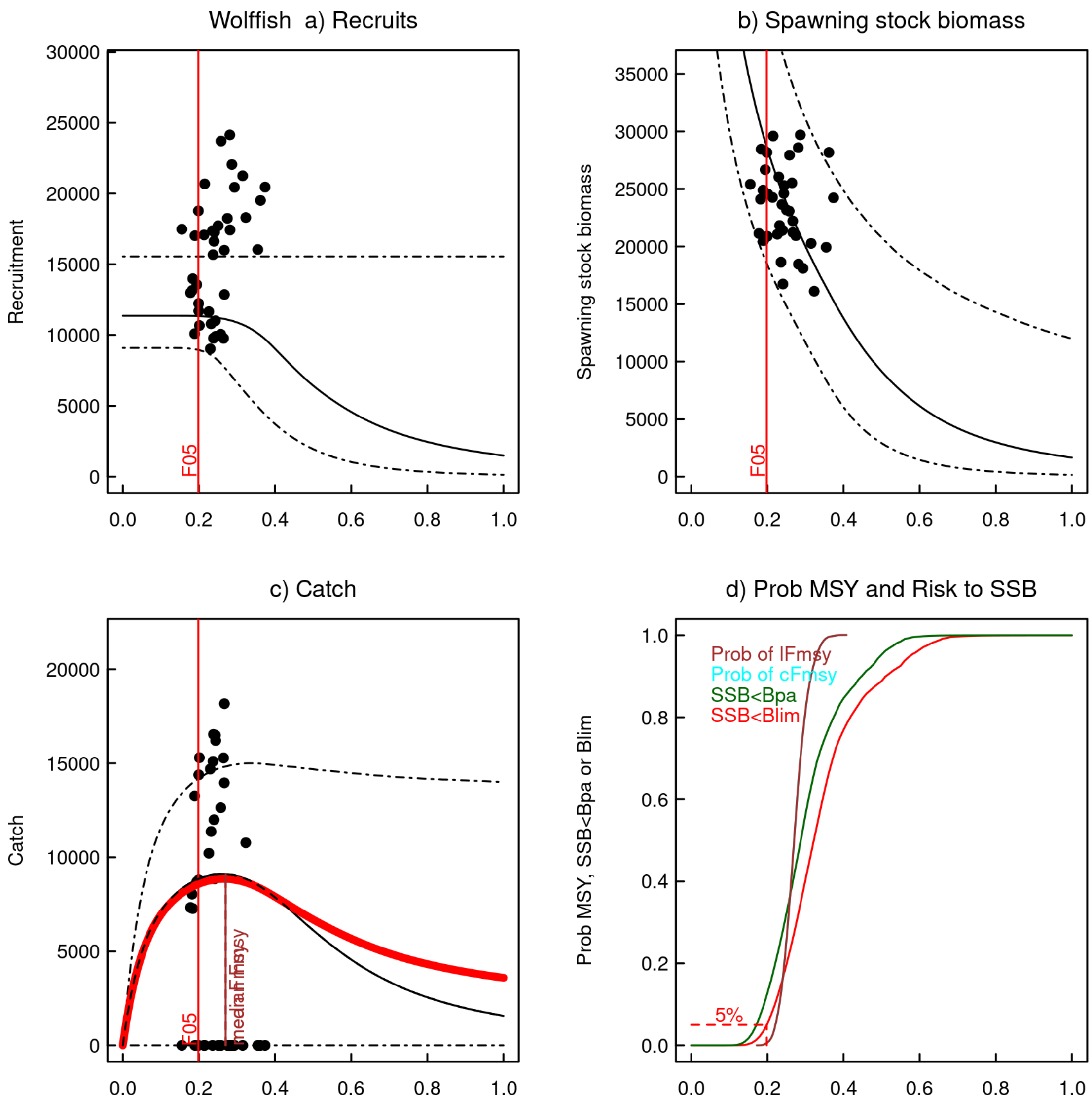

Figure 45: Atlantic wolffish in 5a. Equilibrium catch, recruitment, SSB and risk from forward projections, generated from Eqsim. No trigger was implemented in these projections, used to derive F_{msy}.

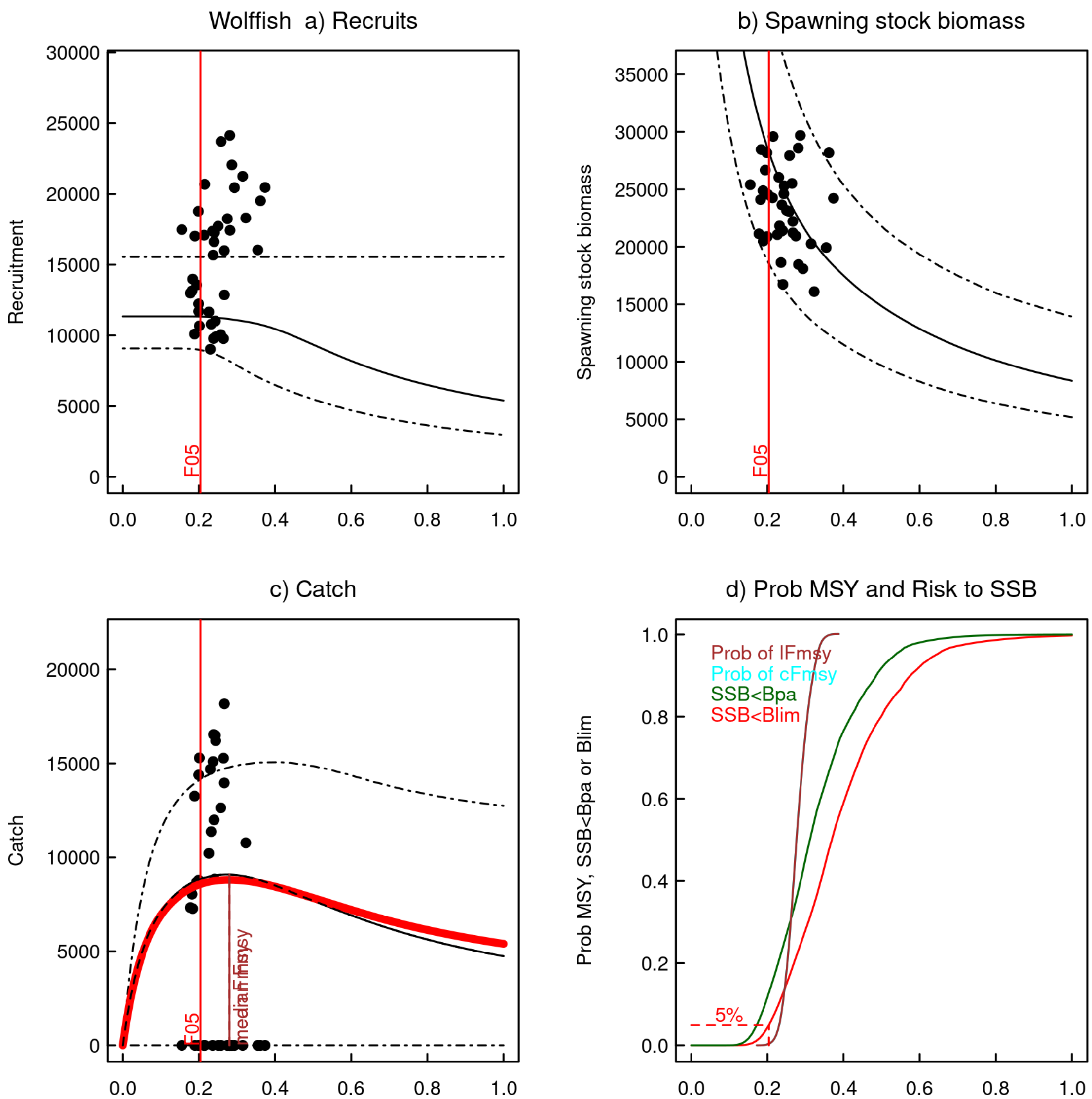

Figure 46: Atlantic wolffish in 5.a. Equilibrium catch, recruitment, SSB and risk from forward projections, generated from Eqsim. The trigger was implemented in these projections, used to derive F_{p05}.

In line with ICES technical guidelines, the MSY $B_{trigger}$ is set as B_{pa} as this is the first time the reference points are evaluated. Maximum yield is estimated to be obtained at a F of 0.2. F_{p05}, i.e. the maximum F that has less than 5% chance of going below B_{lim} when the advice rule is applied, is less than the F maximizing yield 0.26, thus limiting the estimate of F_{msy}. The evolution of the spawning stock biomass is shown in Figure 47 for select F values in the HCR (0.15, F_{msy} 0.2, unconstrained F_{msy} 0.26, and F_{lim} 0.33). The 0.20 F level is also the average over the most recent 5 years. Higher Fs are associated with greater fluctuations in recruitment,catch, and realized F.

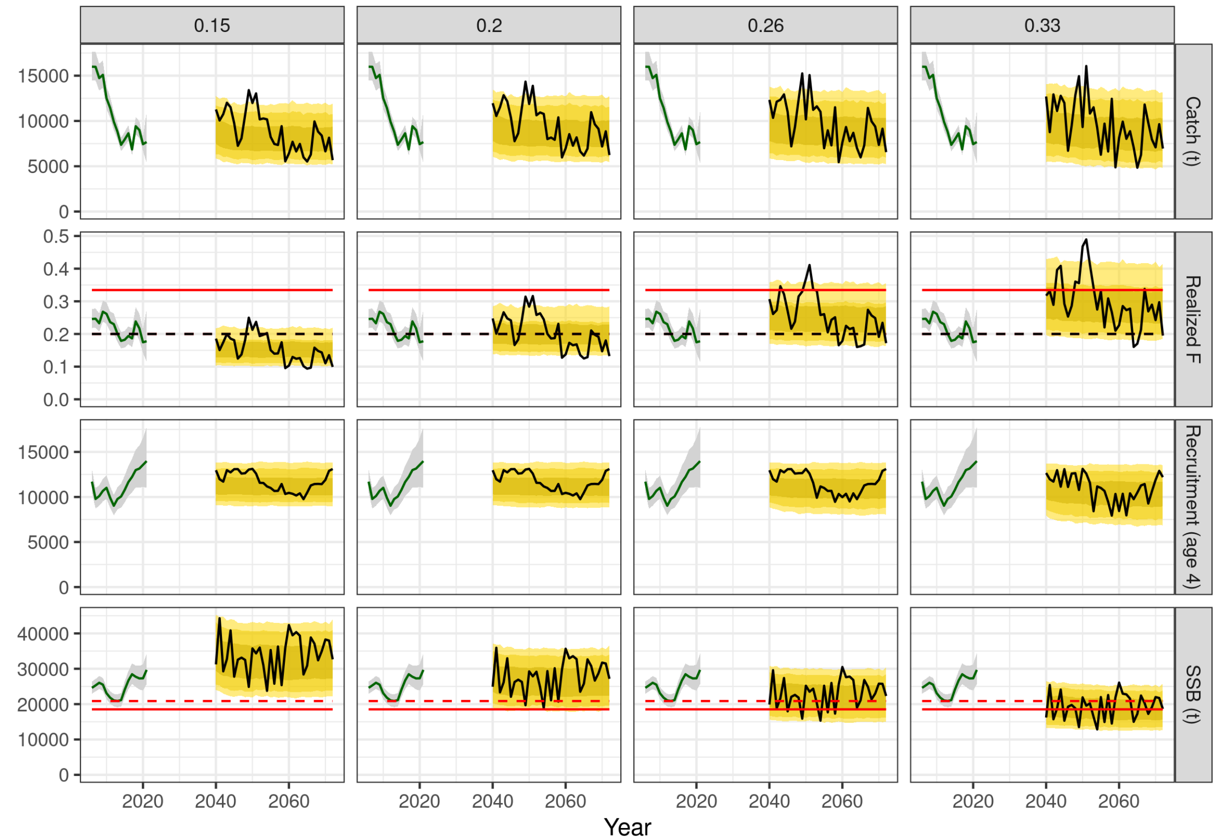

Figure 47: Atlantic wolffish in 5a. Assessment (from 2006 onwards) and projections of recruitment (thousands at age 4), realized F, catch (in t) and SSB (in t) for different F values in the HCR. The different shades of yellow indicate 90%, 80%, and 50% distribution ranges of projections, the black line one iteration. Grey shading indicates 95% confidence intervals on the assessment model results (green line). The red solid and dashed horizontal lines refer to B_{lim} or F_{lim} and $B_{trigger}$, respectively. The black dashed horizontal line refers to F_{msy}.

Atlantic Wolffish in 5a. Overview of estimated reference points

Reference point	Value	Basis
MSYBtrigger	21000	Bpa
5thPerc_SSBmsy	16700	5th quantile of SSB when fishing at Fmsy
Bpa	21000	Lowest SSB (2002) (Type 6)
Blim	18500	Bpa / exp(1.645 sigma_SSB)
Flim	0.33	F leading to P(SSB < Blim) = 0.5
Fp05	0.20	F, when ICES AR is applied, leading to P(SSB > Blim) = 0.05
Fmsy_unconstr	0.26	Unconstrained F leading to MSY

Fmsy	0.20	F leading to MSY

12 Future Research and data requirements

Future research that would help to inform the stock assessment include tests of reliability and error in age-reading methods and more information regarding connectivity with stocks outside 5.a. In addition, more information regarding the biological origins of regional growth variation, bimodal length distributions, and greater selectivity of fast-growing wolffish by the commercial fishery would help to elucidate more biologically appropriate model structures. More tagging data would also elucidate whether homing behaviors are organized enough within the population to yield population substructure.

13 Model configuration

```
## # Configuration saved: Tue Apr 19 00:16:40 2022
## #
## # Where a matrix is specified rows corresponds to fleets and columns to ages.
## # Same number indicates same parameter used
## # Numbers (integers) starts from zero and must be consecutive
## # Negative numbers indicate that the parameter is not included in the model
## #
## $minAge
## # The minimium age class in the assessment
##  4
##
## $maxAge
## # The maximum age class in the assessment
##  16
##
## $maxAgePlusGroup
## # Is last age group considered a plus group for each fleet (1 yes, or 0 no).
##  1 1 1 1
##
## $keyLogFsta
## # Coupling of the fishing mortality states processes for each age (normally only
## # the first row (= fleet) is used).
## # Sequential numbers indicate that the fishing mortality is estimated individually
## # for those ages; if the same number is used for two or more ages, F is bound for
## # those ages (assumed to be the same). Binding fully selected ages will result in a
## # flat selection pattern for those ages.
##    0   1   2   3   4   5   6   7   8   9  10  11  11
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##
## $corFlag
## # Correlation of fishing mortality across ages (0 independent, 1 compound symmetry,
## # 2 AR(1), 3 separable AR(1).
## # 0: independent means there is no correlation between F across age
## # 1: compound symmetry means that all ages are equally correlated;
## # 2: AR(1) first order autoregressive - similar ages are more highly correlated than
## # ages that are further apart, so similar ages have similar F patterns over time.
## # if the estimated correlation is high, then the F pattern over time for each age
## # varies in a similar way. E.g if almost one, then they are parallel (like a
## # separable model) and if almost zero then they are independent.
## # 3: Separable AR - Included for historic reasons . . .  more later
##  2
##
## $keyLogFpar
## # Coupling of the survey catchability parameters (nomally first row is
## # not used, as that is covered by fishing mortality).
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##    0   1   2   3   4   5   6   7   8   9  10  11  11
##   12  13  14  15  16  17  18  19  20  21  22  23  23
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##
```

```
## $keyQpow
## # Density dependent catchability power parameters (if any).
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##
## $keyVarF
## # Coupling of process variance parameters for log(F)-process (Fishing mortality
## # normally applies to the first (fishing) fleet; therefore only first row is used)
##    0   0   0   0   0   0   0   0   0   0   0   0   0
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##
## $keyVarLogN
## # Coupling of the recruitment and survival process variance parameters for the
## # log(N)-process at the different ages. It is advisable to have at least the first age
## # class (recruitment) separate, because recruitment is a different process than
## # survival.
##  0 1 1 1 1 1 1 1 1 1 1 1 1
##
## $keyVarObs
## # Coupling of the variance parameters for the observations.
## # First row refers to the coupling of the variance parameters for the catch data
## # observations by age
## # Second and further rows refers to coupling of the variance parameters for the
## # index data observations by age
##    0   0   0   0   1   1   1   1   1   1   1   1   1
##    2   2   2   2   2   2   3   3   3   3   4   4   4
##    5   5   5   5   5   5   6   6   6   6   7   7   7
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##
## $obsCorStruct
## # Covariance structure for each fleet ("ID" independent, "AR" AR(1), or "US" for unstructured). | Po
##  "ID" "AR" "AR" "ID"
##
## $keyCorObs
## # Coupling of correlation parameters can only be specified if the AR(1) structure is chosen above.
## # NA's indicate where correlation parameters can be specified (-1 where they cannot).
## #4-5 5-6 6-7 7-8 8-9 9-10 10-11 11-12 12-13 13-14 14-15 15-16
##   NA  NA  NA  NA  NA  NA  NA  NA  NA  NA  NA  NA
##    1   1   1   1   1   1   1   1   2   2   2   2
##    0   0   0   0   0   0   3   3   3   3   3   3
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##
## $stockRecruitmentModelCode
## # Stock recruitment code (0 for plain random walk, 1 for Ricker, 2 for Beverton-Holt, 3 piece-wise c
##  0
##
## $noScaledYears
## # Number of years where catch scaling is applied.
##  0
##
```

```
## $keyScaledYears
## # A vector of the years where catch scaling is applied.
##
##
## $keyParScaledYA
## # A matrix specifying the couplings of scale parameters (nrow = no scaled years, ncols = no ages).
##
## $fbarRange
## # lowest and higest age included in Fbar
##  10 15
##
## $keyBiomassTreat
## # To be defined only if a biomass survey is used (0 SSB index, 1 catch index, 2 FSB index, 3 total ca
##  -1 -1 -1 4
##
## $obsLikelihoodFlag
## # Option for observational likelihood | Possible values are: "LN" "ALN"
##  "LN" "LN" "LN" "LN"
##
## $fixVarToWeight
## # If weight attribute is supplied for observations this option sets the treatment (0 relative weight
##  0
##
## $fracMixF
## # The fraction of t(3) distribution used in logF increment distribution
##  0
##
## $fracMixN
## # The fraction of t(3) distribution used in logN increment distribution (for each age group)
##  0 0 0 0 0 0 0 0 0 0 0 0 0
##
## $fracMixObs
## # A vector with same length as number of fleets, where each element is the fraction of t(3) distribut
##  0 0 0 0
##
## $constRecBreaks
## # Vector of break years between which recruitment is at constant level. The break year is included in
##
##
## $predVarObsLink
## # Coupling of parameters used in a prediction-variance link for observations.
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##   NA  NA  NA  NA  NA  NA  NA  NA  NA  NA  NA  NA  NA
##
## $hockeyStickCurve
## #
##  20
##
## $stockWeightModel
## # Integer code describing the treatment of stock weights in the model (0 use as known, 1 use as obser
##  0
##
```

```
## $keyStockWeightMean
## # Coupling of stock-weight process mean parameters (not used if stockWeightModel==0)
##  NA NA NA NA NA NA NA NA NA NA NA NA NA
##
## $keyStockWeightObsVar
## # Coupling of stock-weight observation variance parameters (not used if stockWeightModel==0)
##  NA NA NA NA NA NA NA NA NA NA NA NA NA
##
## $catchWeightModel
## # Integer code describing the treatment of catch weights in the model (0 use as known, 1 use as obse
##  0
##
## $keyCatchWeightMean
## # Coupling of catch-weight process mean parameters (not used if catchWeightModel==0)
##  NA NA NA NA NA NA NA NA NA NA NA NA NA
##
## $keyCatchWeightObsVar
## # Coupling of catch-weight observation variance parameters (not used if catchWeightModel==0)
##  NA NA NA NA NA NA NA NA NA NA NA NA NA
##
## $matureModel
## # Integer code describing the treatment of proportion mature in the model (0 use as known, 1 use as 
##  0
##
## $keyMatureMean
## # Coupling of mature process mean parameters (not used if matureModel==0)
##  NA NA NA NA NA NA NA NA NA NA NA NA NA
##
## $mortalityModel
## # Integer code describing the treatment of natural mortality in the model (0 use as known, 1 use as 
##  0
##
## $keyMortalityMean
## #
##  NA NA NA NA NA NA NA NA NA NA NA NA NA
##
## $keyMortalityObsVar
## # Coupling of natural mortality observation variance parameters (not used if mortalityModel==0)
##  NA NA NA NA NA NA NA NA NA NA NA NA NA
##
## $keyXtraSd
## # An integer matrix with 4 columns (fleet year age coupling), which allows additional uncertainty to
```

14 Input data

14.1 Spring survey at age

year	4	5	6	7	8	9	10	11	12	13	14	15	16
1985	0.483	0.553	0.600	0.707	1.076	0.668	1.055	0.624	0.873	0.475	0.307	0.208	0.268
1986	0.633	0.996	0.760	0.693	0.788	0.646	0.866	0.699	0.714	0.451	0.224	0.130	0.157
1987	0.780	0.844	0.591	0.603	0.858	0.692	0.744	0.623	0.761	0.554	0.288	0.159	0.183
1988	0.560	0.622	0.472	0.434	0.386	0.443	0.631	0.480	0.527	0.322	0.180	0.145	0.180
1989	0.445	0.515	0.611	0.513	0.567	0.566	0.612	0.664	0.627	0.421	0.286	0.158	0.293
1990	0.500	0.612	0.561	0.571	0.537	0.636	0.498	0.424	0.292	0.220	0.104	0.121	0.159
1991	0.964	0.979	0.746	0.797	0.794	0.781	0.688	0.666	0.666	0.363	0.236	0.109	0.142
1992	0.772	0.746	0.734	0.721	0.610	0.639	0.690	0.681	0.550	0.364	0.234	0.116	0.154
1993	0.879	0.909	0.963	0.853	0.770	0.650	0.660	0.600	0.504	0.248	0.195	0.107	0.149
1994	1.008	0.951	0.972	0.960	0.757	0.804	0.787	0.623	0.522	0.283	0.191	0.123	0.169
1995	0.652	0.904	0.879	0.783	0.799	0.756	0.701	0.489	0.448	0.228	0.119	0.085	0.111
1996	0.692	0.789	1.045	1.195	1.251	1.113	0.887	0.498	0.367	0.280	0.141	0.086	0.160
1997	1.065	1.091	0.799	1.226	1.181	1.013	0.708	0.754	0.379	0.293	0.167	0.110	0.312
1998	1.013	0.984	0.978	0.775	1.203	1.061	0.795	0.801	0.434	0.369	0.225	0.171	0.366
1999	0.846	1.023	1.004	0.878	0.698	1.003	0.833	0.565	0.415	0.270	0.262	0.123	0.173
2000	0.744	0.839	1.106	0.802	0.744	0.612	0.696	0.635	0.540	0.396	0.342	0.127	0.289
2001	0.933	0.762	0.679	0.687	0.963	0.616	0.404	0.719	0.402	0.290	0.194	0.177	0.182
2002	0.931	1.039	0.625	0.527	0.623	0.656	0.545	0.471	0.484	0.349	0.208	0.143	0.171
2003	0.824	0.911	0.979	0.621	0.679	0.715	0.686	0.486	0.357	0.479	0.255	0.190	0.259
2004	0.759	0.847	0.649	0.618	0.482	0.456	0.618	0.321	0.313	0.210	0.257	0.147	0.179
2005	0.774	0.834	0.664	0.645	0.592	0.469	0.403	0.547	0.331	0.270	0.178	0.171	0.229
2006	0.581	0.555	0.704	0.541	0.547	0.602	0.467	0.356	0.325	0.294	0.163	0.181	0.225
2007	0.384	0.487	0.543	0.670	0.598	0.549	0.483	0.293	0.368	0.224	0.224	0.146	0.338
2008	0.429	0.502	0.619	0.562	0.633	0.520	0.435	0.460	0.287	0.298	0.244	0.203	0.509
2009	0.514	0.407	0.319	0.395	0.436	0.351	0.342	0.258	0.323	0.213	0.133	0.203	0.337
2010	0.451	0.531	0.363	0.242	0.361	0.220	0.329	0.218	0.237	0.206	0.089	0.119	0.312
2011	0.268	0.378	0.314	0.331	0.247	0.304	0.230	0.283	0.194	0.145	0.100	0.132	0.298
2012	0.337	0.325	0.355	0.290	0.272	0.278	0.285	0.258	0.230	0.162	0.121	0.113	0.282
2013	0.441	0.334	0.474	0.431	0.320	0.316	0.233	0.247	0.167	0.210	0.149	0.123	0.306
2014	0.410	0.405	0.357	0.334	0.514	0.377	0.294	0.184	0.284	0.119	0.147	0.107	0.262
2015	0.374	0.387	0.286	0.223	0.423	0.433	0.308	0.331	0.228	0.162	0.109	0.095	0.250
2016	0.603	0.659	0.386	0.420	0.368	0.476	0.480	0.373	0.316	0.150	0.092	0.101	0.227
2017	0.635	0.509	0.377	0.370	0.367	0.354	0.346	0.352	0.198	0.213	0.102	0.087	0.217
2018	0.560	0.516	0.489	0.319	0.389	0.445	0.359	0.409	0.452	0.204	0.143	0.145	0.358
2019	0.537	0.642	0.443	0.425	0.438	0.327	0.262	0.265	0.202	0.148	0.150	0.105	0.338
2020	0.514	0.465	0.400	0.342	0.324	0.325	0.296	0.316	0.251	0.218	0.145	0.091	0.239
2021	0.756	0.720	0.635	0.462	0.434	0.405	0.456	0.394	0.279	0.158	0.184	0.093	0.238

14.2 Autumn survey at age

year	4	5	6	7	8	9	10	11	12	13	14	15	16
2000	0.168	0.156	0.161	0.231	0.148	0.105	0.164	0.104	0.076	0.038	0.038	0.011	0.018
2001	0.320	0.183	0.203	0.263	0.230	0.173	0.168	0.158	0.112	0.083	0.054	0.055	0.052
2002	0.260	0.284	0.194	0.192	0.229	0.199	0.160	0.125	0.147	0.093	0.072	0.049	0.063
2003	0.414	0.280	0.202	0.176	0.172	0.247	0.150	0.133	0.080	0.111	0.062	0.042	0.028
2004	0.346	0.265	0.250	0.243	0.183	0.171	0.255	0.124	0.115	0.076	0.064	0.040	0.050
2005	0.247	0.324	0.227	0.246	0.274	0.204	0.163	0.147	0.123	0.066	0.084	0.033	0.050
2006	0.229	0.312	0.290	0.226	0.179	0.135	0.106	0.129	0.071	0.066	0.034	0.031	0.039
2007	0.203	0.227	0.176	0.201	0.163	0.122	0.120	0.059	0.086	0.066	0.070	0.053	0.063
2008	0.210	0.200	0.207	0.243	0.211	0.173	0.136	0.182	0.105	0.058	0.096	0.067	0.088
2009	0.310	0.160	0.118	0.149	0.082	0.136	0.081	0.103	0.071	0.038	0.045	0.032	0.070
2010	0.272	0.177	0.182	0.125	0.121	0.079	0.091	0.062	0.032	0.026	0.037	0.021	0.033
2011	0.091	0.082	0.059	0.059	0.052	0.069	0.033	0.041	0.038	0.027	0.020	0.007	0.040
2012	0.214	0.272	0.175	0.129	0.128	0.080	0.087	0.047	0.066	0.040	0.039	0.024	0.052
2013	0.136	0.100	0.078	0.130	0.098	0.079	0.048	0.056	0.041	0.038	0.032	0.028	0.033
2014	0.206	0.127	0.106	0.143	0.138	0.074	0.091	0.055	0.030	0.022	0.019	0.015	0.016
2015	0.266	0.154	0.158	0.137	0.166	0.135	0.136	0.082	0.038	0.018	0.028	0.013	0.068
2016	0.276	0.217	0.169	0.146	0.133	0.119	0.113	0.060	0.056	0.016	0.014	0.011	0.025
2017	0.395	0.293	0.168	0.164	0.184	0.139	0.152	0.135	0.061	0.040	0.039	0.040	0.055
2018	0.237	0.173	0.165	0.135	0.095	0.067	0.073	0.048	0.027	0.032	0.024	0.022	0.042
2019	0.191	0.190	0.149	0.116	0.098	0.084	0.076	0.082	0.042	0.024	0.022	0.016	0.032
2020	0.272	0.238	0.173	0.133	0.124	0.092	0.066	0.059	0.031	0.012	0.012	0.005	0.010
2021	0.186	0.153	0.123	0.102	0.113	0.101	0.083	0.090	0.046	0.027	0.010	0.006	0.012

14.3 Catch at age

year	4	5	6	7	8	9	10	11	12	13	14	15	16
1979	2	2	12	105	216	349	792	618	580	342	184	254	304
1980	0	0	2	74	209	297	755	594	509	282	162	150	120
1981	0	0	7	50	261	454	1046	803	640	247	107	55	74
1982	0	0	4	26	114	227	574	529	470	336	159	211	182
1983	0	0	6	97	339	558	1183	907	774	383	204	120	260
1984	0	0	18	74	242	418	922	723	628	437	198	256	183
1985	0	0	0	1	24	45	67	124	367	244	297	150	867
1986	0	0	7	68	272	465	1159	894	788	396	202	160	190
1987	0	0	14	199	389	541	1478	1017	752	360	172	116	100
1988	0	0	62	365	885	1256	1777	1031	806	377	199	122	110
1989	0	0	17	105	430	690	1340	1000	857	471	229	243	272
1990	1	1	11	145	460	718	1713	1217	982	436	197	174	114
1991	0	6	32	202	728	1043	2087	1645	1311	498	203	122	151
1992	0	0	85	437	864	1150	1733	1191	1025	411	258	173	200
1993	0	0	139	729	1153	1320	1322	750	612	228	165	120	93
1994	1	3	83	431	899	1114	1351	807	660	253	150	115	108
1995	0	0	83	446	848	1103	1272	685	546	251	186	140	111
1996	0	0	17	139	872	1258	2042	1433	1154	331	151	62	84
1997	1	1	23	129	304	708	841	741	1081	518	395	168	234
1998	2	3	27	124	367	944	1015	758	1039	363	210	178	228
1999	5	5	65	337	550	1157	1405	690	766	424	342	294	273
2000	0	16	53	364	573	573	1360	1268	868	466	252	162	259
2001	0	39	162	334	692	972	761	1389	1320	659	408	220	298
2002	0	12	84	265	499	768	973	569	878	616	330	181	168
2003	0	50	159	232	503	669	840	1034	541	933	558	314	399
2004	2	23	72	214	393	661	744	788	691	317	414	281	270
2005	0	8	62	219	544	576	678	760	688	484	341	365	385
2006	0	8	112	372	635	858	856	943	725	678	384	279	527
2007	4	18	91	287	559	790	1011	761	644	490	398	279	560
2008	0	2	33	119	591	690	724	840	430	383	355	249	564
2009	0	6	48	145	385	762	714	651	682	437	357	257	672
2010	0	4	42	132	274	455	736	601	540	450	271	262	571
2011	0	6	26	117	161	365	515	595	469	295	297	208	443
2012	0	1	61	127	277	313	382	478	447	319	233	181	516
2013	0	8	24	148	183	412	368	462	325	333	216	137	266
2014	0	34	57	156	217	355	330	294	305	246	200	138	276
2015	0	0	17	61	201	350	392	455	326	252	192	150	245
2016	0	0	58	187	241	452	511	441	369	238	227	129	186
2017	0	2	42	264	257	180	273	287	239	264	268	162	409
2018	0	7	22	116	281	363	405	524	466	281	177	201	409
2019	0	12	25	105	171	340	380	393	331	222	202	184	400
2020	0	16	44	118	241	238	350	242	278	165	151	130	303

14.4 Catch weights

year	4	5	6	7	8	9	10	11	12	13	14	15	16
1979	1055	1055	1264	1619	1676	1981	2350	2555	2899	3256	3509	4159	5243
1980	907	907	1271	1747	1850	2110	2716	2530	2712	3194	3506	4536	5230
1981	914	941	865	1137	1470	1715	2160	2427	2465	3187	3121	3788	3765
1982	1027	1303	1414	1230	1656	1968	2393	2818	3004	3368	3487	4111	5130
1983	983	983	982	1453	1568	1779	2243	2475	2624	3168	3222	3956	4879
1984	1030	1030	1306	1219	1436	1807	2086	2429	2550	2978	2960	3800	4856
1985	914	941	1184	1719	2560	2181	2331	3328	3722	3694	4062	3570	5730
1986	914	941	833	1469	1628	1878	2381	2502	2669	3320	3486	4319	4839
1987	914	941	1094	1678	1681	1860	2370	2448	2525	3280	3563	4483	3890
1988	914	941	1276	1446	1584	1778	2102	2360	2314	2861	2809	2923	3100
1989	914	1304	1274	1205	1490	1677	2059	2521	2501	3159	3153	4229	5576
1990	1027	999	1068	1520	1547	1737	2184	2402	2443	3271	3292	4389	3831
1991	914	1304	829	1113	1409	1625	2102	2418	2487	3356	3188	3929	4069
1992	914	941	995	1108	1413	1612	2126	2396	2539	2845	3098	3305	3765
1993	914	941	971	1005	1218	1352	1802	2172	2160	2510	2889	2965	3391
1994	376	804	1046	1117	1361	1530	1909	2267	2222	2754	2740	3256	4510
1995	914	941	1237	1331	1534	1680	2011	2364	2369	2573	2924	2942	4244
1996	914	941	966	1122	1383	1532	1955	2177	2187	2816	2895	3767	2826
1997	1038	1038	1353	1422	1515	1686	1847	1922	2066	2652	3414	3805	5536
1998	1015	916	1447	1515	1527	1746	1968	2143	2388	2619	2593	3835	5585
1999	830	751	1046	1135	1443	1734	1987	2235	2471	2797	2835	3331	4913
2000	914	860	1203	1320	1443	1745	2290	2465	2666	3022	3422	3980	4815
2001	914	1078	1245	1413	1606	1980	2303	2623	2866	3029	3166	3760	3780
2002	914	812	1005	1525	1858	2069	2626	2836	2935	3316	3753	3669	4050
2003	914	829	1150	1369	1864	1999	2352	2628	2752	3134	3345	3663	4006
2004	1147	1227	1463	1628	1819	2137	2430	2684	3017	3041	3561	3774	4218
2005	914	1128	1234	1879	2067	2350	2617	3020	3111	3548	3778	3999	4257
2006	914	659	1296	1476	1881	2126	2284	2482	2816	2887	3287	3648	4168
2007	731	733	1220	1675	1835	2192	2439	2670	2876	3266	3585	3739	4325
2008	914	1163	1261	1585	2090	2263	2773	2966	3081	3152	3525	3892	4277
2009	914	830	1224	1534	1954	2257	2611	2887	3180	3484	3826	3843	4068
2010	723	1542	1597	1582	1849	2215	2566	2779	3020	3211	3329	3448	4192
2011	914	697	1317	1807	2124	2349	2647	2971	3279	3491	4021	4106	4913
2012	914	1178	1089	1595	1994	2307	2522	2811	3039	3418	3627	3923	4576
2013	914	589	1302	1710	1962	2337	2673	2874	3127	3437	3832	4292	4885
2014	914	759	1059	1395	1723	2079	2390	2755	3097	3437	3607	3873	4592
2015	914	723	1254	1408	1812	2097	2520	2920	3250	3368	3740	4174	5172
2016	914	941	1183	1503	1706	2001	2373	2866	3300	3608	3856	4701	5362
2017	914	525	1425	1384	1634	1780	2229	2261	2589	2994	3459	3793	4639
2018	914	690	1127	1318	1552	1973	2247	2634	3047	3358	3206	4078	5658
2019	914	884	1348	1401	1780	2102	2558	2882	3229	3518	4130	4560	5943
2020	914	735	1168	1505	1854	2318	2543	2855	3564	3788	4136	4360	5645

14.5 Stock weights

year	4	5	6	7	8	9	10	11	12	13	14	15	16
1979	76	141	262	387	638	834	1216	1521	1813	2176	2611	3184	4430
1980	76	141	262	387	638	834	1216	1521	1813	2176	2611	3184	4430
1981	76	141	262	387	638	834	1216	1521	1813	2176	2611	3184	4430
1982	76	141	262	387	638	834	1216	1521	1813	2176	2611	3184	4430
1983	76	141	262	387	638	834	1216	1521	1813	2176	2611	3184	4430
1984	76	141	262	387	638	834	1216	1521	1813	2176	2611	3184	4430
1985	79	141	253	384	627	840	1219	1519	1796	2129	2568	3115	4312
1986	75	133	269	385	610	845	1204	1519	1781	2164	2618	3158	4427
1987	76	151	264	387	638	834	1216	1521	1813	2176	2611	3184	4430
1988	70	138	249	395	621	839	1188	1494	1859	2174	2606	3106	4357
1989	64	124	232	401	689	935	1224	1527	1923	2102	2447	2886	3969
1990	79	148	280	439	761	1082	1307	1586	1972	2069	2418	2826	3752
1991	70	125	203	414	763	1071	1313	1583	1938	2128	2479	2983	3913
1992	61	118	192	377	673	929	1228	1483	1855	2101	2576	3160	4096
1993	73	146	255	337	555	793	1080	1390	1794	2073	2551	3101	4098
1994	55	115	201	335	531	736	1001	1306	1743	2016	2425	2982	3872
1995	63	114	184	347	546	750	1001	1313	1753	2037	2402	2891	3902
1996	79	141	259	426	621	779	1030	1295	1681	2070	2447	2935	4042
1997	83	175	282	479	734	900	1116	1351	1586	2000	2442	2772	3866
1998	85	158	246	492	757	979	1211	1364	1488	1858	2199	2600	3305
1999	90	154	262	405	677	974	1275	1401	1522	1797	2052	2613	3254
2000	87	139	239	363	594	873	1298	1407	1627	1713	1808	2543	3117
2001	140	197	293	362	591	851	1199	1383	1637	1762	1774	2504	3475
2002	101	267	380	481	606	857	1161	1384	1577	1784	1765	2305	3358
2003	104	215	377	563	670	896	1131	1456	1489	1922	2024	2440	3757
2004	100	189	315	627	672	873	1192	1521	1549	1956	2183	2651	3808
2005	104	166	369	581	706	915	1217	1452	1597	1900	2151	2618	3585
2006	90	161	305	551	712	1000	1264	1381	1636	1977	2051	2595	3593
2007	78	178	242	521	814	1114	1431	1462	1653	2064	2170	2604	3611
2008	102	158	283	492	847	1170	1519	1613	1747	2172	2418	2792	3744
2009	84	150	247	460	814	1146	1556	1739	1952	2134	2641	2854	3766
2010	88	149	375	485	765	1029	1468	1717	2120	2166	2815	3001	3758
2011	96	160	315	452	730	1014	1371	1745	2157	2320	2863	3051	4095
2012	119	182	291	495	744	988	1390	1747	2098	2516	2996	3270	3997
2013	121	176	324	492	732	1110	1441	1769	2019	2657	2895	3238	4141
2014	114	211	336	565	776	1045	1468	1812	2040	2739	2963	3329	4104
2015	112	226	384	560	850	1193	1625	1913	2182	2792	3116	3534	4489
2016	132	251	419	607	885	1168	1700	2116	2355	2886	3370	3872	4727
2017	128	252	311	636	941	1208	1863	2129	2490	2867	3548	4125	5020
2018	110	225	418	678	965	1189	1796	2153	2522	2801	3376	4066	4934
2019	112	186	321	682	1060	1251	1834	2148	2590	2880	3321	3997	5027
2020	134	236	335	633	1054	1359	1826	2320	2622	2870	3142	3828	4923

14.6 Maturity

year	4	5	6	7	8	9	10	11	12	13	14	15	16
1979	0.009	0.024	0.059	0.100	0.187	0.255	0.372	0.457	0.521	0.591	0.658	0.717	0.788
1980	0.009	0.024	0.059	0.100	0.187	0.255	0.372	0.457	0.521	0.591	0.658	0.717	0.788
1981	0.009	0.024	0.059	0.100	0.187	0.255	0.372	0.457	0.521	0.591	0.658	0.717	0.788
1982	0.009	0.024	0.059	0.100	0.187	0.255	0.372	0.457	0.521	0.591	0.658	0.717	0.788
1983	0.009	0.024	0.059	0.100	0.187	0.255	0.372	0.457	0.521	0.591	0.658	0.717	0.788
1984	0.009	0.024	0.059	0.100	0.187	0.255	0.372	0.457	0.521	0.591	0.658	0.717	0.788
1985	0.009	0.024	0.058	0.099	0.184	0.257	0.372	0.456	0.517	0.579	0.649	0.709	0.778
1986	0.009	0.023	0.058	0.099	0.178	0.258	0.369	0.456	0.515	0.588	0.658	0.714	0.790
1987	0.009	0.024	0.059	0.100	0.187	0.255	0.372	0.457	0.521	0.591	0.658	0.717	0.788
1988	0.008	0.023	0.058	0.102	0.181	0.256	0.363	0.451	0.533	0.592	0.655	0.706	0.784
1989	0.008	0.023	0.056	0.105	0.203	0.283	0.368	0.454	0.543	0.570	0.628	0.675	0.755
1990	0.008	0.023	0.058	0.119	0.225	0.328	0.388	0.460	0.545	0.552	0.613	0.664	0.745
1991	0.008	0.022	0.053	0.110	0.226	0.325	0.392	0.460	0.539	0.569	0.629	0.687	0.761
1992	0.008	0.021	0.048	0.097	0.196	0.282	0.373	0.440	0.527	0.570	0.646	0.717	0.774
1993	0.007	0.021	0.045	0.083	0.158	0.242	0.334	0.424	0.523	0.568	0.647	0.707	0.768
1994	0.007	0.020	0.045	0.083	0.150	0.222	0.309	0.399	0.510	0.550	0.620	0.688	0.733
1995	0.007	0.020	0.044	0.087	0.156	0.226	0.308	0.401	0.510	0.553	0.615	0.672	0.736
1996	0.007	0.019	0.045	0.114	0.179	0.233	0.312	0.391	0.491	0.562	0.618	0.676	0.744
1997	0.009	0.025	0.054	0.132	0.215	0.268	0.334	0.402	0.458	0.539	0.610	0.646	0.733
1998	0.011	0.029	0.061	0.136	0.221	0.292	0.357	0.398	0.428	0.501	0.559	0.614	0.669
1999	0.011	0.031	0.060	0.107	0.195	0.289	0.374	0.407	0.433	0.479	0.532	0.611	0.669
2000	0.012	0.027	0.056	0.094	0.170	0.258	0.376	0.404	0.455	0.465	0.489	0.592	0.641
2001	0.016	0.032	0.062	0.094	0.169	0.246	0.340	0.389	0.448	0.481	0.477	0.583	0.674
2002	0.017	0.044	0.076	0.132	0.173	0.251	0.329	0.386	0.430	0.488	0.478	0.552	0.652
2003	0.018	0.051	0.091	0.160	0.194	0.263	0.316	0.399	0.404	0.508	0.518	0.576	0.702
2004	0.015	0.050	0.094	0.182	0.196	0.259	0.339	0.421	0.421	0.505	0.549	0.606	0.704
2005	0.015	0.039	0.092	0.168	0.208	0.270	0.342	0.401	0.432	0.493	0.523	0.605	0.686
2006	0.014	0.034	0.084	0.158	0.207	0.293	0.360	0.384	0.444	0.507	0.512	0.603	0.687
2007	0.012	0.032	0.076	0.148	0.237	0.324	0.393	0.400	0.447	0.525	0.529	0.604	0.696
2008	0.012	0.032	0.066	0.136	0.242	0.334	0.411	0.433	0.464	0.545	0.580	0.618	0.710
2009	0.012	0.031	0.059	0.127	0.232	0.327	0.413	0.457	0.505	0.541	0.606	0.628	0.714
2010	0.013	0.029	0.074	0.132	0.215	0.297	0.398	0.453	0.538	0.531	0.623	0.638	0.710
2011	0.012	0.029	0.078	0.124	0.205	0.292	0.376	0.455	0.540	0.556	0.630	0.653	0.746
2012	0.015	0.032	0.082	0.135	0.208	0.283	0.386	0.457	0.534	0.591	0.665	0.686	0.742
2013	0.018	0.034	0.077	0.137	0.206	0.312	0.396	0.461	0.515	0.635	0.664	0.693	0.764
2014	0.019	0.039	0.079	0.161	0.220	0.295	0.401	0.475	0.528	0.646	0.679	0.715	0.759
2015	0.018	0.043	0.090	0.161	0.246	0.337	0.439	0.503	0.554	0.658	0.698	0.740	0.790
2016	0.019	0.051	0.101	0.176	0.259	0.334	0.463	0.544	0.593	0.672	0.733	0.776	0.807
2017	0.020	0.055	0.098	0.184	0.279	0.349	0.505	0.551	0.613	0.670	0.746	0.790	0.829
2018	0.020	0.055	0.102	0.197	0.288	0.348	0.489	0.558	0.618	0.655	0.714	0.780	0.817
2019	0.018	0.048	0.090	0.199	0.315	0.368	0.496	0.562	0.626	0.660	0.704	0.773	0.820
2020	0.019	0.046	0.093	0.184	0.315	0.400	0.497	0.595	0.628	0.659	0.688	0.760	0.813

14.7 Landings

Year	age	Landings
1979	-1	10775
1980	-1	8857
1981	-1	8621
1982	-1	8435
1983	-1	12214
1984	-1	10249
1985	-1	9708
1986	-1	12147
1987	-1	12605
1988	-1	14611
1989	-1	14128
1990	-1	14534
1991	-1	18015
1992	-1	16079
1993	-1	11112
1994	-1	11344
1995	-1	11393
1996	-1	14781
1997	-1	11737
1998	-1	11995
1999	-1	13961
2000	-1	15101
2001	-1	18169
2002	-1	14385
2003	-1	16536
2004	-1	13260
2005	-1	15294
2006	-1	16488
2007	-1	16205
2008	-1	14694
2009	-1	15280
2010	-1	12634
2011	-1	11372
2012	-1	10217
2013	-1	8798
2014	-1	7328
2015	-1	8041
2016	-1	8699
2017	-1	7275
2018	-1	9694
2019	-1	9215
2020	-1	7340
2021	-1	9063

15 Appendix I. Exploration of possible natural mortality values for Atlantic wolffish (*Anarhichas lupus*) in 5.a

15.1 Data-limited M estimators

The R package Fisheries Stock Analysis (FSA, Ogle et al. [17]) was used to explore a variety of M estimators using life history information estimated from the spring survey length and age data. Growth is relatively linear in Atlantic wolffish (see Appendix I), so Von Bertalanffy growth parameters were estimated as $L_\infty =$ 202 cm, $K = 0.03$ and $t_0 = -0.39$. Replacement of L_∞ with a reasonable max length (the max value, 118 cm, from Icelandic spring survey data) resulted in no appreciable change in M estimations. Max age of the population was taken to be the oldest Atlantic wolffish in the survey data (30), and the temperature experienced was taken to be the mean of 1) the mean of all spring survey bottom temperature records where Atlantic wolffish were caught, 2) the mean of all autumn survey bottom temperature records where Atlantic wolffish were caught, and 3) the mean of all commercial records of Atlantic wolffish. The mean of means was taken to reduce the influence of the number of records as well as seasonality of each data source (5.4°C). Maturation data from the spring survey was used to estimated $L_5 0$ as 65 cm (length at 50% mature from a maturation ogive), which was then translated into $t_5 0 = 12.4$ (age at 50% mature) using the Von Bertalanffy growth parameters. The weight-length power parameter b was estimated to be 3.12 using all Atlantic wolffish caught in the spring survey, and this relationship was also used to set W_∞ as 14 kg, calculated from the the maximum Atlantic wolffish length in all data (118 cm). These values in line with other Atlantic wolffish data recorded.

The **metaM** function in the FSA package calculates a variety of M estimates based on different life history information, two of which vary with length ("Gislason" and "Charnov" methods). Results of using these methods (with length set to 67 cm, the mean length of commercial samples, for the length-variable methods), indicated that M estimates varied widely, ranging 0.05 - 0.25 with both the mean and median of 0.15. Methods that relied on K estimates gave the lowest estimates. Methods that relied on max age were widely distributed, while methods that relied mainly on L_∞ or b were generally high (Fig. 48).

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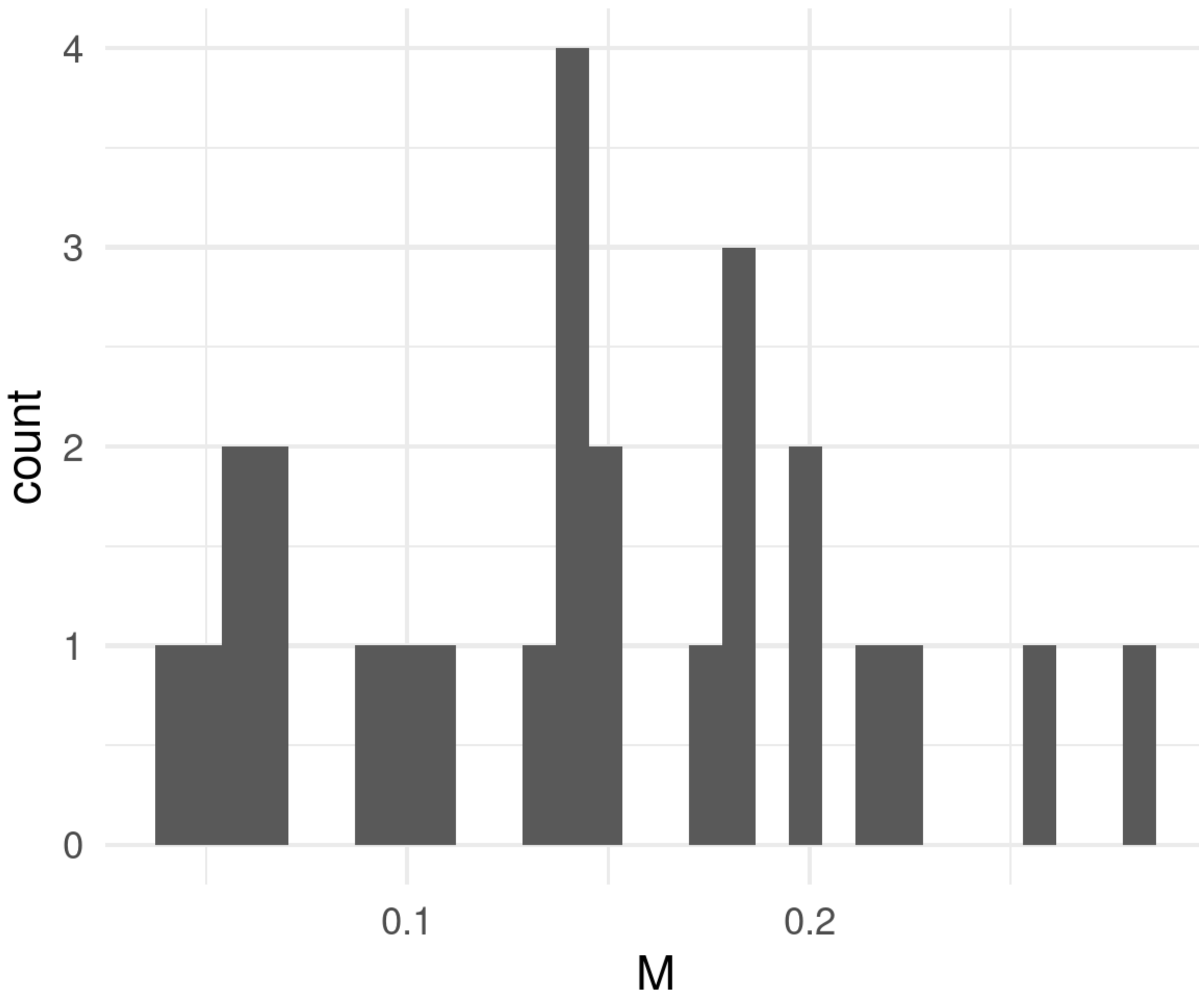

Figure 48: Atlantic wolffish in 5a. Histogram of life-history based natural mortality (M) estimates.

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Tusk *Brosme brosme* in 27.5.a and 27.14

Contents

1 Introduction

The tusk *Brosme brosme* is a gadoid (Lotidae) that reaches ~80 cm maximum in Iceland. It feeds on crustaceans and shellfishes, or small benthic fishes, and forms small shoals or solitary, on rough rocky , gravelly or pebbly bottoms. It is found mainly in deeper offshore areas, mostly caught around 100 to 500 m depth (Fig. 1). Spawning appears diffuse around Iceland but mainly in deeper waters toward the continental slope.

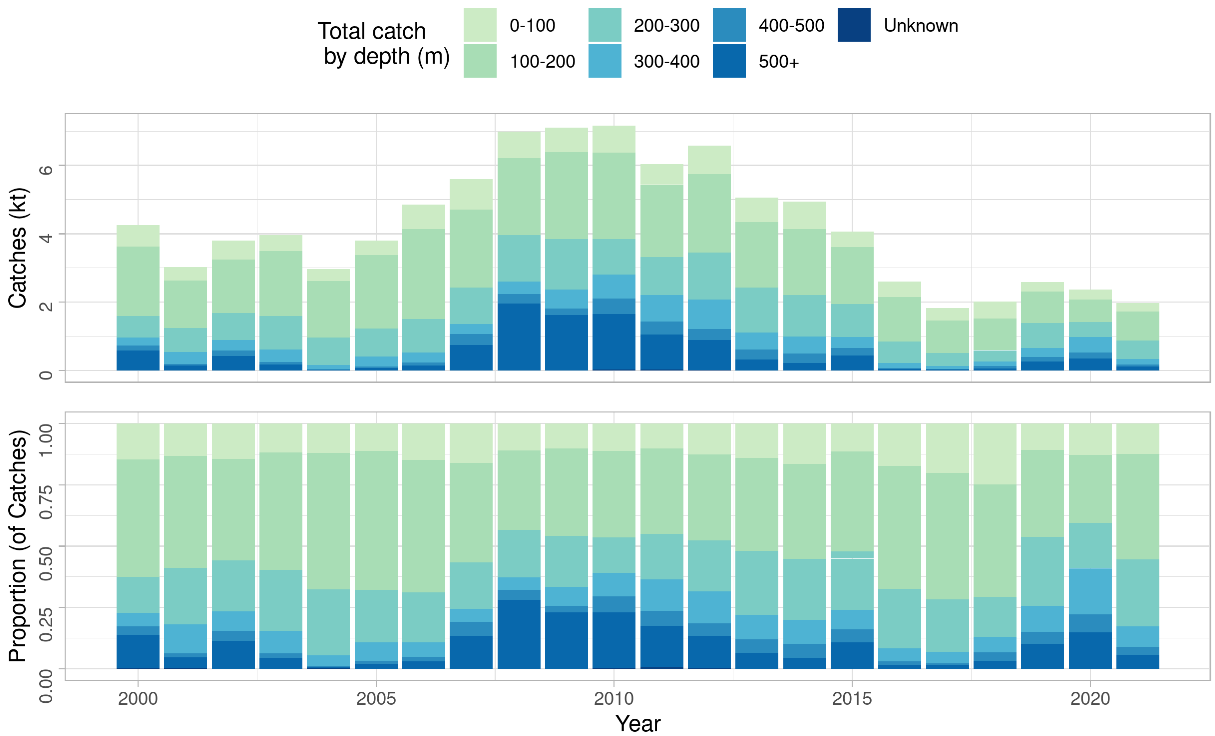

Figure 1: Tusk in 5.a and 14. Catch reported in logbooks by depth and gear, in terms of biomass (top panels) and proportion (bottom panels).

2 Stock ID and sub-stock structure

In the Northwest Atlantic, tusk is distributed along the continental shelf from New Jersey to the Strait of Belle Isle, on the Grand Banks of Newfoundland, and off West Greenland. In the Northeast Atlantic, it is found off East Greenland, around Iceland and the Faroe Islands and along the European shelf from southern Ireland to the Kola Peninsula and Spitzbergen, including the deeper parts of the North Sea and Barents Sea (Svetovidov [22]). The Northwest Atlantic and the Northeast Atlantic populations are considered distinct populations [6]. In Icelandic waters, the highest density of tusks observed from logbooks are on the south, southwestern and western part of the Icelandic shelf (Fig. 2).

Based on the genetic information that has been analyzed in 2007, ICES manages the stock separately between regions and divisions (Norway (ICES Subareas I and II), Iceland (ICES Div. Va and Subarea XIV (Greenland)), Mid-Atlantic Ridge (Subarea XII), Rockall (Div. VIb) and other areas (Divisions IIIa, Vb, VIa, and XIIb, and Subareas IV, VII, VIII,and IX) (Exploration of the Seas [5]; Knutsen et al. [12]).

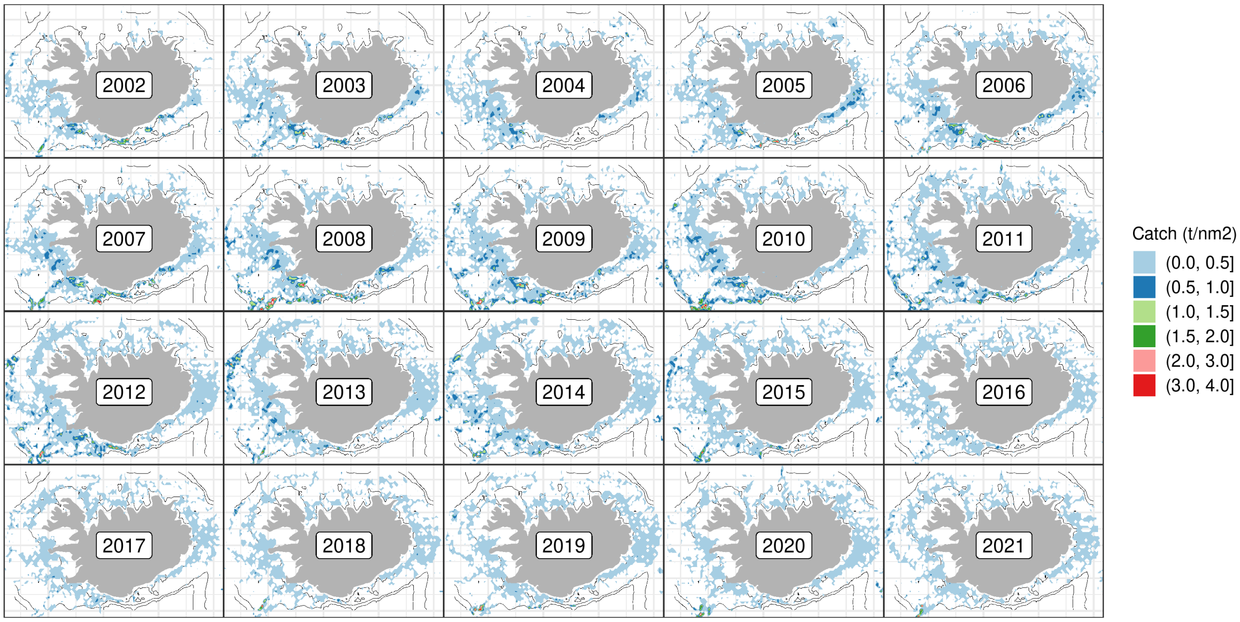

Figure 2: Tusk in 5.a and 14. Spatial distribution of tusk density according to logbooks.

3 Current advisory process

Since 2010 the Gadget model (Globally applicable Area Disaggregated General Ecosystem Toolbox, see https://github.com/gadget-framework/) has been used for the assessment of tusk in Icelandic waters (ICES [10]). As part of a Harvest Control Evaluation requested by Iceland this stock was benchmarked in 2017 (ICES [8]). Several changes were made to the model setup and settings which are described in the stock annex (ICES [9]).

Current advice based on a target harvest rate H applied to a length-based harvestable biomass estimated at the beginning of a calendar year, where the fishing year begins 1. September of the same year. Harvest rate (H) is scaled down according to $SSB/B_{trigger}$ when $SSB < B_{trigger}$. The target H = 0.13, was chosen to be slightly less than H_{MSY}, as it increased long-term expected SSB with little reduction in yield.

The Gadget stock assessment model is length- and age-structured model tuned to 7 length-based spring survey indices, age distributions, and length distributions. Comparisons with age distribution data implemented an 11+ group. The 2021 a chapter for tusk can be found in WGDEEP report (ICES [10]) see here

4 Issue list

In a letter dated at October 18, 2021, the government of Iceland requested that ICES evaluate the performance of the harvest control rules for tusk and update/develop new assessments as appropriate.

One issue regarding the tusk stock is that it spans areas 5.a and 14 are considered a single stock unit, but there are very little biological data from 14. Consultations with researchers on Greenlandic tusk indicate data are not in sufficient quantity or quality to include in assessment. Catches from 14 will be included in the assessment but are usually a small percentage of the total in comparison with those in Iceland. This can change quickly however and must be monitored. In addition, variability and sparsity in age data, likely as a result of high error, makes forming age-length keys (ALKs) difficult. Age data must be grouped across years. Finally, assessments prior to 2020 were based on fits to age distribution data that contained errors. This partially contributed to an overestimation of SSB and a large retrospective discrepancy detected in 2020. Another contributor to the retrospective pattern was likely inconsistency in estimated growth, either as a result of variability in growth, ageing error, or differing signals from length distributions vs. age data. For example, fits to the length distribution of last year's assessment show the growth of a strong cohort beginning in 2014, but the high and low frequencies of this distribution are not closely followed (Fig. 3). More on variability in growth can be found in the **Ecosystem drivers** section.

5 Scorecard on data quality

Scorecard on data quality was not used

6 Multispecies and mixed fisheries issues

In Icelandic waters, the main fishing grounds for tusk in Icelandic waters as observed from logbooks are on the south, southwestern and western part of the Icelandic shelf (Fig. 4). Tusk in Icelandic waters is caught almost exclusively in a mixed longline fishery where they are targeting more valuable species (e.g cod and haddock). Between 150 and 240 Icelandic long-liners report catches of tusk annually, but ~100 more vessels have small amounts of bycatch landings. The number of longliners reporting tusk catches decreased substantially from 308 in 2007 to 255 in 2008 and has continued to decrease since (MFRI [14]).

Year	Months	ICES area	Other
2019	Other	14	566
2020	Other	14	158
2021	Other	14	701

7 Ecosystem drivers

Considerable changes have been observed in the area, both in terms of changes in fishing pressure and the ecosystem. Jónsdóttir et. al. (2019) [11] noted that species diversity in the fjords in the western and northern part of the country shifted dramatically at the turn of the century. These changes were attributed mainly to increases in the abundance of juvenile gadodids such as cod, ling and whiting. These changes coincided with increased temperature, generally lower fishing pressure towards and shifts in distribution of species. An example of these shifts range from the Icelandic haddock stock, with a noticeable northern shift in distribution [14], the minke whale population (Vikingsson et al. 2015) possibly due to shifts in forage fish species and influx of the mackerel to the North Western Atlantic [19]. Projected effects of climate change are also expected to affect species differently depending on their thermal tolerances and habitat affinities (e.g., depth). Some warm-water species such as tusk and ling shifting northward gaining suitable habitat available to them (e.g,. ling, tusk, and haddock) while others lose ground due to depth constraints (e.g., plaice) and most cold-water species lose (e.g., Atlantic wolffish, Mason et al. [13], Campana et al. [2]).

7.1 Variability in biological relationships

As mentioned earlier, it was suspected that time-variable growth may have contributed to the retrospective patterns observed in the last assessment using the Gadget model. Exploratory plots were created to visualize whether variation in biological relationships (maturity at length, length at age, and weight at length), could be detected among sampling types (spring survey, autumn survey, or commercial) or regions around Iceland, between sexes, or over time. Regions were defined according to Bormicon divisions that have been modified slightly to be more easily applicable in Gadget (Stefánsson and Pálsson [21], MRI [15], Fig. 5). Full results are not shown, but the main results included:

- Length-weight relationships appears linear and not strongly variable by region, time, or data source.
- Maturation appears to vary slowly with time, and very slightly by region. These patterns show later maturation in warmer waters (southwest and west Iceland), and may be a side effect of spatial variation in size. In addition, a larger size range of tusk are commonly caught in the gillnet survey taking place in May, indicating that tusk catchability decreases greatly around the same size as maturation, possible

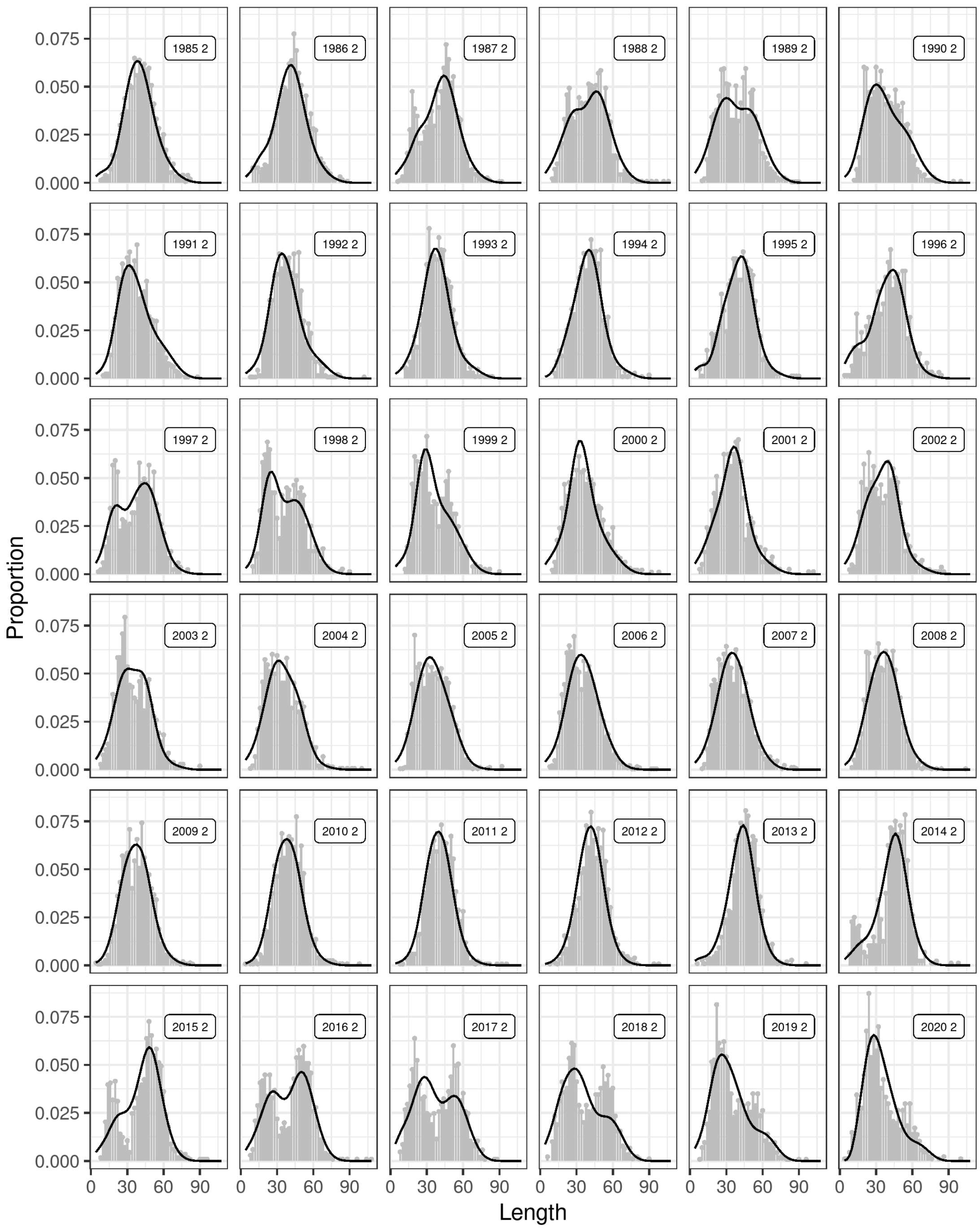

Figure 3: Tusk in 5.a and 14. Fit of the Gadget stock assessment model (black lines) to spring survey length distribution data (grey bars). Note the weak fits to the clear cohort development that begins in 2014. Reproduced from @MFRIstatus2021.

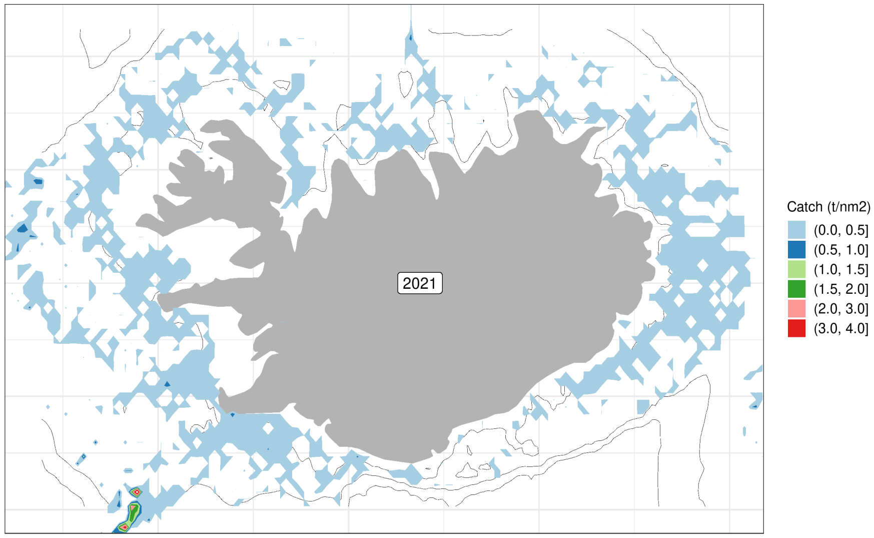

Figure 4: Tusk in 5.a and 14. Spatial distribution of catches in 2021 by all gears.

due to coinciding changes in habitat (toward rough, rocky, untrawlable habitat, Cohen et al. [4]), behavior, and/or spatial location. Therefore individual samples of maturation may be biased if tusk behavior is changing around the same time as maturation. As spring survey data are taken close to tusk spawning time (May - July, Cohen et al. [4]), they may be biased. Autumn survey data showed the lowest size at maturation that did not differ between males and females, these were used as an indicator maturation 8.

- Growth curves appear to vary slightly by region and time (Figs. 6, 7, 9, 10), but not by sex or sampling type. Differences by region, however, were not considered strong enough to consider further given the high variation in length at age. Due to the changes in catchability that occur at maturation (see previous bullet), growth data especially for larger tusk is sparse. However, as no age data are taken from the gillnet survey, they are the best data available.

8 Stock Assessment

8.1 Catch – quality, misreporting, discards

Annual estimates of landings of tusk from Icelandic waters are available since 1905 (Figure 11). The historical information are largely derived from the Statistical Bulletin, with unknown degree of accuracy, and retrieved from Statlant. For the period between 1980 to 1993, landings of Icelandic vessels were recorded by Fiskifélagið (a precursor to the Directorate of Fisheries). The more recent landings (from 1993 onwards) are from the Directorate of Fisheries as annually reported to ICES. After 2013, all landings in 5.a are recorded by the Directorate, while foreign vessel landings were obtained from Statlant.

The estimates by the Directorate of Fisheries are based on a full census by weighing fish at the dock when landed or in fish processing factories prior to processing. Information on the landings of each trip are stored in a centralised database of which the Marine and Freshwater Research Institutes (MFRI) employees have full access. Captains are required to keep up-to-date logbooks that contain information about timing (day and time), location (latitude and longitude), fishing gear and amount of each species in each fishing operation. Logbooks are especially useful for providing information on catch location and monitoring its change over time (12). The Directorate of Fisheries and the Coast Guard can, during each fishing trip, check if amount of fish stored aboard the vessel matches what has been recorded in the logbooks, in part to act as a deterrent for potential illegal and unrecorded landings.

Nearly all tusk is landed gutted and converted to ungutted using the conversion factor 1/0.90 (see the

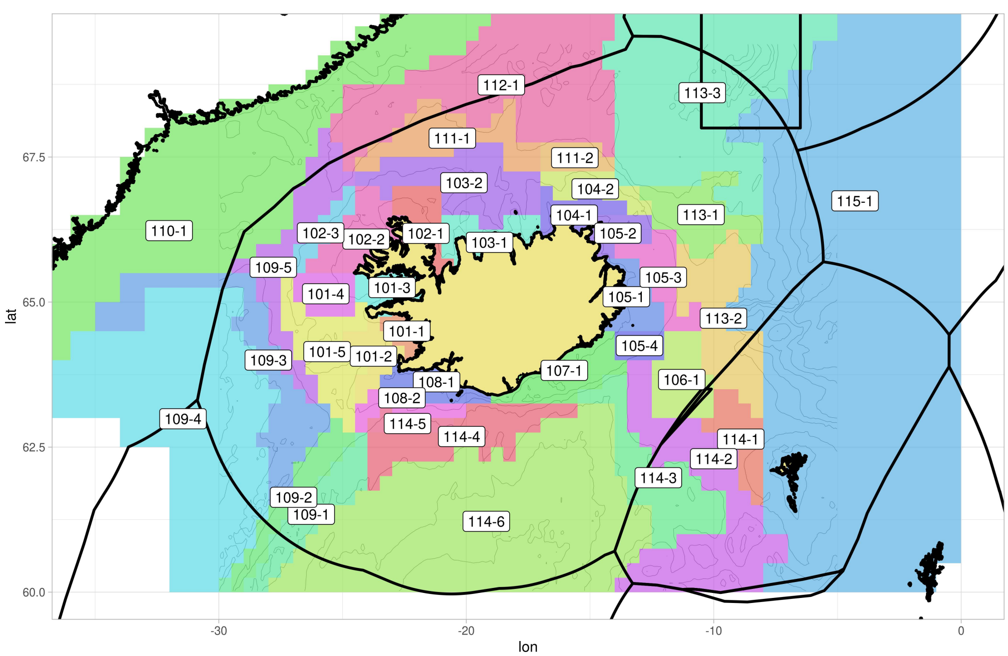

Figure 5: Tusk in 5.a and 14. Illustration of Gadget divisions, originally based on Bormicon divisions, used to analyse regional variation. The first three numbers (generally 101-116) indicate division number labels that correspond with plots showing regional variation in life history.

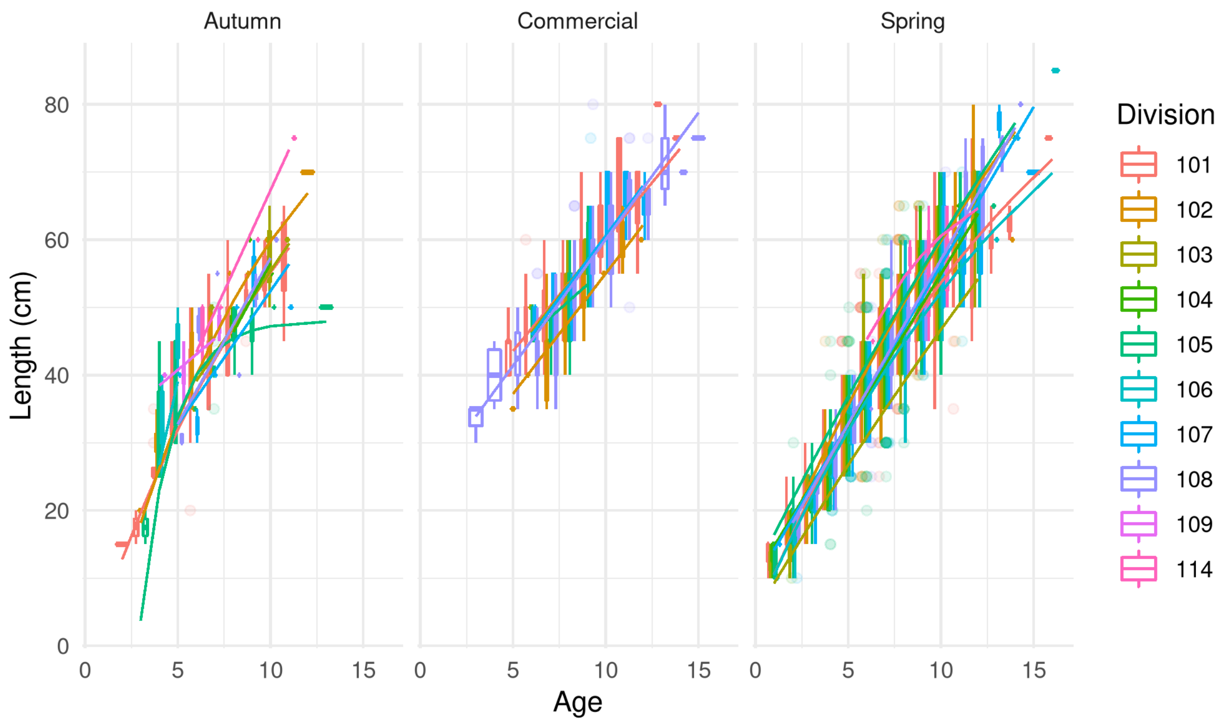

Figure 6: Tusk in 5.a and 14. Length at ages of females by region, plotted as boxplots with logistic maturation ogives overlaid where model fits were possible.

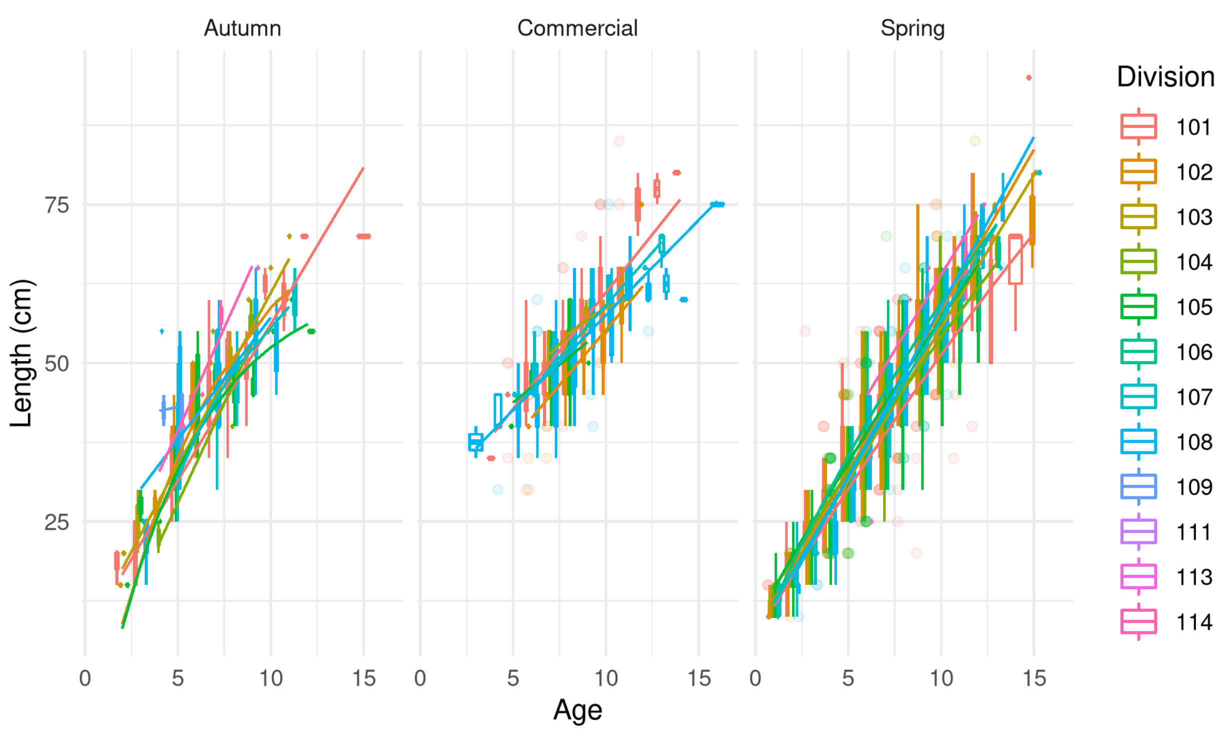

Figure 7: Tusk in 5.a and 14. Length at ages of females by region, plotted as boxplots with logistic maturation ogives overlaid where model fits were possible.

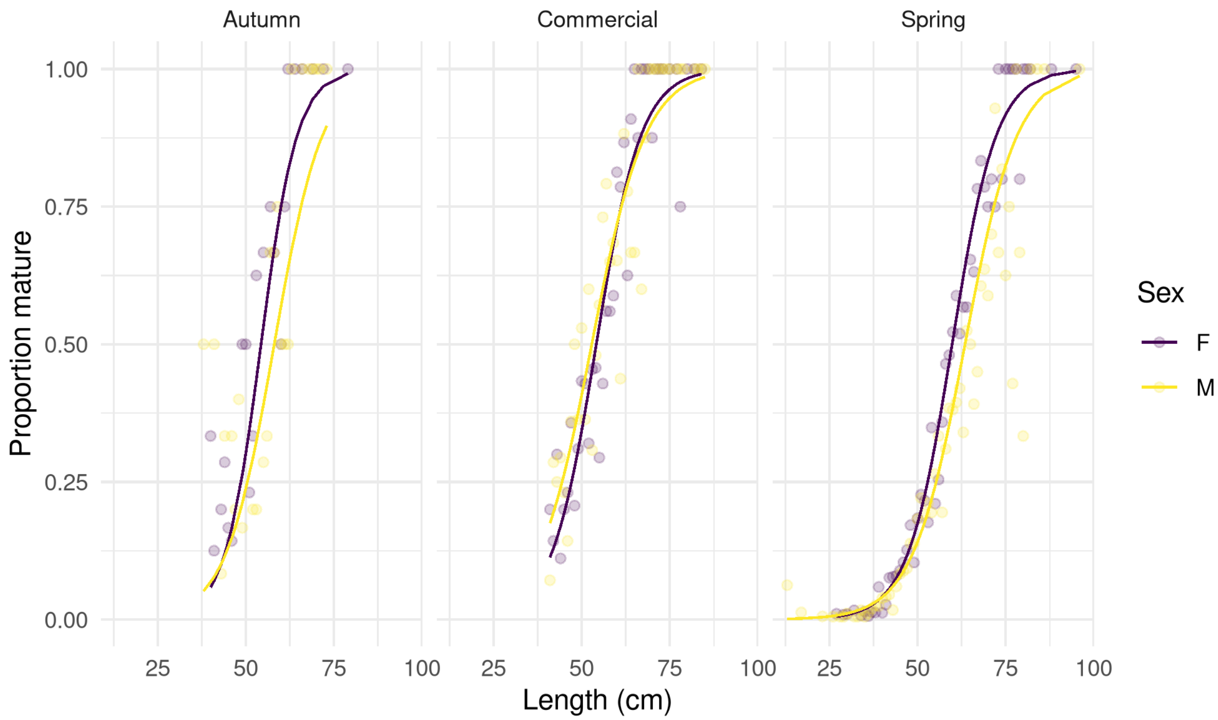

Figure 8: Tusk in 5.a and 14. Maturation at length by sex and data source.

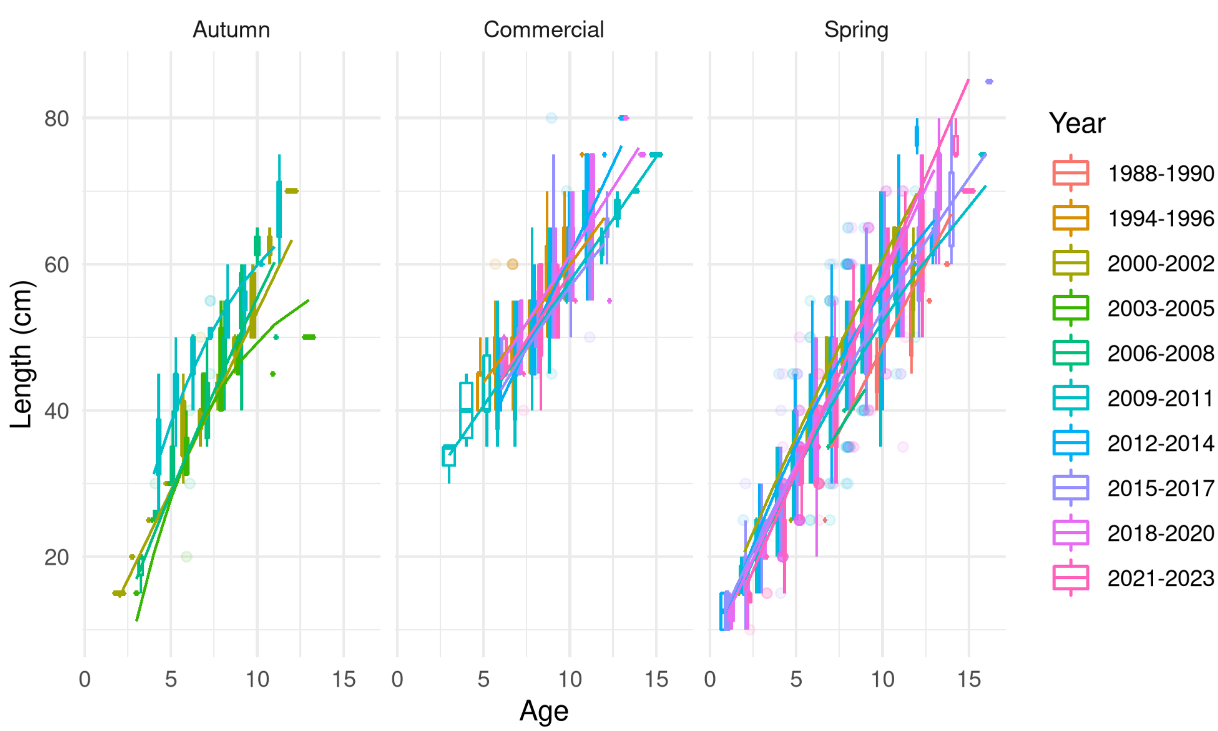

Figure 9: Tusk in 5.a and 14. Length at ages of females by year, plotted as boxplots with Von Bertalanffy growth curves overlaid where model fits were possible.

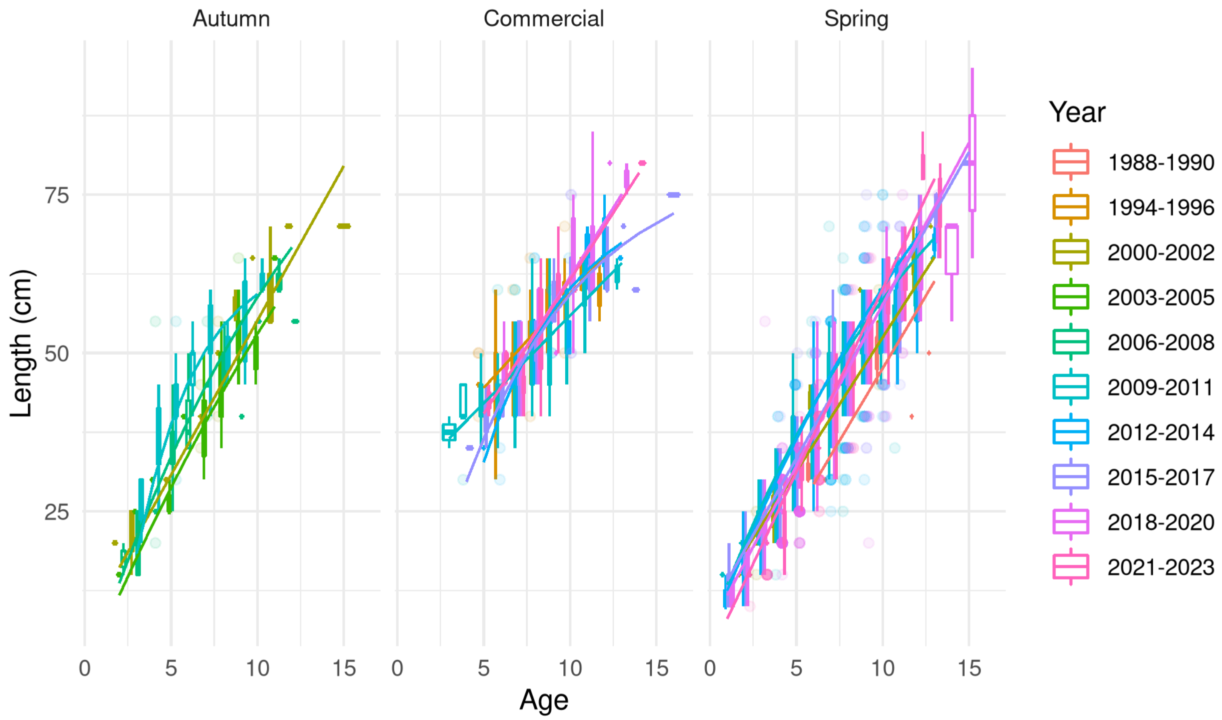

Figure 10: Tusk in 5.a and 14. Length at ages of males by year, plotted as boxplots with Von Bertalanffy growth curves overlaid where model fits were possible.

Directorate of Fisheries website here).

The real gutting factor can vary year to year so the amount of ungutted tusk landed may be different than the estimated value. All the bookkeeping of catch is in terms of gutted fish and the reference to ungutted catch is just gutted divided by 0.90 so this does not matter in the assessment.

Discards are illegal in Icelandic waters but are assumed to take place to some degree. A discard monitoring program of the MFRI, designed to estimate highgrading of cod and haddock, has been in place since 2001, but no estimates of discards exist for tusk in Icelandic waters.

8.2 Surveys

8.2.1 Research cruises

Information on abundance and biological parameters from Tusk in 5.a is available from two surveys, the Icelandic groundfish survey in the spring and the Icelandic autumn survey.

The Icelandic groundfish survey in the spring, which has been conducted annually since 1985, covers the most important distribution area of the fishable biomass. The autumn survey commenced in 1996 and expanded in 2000 to include deep water stations. It provides additional information on the development of the stock. The autumn survey has been conducted annually with the exception of 2011 when a full autumn survey could not be conducted due to a fisherman strike. Although both surveys were originally designed to monitor the Icelandic cod stock, the surveys are considered to give a fairly good indication of the stock. In addition, a gillnet survey is conducted in areas closer inshore every April during cod spawning periods, designed to sample the cod spawning stock (Fig. 13. Detailed descriptions of the Icelandic spring and autumn groundfish surveys and the April gillnet survey are given in (Sólmundsson et al. [20], ICES [9]). Fig. 14) shows both a recruitment index and the trends in various biomass indices. Changes in spatial distribution observed in the spring survey is shown in Fig. 15). The figure shows that a larg proportion of the observed biomass recently

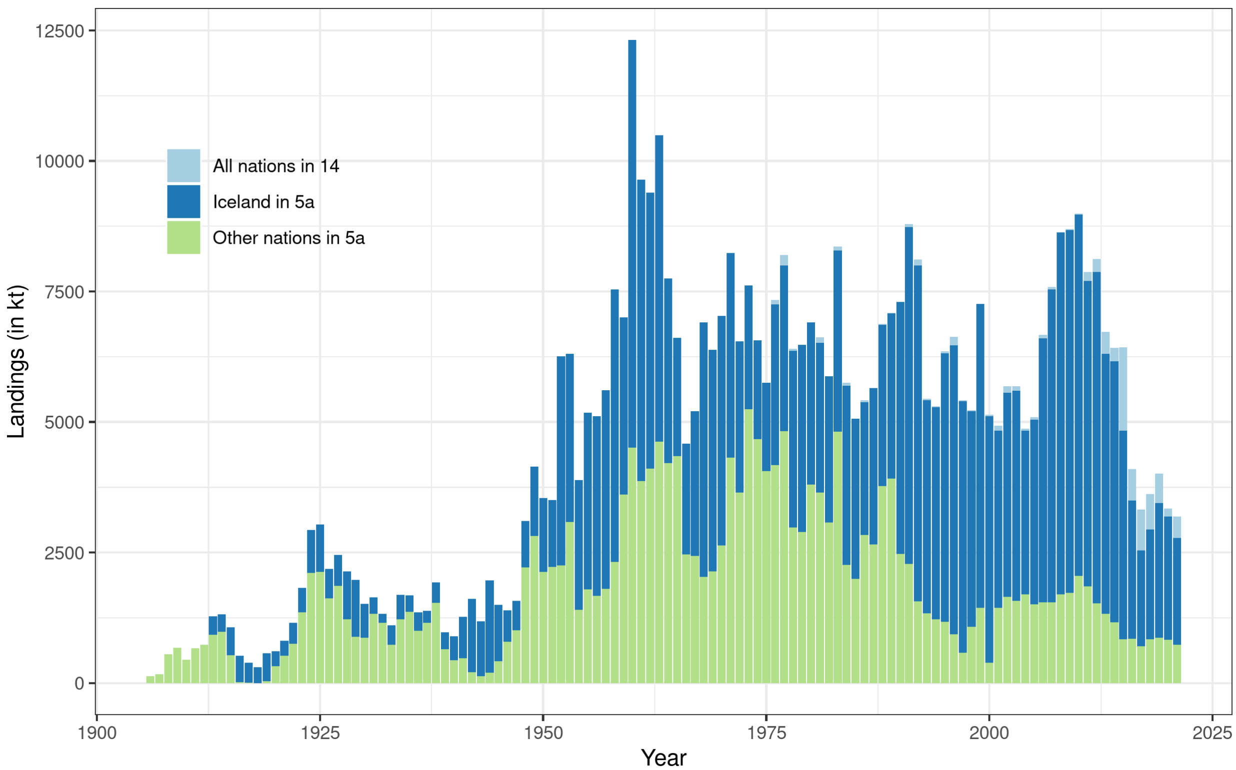

Figure 11: Tusk in 5.a and 14. Landings in 5.a and 14.

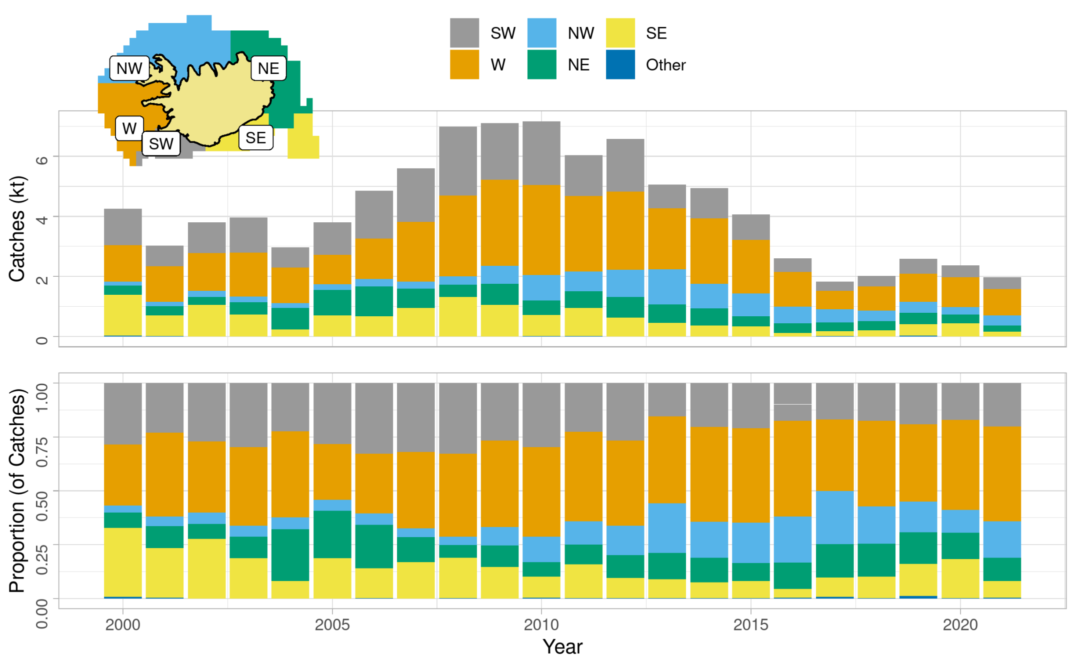

Figure 12: Tusk in 5.a and 14. Changes in spatial distribution of the Icelandic fishery as reported in logbooks. All gears combined.

shifted to the north (areas NW and NE).

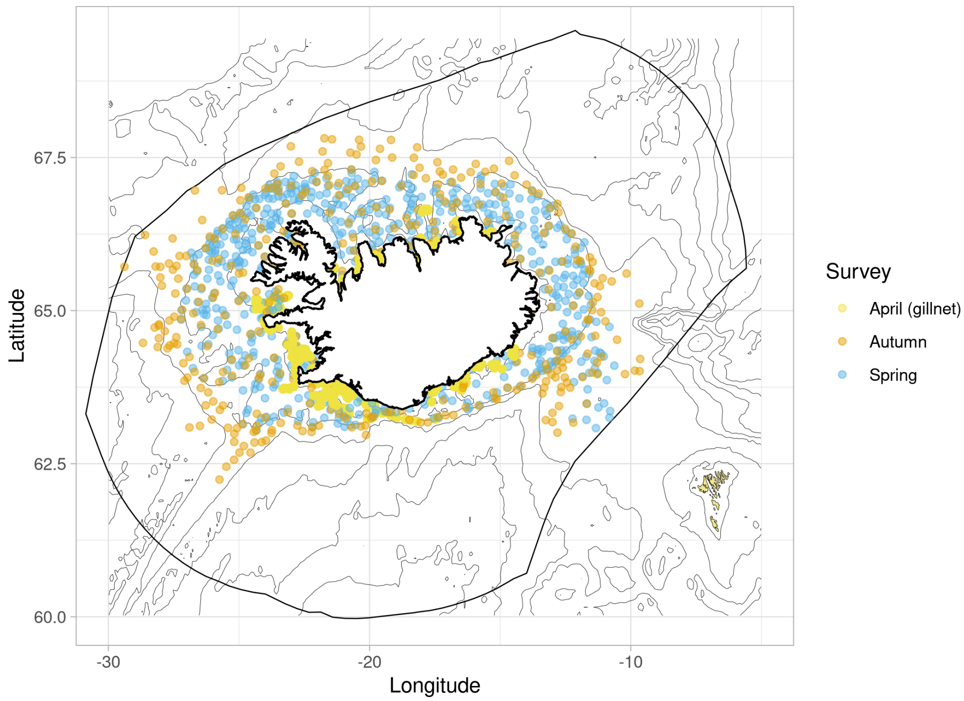

Figure 13: Tusk in 5.a and 14. Survey stations collected in a typical year (2021) from each of the three surveys.

Although the spring and autumn trawl surveys are the most commonly used for demersal fish assessment in Iceland, there is also a gillnet survey designed to sample cod spawning stock aggregations that has been conduced in April annually since 1998 (ADD cod stock annex). The tusk fishery is mainly a longline fishery and it is thought that trawls are not as effective at capturing large tusk (due to their shift toward untrawlable rocky bottom habitats, Cohen et al. [4]). The main length distribution covered by the gillnet survey overlaps only with the largest fish from the trawl surveys, slightly larger than the lengths of fished tusk (Fig. 16). Therefore, incorporation of a gillnet survey index (referred to as the April survey) was considered also.

8.3 Weights, maturities, growth

Little research specifically on tusk in Iceland. Targeted, but often as a 'bycatch' to more valuable species in a demersal mixed fisheries. Tusk are almost exclusively caught by long lines, but is usually not targeted in large quantities (unless other quotas are filled) because difficult to remove hooks. Shoals of small tusk found close to the Faroese ridge (southeast of Iceland, Fig. 17). These need to be excluded from survey indices due to inconsistent sampling of this area. However, they indicate a general gradient of smaller tusk found in the east and larger tusk found in the west (Fig. 18).

Biological data from the commercial longline and trawl fleet catches are collected from landings by scientists and technicians of the Marine and Freshwater Research Institute (MFRI) in Iceland. The biological data collected are length (to the nearest cm), sex and maturity stage (if possible since most ling is landed gutted), and otoliths for age reading. Most of the fish that otoliths were collected from were also weighed (to the nearest gram).

Sampling from commercial catches of tusk is considered good; both in terms of spatial and temporal distribution of samples (Figs. 19 and 20). Commercial age readings are available in 1981 - 1983,1994, and 2008 - present (Fig. 21).

In the scientific surveys, length data are available from all three considered (spring, autumn, and April),

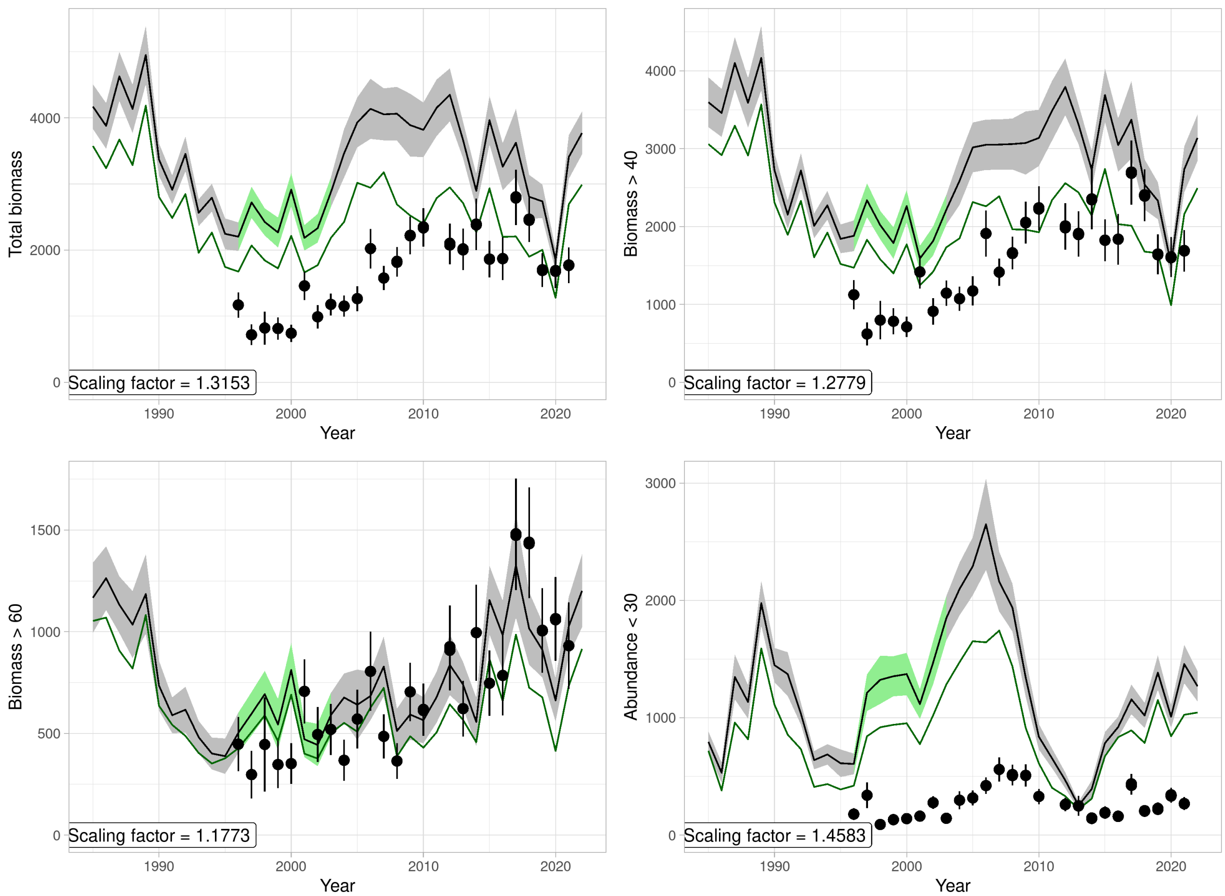

Figure 14: Tusk in 5.a and 14. Biomass trajectories from the spring and autumn surveys.

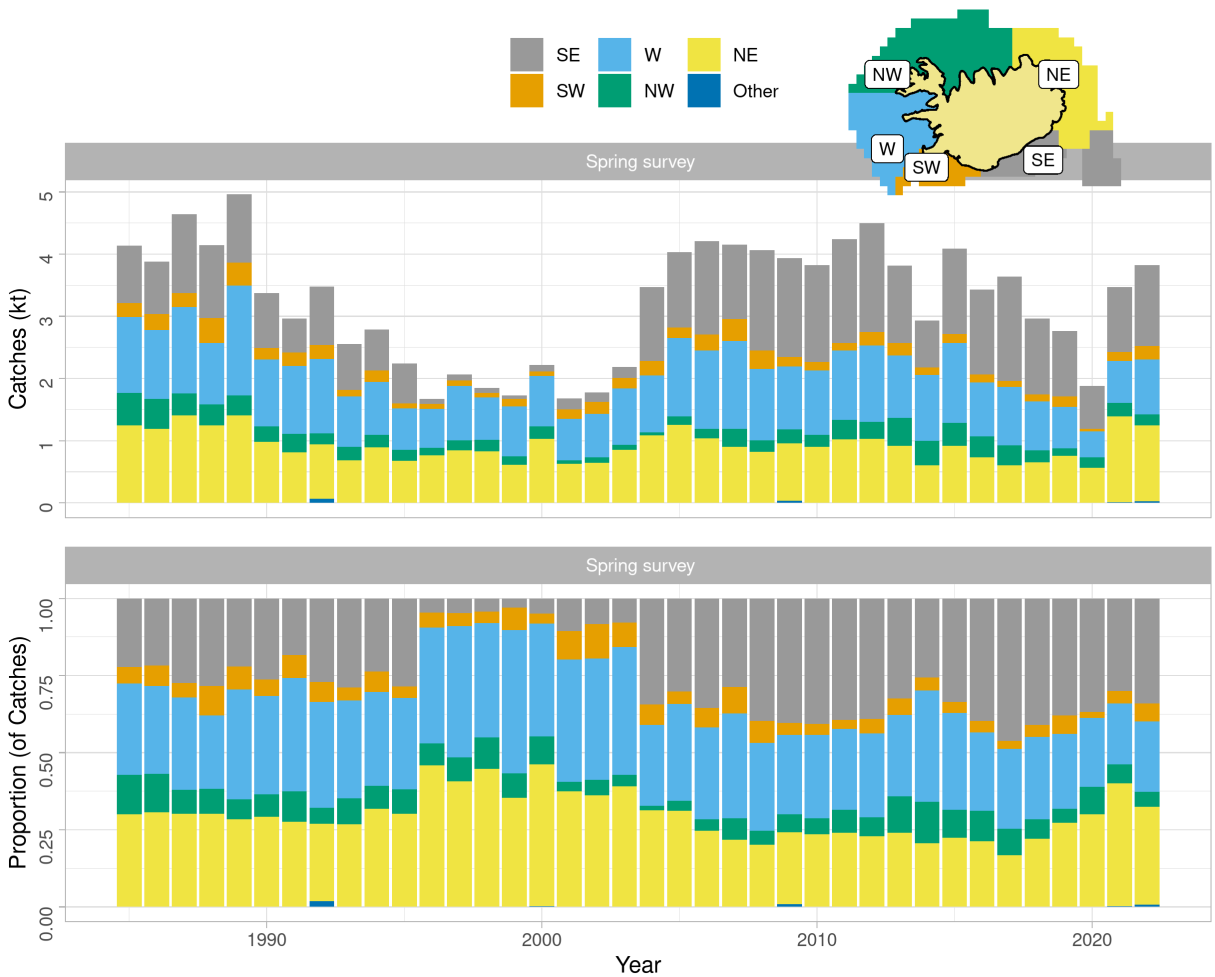

Figure 15: Tusk in 5.a and 14. Biomass by area from the spring survey.

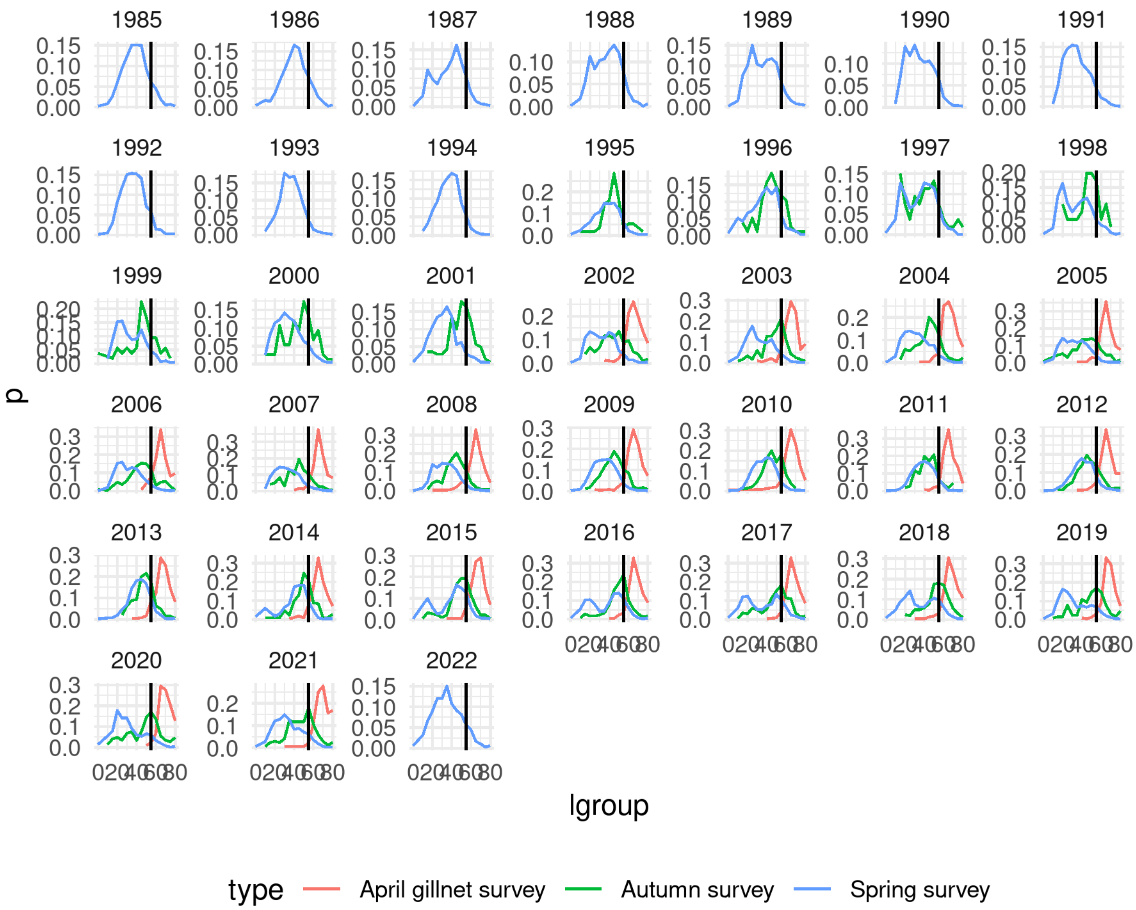

Figure 16: Tusk in 5.a and 14. Biomass by area from the spring survey.

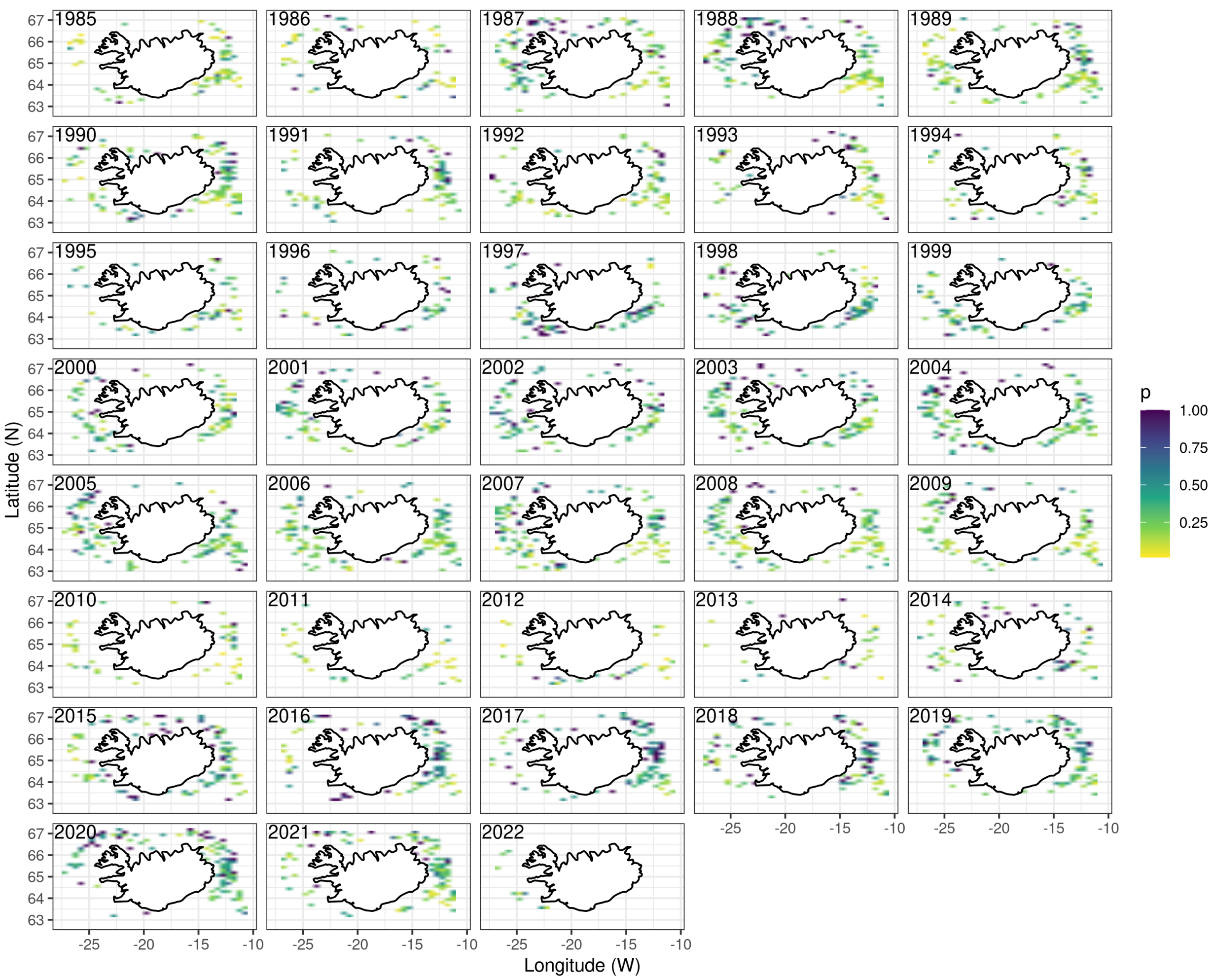

Figure 17: Tusk in 5.a and 14. Percentage of tusk < 25 cm in spring survey hauls.

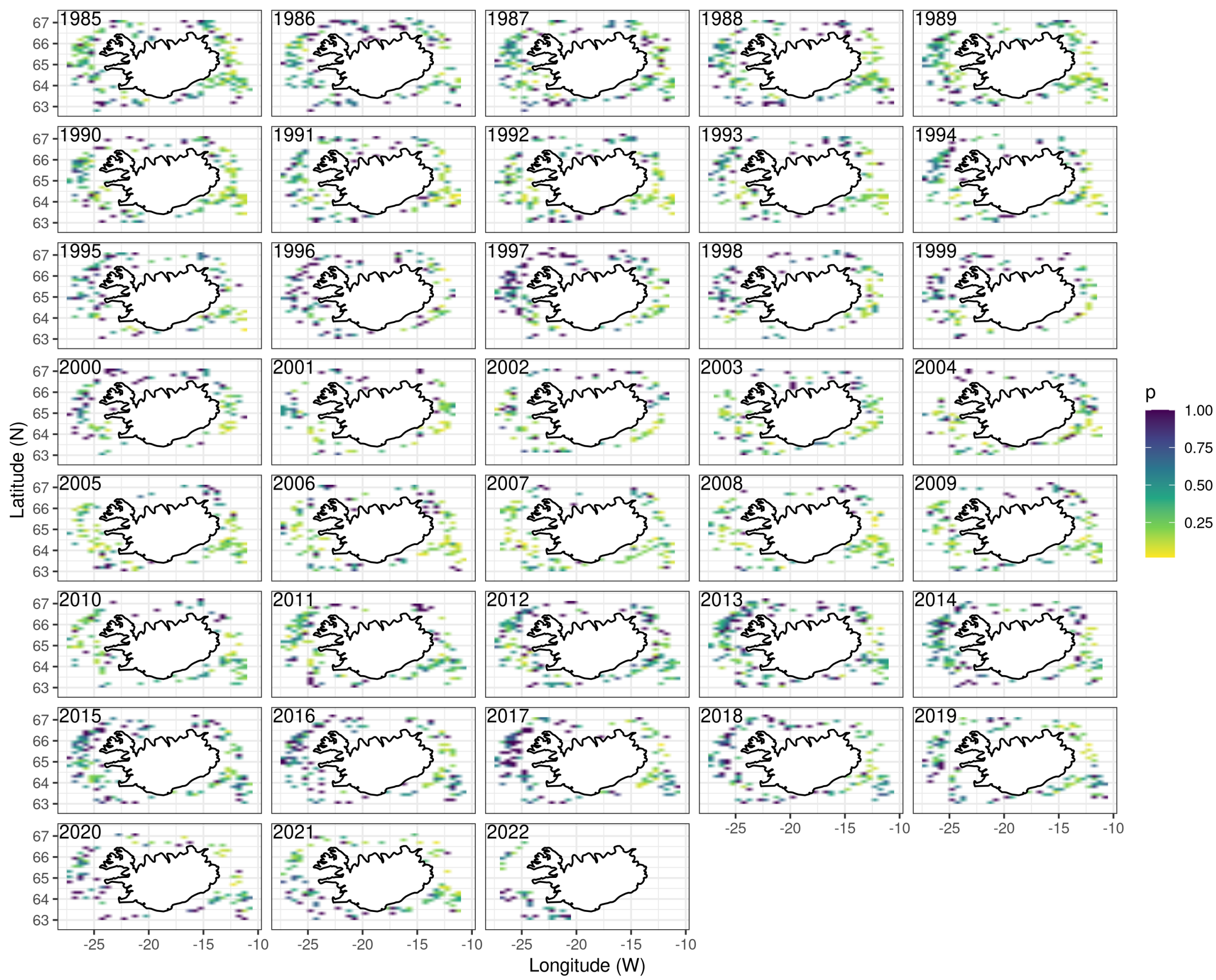

Figure 18: Tusk in 5.a and 14. Percentage of tusk 50-74 cm in spring survey hauls.

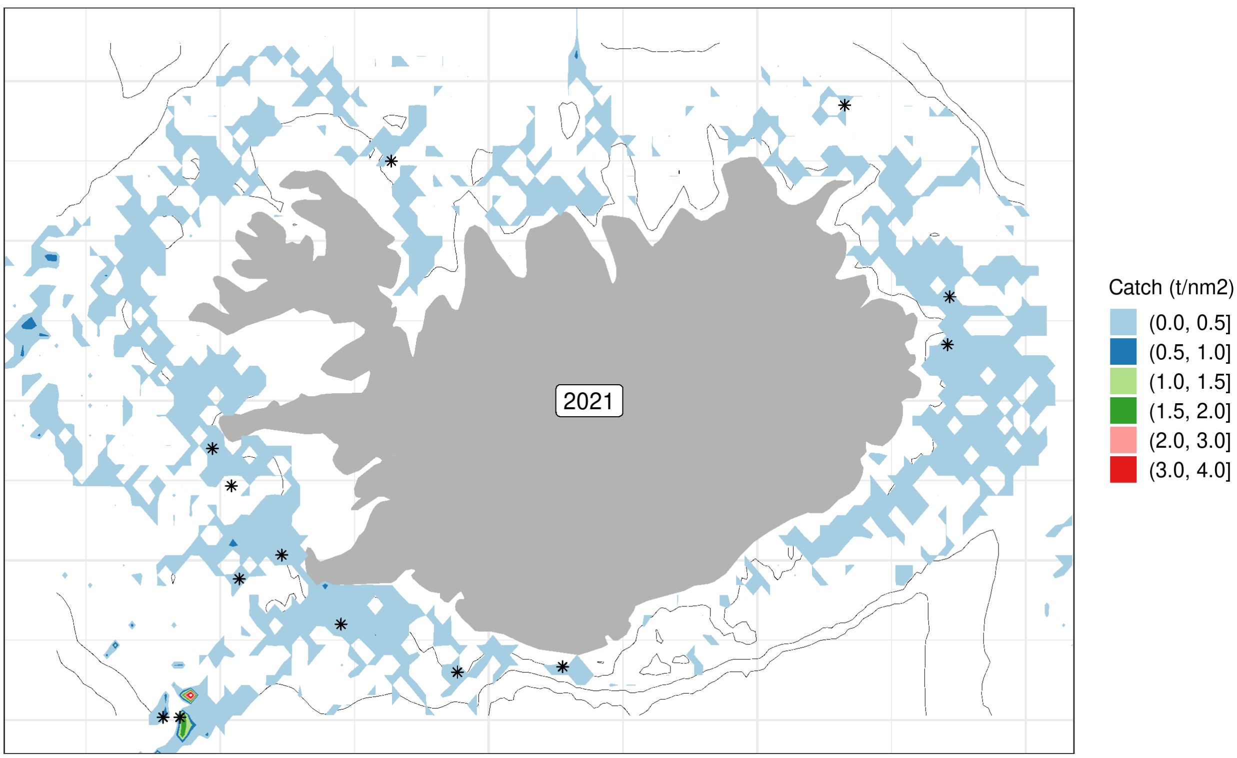

Figure 19: Tusk in 5.a and 14. Fishing grounds in 2021 as reported by catch in logbooks (tiles) and positions of samples taken from landings (asterisks) by longliners and trawlers.

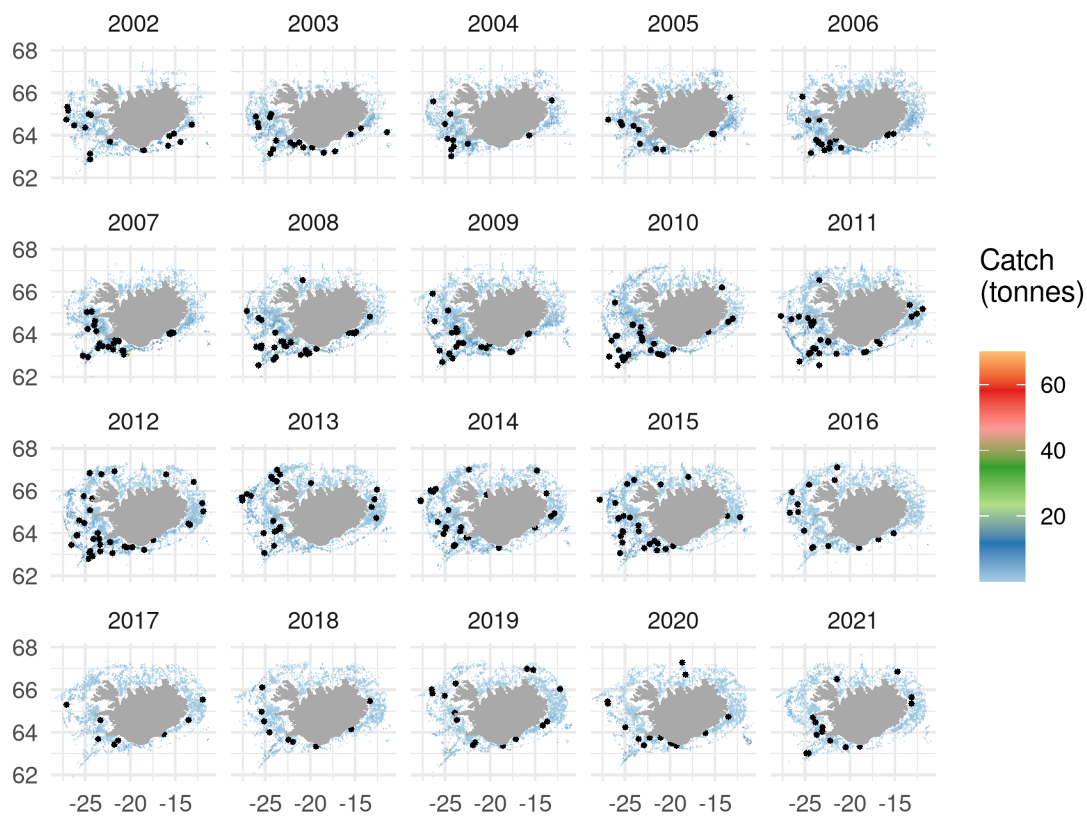

Figure 20: Tusk in 5.a and 14. Fishing grounds across years as reported by catch in logbooks (tiles) and positions of samples taken from landings (asterisks) by longliners and trawlers.

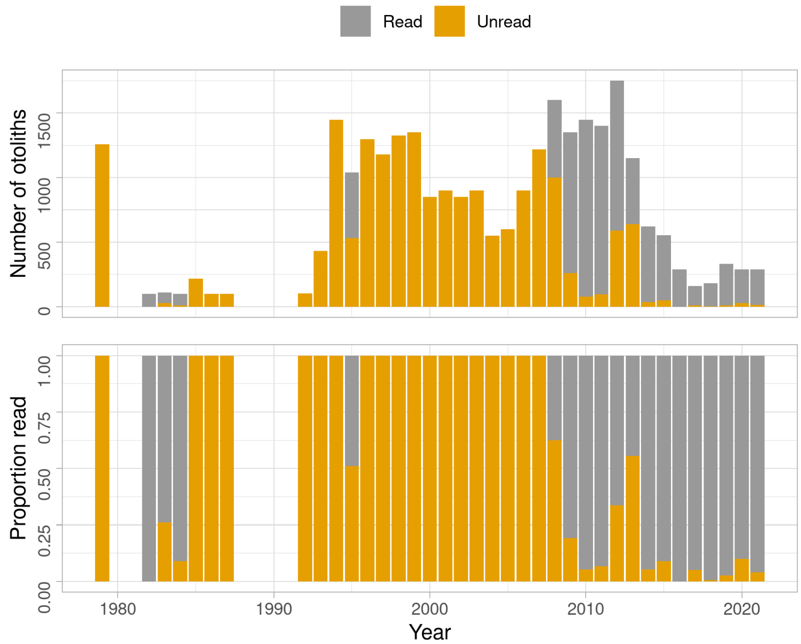

Figure 21: Tusk in 5.a and 14. Total number of otoliths read versus unread from commercial samples (upper panel) as well as their proportions (bottom panel).

weight and maturity data are available only from the trawl surveys (spring and autumn), and age readings are only available from the spring survey, mainly from 1985, 1990-1991, 1995, and 2000-present (Fig. 22.

8.4 Growth

Ageing is very difficult, and gets more difficult at older ages. In addition, the capture of larger and older fish also becomes less frequent at higher ages both due to natural mortality and a likely behavioral shift away from trawlable habitats. As a result, age readings of fish greater than 65 cm is especially sparse. Ten plus was used as a plus group in the last-benchmarked Gadget stock assessment.

Fish weights at length are available from both surveys and commercial data (Figs. 23 and 24). Stock weights were calculated as the mean weight at age taken from the spring survey in March, after converting lengths to weights using an estimated power relationship from survey samples. Catch weights were calculated as the mean weight at age taken from commercial samples, after converting lengths to weights using an estimated power relationship from commercial samples. Weights were calculated as the expected weight from the length distribution observed for that year. Before 1985, survey data were replaced with catch weight data, which are available from 1980. Where weight at a certain age were missing which occurred only in very rare cases, mean stock weights over all years were used to fill the gap. To reduce interannual variability, survey weights of tusk in the 10+ age group were calculated as a moving average of the current year and the previous four years.

8.5 Maturities

At roughly 54 cm around 25% of tusk in Icelandic waters is mature, at 62 cm 50% of tusk is mature and at 70 cm 75% of tusk is mature based on the spring survey data. This means that most of the maturation occurs at when ageing becomes less reliable, and mature fish are less likely to be caught by the trawl surveys.

Maturity-at-age data are given in Figs. 25 and 26. Maturity at age data was taken from the autumn groundfish survey, calculated based on maturity at length each year and length distributions of fish assigned

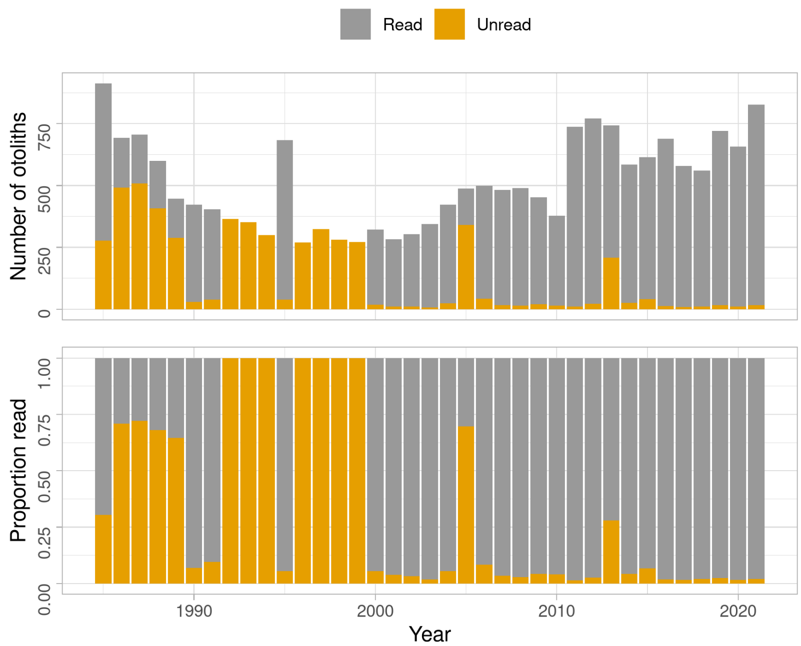

Figure 22: Tusk in 5.a and 14. Total number of otoliths read versus unread from spring survey samples (upper panel) as well as their proportions (bottom panel).

to each age. The spring survey data was not used because maturation patterns appeared to occur at larger fish and differed between sexes. As spawning is thought to occur in late spring or summer (Cohen et al. [4]), these patterns could indicate a biased sample of maturation due to the beginning of maturation-induced behavioural changes such as migration away from the survey areas. This was done annually to account for annual variation in maturity ogives and growth. As maturity data are randomly sampled in surveys at the same rate across all regions of Iceland, calculating a mean maturation takes into account regional differences in maturation. Maturity data were calculated as prediction from an maturity ogive estimated with year as a factor to produce annual esimates. Prior to 2000 the proportion mature is assumed fixed at the mean values from 2000 to 2002. To reduce interannual variability, maturity values were calculated as a moving average of the current and previous 4 years.

8.5.1 Natural mortality

Natural mortality M was set to 0.15, after explorations using M estimators based on a profile of likelihoods of the model with various M values showed a slightly lower negative log likelihood at higher values (minimum close to 0.3, Appendix I). However, differences negative log likelihood were extremely small (<2) for all values for M above 0.15, so 0.15 was retained life history parameters do not corroborate a high value of M, but rather indicate a wide range of M values could be appropriate.

8.6 Assessment model

Two main modeling frameworks have been explored with tusk in Iceland: the current Gadget model and the state-space age-based assessment model (SAM, Nielsen and Berg [17], Berg and Nielsen [1]). Here we only present results from the SAM best model chosen to continue with harvest control rule evaluation. Developments in the Gadget model have begun to improve stability but we continue with the SAM modeling framework as retrospective patterns appear less at this time.

SAM model development began with ALK refinement and choice of model age structure that emphasized correlations among consecutive cohort observations within catch-at-age and survey index data. Generally,

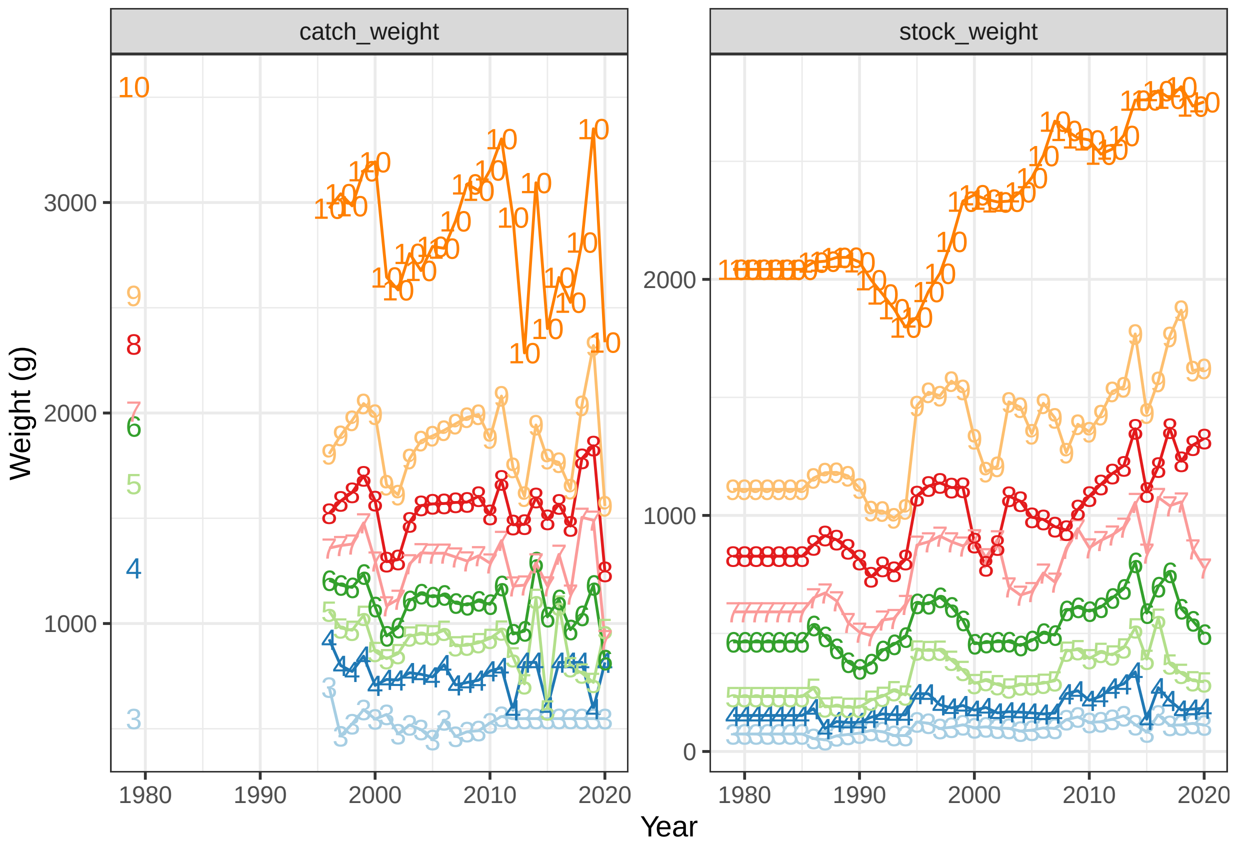

Figure 23: Tusk in 5.a amd 14. Weight at age observed in the spring survey and from the commercial catches over years.

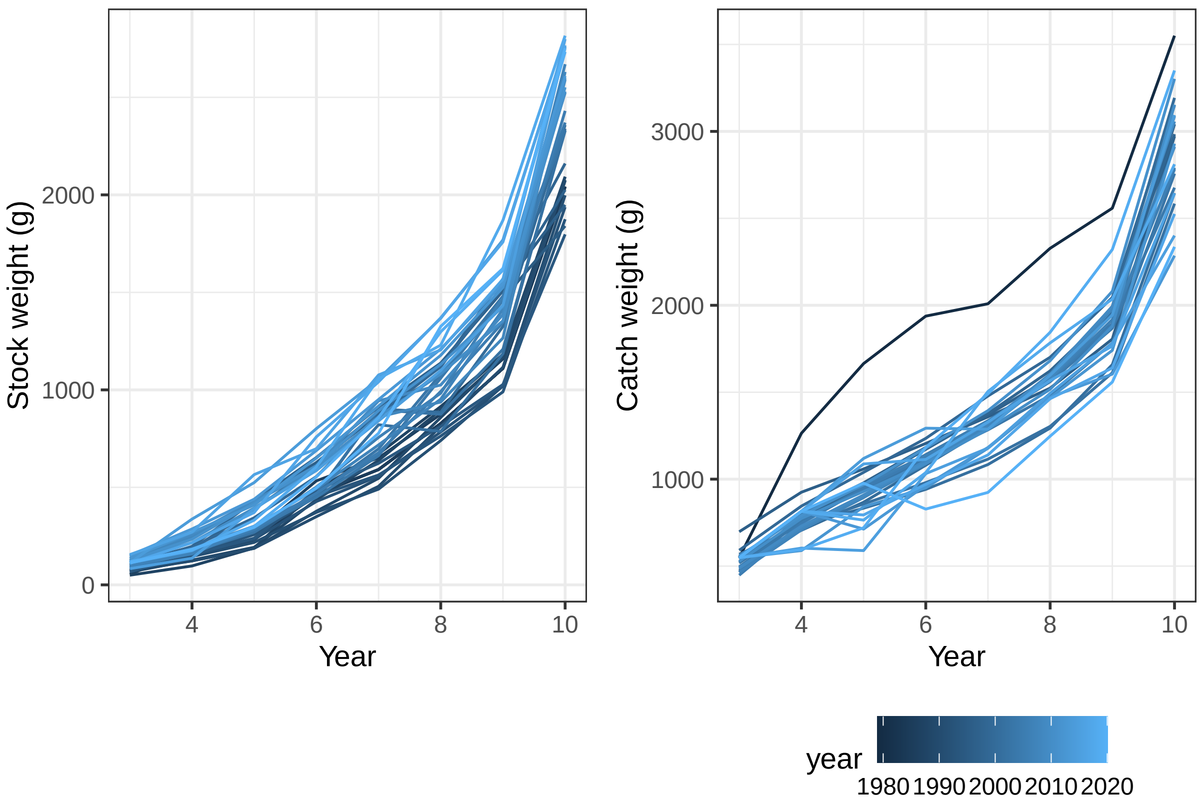

Figure 24: Tusk in 5.a and 14. Weight at age observed in the spring survey and from the commercial catches over age.

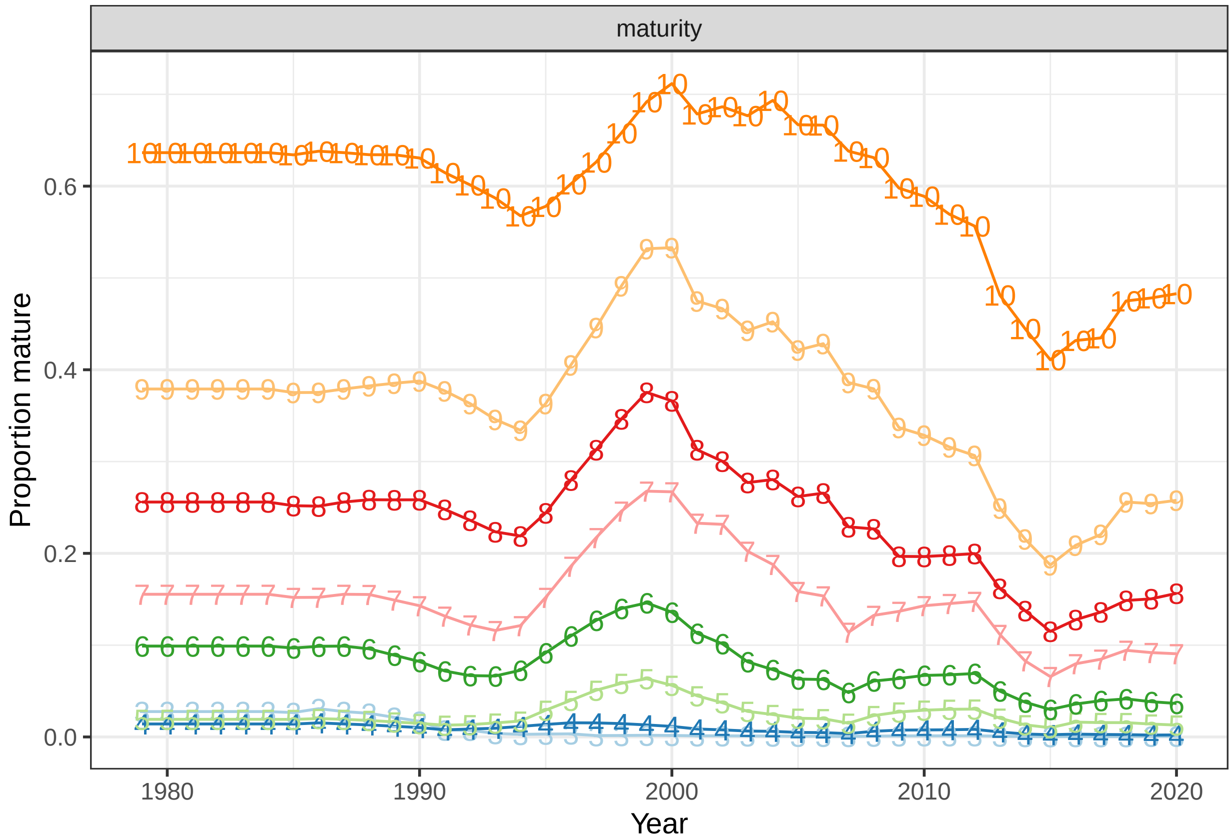

Figure 25: Tusk in 5.a and 14. Proportion mature at age from the autumn survey.

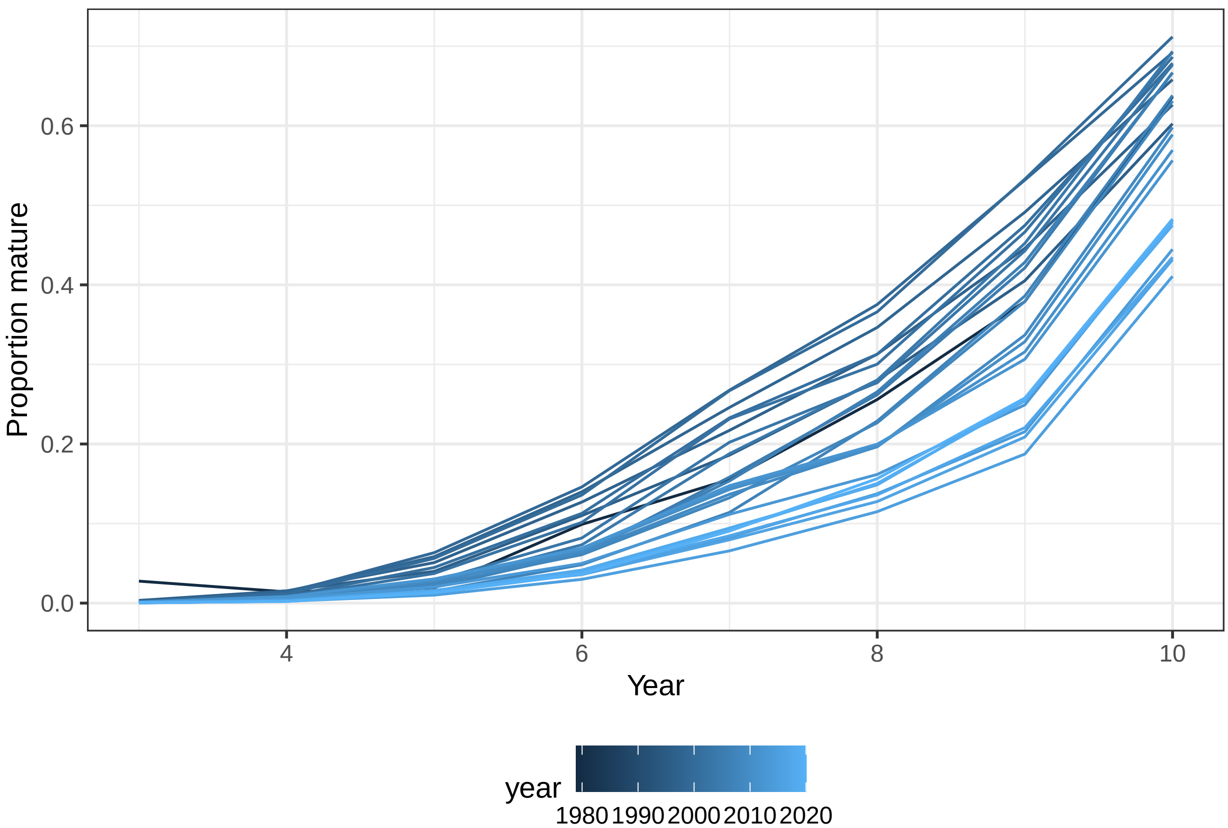

Figure 26: Tusk in 5.a and 14. Proportion mature at age from the autumn survey over age.

the youngest ages were maintained while largest ages were grouped when correlations among consecutive ages declined, likely as a result of ageing error. These correlations are presented in the next section.

Initial explorations were then used to find the most important configuration settings for stability in optimization and model fit. Model choice was based on AIC & Mohn's ρ values for 5-year peels of SSB, recruitment, and Fbar. The best model was chosen as that which had the lowest AIC.

The set of models considered was created using an informed shotgun method for comparing several models with minor adjustments to configuration settings determined as those that had the greatest impact on AIC reduction. These settings included some combination of varying the pattern of linkages among ages of log observation error variances estimated, the pattern of power parameter in non-linear catchability relationships, the pattern of correlations among ages when AR(1) correlations were included in residuals of survey data, and the pattern of F variances estimated.

8.7 Input data

The spring survey indices at length were converted to age using age-length keys (ALKs, (Fig. 27). Survey indices at age were generated from the spring survey data using standard stratification procedures (ICES [9]). All ALKs were created using 5 cm length bins from 10 - 80 cm, with longer bins at lengths 0 – 10 and 80+. Length data are available from 1985, but sparse data before 2014 sometimes did not cover the full ranges of lengths so data are grouped across years. Age data from 1985:1994 was applied to this same range, data from 1995:2001 was applied to 1995 - 1999, data from 2000 - 2002 was appled to this same range, and data 2003 - 2013 were applied in biannual groupings (i.e., 2003 - 2004 applied to its same range, etc.). Annual ALKs were applied from 2014 onwards. In addition, to counter sparse age readings at larger sizes, ALKs for fish length 60 cm and greater were based on all years of data combined. At length 60 cm and greater, 75% are 10+, so this procedure mainly affects the plus group. Lagged correlations among adjacent ages in both the spring indices indicate that the indices are highly informative for tracking cohorts (Figs. 28).

Autumn survey indices at length and age were available from 2000 using a standard stratification procedure. Extensions to the survey were added in 2000 so 1996 - 1999 data were excluded (Fig. 29. Most ages are not read from this survey, so ALKs from the spring survey were used, but adjusted to apply to the previous year and age group after preliminary analyses indicated better alignment with commercial age samples taken at the same time as the autumn survey was conducted. In the last year of autumn survey data, the same ALK as the previous year was used. Lagged correlations among adjacent ages in both the autumn indices indicate that the indices are highly informative for tracking cohorts (Figs. 30).

April (gillnet) survey indices at length and age were available from 2002. Extensions to the survey were added in 2002 so 1998 - 2001 data were excluded. ALKs from the spring survey were used directly as this survey occurs directly after that spring survey. Only age 10+ were included in the model due to very low indices at younger ages.

Catch at age and total landings are available from the 1970s, but only those from 1980 are used. Annual ALKs were created from 2012 onwards, but age readings were possibly unreliable or unavailable before 2005. Age-length keys using age data from commercial samples from 2005-2011 were applied to annual length distributions through 2011, and annual age-length keys were applied thereafter. Within year groups, ALKs are season-specific (January - June vs. July - December), but not grouped by region or gear (because the fishery is mainly a longline fishery). Because grouping by season increases sparsity of the data, these season-specific ALKs were combined with ALKs with data across all seasons, using a weighting of a 0.9 contribution of the season-specific ALK and 0.1 contribution of the ALK across seasons. This procedure was done within years (post-2011) or year group (through 2011). ALKs were rescaled if necessary to ensure sums to 1 within a length bin. This procedure was maintained even though exploratory analysis indicated that ALKs changed very little with its inclusion, to ensure that no data were lost (samples from length bins with no corresponding age data).

Time-specific ALKs were then applied to the approximate amount of catch from the corresponding time period. Total catch-at-age over time was used as input (Fig. 31. Lagged correlations among adjacent ages in the catch at age data indicate that they are highly informative for tracking cohorts (Fig. 32).

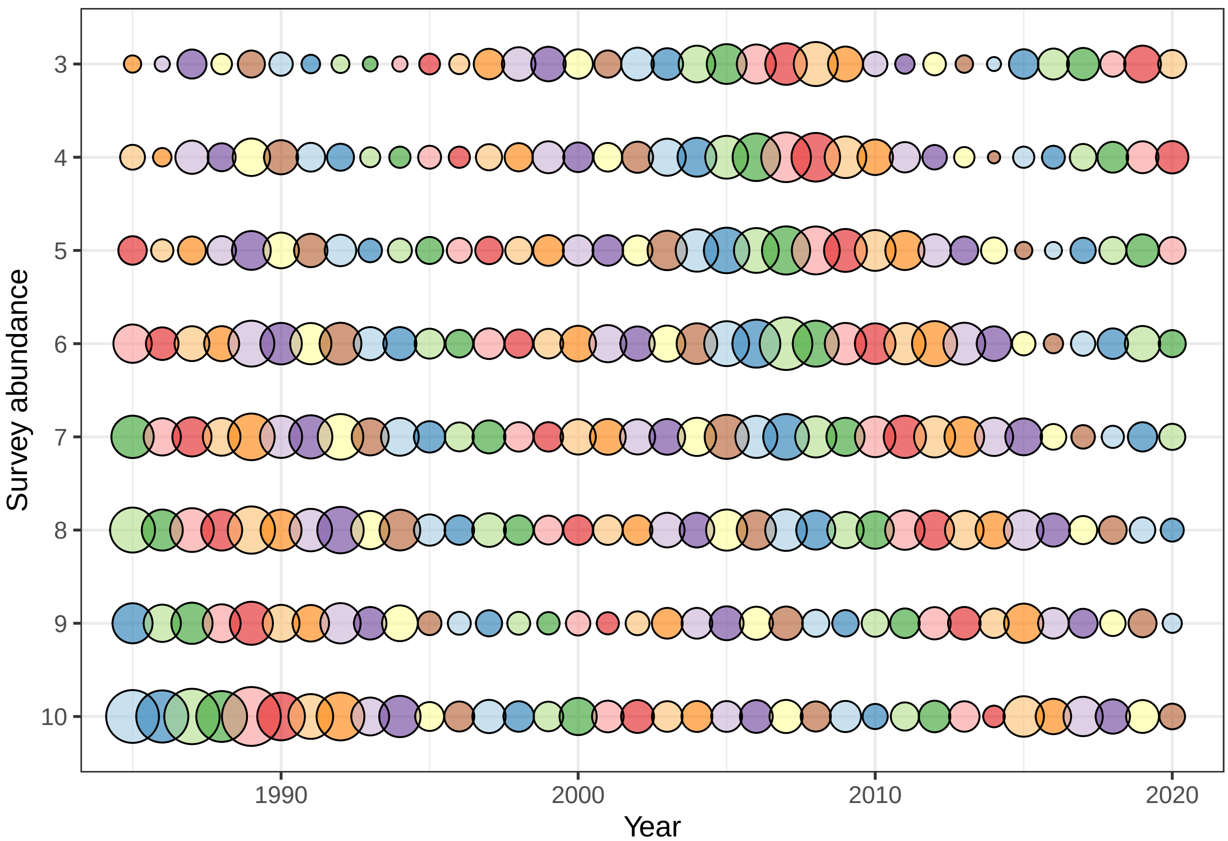

Figure 27: Tusk in 5a and 14. Survey numbers at age from the spring survey, point sizes indicate the estimated swept area abundance by age. Points are colored by year class.

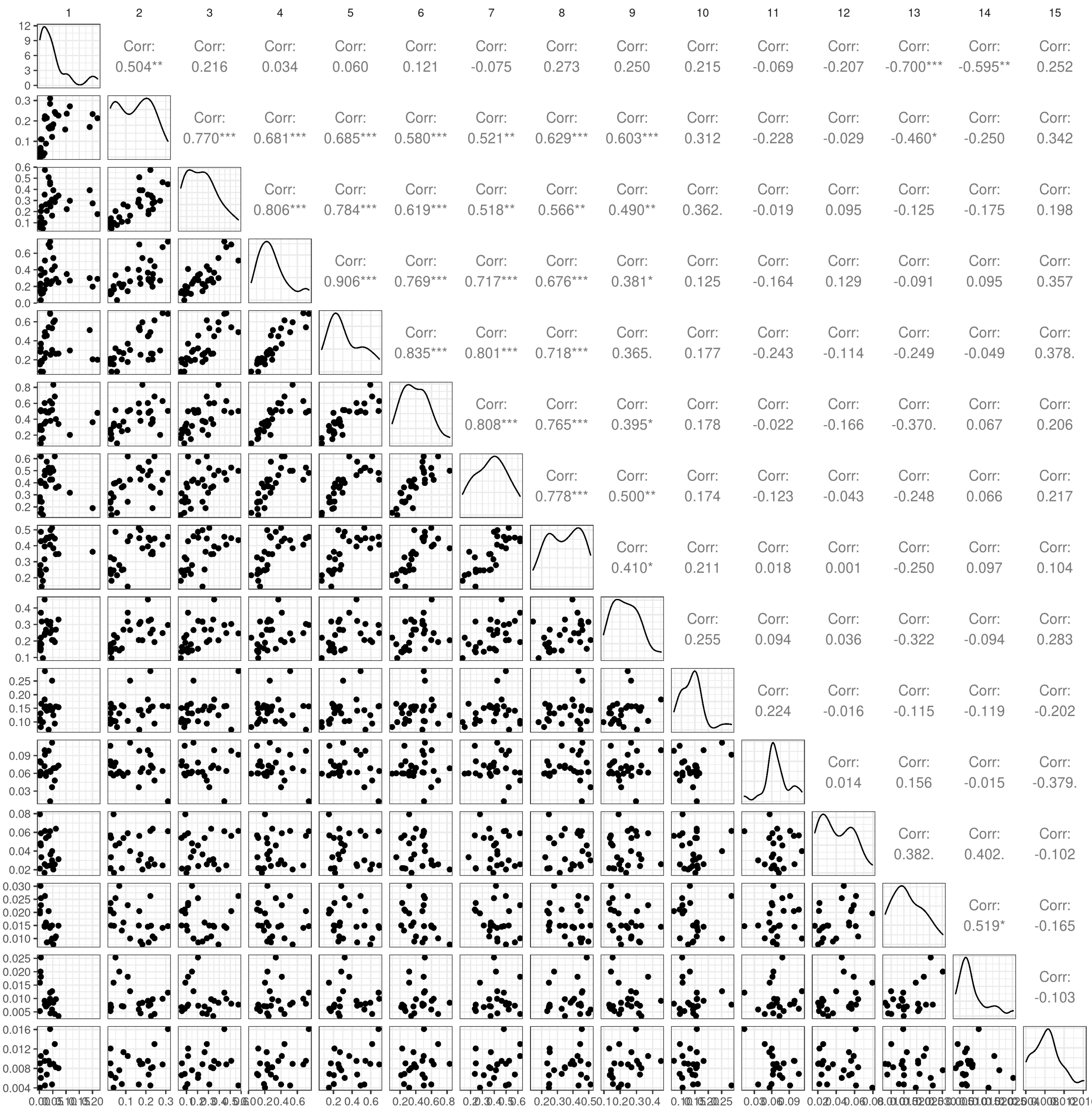

Figure 28: Tusk in 5.a and 14. Correlations among observations with a cohort observed at each age in spring survey indices.

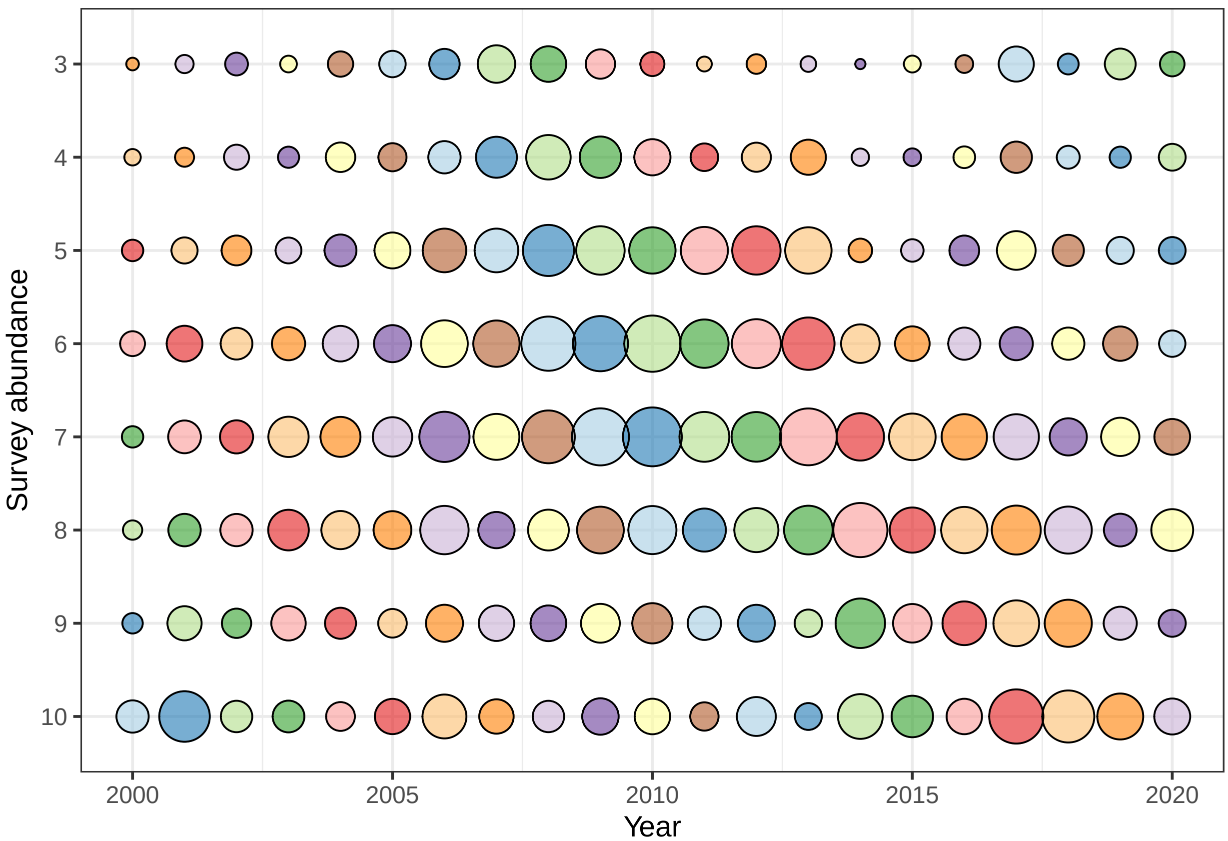

Figure 29: Tusk in 5a and 14. Survey numbers at age from the autumn survey, point sizes indicate the estimated swept area abundance by age. Points are colored by year class.

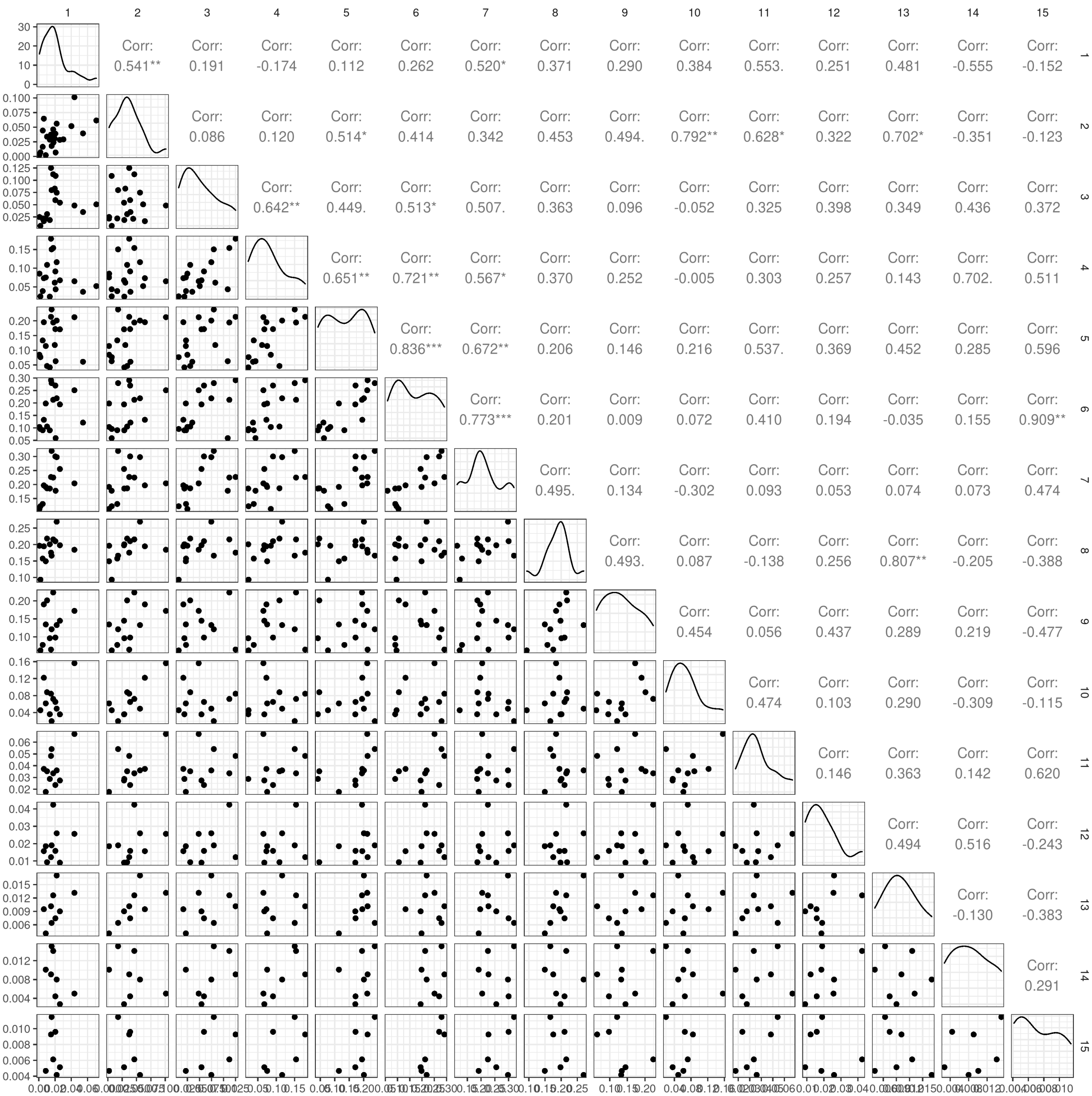

Figure 30: Tusk in 5.a and 14. Correlations among observations with a cohort observed at each age in autumn survey indices.

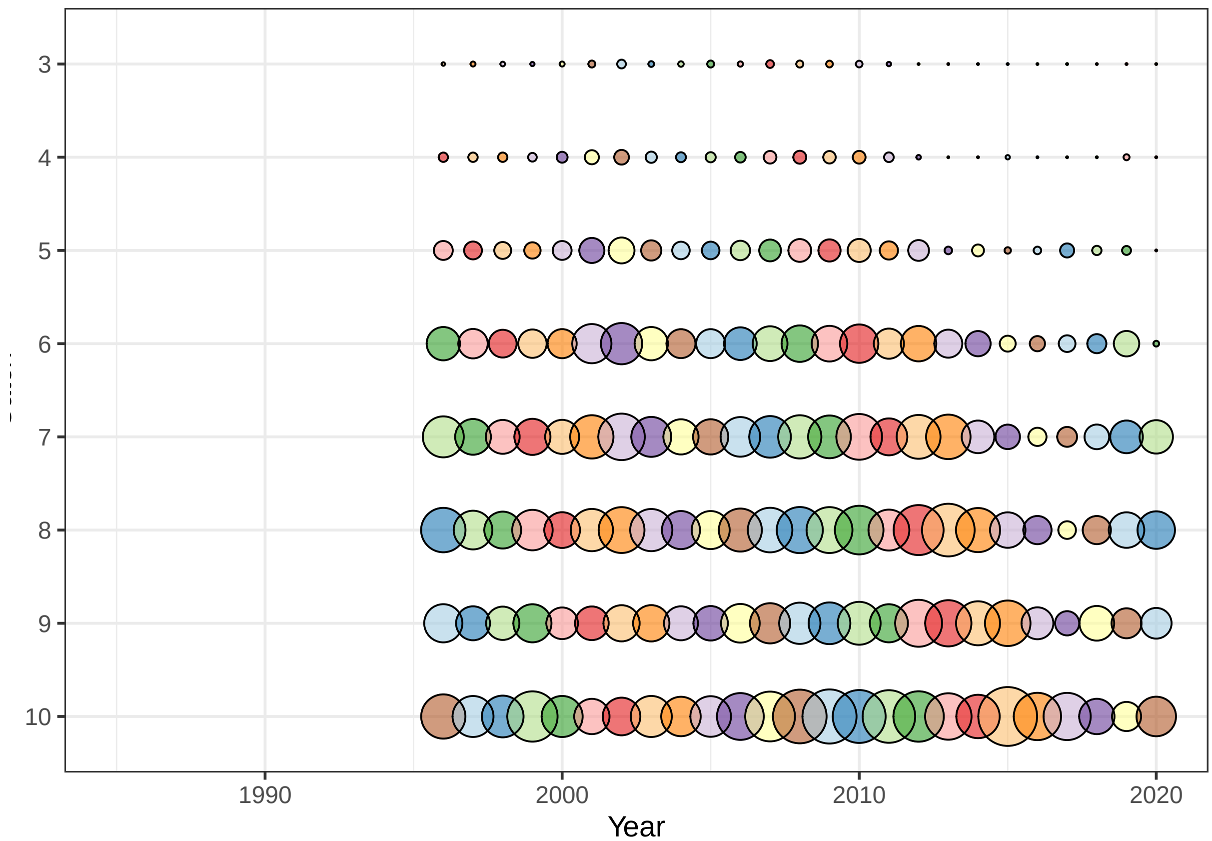

Figure 31: Tusk in 5a and 14. Catch at age, point sizes indicate the numbers by age. Points are colored by year class.

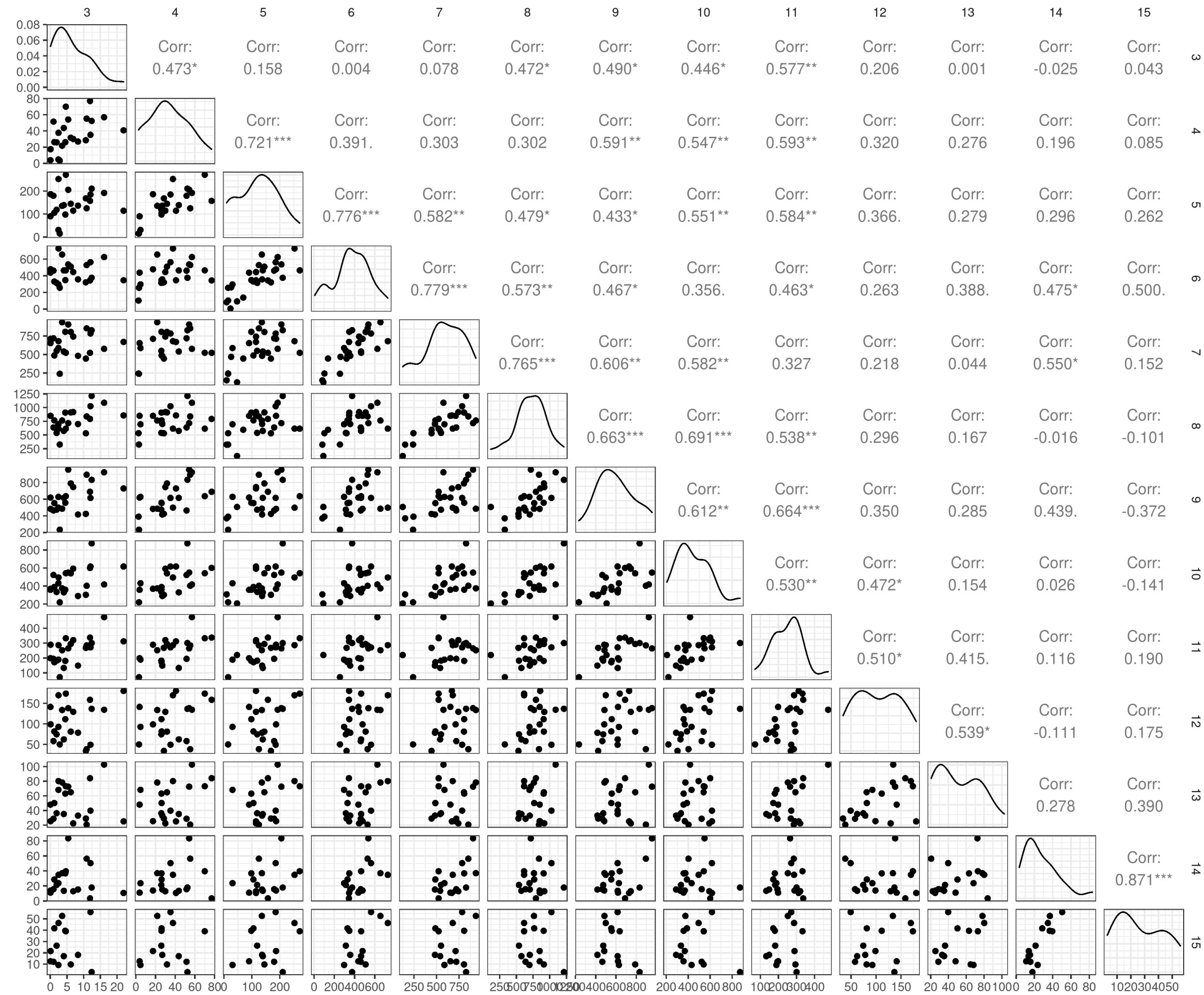

Figure 32: Tusk in 5.a and 14. Correlations among observations with a cohort observed at each age in catch at age data.

8.8 Results

8.8.1 Proposed model

Years ranged 1975 - 2021, with ages 1 - 10+ tracked (catch data ranged 3 - 10+).

After fitting several configurations, the configuration that provided the greatest improvement to the fit of the default model configuration, while still converging, included AR(1) correlations in the autumn survey residuals as a single parameter for the correlations, indicated with '/' between ages, for 1/2, 2/3, and 3/4 grouped together and a single parameter for all correlations 4/5–9/10+ grouped together. edIt was attempted to include spring survey AR(1) residual correlations, but this resulted in lower model stability and process error parameters approaching zero, with little benefit in terms of a better fit to spring survey residuals. The maximal age fishing mortality parameter, which is by default fixed to the the same value as next-oldest age, was instead estimated separately. For both surveys, the observation variance parameters were estimated estimated separately for ages 1–2 from ages 3–10+, and for the catch-at-age variances, the maximal two ages were estimated separately (9–10+) from all other ages (1–8). Explorations of estimating power parameters in catchability parameters did not improve model fit.All other default settings were used.

8.8.2 Diagnostics

Fits to the catch data and trawl survey numbers-at-age indices can be found in Fig. 33 and the fit to catch, gillnet survey, and landings data in Figs. 34 and 35. Note that ages 1 and 2 can be found in the bottom two panel rows of Fig. 33, and that the gillnet survey is only represented by age 10+. Catch and spring survey data are followed the closest by the model, whereas fits to the other data series are slightly more noisy but follow a similar pattern. The spring survey data in particular support the pattern of two low periods of recruitment in the history of the stock: at age 1 they can be observed during 1987 - 1989 and 2010 - 2012.

Observation error (Fig. 36) residuals show some square-shaped and residual patterns in spring survey residuals; however, the addition of residual parameters had the effect of improving the fit of only portions of the residual plots at the expense of other portions that showed a worse fit. Therefore the data did not appear consistent enough to include a spring survey correlation pattern (Figs. 36). Process residuals showed only minor trends (Fig. 37).

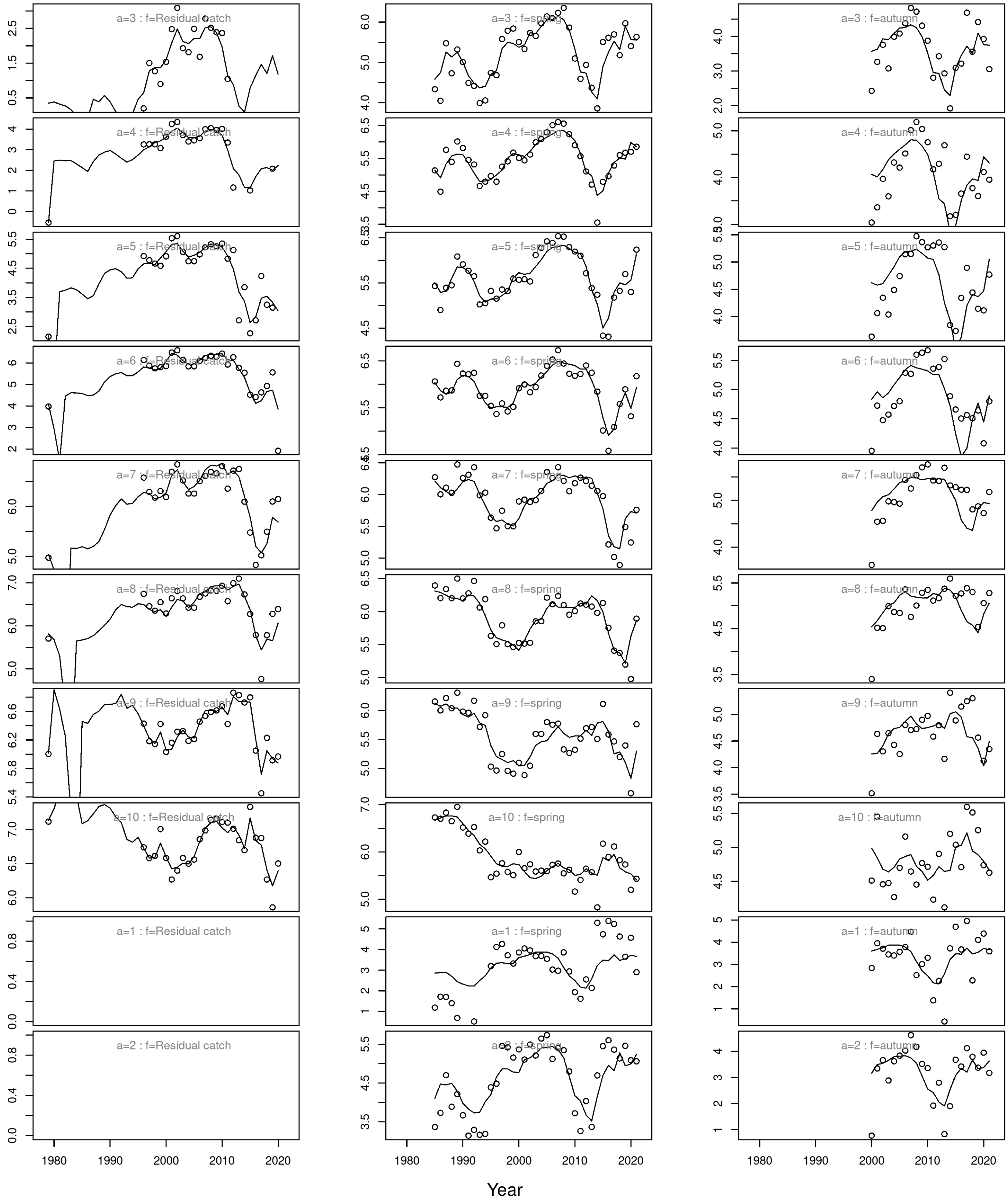

Figure 33: Tusk in 5.a and 14. Fit to the numbers at age input data to the proposed SAM model (columns left to right: catch, spring survey, autumn survey, and gillnet (April) survey.

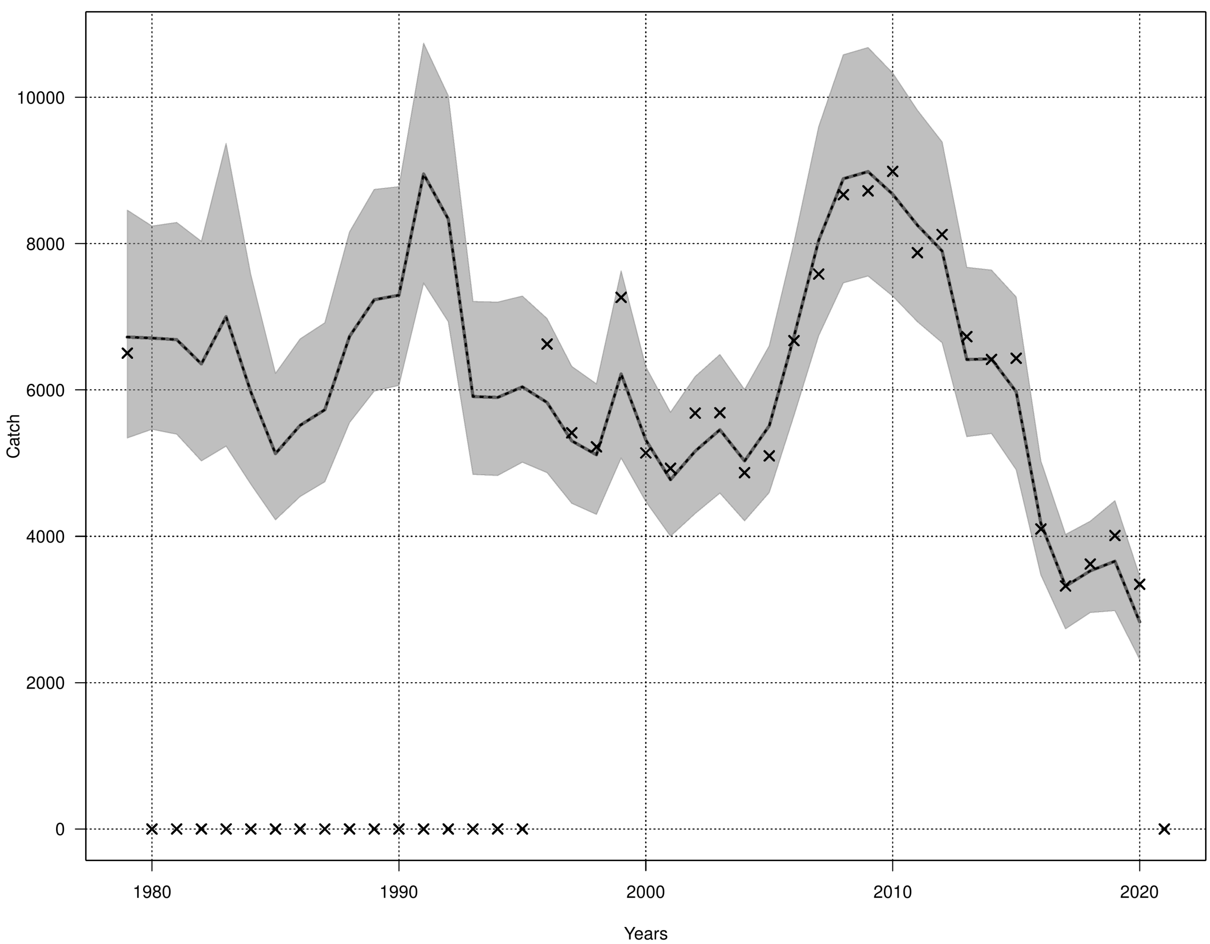

Figure 34: Tusk in 5.a and 14. Fit to the total catch in the proposed SAM model.

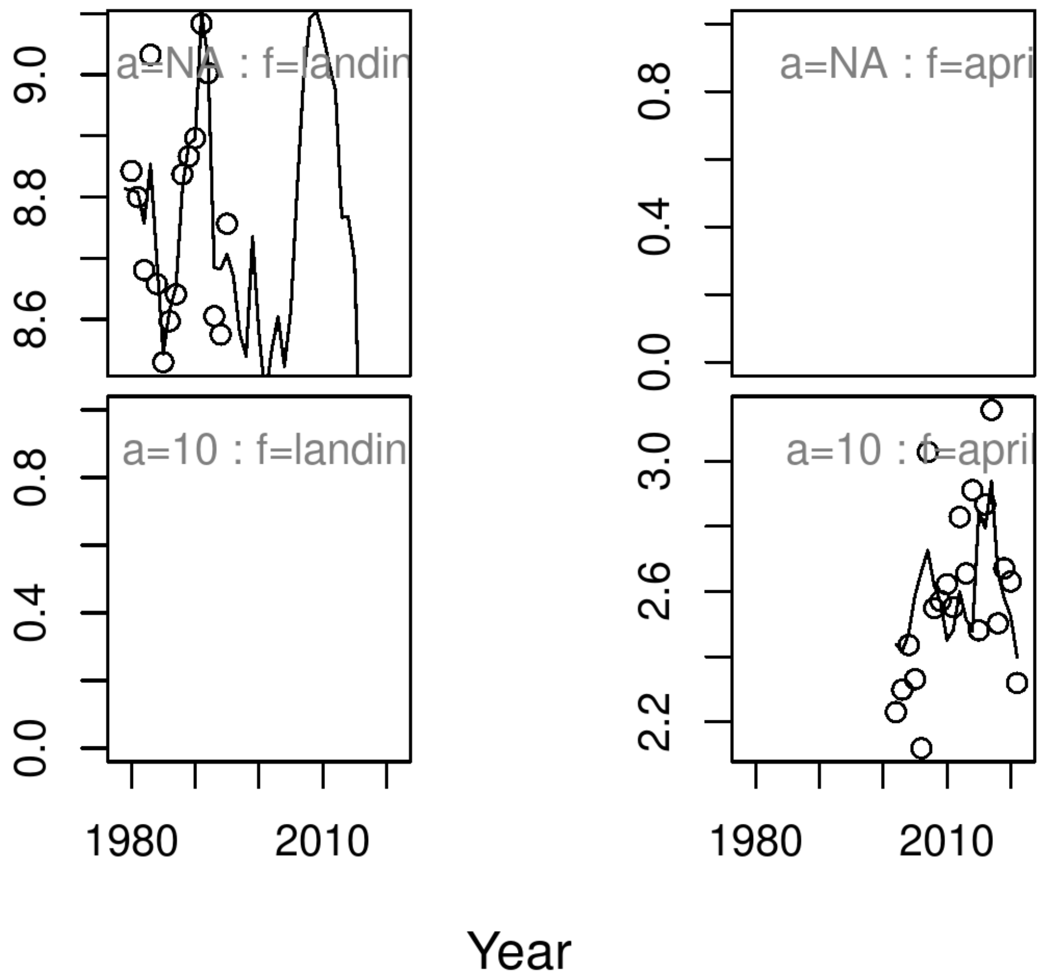

Figure 35: Tusk in 5.a and 14. Fit to the landings (left) and gillnet survey (right) input data to the proposed SAM model.

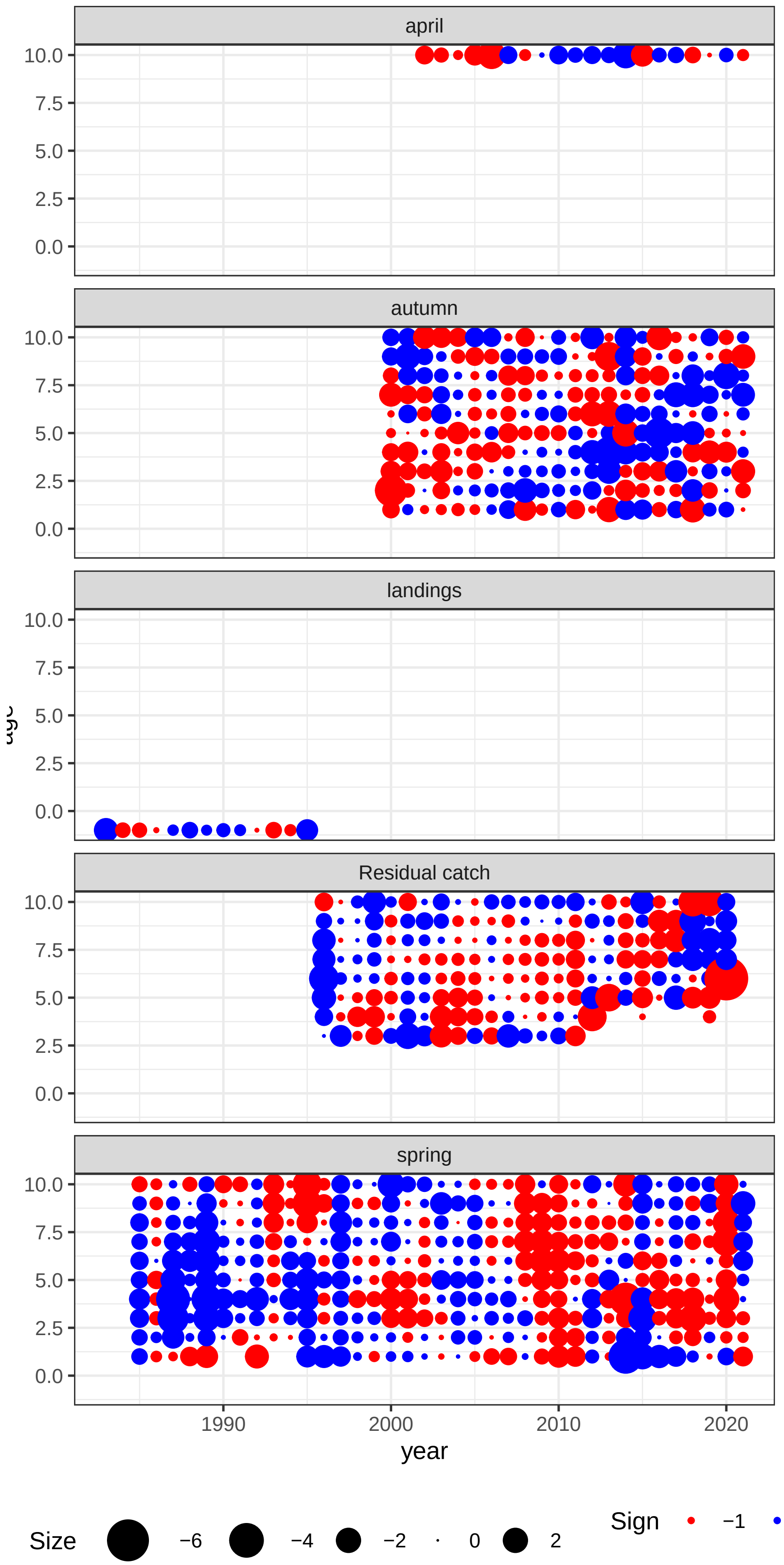

Figure 36: Tusk in 5.a and 14. Observation error residuals of the proposed SAM model.

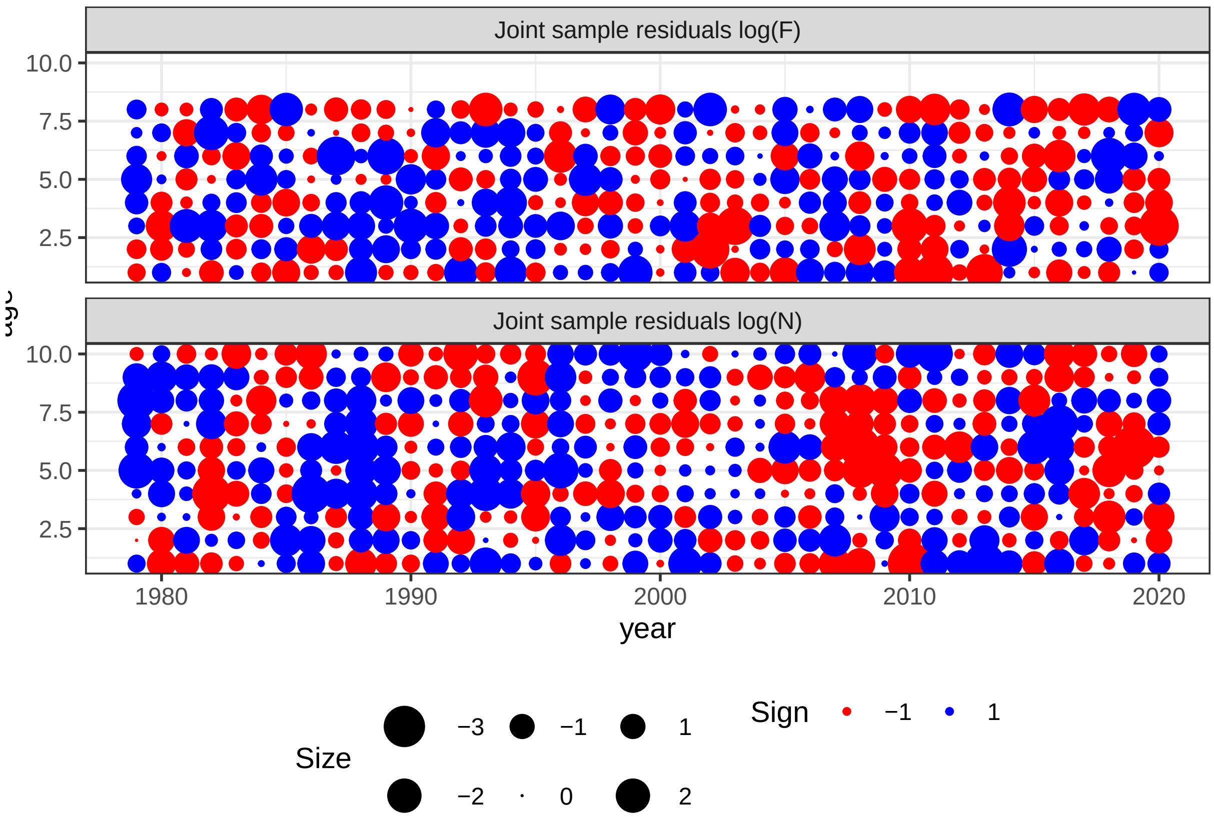

Figure 37: Tusk in 5.a and 14. Process error residuals of the proposed SAM model.

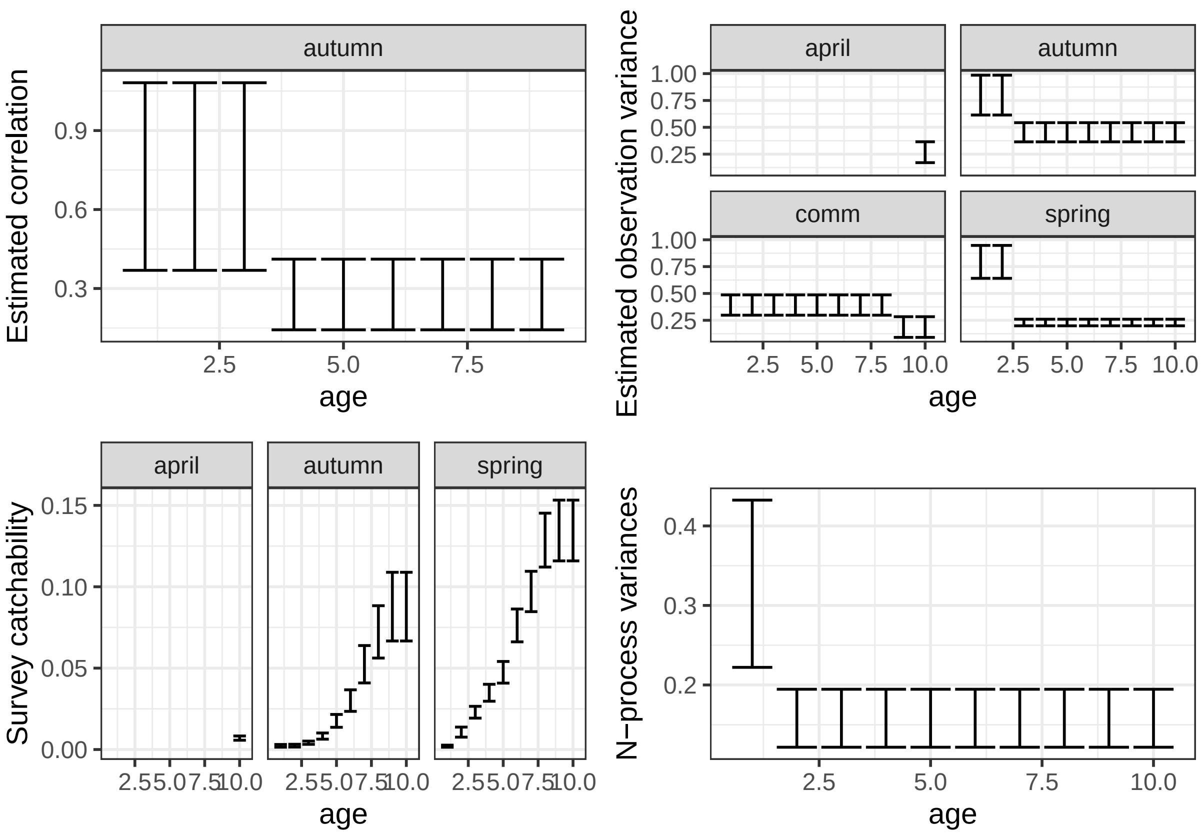

Figure 38: Tusk in 5.a and 14. Overview of the proposed SAM model parameter estimates.

8.8.3 Stock overview

Population dynamics of the tusk estimated in this model show a higher spawning stock biomass level prior to 1990 Fig. 39. However, it should be kept in mind that this period has very little compositional data to support it, being fit with mainly landings and the earliest spring survey data. After 1990, levels are variable but with a gradual decrease after 2005 that has a low point in 2019 (4062 tonnes). At the same time, fishing mortality values have decreased from highest levels of 0.45 in 2008 - 2010 to roughly 0.3 in the most recent years. It is clear from the estimated recruitment pattern that this period of low spawning stock biomass is largely due to a recent period of recruitment failure visible in age 1 in years 2009 - 2013) - these low numbers have now reached spawning size, as the fit plots indicate (Fig. 33). However, this apparent recruitment failure was followed by some of the highest recruitment estimates observed, so these low spawning stock biomass levels are not expected to last for more than a few years, given reasonable fishing mortalities. It also indicates that these lowe spawning stock biomass levels are not likely to have impaired recruitment.

Figure 39: Tusk in 5.a and 14. Model results of population dynamics overview: estimated catch, average fishing mortality over ages 7 - 10+ (Fbar), recruitment (age 1), and spawning stock biomass (SSB).

The spawning stock biomass and fishing mortality levels are on a similar scale as those estimated in the previous Gadget model (Fig. 40). However, the same population trends were not apparent in the Gadget model, likely due to an inability to closely track length distributions, including the recent recruitment failure and following recruitment spike (Fig. 3).

8.8.4 Retrospective analyses

The proposed model had relatively low Mohn's ρ statistic values for spawning stock biomass and fishing mortality (Table 1). For the purposes of this report, recruitment is shown at age 1, but retrospective patterns are not considered for recruitment because uncertainty in estimation of age 1 is extremely high, as tusk do not enter the fishery until age 3 - 4. Analytical retrospective plots indicate that the values are mainly

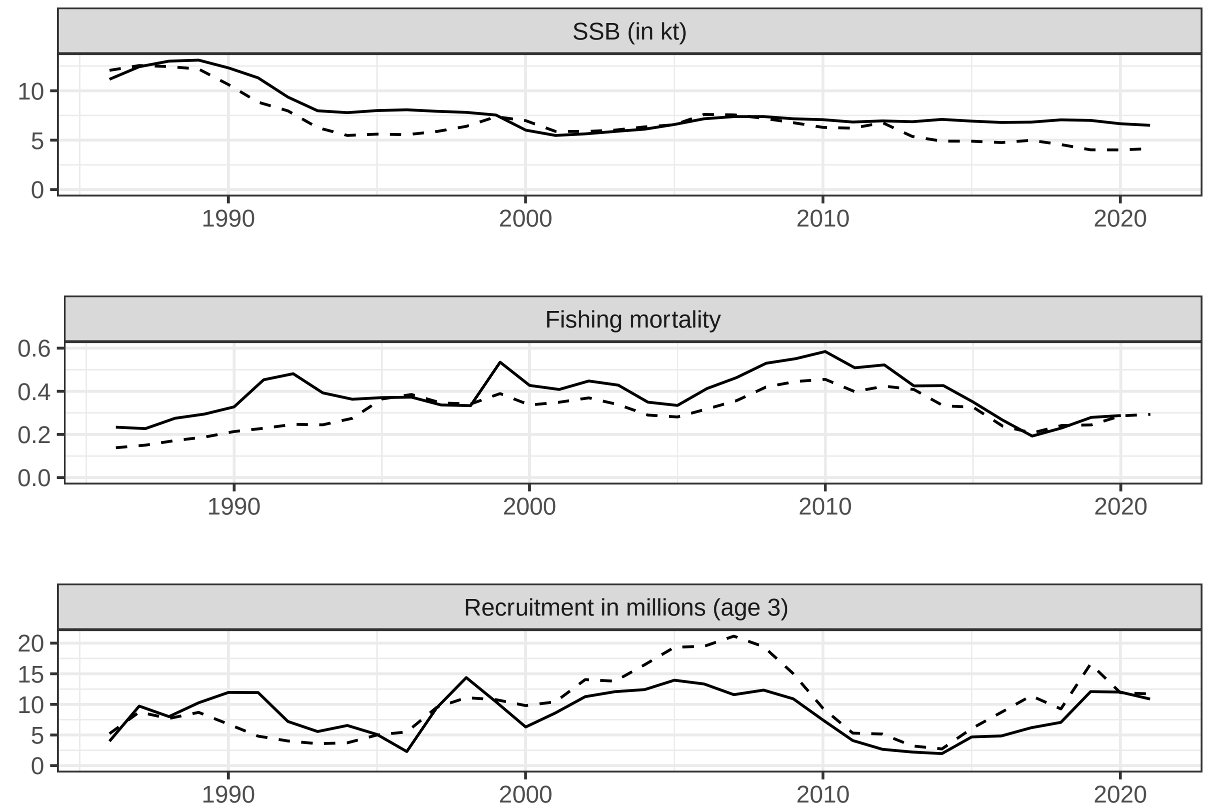

Figure 40: Tusk in 5.a and 14. Comparison of proposed SAM assessment results (dashed) with the previous Gadget assessment results (solid).

Table 1: Tusk in 5.a and 14. Mohn's rho calculated from analytical retrospective analyses of the proposed model.

R(age 1)	SSB	Fbar(7-10)
0.952	0.101	-0.001

due to the oldest peels which showed the steepest decline in biomass after the effect of the recruitment peak passed (41). Although these Mohn's ρ values are not small, they are within the range recommended by Carvalho et al. [3] and are less than those exhibited by the previously benchmarked model (Table 1):

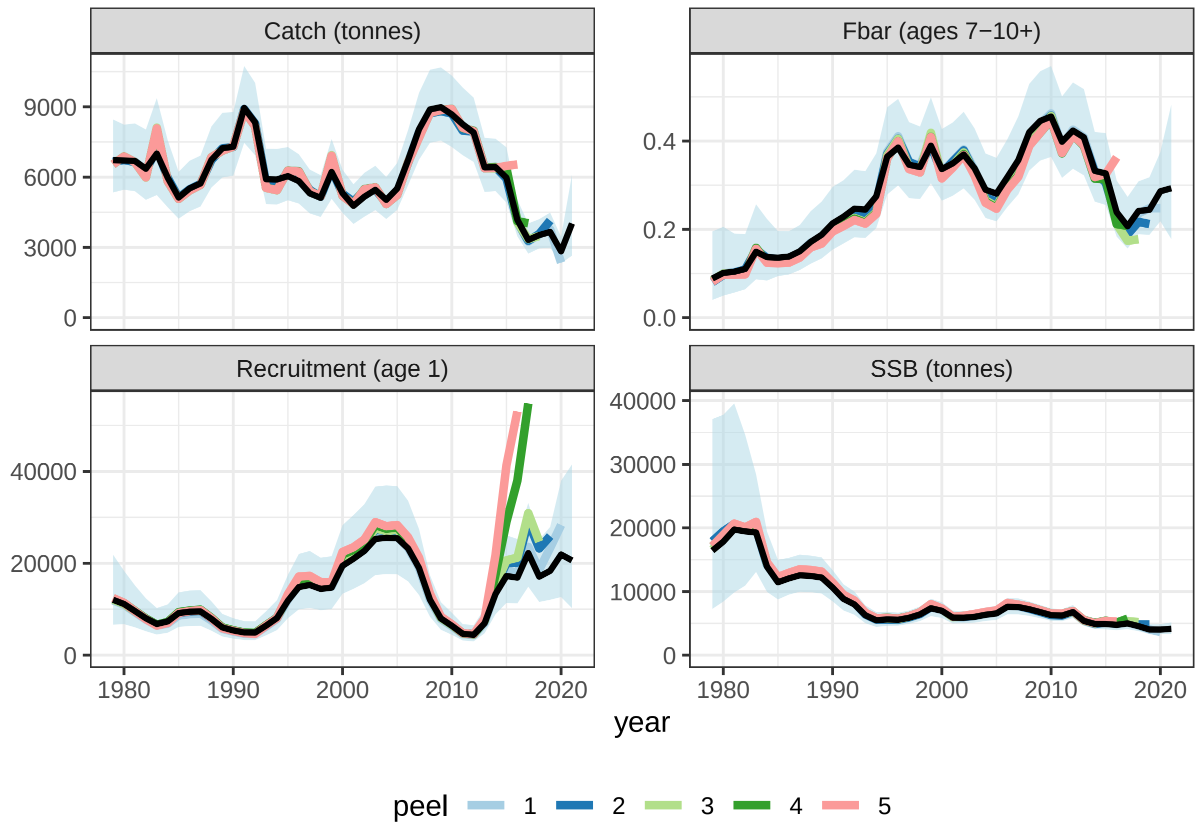

Figure 41: Tusk in 5.a and 14. Retrospective analyses: estimated catch, average fishing mortality over ages 7 - 10+ (Fbar), recruitment (age 1), and spawning stock biomass (SSB).

8.9 Leave-out analysis

When the spring survey index or landings series were excluded, the model did not converge. Leave-out analysis of the other two data sources show that there was very little contribution of the landings, autumn survey, or April gillnet survey to the model fit, but removal of any of them led to a similar change toward greater dependence on the spring and/or catch at age data. The spring survey could not be removed without destabilizing the model.

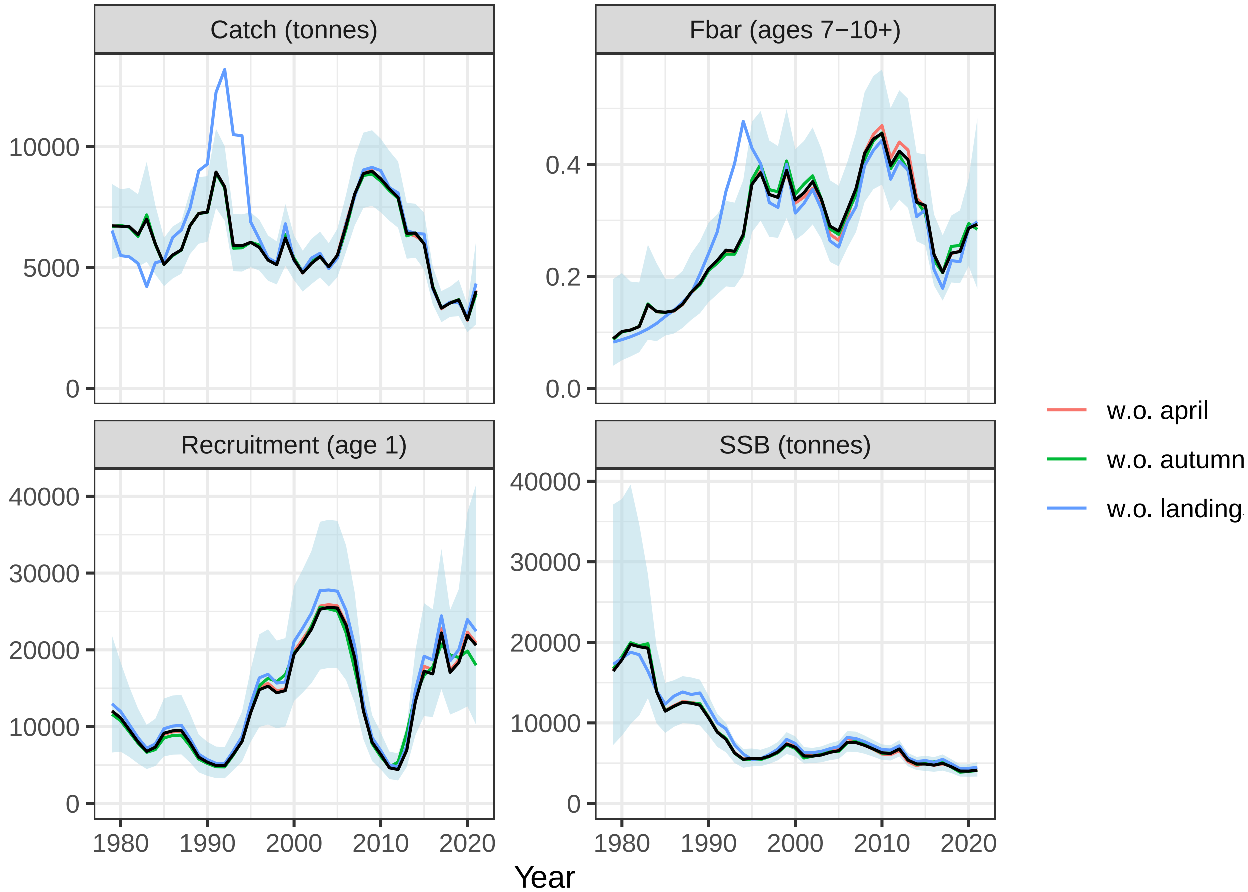

Figure 42: Tusk in 5.a and 14. Leave-out estimates of SSB, catch, fishing mortality and recruitment.

8.10 Ranges of natural mortality

A range of Ms was investigated (see Fig. 43) along with size dependent M using both the Gislason and Chernov method. The profile likelihood shows a minimum close to 0.3 but with wide confidence intervals and no other indicator based on life history attributes showed a clear indication of M. Therefore the assumption of natural mortality as 0.15 for all ages was maintained. See Appendix I for more detail.

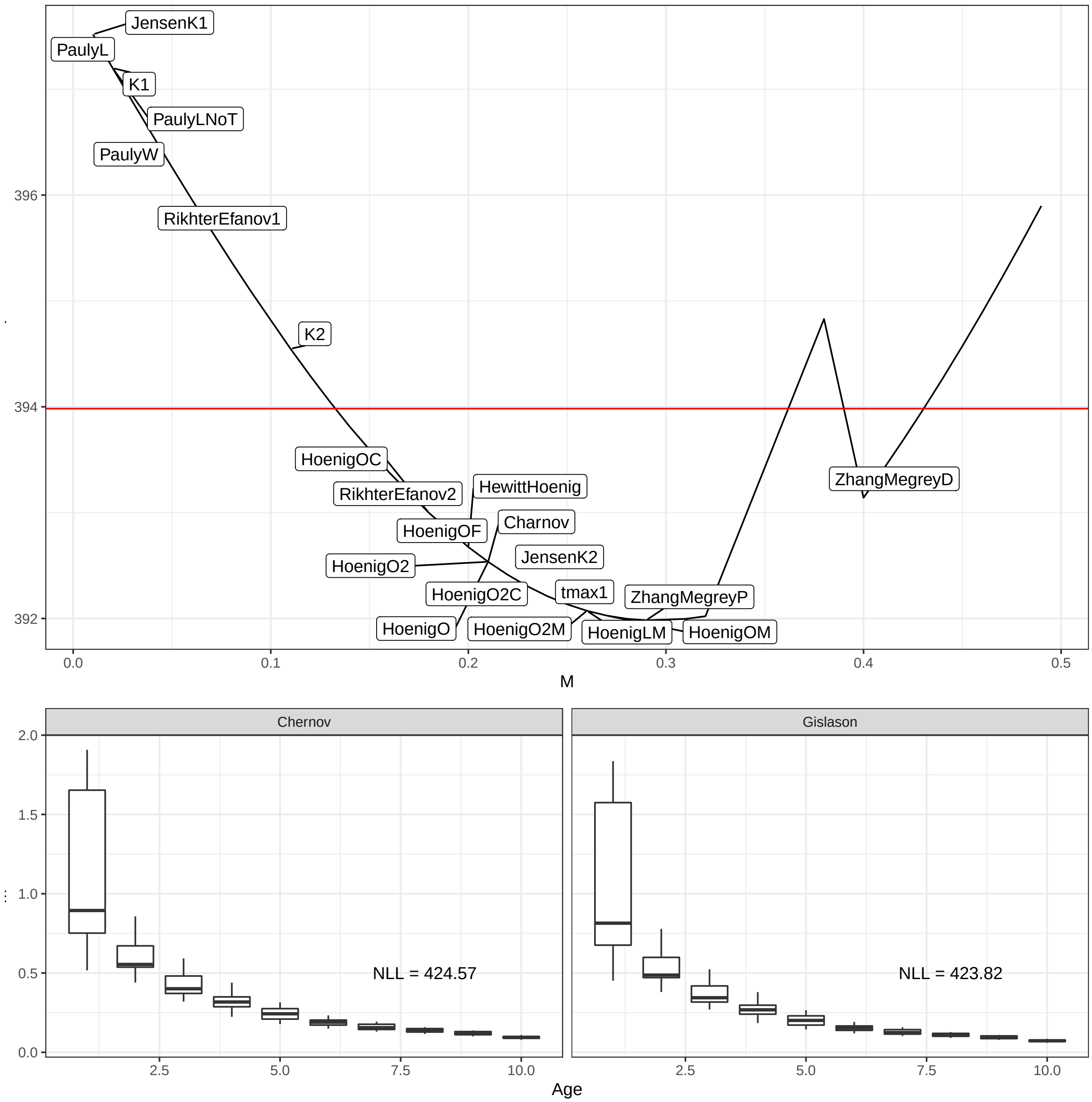

Figure 43: Tusk in 5a and 14. Left panel shows a profile likelihood plot (negative log likelihood) for different values of fixed M. Results from different M derivations based on life-history parameters are overlayed. Red line indicates 95% confidence regions. Bottom panels show boxplots of size based M values along with the negative log-likelihood values from the fitted SAM model.

9 Short term projections

Short term projections are performed using the standard procedure in SAM using the `forecast` function. Three year averages are used for stock and catch weights, and maturity. From this projection the advice is derived. The advice is based on the Icelandic fishing year starting in September each year. This causes a mismatch between the assessment model, which is based on the calendar year. So in order to provide advice for the fishing year, the standard projection procedure in SAM will need to be adapted to accommodate these differences. So given the assessment in year y the interim year catches are based on the following fishing mortality:

$$F_y = \left(\frac{8}{12}F_{sq} + \frac{4}{12}F_{mgt}\right)$$

and therefore the total catches for year y will be:

$$C_y = \frac{F_y}{F_y + M}\left(1 - e^{-(F_y+M)}\right) B_y$$

and the part of the catch in the fishing year y-1/y will be

$$\frac{\frac{8}{12}F_{sq}}{\left(\frac{8}{12}F_{sq} + \frac{4}{12}F_{mgt}\right)}C_y$$

and the catch in fishing year y/y+1 will be:

$$C_{y/y+1} = \frac{\frac{4}{12}F_{mgt}}{\left(\frac{8}{12}F_{sq} + \frac{4}{12}F_{mgt}\right)}C_y + \frac{8}{12}C_{y+1}$$

where

$$C_{y+1} = \frac{F_{mgt}}{F_{mgt} + M}\left(1 - e^{-(F_{mgt}+M)}\right) B_y$$

Table 2: Tusk in 5.a and 14. Listing of the CV for key model outputs.

variable	cv
SSB (tonnes)	0.120
Fbar (ages 7-10+)	0.155
Recruitment (age 1)	0.507
Catch (tonnes)	0.110

10 Appropriate Reference Points (MSY)

According ICES technical guidelines (ICES [7]), two types of reference points are referred to when giving advice for category 1 stocks: *precautionary approach* (PA) reference points and *maximum sustainable yield* (MSY) reference points. The PA reference points are used when assessing the state of stocks and their exploitation rate relative to the precautionary approach objectives. The MSY reference points are used in the advice rule applied by ICES to give advice consistent with the objective of achieving MSY.

Generally ICES derives these reference points based on the level of the spawning stock biomass and fishing mortality. The following sections describe the derivation of the management reference points in terms of fishing mortality (F) and SSB (B). It further describes the model for stock–recruitment, weight and maturity at age, and assessment error which is used to project the stock stochastically in order to derive the PA and MSY reference points.

10.0.1 Setting B_{lim} and B_{pa}

B_{lim} was considered from examination of the SSB–Recruitment (at age 1) scatterplot based on the estimates from the stock assessment, as illustrated in Fig. 44. The figure shows that the recruitment is fairly independent of the size of SSB, and if any trend is to be drawn than it looks like an increase in recruitment with lower spawning stock levels, with relatively high recruitment being observed during the recent low spawning stock biomass levels. This pattern suggests that impaired recruitment is unlikely, and the situation resembles a Stock Category Type 4 (ICES [7]). The lowest observed SSB, given that it occurs during a period of high productivity, can be used set B_{pa}, (i.e. B_{pa} = SSB(2016) = 4758). The most recent low of SSB in 2019 was not chosen due to greater uncertainty toward the end of the model time series. In line with ICES technical guidelines B_{lim} is then calculated based on dividing B_{pa} with the standard factor, $e^{\sigma*1.645}$ where σ is the CV in the assessment year of SSB or 0.2, used for calculating B_{pa} from B_{lim}. Thus the CV used here to determine B_{pa} is 0.2, which is likewise the default ICES value for assessment error. Default values were taken because estimates derived from the the model as listed in Table 2 are likely to be underestimates given the uncertainty in age data. Therefore B_{lim} should be set at $B_{pa} \div e^{1.645*0.2} = 4758kt \div 1.4 = 3424kt$.

Because interpretation of the stock-recruitment pattern depends partially on high recruitment values estimated in recent years alongside low SSB values, it should be revisited after several years in the next benchmark to be confident that the recruitment estimates have not been corrected downward. A downward correction in recruitment could lead this stock to be instead deemed a Category 5 stock, with B_{lim} instead set to the minimum spawning stock biomass level.

10.0.2 Management procedure in forward projections

Illegal landings and discards by Icelandic fishing vessels are considered to be negligible (as noted above). Current knowledge of tusk in 5.a and 14, discussed above, suggests that it should be assessed as a single stock unit. The currently proposed assessment model is more stable than historical assessments. In the projections described below the effect of assessment model is modeled as auto correlated log-normal variable with the mean as the true state of the stock. The values for the CV and correlation in the assessment error are based on the default values from the ICES guidelines of 0.212 with the correlation ϕ of 0.423, as deriving such estimates from historical retros would be problematic due to the shift in modeling framework and large retrospective pattern exhibited by the Gadget plot used previously.

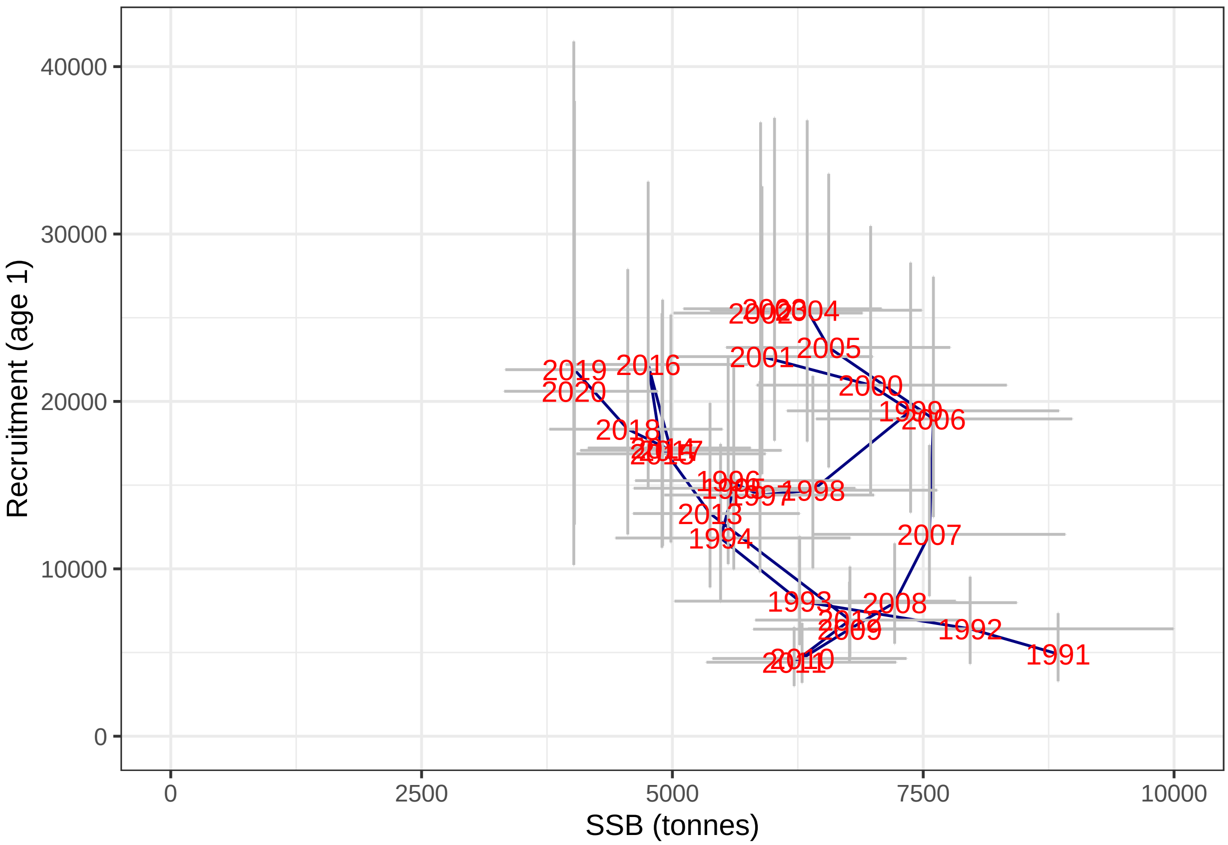

Figure 44: Tusk in 5.a and 14. Estimated stock recruitment plot. Grey crossed indicate uncertainty, red text point estimate with the associated year and black lines show the progression of the stock recruitment relationship.

10.0.3 Stock recruitment relationship

A variety of approaches are common when estimating a stock–recruitment relationship. In the absence of a stock-recruitment signal from the available historical data (Fig. 44, the ICES guidelines suggest that the `hockey-stick` recruitment function is used, i.e.

$$R_y = \bar{R}_y \min(1, S_y/B_{break})$$

where R_y is annual recruitment, S_y the spawning stock biomass, B_{break} the break point in hockey stick function and $\bar{R}_y$ is the recruitment when not impaired due to low levels of SSB. Here $\bar{R}_y$ is considered to be drawn from an auto–correlated log–normal distribution with a mean, CV and ρ estimated based on the estimated recruits. This is done to account for possible auto-correlation in the recruitment time–series.

Fig. 45 shows the fit to a segmented regression setting B_{lim} to B_{loss}.

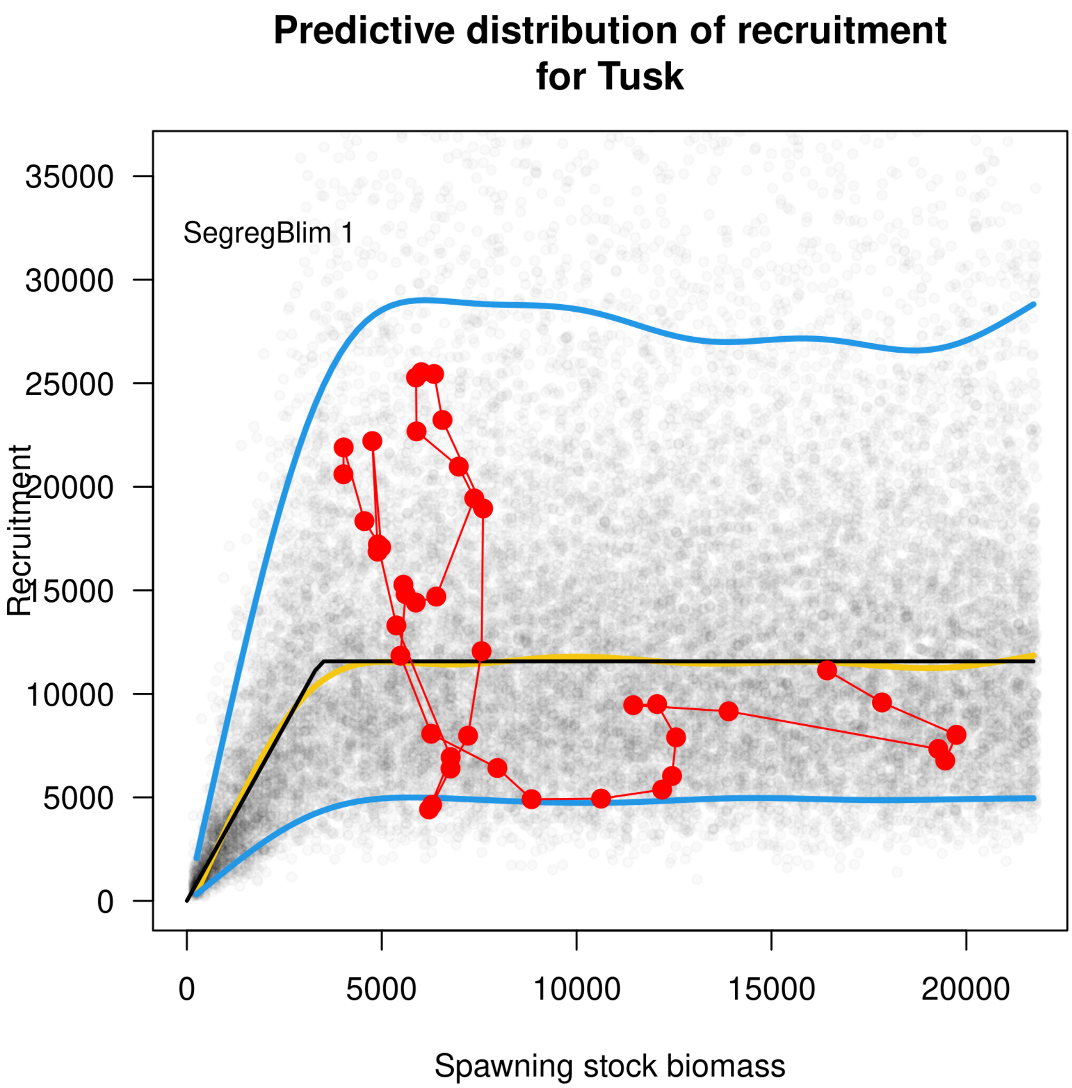

Figure 45: Tusk in 5a and 14. Fit segmented regression to spawning stock biomass and recruitment (age 1) relationship.

10.0.4 Stock– and catchweights

Prediction of weight at age in the stock, selectivity and the maturity at age follow the traditional process from the ICES guidelines, that is the average of the last 10 years of values for weight, selectivity and maturity at age used in the projections. These values are illustrated in Figures 46 to 48.

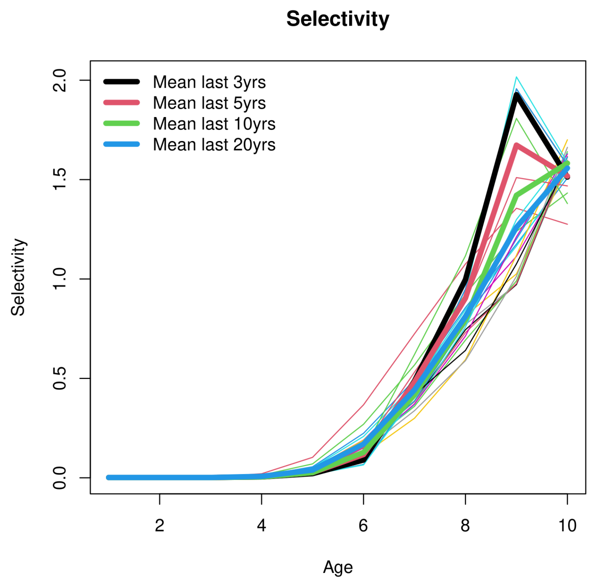

Figure 46: Tusk in 5a and 14. Settings for the projections. Estimated selectivity at age by year (narrow coloured lines) illustrated with 3, 5, 10 and 20 year averages (thick lines).

10.0.5 Setting F_{lim} and F_{pa}

According to the ICES guidelines, the precautionary reference points are set by simulating the stock using the stock-recruitment, growth and maturity relationship described above, based on a wide range of harvest rates, ranging from 0 to 1 and setting F_{lim} as the F that, in equilibrium, gives a 50% probability of SSB $> B_{lim}$ without assessment error.

For each replicate the stock status was projected forward 50 years as simulations, and average of those projected values used to estimate the MSY reference points.

The results from the long–term simulations estimate the value of F, F_{lim}, resulting in 50% long–term probability of SSB $> B_{lim}$ to be at 0.44.

10.0.6 MSY reference points

As an additional simulation experiment where, in addition to recruitment and growth variations, assessment error was added. The harvest rate that would lead to the maximum sustainable yield, F_{msy}, was then estimated. Average annual landings and 90% quantiles were used to determine the yield by F. Fig. 51 shows the evolution of catches, SSB and fishing mortality for select values of F. The equilibrium yield curve is shown in fig. 49, where the maximum median yield, under the recruitment assumptions, is close to 7 thousand tonnes, and fishing at F_{p05} (to maintain SSB over B_{lim} 95% of the time) only slightly reduced.

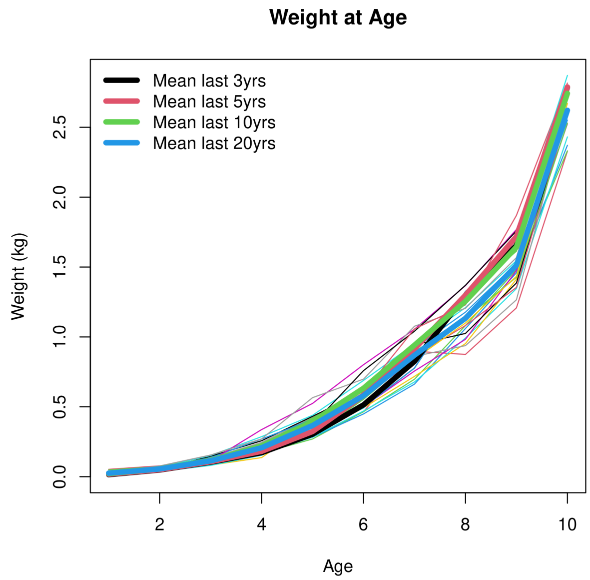

Figure 47: Tusk in 5a and 14. Settings for the projections. Estimated weight at age by year (narrow coloured lines) illustrated with 3, 5, 10 and 20 year averages (thick lines)

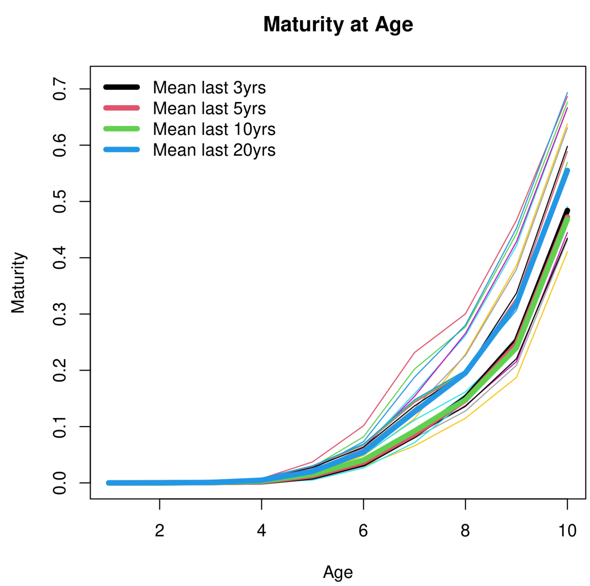

Figure 48: Tusk in 5a and 14. Settings for the projections. Estimated maturity at age by year (narrow coloured lines) illustrated with 3, 5, 10 and 20 year averages (thick lines)

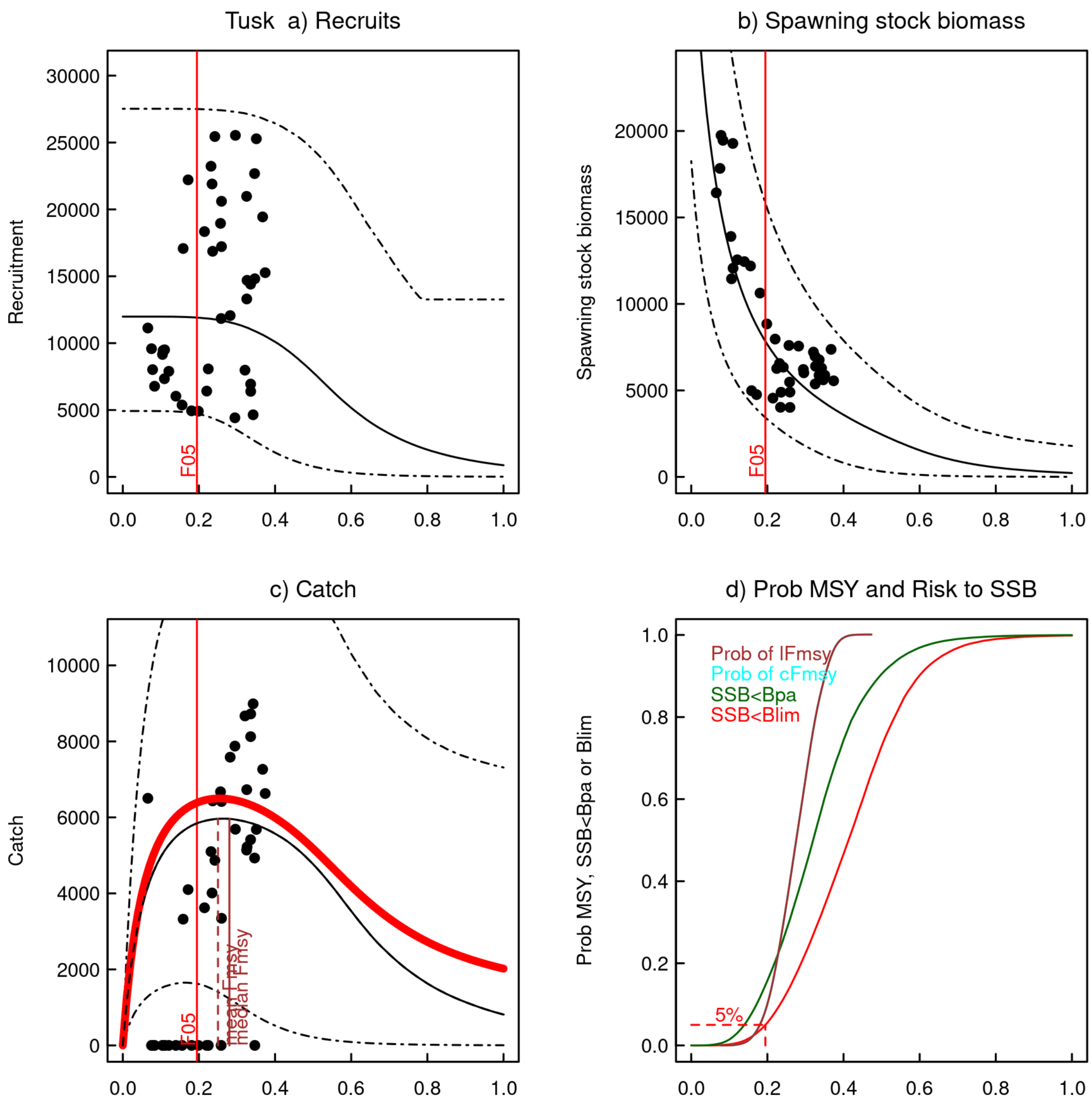

Figure 49: Tusk in 5.a and 14. Equilibrium catch, recruitment, SSB and risk from forward projections, generated from Eqsim. No trigger values used.

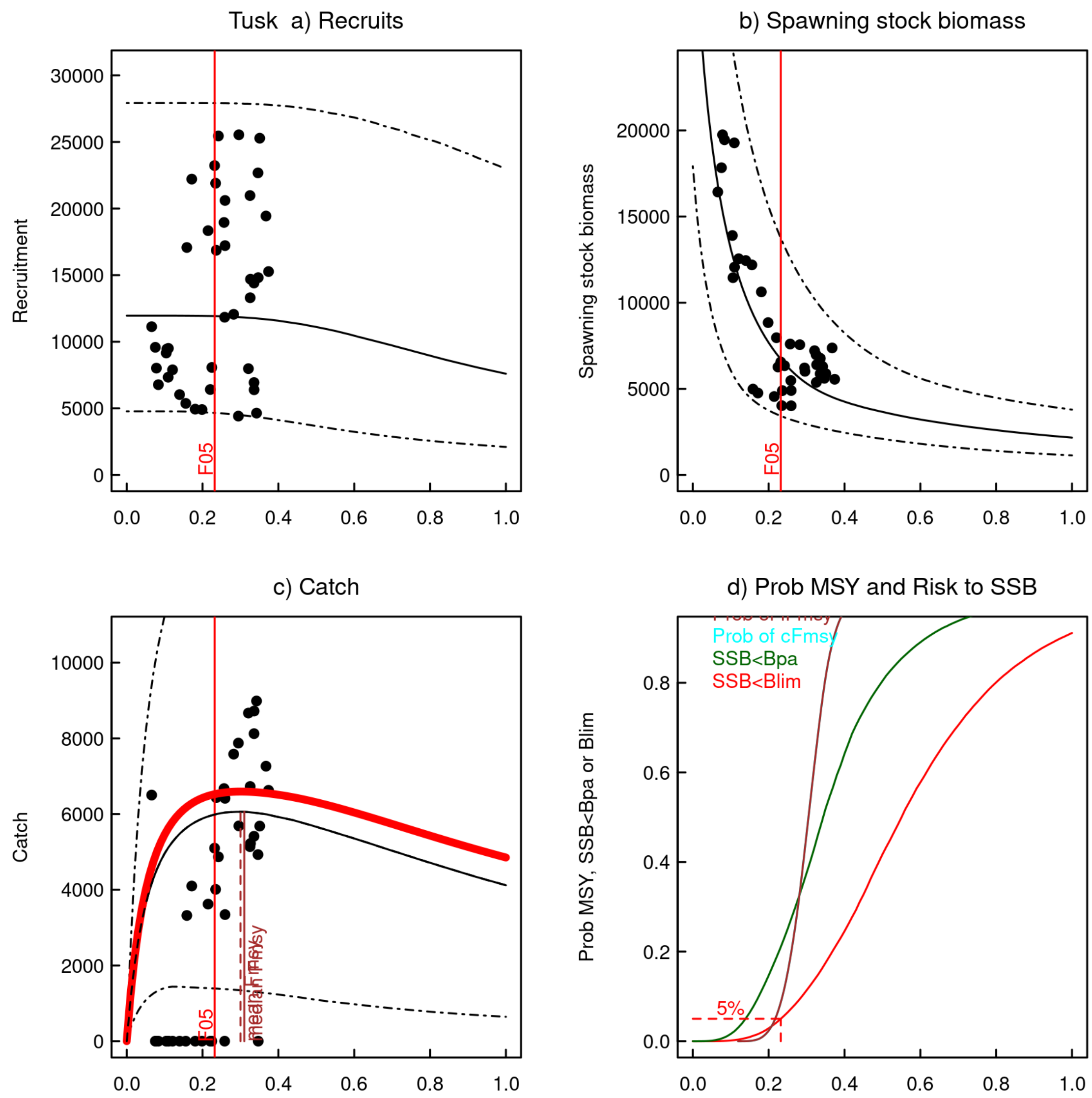

Figure 50: Tusk in 5.a and 14. Equilibrium catch, recruitment, SSB and risk from forward projections, generated from Eqsim. The trigger was implemented in these projections, used to derive F_{p05}.

In line with ICES technical guidelines, the MSY $B_{trigger}$ is set as B_{pa} as this is the first time the reference points are evaluated. Maximum yield is estimated to be obtained at a F of 0.23. $F_{p05} = 0.23$, i.e. the maximum F that has less than 5% chance of going below B_{lim} when the advice rule is applied, is less than the F maximizing yield 0.26, thus limiting the estimate of F_{msy}. The evolution of the spawning stock biomass is shown in Figure 51 for select F values in the HCR (0.15, F_{msy} 0.23, unconstrained F_{msy} 0.26, and 0.35). The 0.26 F level is also the average over the most recent 3 years.

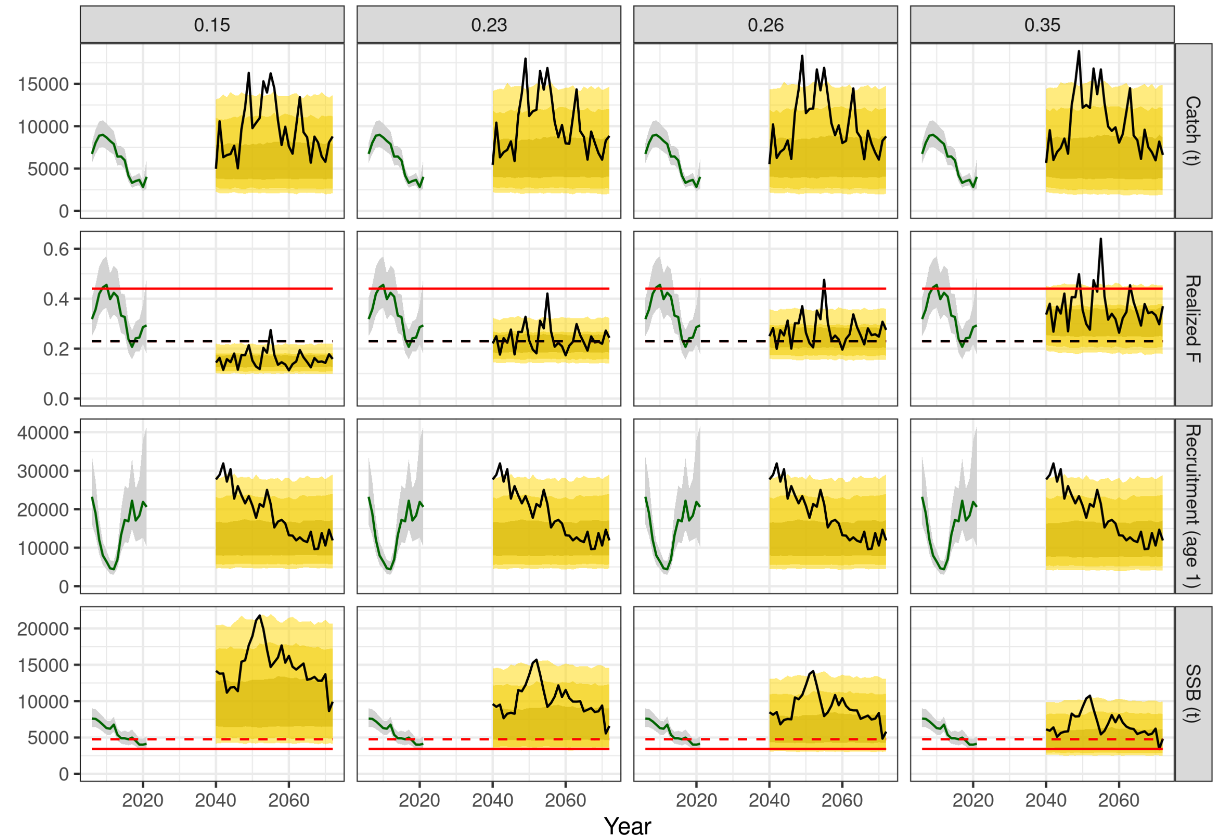

Figure 51: Tusk in 5a and 14. Assessment (from 2006 onwards) and projections of recruitment (thousands at age 4), realized F, catch (in t) and SSB (in t) for different F values in the HCR. The different shades of yellow indicate 90%, 80%, and 50% distribution ranges of projections, the black line one iteration. Grey shading indicates 95% confidence intervals on the assessment model results (green line). The red solid and dashed horizontal lines refer to B_{lim} or F_{lim} and $B_{trigger}$, respectively. The black dashed horizontal line refers to F_{msy}.

Tusk in 5a and 14. Overview of estimated reference points

Reference point	Value	Basis
MSYBtrigger	4800	Bpa
5thPerc_SSBmsy	2400	5th quantile of SSB when fishing at Fmsy
Bpa	4800	Lowest SSB (2016) (Type 4)
Blim	3400	Blim / exp(1.645 sigma_SSB)
Flim	0.44	F leading to P(SSB < Blim) = 0.5
Fp05	0.23	F, when ICES AR is applied, leading to P(SSB > Blim) = 0.05
Fmsy_unconstr	0.26	Unconstrained F leading to MSY
Fmsy	0.23	F leading to MSY

11 Future research and data requirements

The most important information lacking in the assessment of tusk is reliable age readings. It would be best to include tusk in workshops that cross-validate age reading methods.

In addition, it is unclear where spawning grounds exist around Iceland, or if spawning is diffuse. Mature individuals are found diffusely around Iceland, with the largest individuals in the west and northwest. It is thought that spawning grounds are spread around the tusk's distribution, but important ones are located southwest of Iceland (Muus et al. [16]) and between Iceland and Scotland (Cohen et al. [4]). Data from the gillnet survey corroborate the idea that important spawning grounds may be in the southwest; however, the current trawl sampling methods are unlikely to be able to corroborate these data. Tagging data would also be useful to understand movements around Iceland, and whether the size gradient observed across Iceland is the result of a general pattern of tusk movement from the southeast toward the west.

Referenced information on tusk is often from the 1990s and ecosystem changes appear to have occurred around Iceland in the past couple decades (see section on **Ecosystem drivers**). It is unclear why recruitment failure happened during 2010 - 2013. One hypothesis could be interference of spawning processes due to increased freshwater run-off from the 2010 Eyjafjalljökull eruption, but this is speculation. Another hypothesis could be greater predation on age 1 or younger tusk at this time, as several predatory stocks had concomitantly exhibited severe stock increases (e.g., cod, ling). If recruitment failur occurs again it should be taken as a research opportunity to better understand dynamics of this species.

12 Model configuration

```
## # Configuration saved: Tue Apr 19 01:14:58 2022
## #
## # Where a matrix is specified rows corresponds to fleets and columns to ages.
## # Same number indicates same parameter used
## # Numbers (integers) starts from zero and must be consecutive
## # Negative numbers indicate that the parameter is not included in the model
## #
## $minAge
## # The minimium age class in the assessment
##  1
##
## $maxAge
## # The maximum age class in the assessment
##  10
##
## $maxAgePlusGroup
## # Is last age group considered a plus group for each fleet (1 yes, or 0 no).
##  1 1 1 1 1
##
## $keyLogFsta
## # Coupling of the fishing mortality states processes for each age (normally only
## # the first row (= fleet) is used).
## # Sequential numbers indicate that the fishing mortality is estimated individually
## # for those ages; if the same number is used for two or more ages, F is bound for
## # those ages (assumed to be the same). Binding fully selected ages will result in a
## # flat selection pattern for those ages.
##   -1  -1   0   1   2   3   4   5   6   7
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##
## $corFlag
## # Correlation of fishing mortality across ages (0 independent, 1 compound symmetry,
## # 2 AR(1), 3 separable AR(1).
## # 0: independent means there is no correlation between F across age
## # 1: compound symmetry means that all ages are equally correlated;
## # 2: AR(1) first order autoregressive - similar ages are more highly correlated than
## # ages that are further apart, so similar ages have similar F patterns over time.
## # if the estimated correlation is high, then the F pattern over time for each age
## # varies in a similar way. E.g if almost one, then they are parallel (like a
## # separable model) and if almost zero then they are independent.
## # 3: Separable AR - Included for historic reasons . . .  more later
##  2
##
## $keyLogFpar
## # Coupling of the survey catchability parameters (nomally first row is
## # not used, as that is covered by fishing mortality).
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##    0   1   2   3   4   5   6   7   8   8
##    9  10  11  12  13  14  15  16  17  17
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  18
```

```
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##
## $keyQpow
## # Density dependent catchability power parameters (if any).
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##
## $keyVarF
## # Coupling of process variance parameters for log(F)-process (Fishing mortality
## # normally applies to the first (fishing) fleet; therefore only first row is used)
##    0   0   0   0   0   0   0   0   0   0
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##
## $keyVarLogN
## # Coupling of the recruitment and survival process variance parameters for the
## # log(N)-process at the different ages. It is advisable to have at least the first age
## # class (recruitment) separate, because recruitment is a different process than
## # survival.
##  0 1 1 1 1 1 1 1 1 1
##
## $keyVarObs
## # Coupling of the variance parameters for the observations.
## # First row refers to the coupling of the variance parameters for the catch data
## # observations by age
## # Second and further rows refers to coupling of the variance parameters for the
## # index data observations by age
##    0   0   0   0   0   0   0   0   6   6
##    1   1   2   2   2   2   2   2   2   2
##    3   3   4   4   4   4   4   4   4   4
##   -1  -1  -1  -1  -1  -1  -1  -1  -1   5
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##
## $obsCorStruct
## # Covariance structure for each fleet ("ID" independent, "AR" AR(1), or "US" for unstructured). | Po
##  "ID" "ID" "AR" "ID" "ID"
##
## $keyCorObs
## # Coupling of correlation parameters can only be specified if the AR(1) structure is chosen above.
## # NA's indicate where correlation parameters can be specified (-1 where they cannot).
## #1-2 2-3 3-4 4-5 5-6 6-7 7-8 8-9 9-10
##   NA  NA  NA  NA  NA  NA  NA  NA  NA
##   NA  NA  NA  NA  NA  NA  NA  NA  NA
##    0   0   0   1   1   1   1   1   1
##   -1  -1  -1  -1  -1  -1  -1  -1  -1
##   -1  -1  -1  -1  -1  -1  -1  -1  -1
##
## $stockRecruitmentModelCode
## # Stock recruitment code (0 for plain random walk, 1 for Ricker, 2 for Beverton-Holt, 3 piece-wise c
```

```
##  0
##
## $noScaledYears
## # Number of years where catch scaling is applied.
##  0
##
## $keyScaledYears
## # A vector of the years where catch scaling is applied.
##
##
## $keyParScaledYA
## # A matrix specifying the couplings of scale parameters (nrow = no scaled years, ncols = no ages).
##
## $fbarRange
## # lowest and higest age included in Fbar
##  7 10
##
## $keyBiomassTreat
## # To be defined only if a biomass survey is used (0 SSB index, 1 catch index, 2 FSB index, 3 total ca
##  -1 -1 -1 -1 4
##
## $obsLikelihoodFlag
## # Option for observational likelihood | Possible values are: "LN" "ALN"
##  "LN" "LN" "LN" "LN" "LN"
##
## $fixVarToWeight
## # If weight attribute is supplied for observations this option sets the treatment (0 relative weight
##  0
##
## $fracMixF
## # The fraction of t(3) distribution used in logF increment distribution
##  0
##
## $fracMixN
## # The fraction of t(3) distribution used in logN increment distribution (for each age group)
##  0 0 0 0 0 0 0 0 0 0
##
## $fracMixObs
## # A vector with same length as number of fleets, where each element is the fraction of t(3) distribut
##  0 0 0 0 0
##
## $constRecBreaks
## # Vector of break years between which recruitment is at constant level. The break year is included in
##
##
## $predVarObsLink
## # Coupling of parameters used in a prediction-variance link for observations.
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##   NA  NA  NA  NA  NA  NA  NA  NA  NA  NA
##   NA  NA  NA  NA  NA  NA  NA  NA  NA  NA
##
## $hockeyStickCurve
```

```
## #
##  20
##
## $stockWeightModel
## # Integer code describing the treatment of stock weights in the model (0 use as known, 1 use as obse
##  0
##
## $keyStockWeightMean
## # Coupling of stock-weight process mean parameters (not used if stockWeightModel==0)
##  NA NA NA NA NA NA NA NA NA NA
##
## $keyStockWeightObsVar
## # Coupling of stock-weight observation variance parameters (not used if stockWeightModel==0)
##  NA NA NA NA NA NA NA NA NA NA
##
## $catchWeightModel
## # Integer code describing the treatment of catch weights in the model (0 use as known, 1 use as obse
##  0
##
## $keyCatchWeightMean
## # Coupling of catch-weight process mean parameters (not used if catchWeightModel==0)
##  NA NA NA NA NA NA NA NA NA NA
##
## $keyCatchWeightObsVar
## # Coupling of catch-weight observation variance parameters (not used if catchWeightModel==0)
##  NA NA NA NA NA NA NA NA NA NA
##
## $matureModel
## # Integer code describing the treatment of proportion mature in the model (0 use as known, 1 use as
##  0
##
## $keyMatureMean
## # Coupling of mature process mean parameters (not used if matureModel==0)
##  NA NA NA NA NA NA NA NA NA NA
##
## $mortalityModel
## # Integer code describing the treatment of natural mortality in the model (0 use as known, 1 use as
##  0
##
## $keyMortalityMean
## #
##  NA NA NA NA NA NA NA NA NA NA
##
## $keyMortalityObsVar
## # Coupling of natural mortality observation variance parameters (not used if mortalityModel==0)
##  NA NA NA NA NA NA NA NA NA NA
##
## $keyXtraSd
## # An integer matrix with 4 columns (fleet year age coupling), which allows additional uncertainty to
```

13 Input data

13.1 Spring survey at age

year	1	2	3	4	5	6	7	8	9	10
1985	0.003	0.029	0.076	0.170	0.228	0.429	0.529	0.599	0.471	0.839
1986	0.006	0.042	0.057	0.089	0.134	0.305	0.404	0.495	0.405	0.816
1987	0.005	0.110	0.239	0.318	0.219	0.352	0.449	0.567	0.500	0.927
1988	0.004	0.049	0.113	0.220	0.232	0.355	0.414	0.494	0.419	0.774
1989	0.002	0.068	0.204	0.410	0.439	0.625	0.647	0.665	0.548	1.049
1990	0.000	0.039	0.150	0.336	0.369	0.508	0.523	0.493	0.396	0.678
1991	0.000	0.023	0.089	0.233	0.321	0.501	0.550	0.532	0.388	0.595
1992	0.002	0.027	0.083	0.204	0.284	0.515	0.619	0.641	0.478	0.683
1993	0.000	0.024	0.054	0.106	0.152	0.316	0.398	0.429	0.304	0.418
1994	0.000	0.024	0.058	0.121	0.156	0.316	0.415	0.487	0.372	0.503
1995	0.024	0.080	0.115	0.143	0.205	0.255	0.280	0.279	0.153	0.237
1996	0.062	0.088	0.108	0.121	0.172	0.214	0.237	0.246	0.143	0.255
1997	0.072	0.234	0.265	0.191	0.211	0.268	0.312	0.328	0.190	0.319
1998	0.041	0.226	0.325	0.224	0.204	0.226	0.245	0.246	0.142	0.265
1999	0.028	0.174	0.344	0.292	0.269	0.249	0.244	0.235	0.136	0.248
2000	0.047	0.214	0.246	0.248	0.262	0.370	0.362	0.251	0.164	0.403
2001	0.058	0.165	0.207	0.231	0.266	0.402	0.372	0.248	0.132	0.287
2002	0.052	0.243	0.309	0.276	0.253	0.341	0.358	0.251	0.155	0.311
2003	0.040	0.183	0.286	0.400	0.455	0.380	0.369	0.348	0.269	0.267
2004	0.040	0.284	0.392	0.442	0.532	0.486	0.427	0.348	0.269	0.273
2005	0.035	0.311	0.464	0.542	0.615	0.598	0.575	0.498	0.330	0.270
2006	0.021	0.168	0.446	0.674	0.595	0.685	0.523	0.451	0.316	0.307
2007	0.020	0.223	0.509	0.741	0.691	0.833	0.619	0.512	0.322	0.317
2008	0.048	0.210	0.574	0.705	0.683	0.628	0.499	0.445	0.206	0.257
2009	0.019	0.121	0.352	0.512	0.542	0.505	0.424	0.384	0.194	0.277
2010	0.007	0.041	0.163	0.366	0.491	0.484	0.482	0.407	0.205	0.175
2011	0.005	0.026	0.099	0.262	0.447	0.503	0.526	0.456	0.248	0.224
2012	0.013	0.056	0.139	0.165	0.303	0.603	0.498	0.448	0.297	0.284
2013	0.008	0.029	0.079	0.111	0.218	0.517	0.463	0.435	0.303	0.264
2014	0.200	0.109	0.047	0.035	0.188	0.346	0.426	0.396	0.246	0.125
2015	0.115	0.234	0.246	0.121	0.076	0.151	0.393	0.459	0.452	0.482
2016	0.219	0.272	0.274	0.143	0.074	0.098	0.184	0.315	0.267	0.364
2017	0.189	0.213	0.297	0.197	0.177	0.163	0.151	0.223	0.236	0.454
2018	0.103	0.170	0.178	0.271	0.205	0.265	0.133	0.215	0.181	0.340
2019	0.039	0.235	0.392	0.291	0.298	0.363	0.242	0.181	0.220	0.310
2020	0.097	0.162	0.222	0.300	0.200	0.204	0.190	0.145	0.097	0.182

13.2 Autumn survey at age

year	1	2	3	4	5	6	7	8	9	10
2000	0.009	0.002	0.011	0.021	0.038	0.052	0.037	0.030	0.034	0.091
2001	0.026	0.028	0.026	0.029	0.058	0.113	0.094	0.092	0.103	0.233
2002	0.020	0.039	0.043	0.053	0.077	0.088	0.096	0.091	0.074	0.086
2003	0.016	0.018	0.022	0.036	0.056	0.097	0.145	0.148	0.104	0.088
2004	0.015	0.037	0.054	0.075	0.089	0.112	0.143	0.130	0.084	0.071
2005	0.018	0.046	0.059	0.068	0.114	0.122	0.138	0.127	0.070	0.110
2006	0.022	0.056	0.080	0.091	0.171	0.198	0.230	0.213	0.122	0.174
2007	0.044	0.101	0.125	0.150	0.172	0.194	0.191	0.116	0.111	0.104
2008	0.006	0.064	0.112	0.179	0.239	0.270	0.255	0.149	0.113	0.086
2009	0.010	0.034	0.075	0.154	0.214	0.280	0.300	0.198	0.134	0.118
2010	0.014	0.029	0.048	0.116	0.194	0.291	0.320	0.210	0.145	0.112
2011	0.002	0.007	0.016	0.065	0.201	0.213	0.227	0.166	0.098	0.069
2012	0.005	0.016	0.031	0.073	0.212	0.219	0.225	0.176	0.121	0.135
2013	0.001	0.002	0.019	0.109	0.195	0.251	0.298	0.216	0.064	0.061
2014	0.021	0.007	0.007	0.024	0.046	0.133	0.204	0.269	0.223	0.181
2015	0.054	0.039	0.022	0.025	0.042	0.106	0.197	0.184	0.133	0.154
2016	0.020	0.030	0.025	0.039	0.077	0.090	0.187	0.195	0.172	0.111
2017	0.071	0.061	0.109	0.085	0.133	0.096	0.186	0.218	0.190	0.270
2018	0.005	0.044	0.035	0.043	0.085	0.091	0.122	0.201	0.201	0.248
2019	0.030	0.029	0.083	0.037	0.063	0.104	0.131	0.094	0.096	0.191
2020	0.040	0.052	0.051	0.061	0.061	0.059	0.113	0.158	0.062	0.114

13.3 Catch at age

year	1	2	3	4	5	6	7	8	9	10
1975	0	0	0	22	113	516	917	1085	805	625
1979	0	0	0	1	9	54	145	300	405	1228
1981	0	0	2	36	175	523	785	900	635	801
1982	0	0	1	30	150	484	733	845	578	707
1983	0	0	6	38	166	593	1007	1283	1064	1100
1985	0	0	2	21	111	368	563	668	504	679
1987	0	0	0	15	106	397	640	774	546	714
1991	0	0	0	4	31	147	331	544	633	1565
1992	0	0	1	17	90	297	495	660	617	1340
1993	0	0	4	52	186	438	587	635	498	771
1994	0	0	8	44	180	479	653	695	469	646
1995	0	0	2	27	139	461	711	849	628	824
1996	0	0	1	26	137	464	719	850	620	844
1997	0	0	4	26	119	357	540	637	484	719
1998	0	0	4	26	106	314	482	575	465	744
1999	0	0	2	22	98	331	549	700	617	1102
2000	0	0	5	38	136	348	486	538	416	721
2001	0	0	12	70	253	655	806	767	474	526
2002	0	0	22	77	271	728	935	909	554	600
2003	0	0	7	41	157	465	679	764	558	722
2004	0	0	6	30	115	344	522	616	486	663
2005	0	0	12	32	115	346	522	615	499	705
2006	0	0	5	35	145	445	670	793	637	948
2007	0	0	16	54	185	509	741	857	690	1080
2008	0	0	12	57	206	563	804	918	730	1260
2009	0	0	11	52	192	536	783	912	746	1284
2010	0	0	11	55	210	625	905	1025	790	1223
2011	0	0	3	28	125	376	576	716	616	1211
2012	0	0	0	3	168	528	827	1088	955	1107
2013	0	0	0	0	15	321	852	1212	924	934
2014	0	0	0	0	47	256	444	839	833	809
2015	0	0	0	3	10	92	239	531	895	1525
2016	0	0	0	0	15	83	125	326	424	970
2017	0	0	0	0	69	103	152	117	234	966
2018	0	0	0	0	26	138	243	325	507	527
2019	0	0	0	8	23	261	445	533	371	350
2020	0	0	0	0	0	7	468	596	391	666

13.4 Catch weights

year	1	2	3	4	5	6	7	8	9	10
1975	5	35	548	1168	1260	1279	1348	1423	1577	1714
1976	5	35	548	815	977	1159	1349	1589	1902	2802
1977	5	35	548	815	977	1159	1349	1589	1902	2802
1978	5	35	548	815	977	1159	1349	1589	1902	2802
1979	5	35	548	1264	1665	1938	2009	2328	2558	3550
1980	5	35	548	815	977	1159	1349	1589	1902	2802
1981	5	35	594	813	1014	1228	1426	1610	1918	2493
1982	5	35	602	866	1046	1231	1398	1560	1875	2382
1983	5	35	565	836	1044	1200	1370	1533	1730	2058
1984	5	35	548	815	977	1159	1349	1589	1902	2802
1985	5	35	521	899	1068	1197	1355	1548	1816	2608
1986	7	21	548	815	977	1159	1349	1589	1902	2802
1987	4	32	679	1063	1170	1312	1469	1592	1909	2496
1988	7	34	548	815	977	1159	1349	1589	1902	2802
1989	7	42	548	815	977	1159	1349	1589	1902	2802
1990	22	52	548	815	977	1159	1349	1589	1902	2802
1991	22	50	573	1042	1409	1675	1923	2145	2465	3290
1992	5	43	662	860	1058	1278	1562	1846	2258	3170
1993	22	33	599	698	833	1036	1246	1566	1982	2719
1994	22	36	463	770	903	1075	1232	1430	1751	3041
1995	25	56	599	897	1052	1208	1368	1537	1829	2663
1996	17	43	697	925	1059	1205	1358	1523	1806	2973
1997	20	52	466	801	979	1183	1370	1582	1894	3041
1998	27	55	524	772	968	1171	1378	1623	1965	2984
1999	30	57	591	845	1039	1235	1478	1701	2045	3150
2000	28	50	546	706	867	1080	1297	1583	1994	3193
2001	22	55	568	734	833	941	1084	1294	1659	2646
2002	26	52	476	732	857	980	1115	1304	1612	2585
2003	17	45	518	766	941	1109	1284	1482	1783	2757
2004	22	48	496	759	950	1141	1336	1560	1868	2677
2005	29	51	448	746	947	1127	1334	1568	1891	2791
2006	15	47	542	804	968	1135	1334	1570	1918	2783
2007	22	48	464	708	894	1097	1316	1575	1949	2912
2008	27	53	486	720	897	1088	1297	1577	1979	3088
2009	29	51	491	730	909	1107	1322	1604	1993	3057
2010	53	78	527	774	929	1091	1287	1517	1880	3154
2011	49	72	558	790	968	1180	1394	1681	2081	3302
2012	35	69	548	589	841	950	1178	1469	1741	2930
2013	26	69	548	815	713	964	1182	1471	1604	2285
2014	19	55	548	815	1119	1293	1287	1598	1943	3094
2015	20	47	548	603	589	1032	1178	1494	1782	2401
2016	32	77	548	815	1087	1113	1328	1567	1765	2644
2017	25	56	548	815	794	971	1139	1463	1640	2525
2018	21	50	548	815	764	1038	1504	1784	2035	2811
2019	22	53	548	595	720	1183	1491	1845	2321	3350
2020	17	53	548	815	977	828	924	1247	1558	2336

13.5 Stock weights

year	1	2	3	4	5	6	7	8	9	10
1975	5	35	74	153	233	464	591	827	1110	2042
1976	5	35	74	153	233	464	591	827	1110	2042
1977	5	35	74	153	233	464	591	827	1110	2042
1978	5	35	74	153	233	464	591	827	1110	2042
1979	5	35	74	153	233	464	591	827	1110	2042
1980	5	35	74	153	233	464	591	827	1110	2042
1981	5	35	74	153	233	464	591	827	1110	2042
1982	5	35	74	153	233	464	591	827	1110	2042
1983	5	35	74	153	233	464	591	827	1110	2042
1984	5	35	74	153	233	464	591	827	1110	2042
1985	5	35	74	153	233	464	591	827	1110	2042
1986	7	21	55	181	268	534	651	875	1158	2073
1987	4	32	50	97	189	487	671	915	1181	2077
1988	7	34	66	127	193	437	638	897	1182	2093
1989	7	42	72	123	187	378	546	858	1168	2093
1990	22	52	78	123	188	350	505	813	1116	2074
1991	22	50	89	145	218	372	491	740	1020	1998
1992	5	43	84	159	234	427	557	784	1018	1938
1993	22	33	68	156	258	454	563	763	990	1875
1994	22	36	68	155	240	485	623	813	1027	1798
1995	25	56	125	245	430	627	874	1084	1465	1841
1996	17	43	120	244	428	626	888	1125	1522	1948
1997	20	52	97	198	430	653	912	1138	1507	2026
1998	27	55	103	185	387	613	889	1118	1569	2161
1999	30	57	113	195	344	555	871	1120	1534	2331
2000	28	50	101	175	289	457	902	885	1325	2359
2001	22	55	105	186	301	462	821	787	1186	2340
2002	26	52	99	164	284	465	897	875	1208	2328
2003	17	45	98	168	270	465	698	1081	1481	2331
2004	22	48	87	167	283	449	663	1060	1459	2371
2005	29	51	90	163	284	470	678	992	1346	2431
2006	15	47	100	159	290	501	756	983	1475	2524
2007	22	48	98	163	300	493	718	953	1413	2670
2008	27	53	135	245	426	598	861	938	1266	2631
2009	29	51	146	257	432	611	944	1025	1386	2599
2010	53	78	123	217	394	595	863	1082	1354	2590
2011	49	72	126	234	420	611	894	1131	1427	2530
2012	35	69	136	270	410	650	917	1177	1525	2552
2013	26	69	151	287	439	689	951	1210	1545	2610
2014	19	55	114	337	525	801	1056	1367	1769	2759
2015	20	47	83	137	391	586	841	1100	1434	2761
2016	32	77	155	271	566	698	1077	1205	1568	2799
2017	25	56	111	216	371	759	1041	1370	1758	2767
2018	21	50	113	176	332	605	1057	1229	1870	2816
2019	22	53	119	180	300	554	859	1298	1613	2734
2020	17	53	113	183	295	497	777	1326	1623	2752

13.6 Maturity

year	1	2	3	4	5	6	7	8	9	10
1975	0.667	0.099	0.028	0.014	0.019	0.099	0.155	0.256	0.379	0.636
1976	0.571	0.099	0.028	0.014	0.019	0.099	0.155	0.256	0.379	0.636
1977	0.500	0.099	0.028	0.014	0.019	0.099	0.155	0.256	0.379	0.636
1978	0.500	0.099	0.028	0.014	0.019	0.099	0.155	0.256	0.379	0.636
1979	0.500	0.099	0.028	0.014	0.019	0.099	0.155	0.256	0.379	0.636
1980	0.500	0.099	0.028	0.014	0.019	0.099	0.155	0.256	0.379	0.636
1981	0.500	0.099	0.028	0.014	0.019	0.099	0.155	0.256	0.379	0.636
1982	0.500	0.099	0.028	0.014	0.019	0.099	0.155	0.256	0.379	0.636
1983	0.500	0.099	0.028	0.014	0.019	0.099	0.155	0.256	0.379	0.636
1984	0.500	0.099	0.028	0.014	0.019	0.099	0.155	0.256	0.379	0.636
1985	0.600	0.102	0.027	0.014	0.019	0.097	0.152	0.252	0.375	0.634
1986	0.800	0.108	0.031	0.015	0.020	0.099	0.152	0.251	0.375	0.638
1987	1.000	0.099	0.028	0.014	0.019	0.099	0.155	0.256	0.379	0.636
1988	1.000	0.096	0.026	0.013	0.018	0.096	0.155	0.258	0.382	0.634
1989	1.000	0.082	0.021	0.012	0.016	0.089	0.149	0.258	0.385	0.634
1990	0.900	0.059	0.017	0.010	0.015	0.082	0.143	0.258	0.388	0.631
1991	0.700	0.032	0.007	0.008	0.013	0.072	0.132	0.248	0.377	0.615
1992	0.600	0.035	0.007	0.009	0.013	0.067	0.122	0.236	0.363	0.601
1993	0.700	0.018	0.004	0.010	0.015	0.066	0.116	0.223	0.346	0.587
1994	0.700	0.013	0.003	0.011	0.017	0.073	0.121	0.219	0.334	0.568
1995	0.307	0.013	0.003	0.014	0.029	0.092	0.152	0.244	0.363	0.578
1996	0.155	0.013	0.003	0.015	0.040	0.110	0.186	0.280	0.405	0.603
1997	0.140	0.001	0.001	0.015	0.051	0.127	0.217	0.313	0.446	0.626
1998	0.162	0.001	0.002	0.015	0.058	0.140	0.246	0.346	0.491	0.658
1999	0.100	0.001	0.002	0.013	0.063	0.146	0.268	0.375	0.532	0.692
2000	0.021	0.001	0.002	0.012	0.056	0.136	0.267	0.366	0.533	0.712
2001	0.089	0.001	0.001	0.009	0.045	0.113	0.233	0.313	0.475	0.679
2002	0.170	0.001	0.001	0.008	0.037	0.102	0.232	0.300	0.467	0.686
2003	0.267	0.001	0.001	0.006	0.028	0.082	0.202	0.277	0.443	0.677
2004	0.284	0.001	0.001	0.006	0.024	0.073	0.188	0.280	0.452	0.693
2005	0.239	0.000	0.001	0.005	0.020	0.063	0.158	0.262	0.421	0.667
2006	0.169	0.000	0.001	0.005	0.020	0.063	0.154	0.266	0.428	0.666
2007	0.099	0.000	0.001	0.004	0.015	0.048	0.114	0.229	0.386	0.638
2008	0.063	0.000	0.001	0.006	0.023	0.061	0.132	0.227	0.379	0.631
2009	0.000	0.000	0.001	0.007	0.027	0.064	0.137	0.197	0.337	0.598
2010	0.000	0.000	0.001	0.008	0.029	0.067	0.143	0.196	0.329	0.589
2011	0.000	0.000	0.001	0.008	0.030	0.068	0.145	0.198	0.316	0.569
2012	0.000	0.000	0.001	0.008	0.030	0.069	0.148	0.200	0.307	0.556
2013	0.000	0.000	0.001	0.005	0.020	0.050	0.112	0.162	0.249	0.481
2014	0.037	0.000	0.000	0.003	0.013	0.038	0.083	0.137	0.215	0.445
2015	0.103	0.000	0.000	0.002	0.010	0.030	0.066	0.115	0.187	0.411
2016	0.109	0.000	0.000	0.003	0.016	0.036	0.080	0.128	0.209	0.432
2017	0.084	0.000	0.000	0.003	0.016	0.039	0.085	0.136	0.221	0.435
2018	0.087	0.000	0.000	0.003	0.016	0.041	0.094	0.149	0.256	0.475
2019	0.093	0.000	0.001	0.002	0.014	0.038	0.092	0.150	0.254	0.478
2020	0.137	0.000	0.001	0.002	0.013	0.037	0.091	0.156	0.258	0.483

13.7 Landings

Year	Landings
1975	5949
1976	7392
1977	8220
1978	6451
1979	6502
1980	6923
1981	6633
1982	5887
1983	8371
1984	5755
1985	5065
1986	5416
1987	5659
1988	6885
1989	7090
1990	7305
1991	8806
1992	8122
1993	5459
1994	5298
1995	6351
1996	6628
1997	5413
1998	5223
1999	7265
2000	5139
2001	4930
2002	5683
2003	5688
2004	4870
2005	5100
2006	6674
2007	7584
2008	8669
2009	8722
2010	8988
2011	7876
2012	8125
2013	6729
2014	6417
2015	6434
2016	4100
2017	3321
2018	3621
2019	4011
2020	3344

14 Appendix I. Exploration of possible natural mortality values for tusk (*Brosme brosme*) in 5.a and 14

14.1 Data-limited M estimators

The R package Fisheries Stock Analysis (FSA, Ogle et al. [18]) was used to explore a variety of M estimators using life history information estimated from the spring survey length and age data. Growth is relatively linear in tusk (see Appendix I), so Von Bertalanffy growth parameters were estimated as $L_\infty = 397$ cm, $K = 0.01$ and $t_0 = -1.54$. Replacement of L_∞ with a reasonable max length (the 99.95th percentile, 100 cm, from Icelandic spring survey data) resulted in no appreciable change in M estimations. Max age of the population was taken to be the oldest tusk in the survey data (21), and the temperature experienced was taken to be the mean of 1) the mean of all spring survey bottom temperature records where tusk were caught, 2) the mean of all autumn survey bottom temperature records where tusk were caught, and 3) the mean of all commercial records of tusk. The mean of means was taken to reduce the influence of the number of records as well as seasonality of each data source (6°C). Maturation data from the spring survey was used to estimated $L_5 0$ as 63 cm (length at 50% mature from a maturation ogive), which was then translated into $t_5 0 = 15.75$ (age at 50% mature) using the Von Bertalanffy growth parameters. The weight-length power parameter b was estimated to be 3.24 using all tusk caught in the spring survey, and this relationship was also used to set W_∞ as 11.6 kg, calculated from the the 99.95th percentile tusk length in the spring survey (100 cm). Weights calculated for tusk longer than this were heavier than any tusk recorded in survey data, so were not used.

The **metaM** function in the FSA package calculates a variety of M estimates based on different life history information, two of which vary with length ("Gislason" and "Charnov" methods). Results of using these methods (with length set to 54 cm, the mean length of commercial samples, for the length-variable methods), indicated that M estimates varied widely, ranging 0.01 - 0.40 with both the mean of 0.19 and median of 0.2. Methods that relied on K estimates gave the lowest estimates. Methods that relied on max age yielded high Ms, while methods that relied mainly on L_∞ or b were generally variable (Fig. 52).

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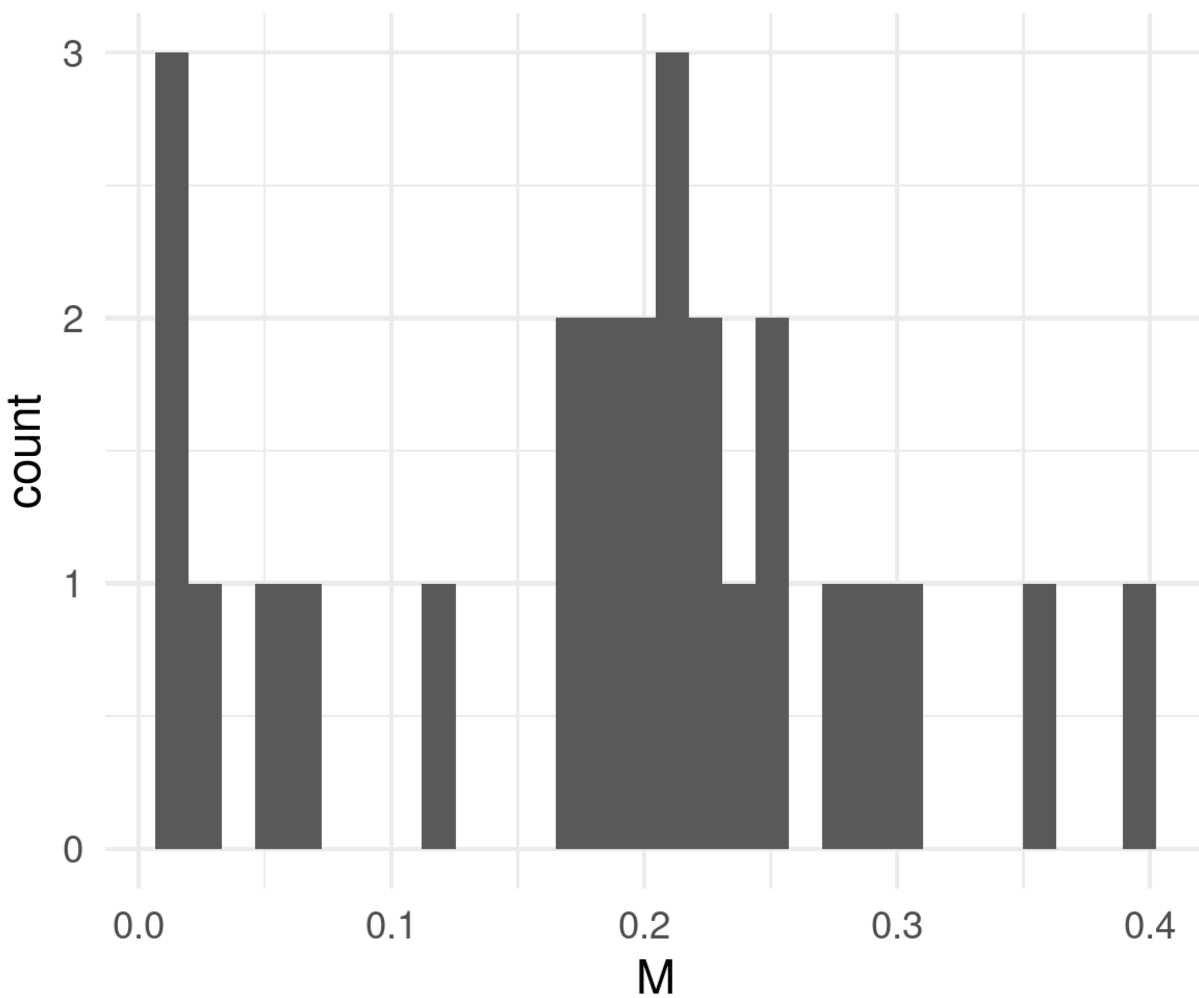

Figure 52: Tusk in 5a and 14. Histogram of life-history based natural mortality (M) estimates.

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Ling (*Molva molva*) in 5.a

Contents

1 Introduction

The ling *Molva molva* (Lotidae) is one of the longest and largest gadiforms (up to ~200 cm and ~30 kg). It has a small head and large jaws, and feeds mainly on fish and occasionally on crustaceans, cephalopods and echinoderms. It is a relatively slow-growing species and can reaching approximately 14 years of age. It solitary or in small aggregations, found mostly on hard seabed, or sandy seabed with large rocks. In Iceland the species is considered a 'warm-water' or 'southern' stock, found on the edges southern of the continental shelf at depths between 100-400 meters (Fig. 1).

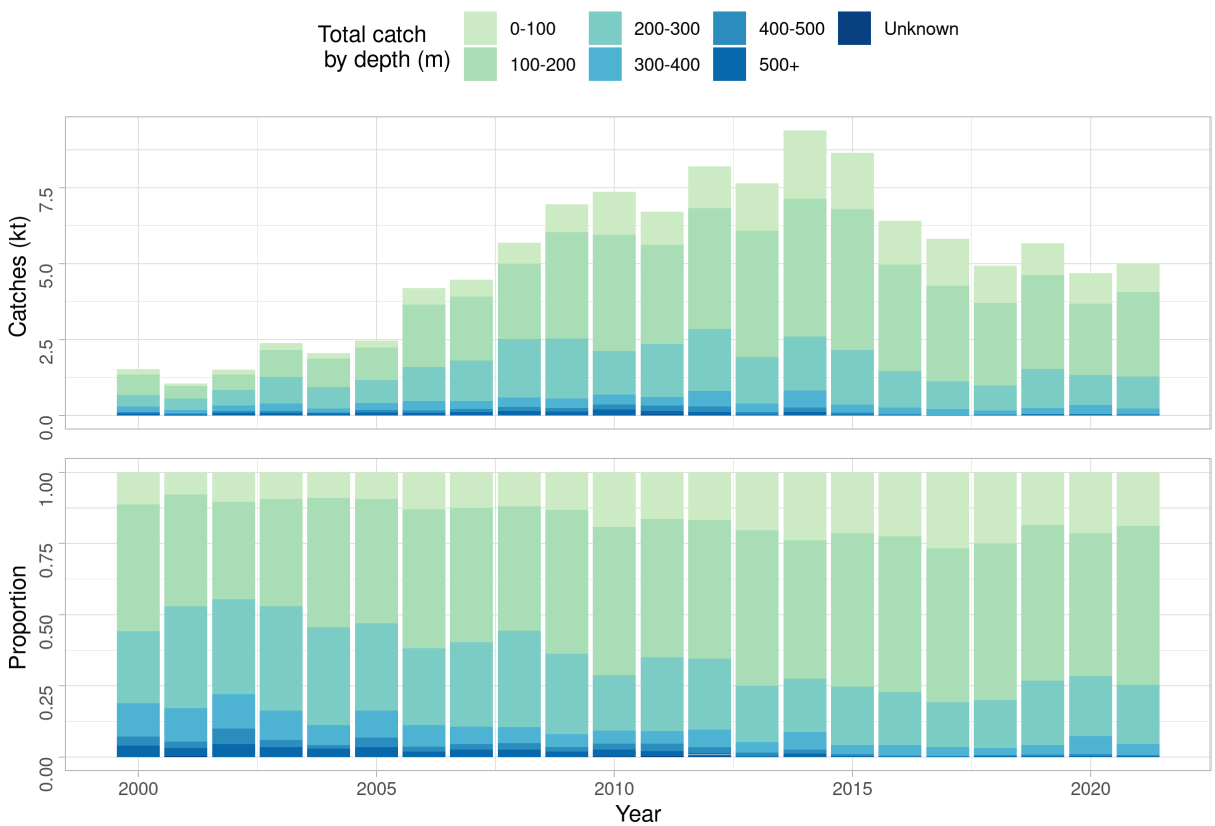

Figure 1: Ling in 5.a. Catch reported in logbooks by depth and gear, in terms of biomass (top panels) and proportion (bottom panels).

2 Stock ID and sub-stock structure

Ling (*Molva molva*) is a North Atlantic species and is distributed in the north eastern Atlantic from the Barents Sea, around the coast of the UK and the British Isles, south to the Straits of Gibraltar and onto the north-western coast of the the Mediterranean Sea. It is also found off the coast of Canada, off the southern tip of Greenland and around Iceland and the Faroe islands. In Icelandic waters, it is mainly distributed on the edges of the south, southwest and west of the Icelandic continental shelf (MFRI [15], Fig. 2). Main spawning areas are in the south, southwest and west of the Icelandic continental shelf in May and June. In the ICES area, the stock has widely separated fishing grounds and in 2012, ICES decided to manage them separately (Iceland (ICES Div. Va), the Faroes (Vb), and Norway (ICES Subareas I and II) and the northern

North Sea (ICES subareas IV,VI,VII,VIII)) [6]. A study found the stocks to be genetically different between divisions and subareas (Blanco Gonzalez et al. [2]), thus supporting the decision.

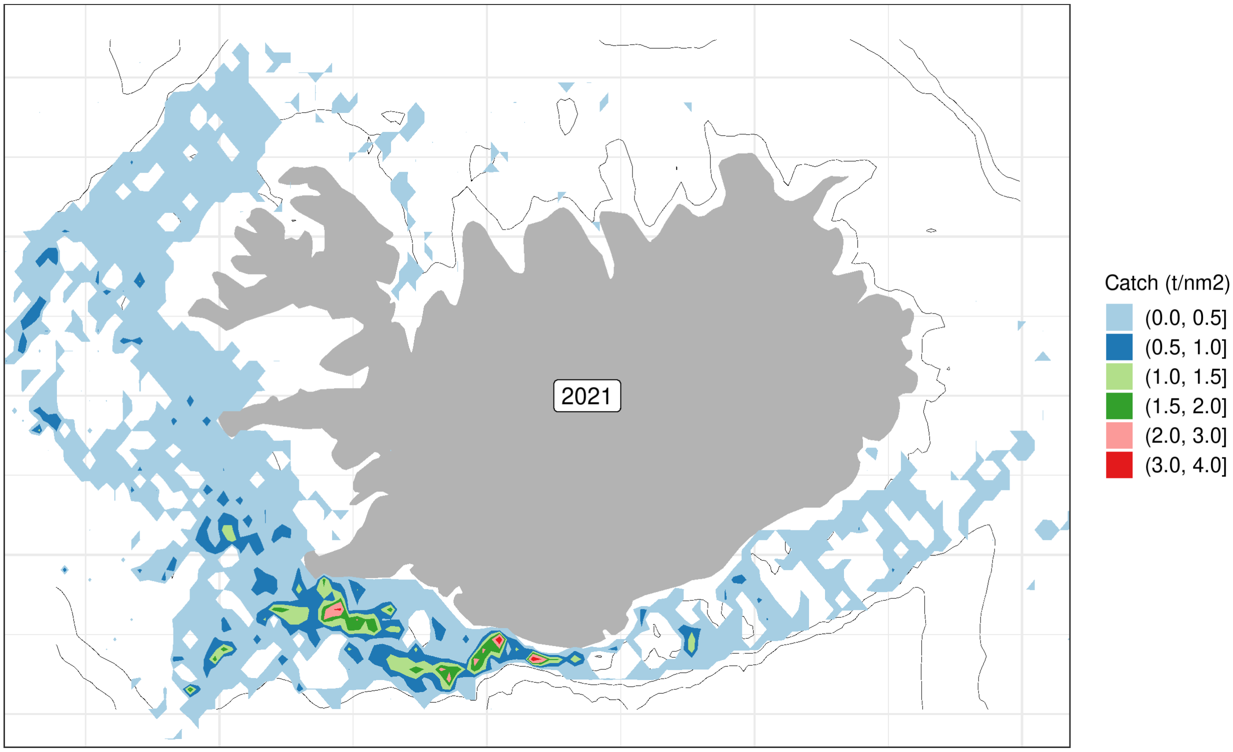

Figure 2: Ling in 5.a. Spatial distribution of ling density in 2021 according to logbooks.

2.1 Current advisory process

Since 2010 the Gadget model (Globally applicable Area Disaggregated General Ecosystem Toolbox, see https://github.com/gadget-framework/) has been used for the assessment of ling in Icelandic waters (ICES [11]). As part of a Harvest Control Evaluation requested by Iceland this stock was benchmarked in 2017 (ICES [9]). Several changes were made to the model setup and settings which are described in the stock annex (ICES [10]).

Current advice based on a target harvest rate H applied to a length-based harvestable biomass estimated at the beginning of a calendar year, where the fishing year begins 1. September of the same year. Harvest rate (H) is scaled down according to $SSB/B_{trigger}$ when $SSB < B_{trigger}$. The target H = 0.18, was chosen to be slightly less than H_{MSY}, as it increased long-term expected SSB with little reduction in yield.

The Gadget stock assessment model is length- and age-structured model tuned to 7 length-based spring survey indices, age distributions, and length distributions. Comparisons with age distribution data implemented an 11 group. The 2021 a chapter for ling can be found in WGDEEP report (ICES [11]) see here

3 Issue list

In a letter dated at October 18, 2021, the government of Iceland requested that ICES evaluate the performance of the harvest control rules for ling and update/develop new assessments as appropriate.

In responding to this request, a few issues should be kept in mind that have been discussed during past WGDEEP meetings. First, retrospective patterns have become visible in the Gadget assessment since the last benchmark. Possibly this is a result of time-variable growth. Second, Ageing may become unreliable

Table 1: Ling in 5.a. Distribution of landings among gears and time periods.

Year	Months	Long- and hand-lines	Other	Trawls and seines
2018	Jan-June	3967	329	1483
2018	July-Dec	1406	68	809
2019	Jan-June	4237	92	1584
2019	July-Dec	1733	25	596
2020	Jan-June	3091	74	1367
2020	July-Dec	1683	70	777
2021	Jan-June	3596	69	1394
2021	July-Dec	1240	59	770
2022	Jan-June	1621	54	741

at ages roughly over 11. Third, the peak in spawning stock biomass observable in the past decade appears driven by an increase in occurrence of very large ling (>110 cm), which are sometimes also heavier than expected from a length-weight relationship (see **Ecosystem drivers** section). These numbers have likewise started to decline again in recent years.

4 Scorecard on data quality

Scorecard on data quality was not used

5 Multispecies and mixed fisheries issues

Ling is mainly targeted by the longline fishery and in 2021, longliners accounted for approximately 68% of ling landings (Table 1). Ling is also caught as bycatch in the bottom trawl and gillnet fishery. Appart from the spawning season in May and June, ling is believed to occur alone or in small schools (Gordon [7]).

6 Ecosystem drivers

Considerable changes have been observed in the area, both in terms of changes in fishing pressure and the ecosystem. [12] noted that species diversity in the fjords in the western and northern part of the country shifted dramatically at the turn of the century. These changes were attributed mainly to increases in the abundance of juvenile gadodids such as cod, ling and whiting. These changes coincided with increased temperature, generally lower fishing pressure towards and shifts in distribution of species. An example of these shifts range from the Icelandic haddock stock, with a noticeable northern shift in distribution [15], the minke whale population [24] possibly due to shifts in forage fish species and influx of the mackerel to the North Western Atlantic [19]. Projected effects of climate change are also expected to affect species differently depending on their thermal tolerances and habitat affinities (e.g., depth). Some warm-water species such as tusk and ling shifting northward gaining suitable habitat available to them (e.g,. ling, tusk, and haddock) while others lose ground due to depth constraints (e.g., plaice) and most cold-water species lose (e.g., Atlantic wolffish, Mason et al. [14], Campana et al. [3]).

Ling prefers hard seabed, or sandy seabed with large rocks. In Icelandic waters, ling can be found at depths 10 and 1300 meters but is most commonly caught at depths between 100 and 400 meters (MFRI [15]). Ling is piscivorous (feeding both on demersal and pelagic species), but have also been found to feed on crustaceans, cephalopods and echinoderms. Ling is a slow growing species (K~0.1) (Magnussen [13]) and can reach up to 20 years of age. Ling in Icelandic waters are mature at the age of 5-8 years and 60-80 cm total length and the main spawning area is along the edges south, southwest and west of the Icelandic continental shelf in May to June. Larvae have been found to occur in Atlantic water masses of temperatures 6-7°C (Ehrenbaum [5]; Schmidt [20]; Schmidt [21]). On the Icelandic shelf, the species is a southern stock, i.e. is a ‘warm-water’

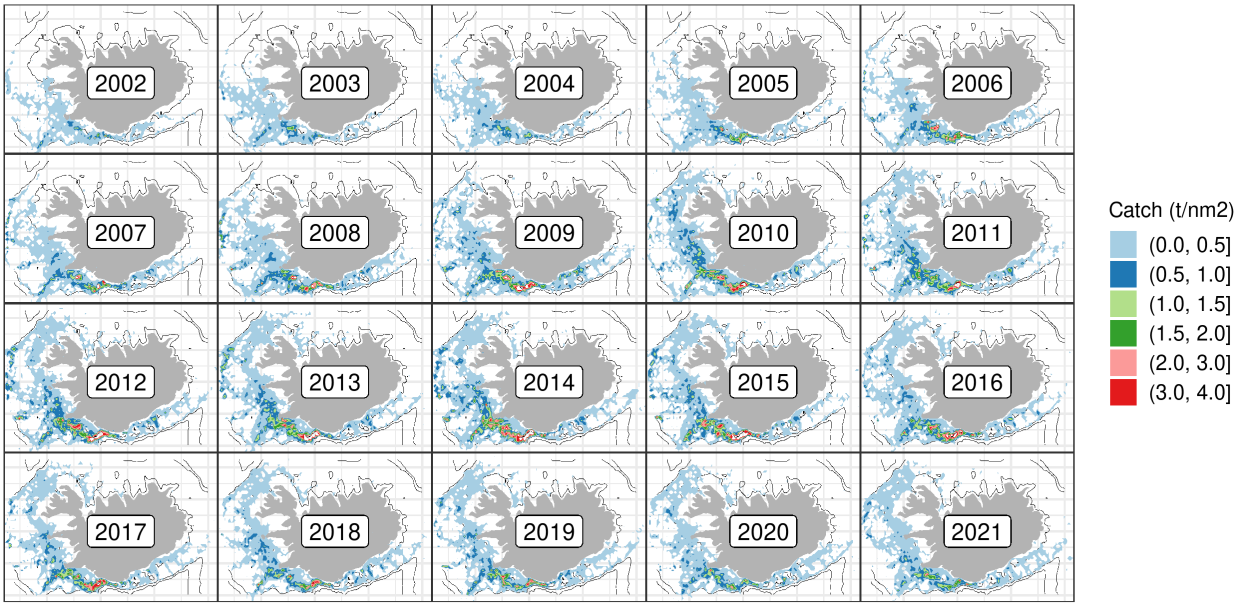

Figure 3: Ling in 5.a. Spatial distribution of catches by all gears.

species. With the warming of the continental shelf around Iceland, especially along the western and north-western part of the shelf that started around the year 2000 an increase in ling biomass and distributional range has been observed. Therefore the increases in temperature may have been a driver for the increase in biomass of ling in 2000 to 2009 (ICES [10]).

6.1 Variability in biological relationships

As mentioned earlier, the recent peak in ling biomass was marked by a large number of very large ling being present in the population. This pattern can be seen in a fatter right tail in length distributions from years 2011 - 2017, which in more recent years has rescinded (Fig. 4). Mean length has increased in the period and in 2020, the highest mean length was recorded, or 90 cm, as the high recruitment observed in 2003 - 2012 has aged.

It was also mentioned that time-variable growth was suspected to have contributed to the retrospective patterns observed in the last assessment using the Gadget model. Exploratory plots were created to visualize whether variation in biological relationships (maturity at length, length at age, and weight at length), could be detected among sampling types (spring survey, autumn survey, or commercial) or regions around Iceland, between sexes, or over time. Regions were defined according to Bormicon divisions that have been modified slightly to be more easily applicable in Gadget (Stefánsson and Pálsson [23], MRI [16], Fig. 5). Full results are not shown, but the main results included:

- Commercial samples generally excluded the smallest and largest individuals.
- Weight at lengths appear stable across time, space and sexes, but several of the rare largest individuals (>110 cm) are heavier than expected according to the weight-length relationship.
- Growth curves and maturity ogives appear to vary over time, and not by sex or sampling type (Figs. 10, 11, 12, and 13).Any regional differences appear very small with large overlap in spread of length at age (Figs. 6, 7, 8, and 9).

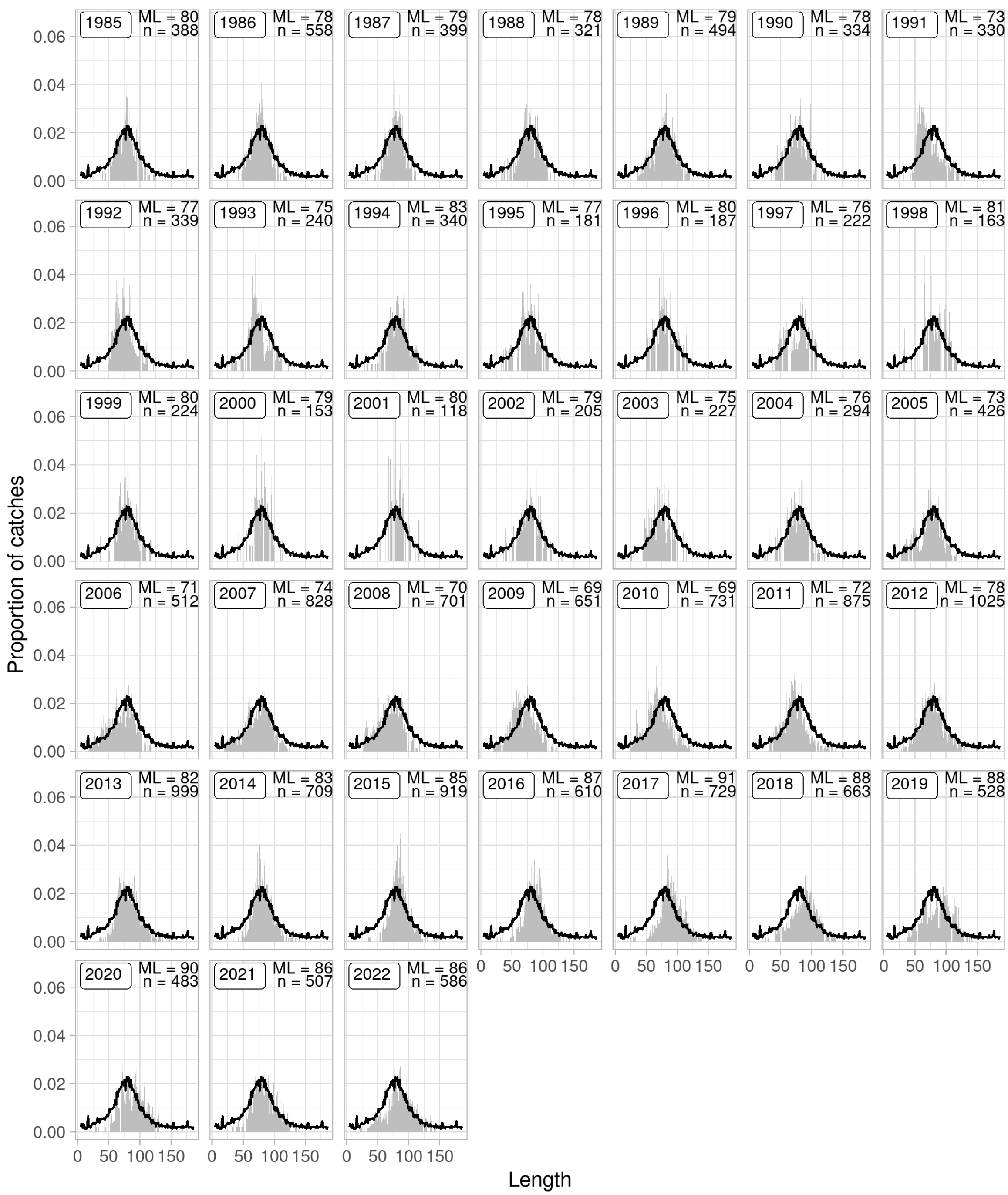

Figure 4: Ling in 5.a. Spring survey length distributions by year with the mean over all years represented by the black line.

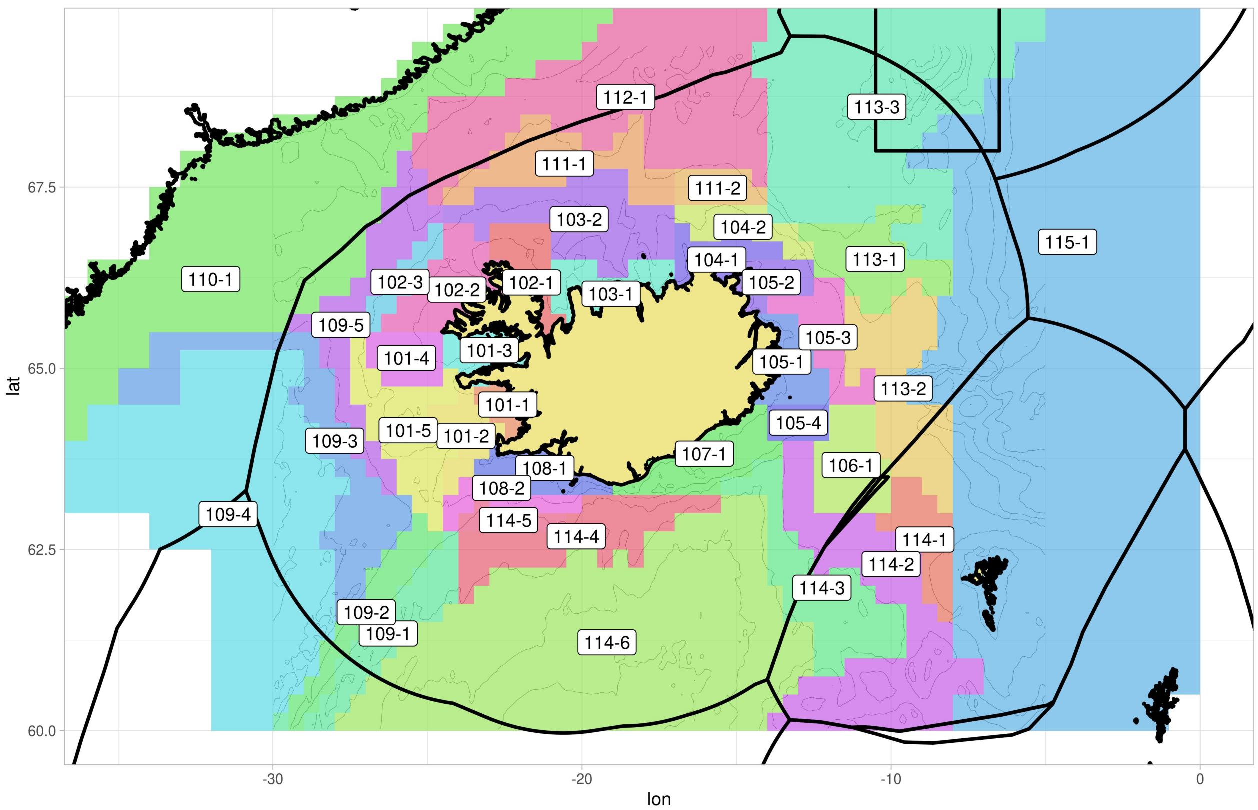

Figure 5: Ling in 5.a. Illustration of Gadget divisions, originally based on Bormicon divisions, used to analyse regional variation. The first three numbers (generally 101-116) indicate division number labels that correspond with plots showing regional variation in life history.

7 Stock Assessment

7.1 Catch – quality, misreporting, discards

Annual estimates of landings of ling from Icelandic waters are available since 1905 and in recent decades, recorded by gear (Figs. 14, 16). The historical information are largely derived from the Statistical Bulletin, with unknown degree of accuracy, and retrieved from Statlant. For the period between 1980 to 1993, landings of Icelandic vessels were recorded by Fiskifélagið (a precursor to the Directorate of Fisheries). The more recent landings (from 1993 onwards) are from the Directorate of Fisheries as annually reported to ICES. After 2013, all landings in 5.a are recorded by the Directorate, while foreign vessel landings were obtained from Statlant.

The estimates by the Directorate of Fisheries are based on a full census by weighing fish at the dock when landed or in fish processing factories prior to processing. Information on the landings of each trip are stored in a centralised database of which the Marine and Freshwater Research Institutes (MFRI) employees have full access. Captains are required to keep up-to-date logbooks that contain information about timing (day and time), location (latitude and longitude), fishing gear and amount of each species in each fishing operation. Logbooks are especially useful for providing information on catch location and monitoring its change over time (15). The Directorate of Fisheries and the Coast Guard can, during each fishing trip, check if amount

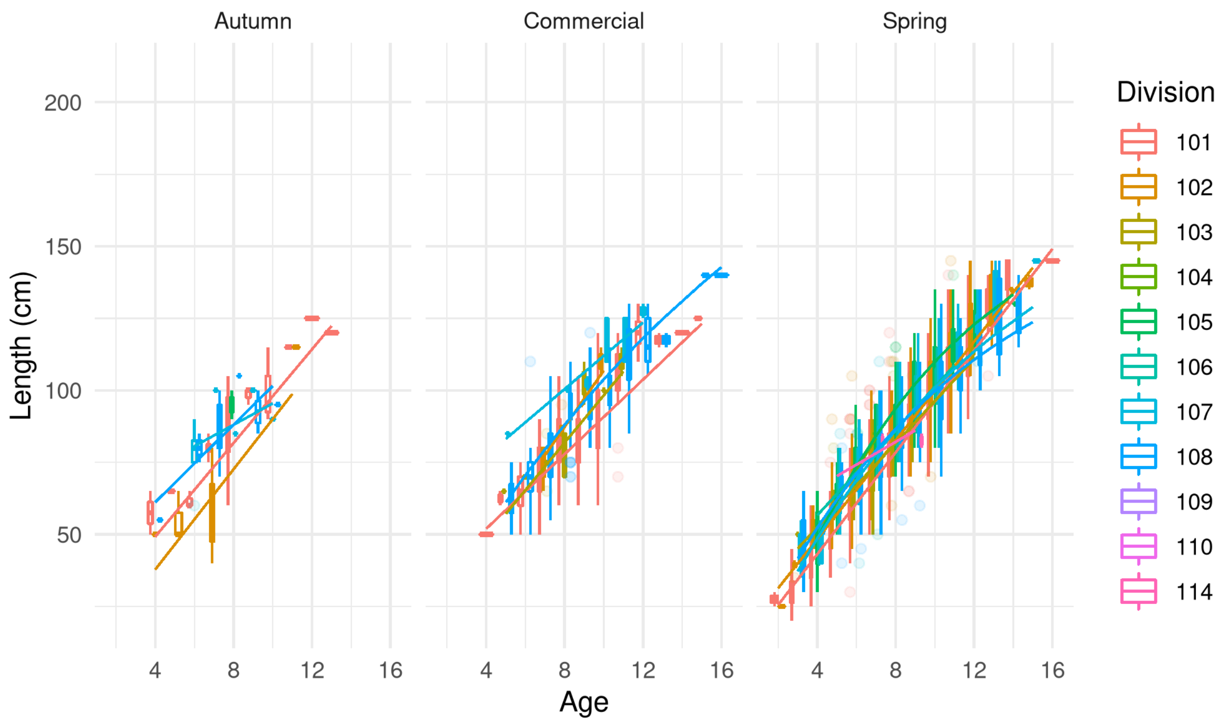

Figure 6: Ling in 5.a. Length at ages of females by region, plotted as boxplots with Von Bertalanffy growth curves overlaid where model fits were possible.

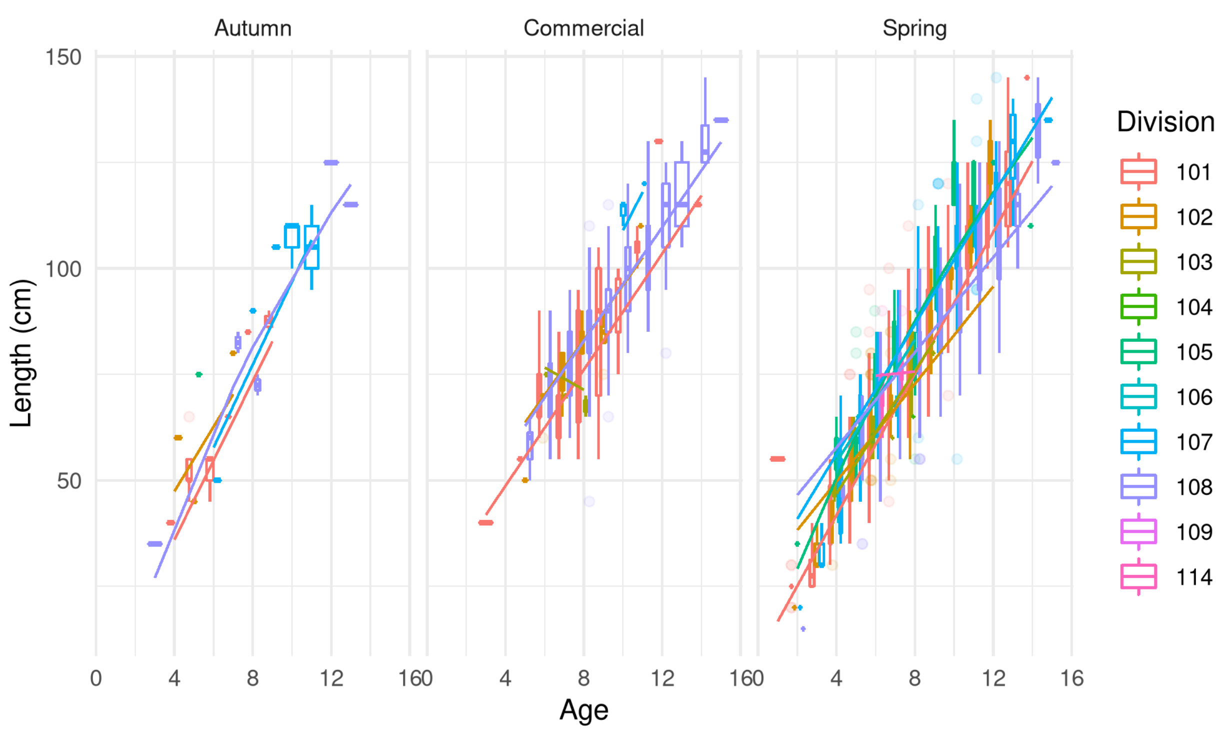

Figure 7: Ling in 5.a. Length at ages of females by region, plotted as boxplots with Von Bertalanffy growth curves overlaid where model fits were possible.

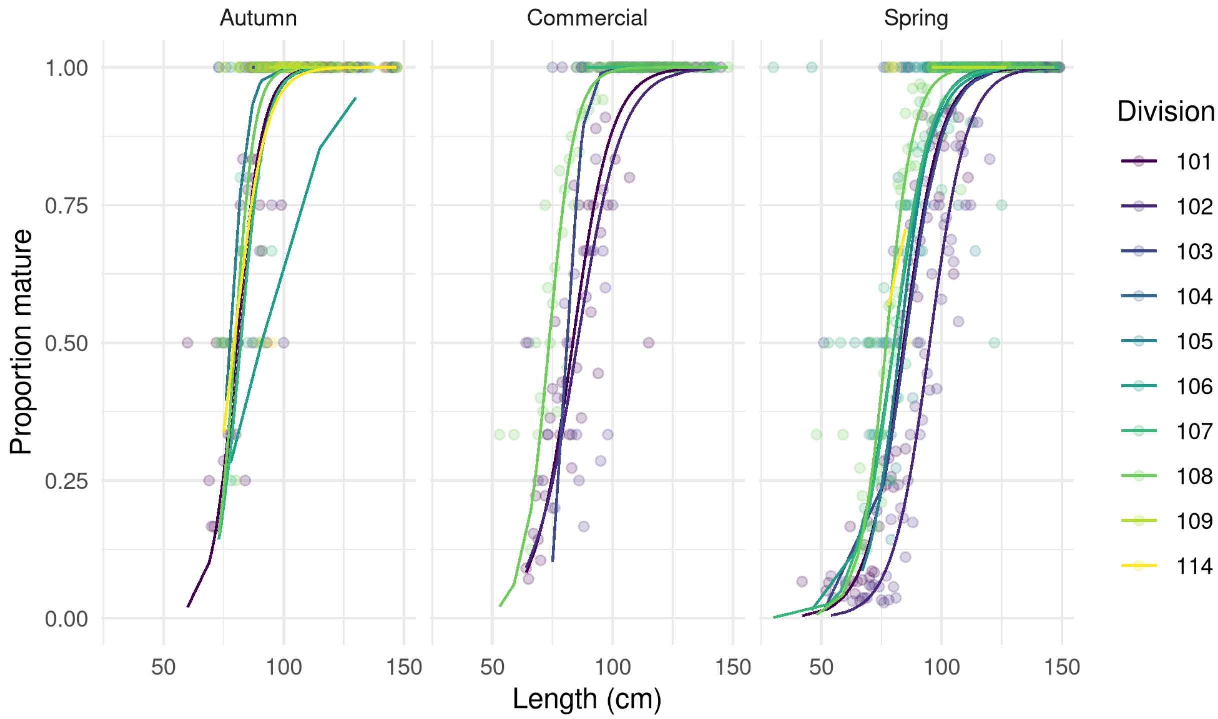

Figure 8: Ling in 5.a. Length at ages of females by region, plotted as boxplots with logistic maturation ogives overlaid where model fits were possible.

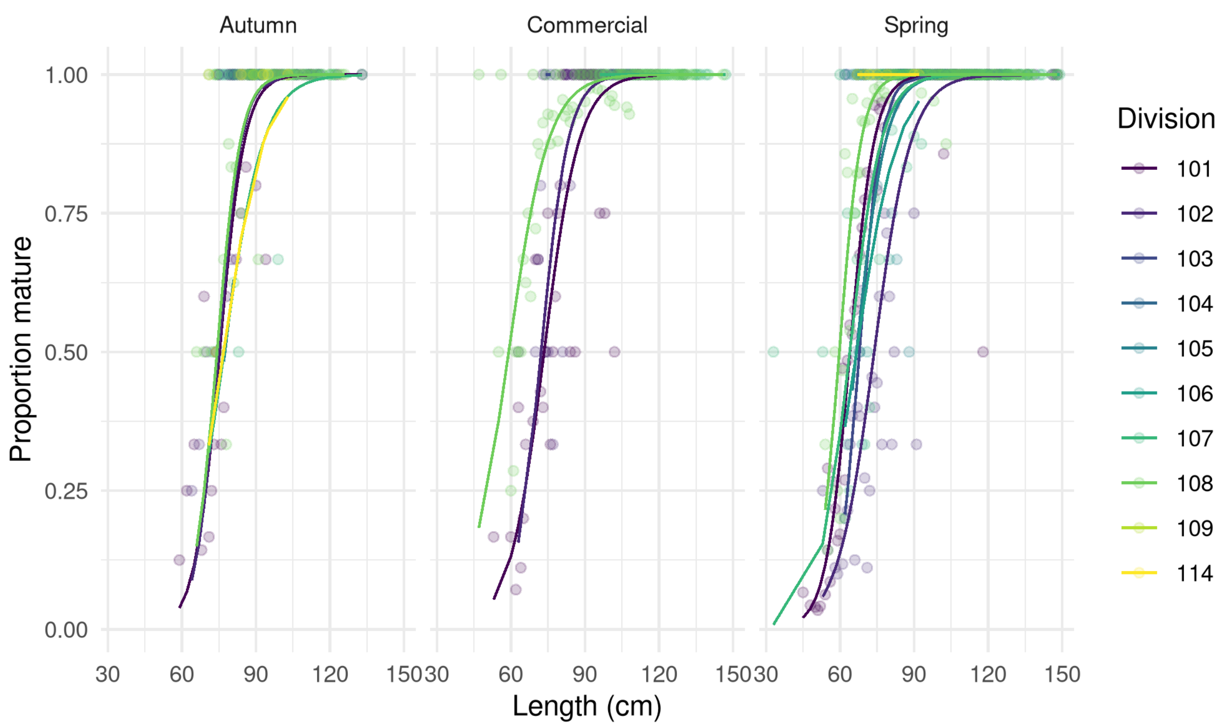

Figure 9: Ling in 5.a. Length at ages of females by region, plotted as boxplots with logistic maturation ogives overlaid where model fits were possible.

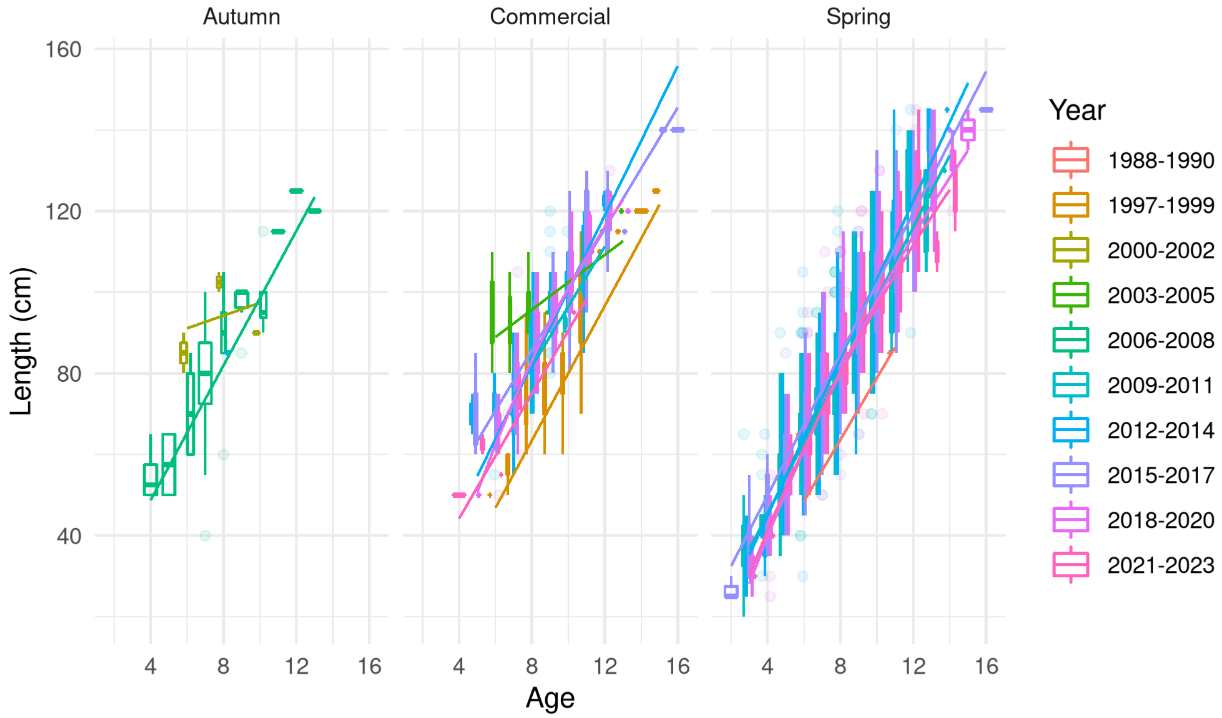

Figure 10: Ling in 5.a. Length at ages of females by year, plotted as boxplots with Von Bertalanffy growth curves overlaid where model fits were possible.

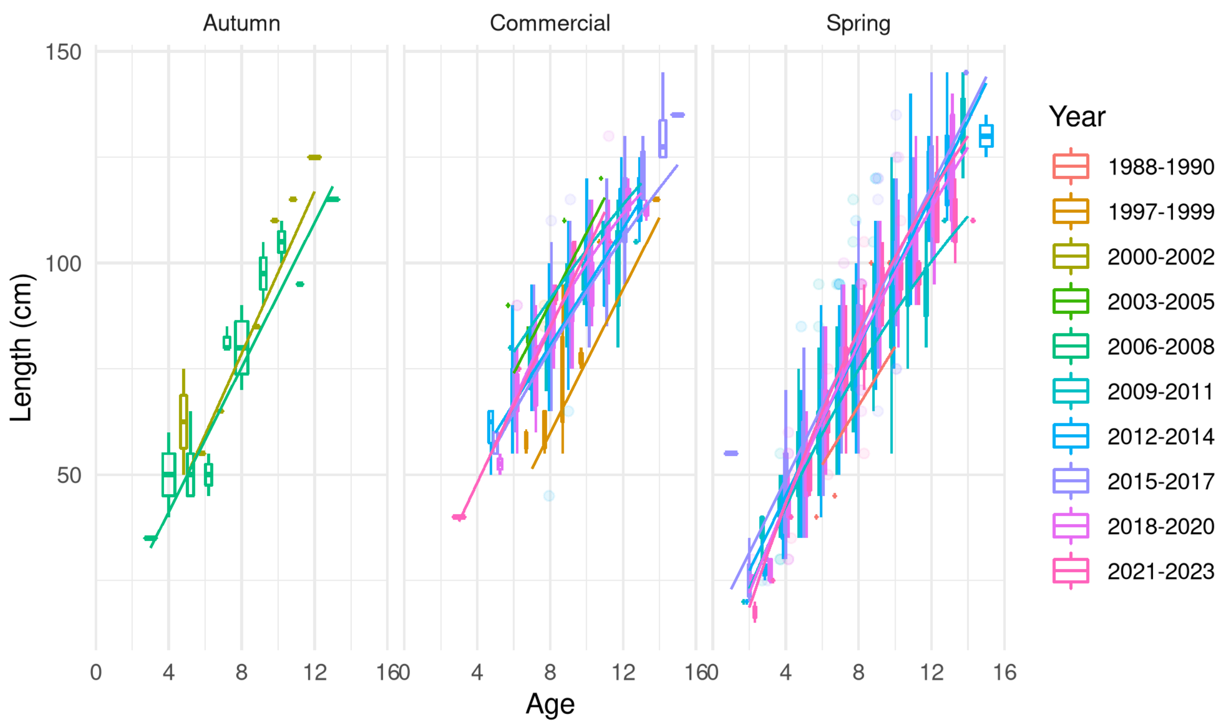

Figure 11: Ling in 5.a. Length at ages of males by year, plotted as boxplots with Von Bertalanffy growth curves overlaid where model fits were possible.

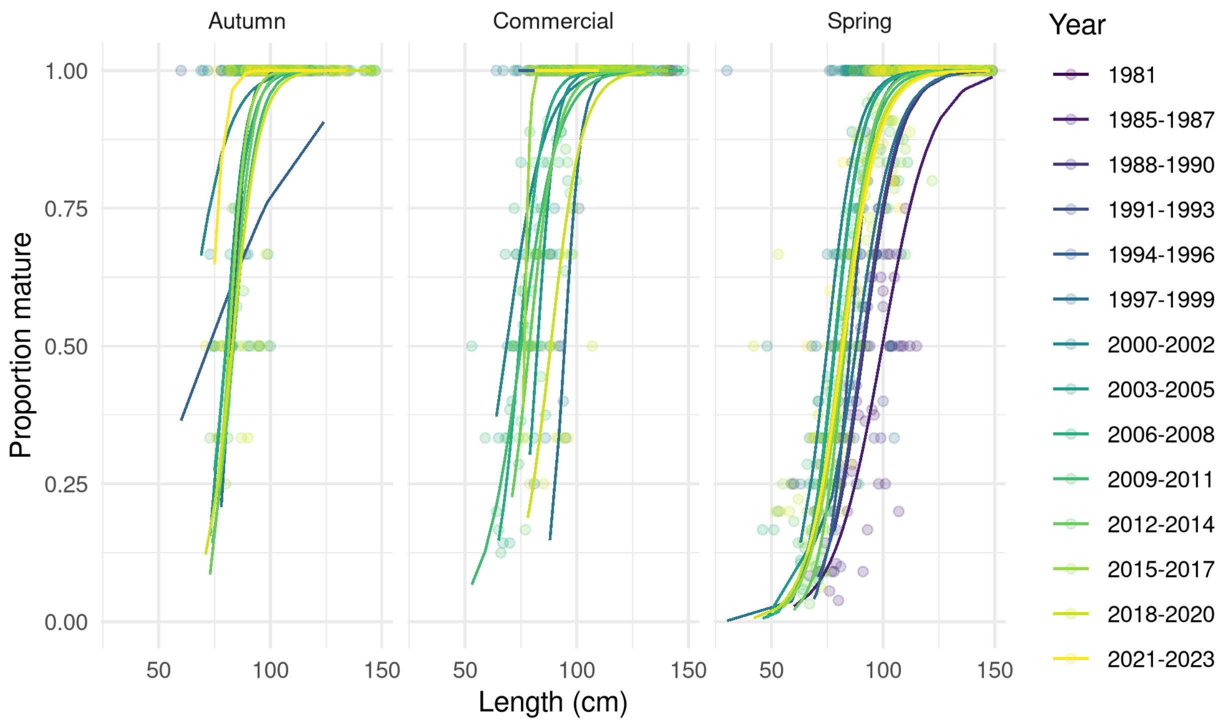

Figure 12: Ling in 5.a. Length at ages of females by year, plotted as boxplots with logistic maturation ogives overlaid where model fits were possible.

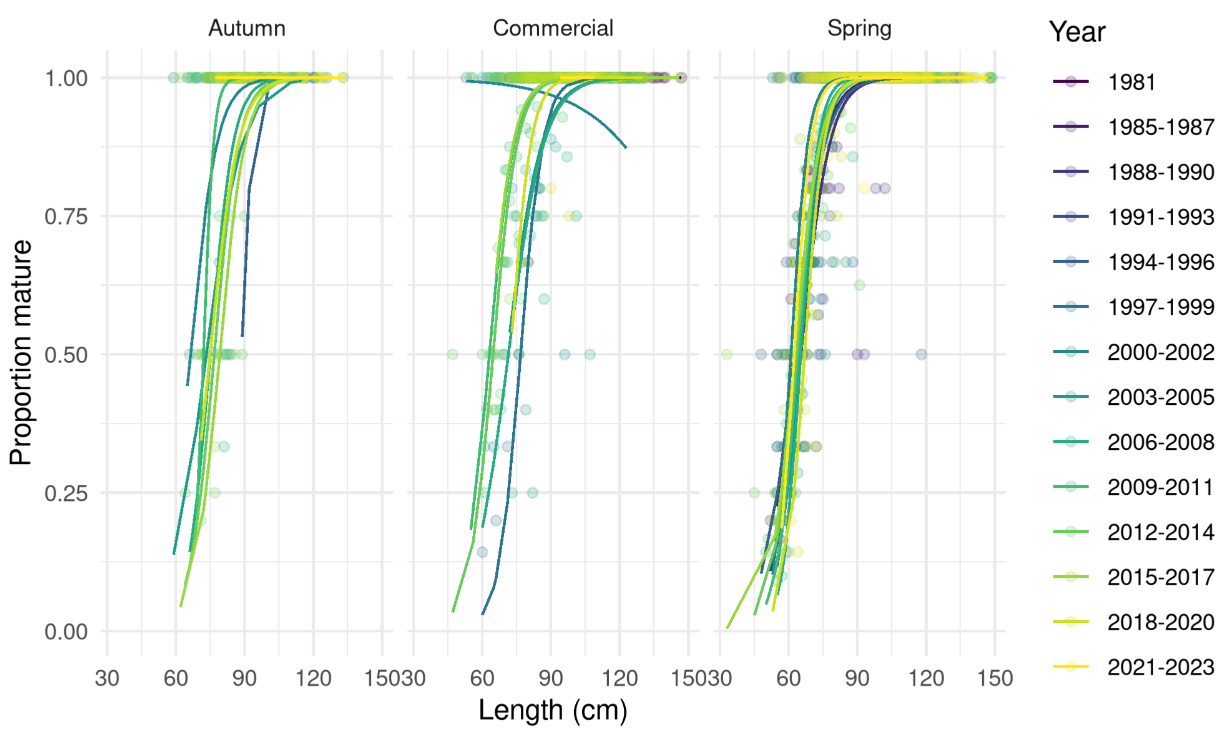

Figure 13: Ling in 5.a. Length at ages of males by year, plotted as boxplots with logistic maturation ogives overlaid where model fits were possible.

of fish stored aboard the vessel matches what has been recorded in the logbooks, in part to act as a deterrent for potential illegal and unrecorded landings.

Nearly all ling is landed gutted and converted to ungutted using the conversion factor 1/0.80 (see the Directorate of Fisheries website here).

The real gutting factor can vary year to year so the amount of ungutted ling landed may be different than the estimated value. All the bookkeeping of catch is in terms of gutted fish and the reference to ungutted catch is just gutted divided by 0.80 so this does not matter in the assessment.

Discards are illegal in Icelandic waters but are assumed to take place to some degree. A discard monitoring program of the MFRI, designed to estimate high-grading of cod and ling, has been in place since 2001, but no estimates of discards exist for ling in Icelandic waters.

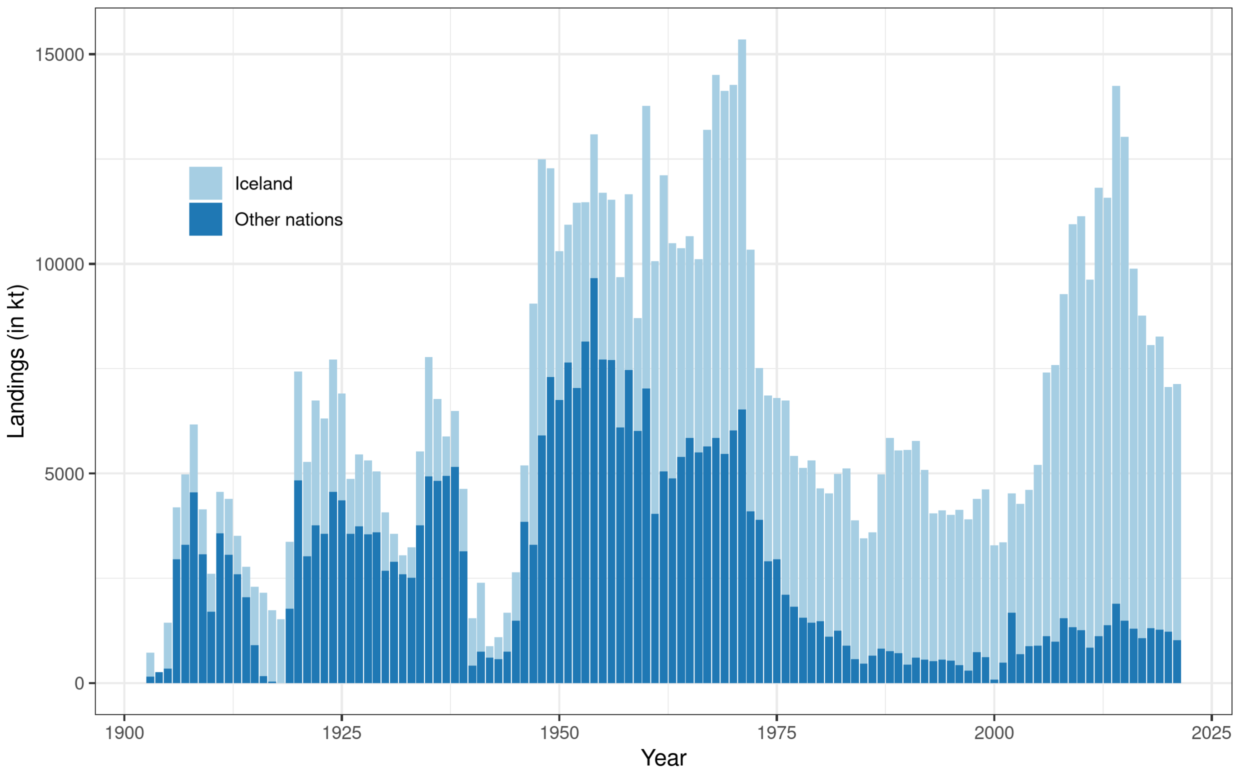

Figure 14: Ling in 5.a. Landings in 5.a.

7.2 Surveys

7.2.1 Research cruises

Information on abundance and biological parameters from ling in 5.a is available from three surveys, the Icelandic groundfish survey in the spring (IGFS) and the Icelandic autumn survey (IAGS).

The Icelandic groundfish survey in the spring, which has been conducted annually since 1985, covers the most important distribution area of the fishable biomass. The autumn survey commenced in 1996 and expanded in 2000 to include deep water stations. It therefore only covers roughly 1/3 of the shallower water stations that the spring survey includes, and is more appropriate for deeper water species. Most common species found in the cod mixed fishery are represented by the spring survey indices, but if a portion of the population is found in deeper waters, the autumn survey may provide additional information on the development of the stock. The autumn survey has been conducted annually with the exception of 2011 when a full autumn survey could not be conducted due to a fisherman strike. Although both surveys were originally designed to

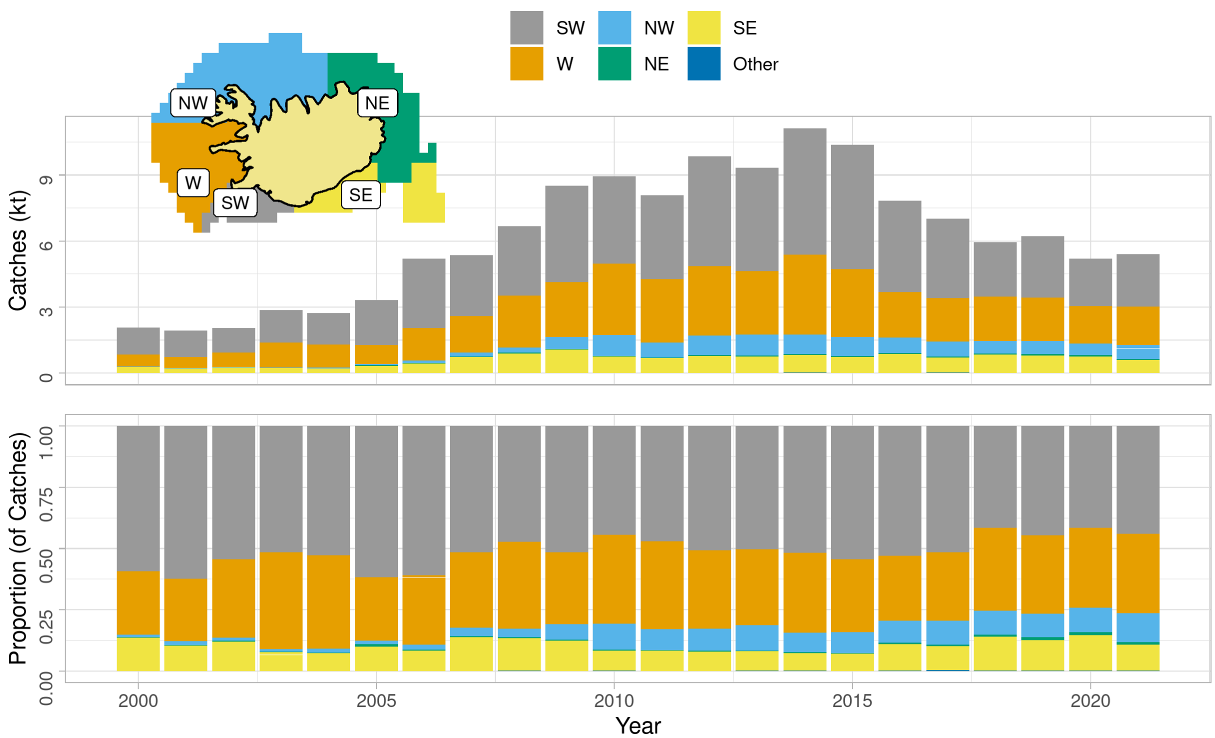

Figure 15: Ling in 5.a. Changes in spatial distribution of the Icelandic fishery as reported in logbooks. All gears combined.

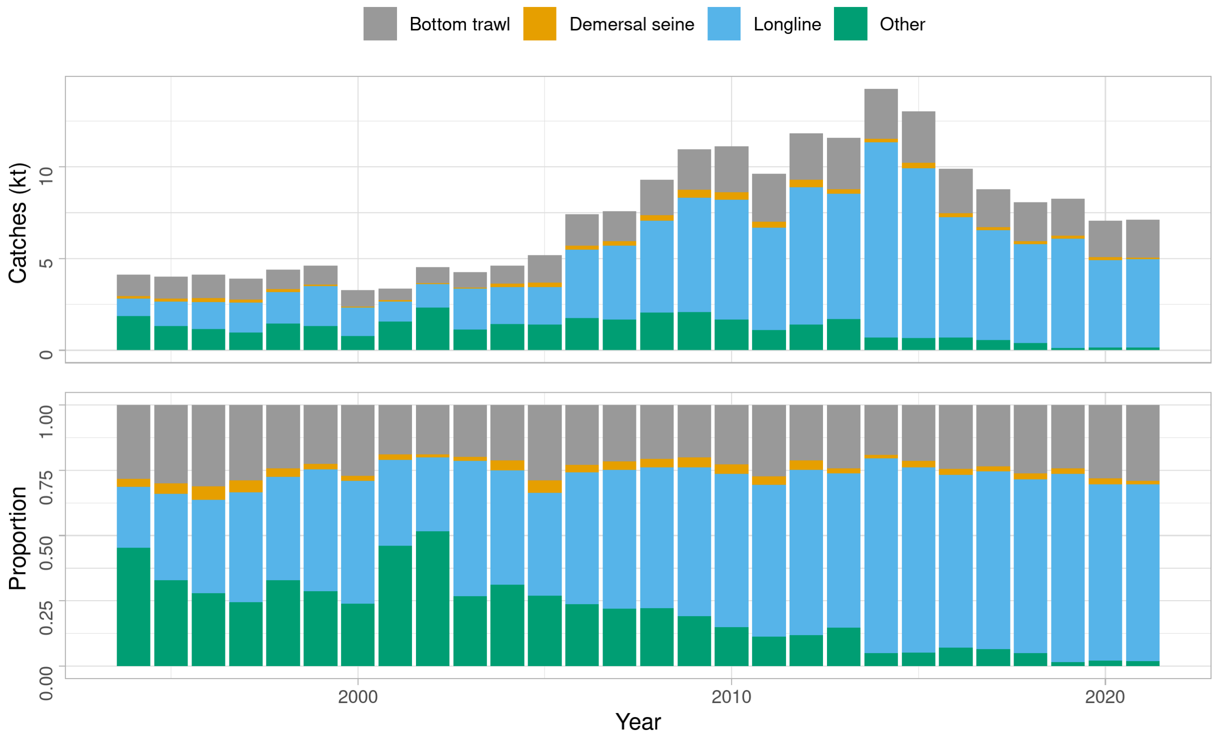

Figure 16: Ling in 5.a. Commercial landings by gear as registered in landings data.

monitor the Icelandic cod stock, the surveys are considered to give a fairly good indication of the fishable stock. In addition, a gillnet survey is conducted in areas closer inshore every April during cod spawning periods, designed to sample the cod spawning stock (Fig. 17. Detailed descriptions of the Icelandic spring and autumn groundfish surveys and the April gillnet survey are given in Sólmundsson et al. [22], ICES [10]. Fig. 18 shows both a recruitment index and the trends in various biomass indices. Changes in spatial distribution observed in the spring survey is shown in Fig. 19. The figure shows that a larger proportion of the observed biomass now resides in the west and southwest regions off Iceland, where most of the fishing occurs.

7.3 Weights, maturities, growth

Biological data from the commercial longline and trawl fleet catches are collected from landings by scientists and technicians of the Marine and Freshwater Research Institute (MFRI) in Iceland. The biological data collected are length (to the nearest cm), sex and maturity stage (if possible since most ling is landed gutted), and otoliths for age reading. Most of the fish that otoliths were collected from were also weighed (to the nearest gram).

Sampling from commercial catches of ling is considered good; both in terms of spatial and temporal distribution of samples (Figs. 20, 21). Commercial age readings are available in 1981 - 1983,1994, and 2008 - present (Fig. 22).

In the scientific surveys, length data are available from all three considered (spring, autumn, and April), weight and maturity data are available only from the trawl surveys (spring and autumn), and age readings are only available from the spring survey, mainly from 1985, 1990-1991, 1995, and 2000-present (Fig. 23.

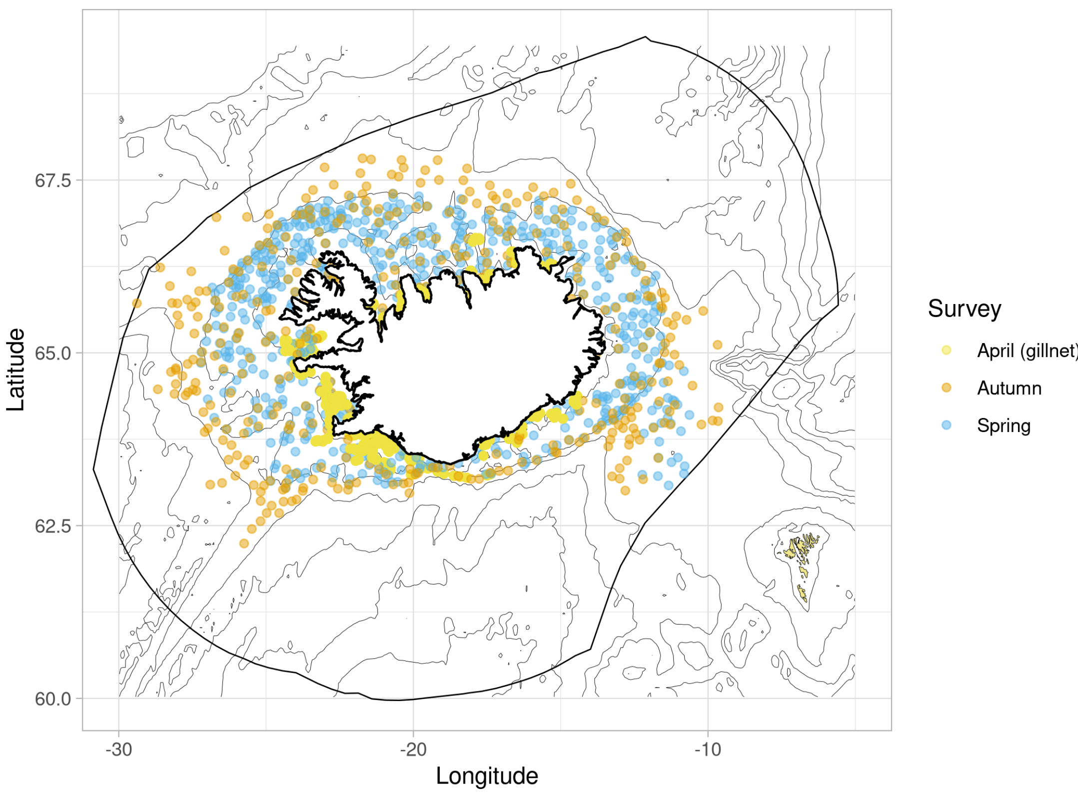

Figure 17: Ling in 5.a. Ling in 5.a and 14. Survey stations collected in a typical year (2021) from each of the three surveys.

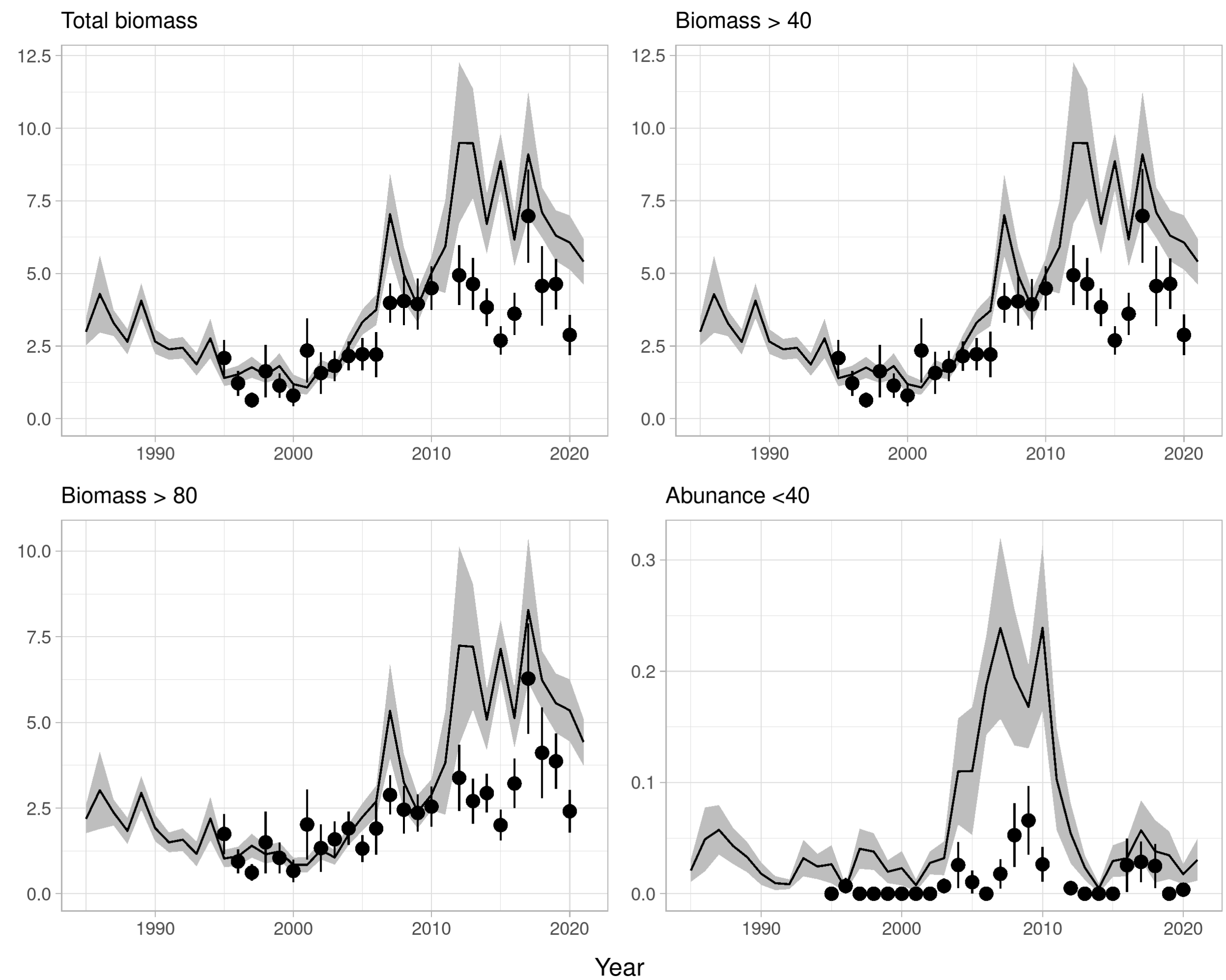

Figure 18: Ling in 5.a. Biomass trajectories from the spring and autumn surveys.

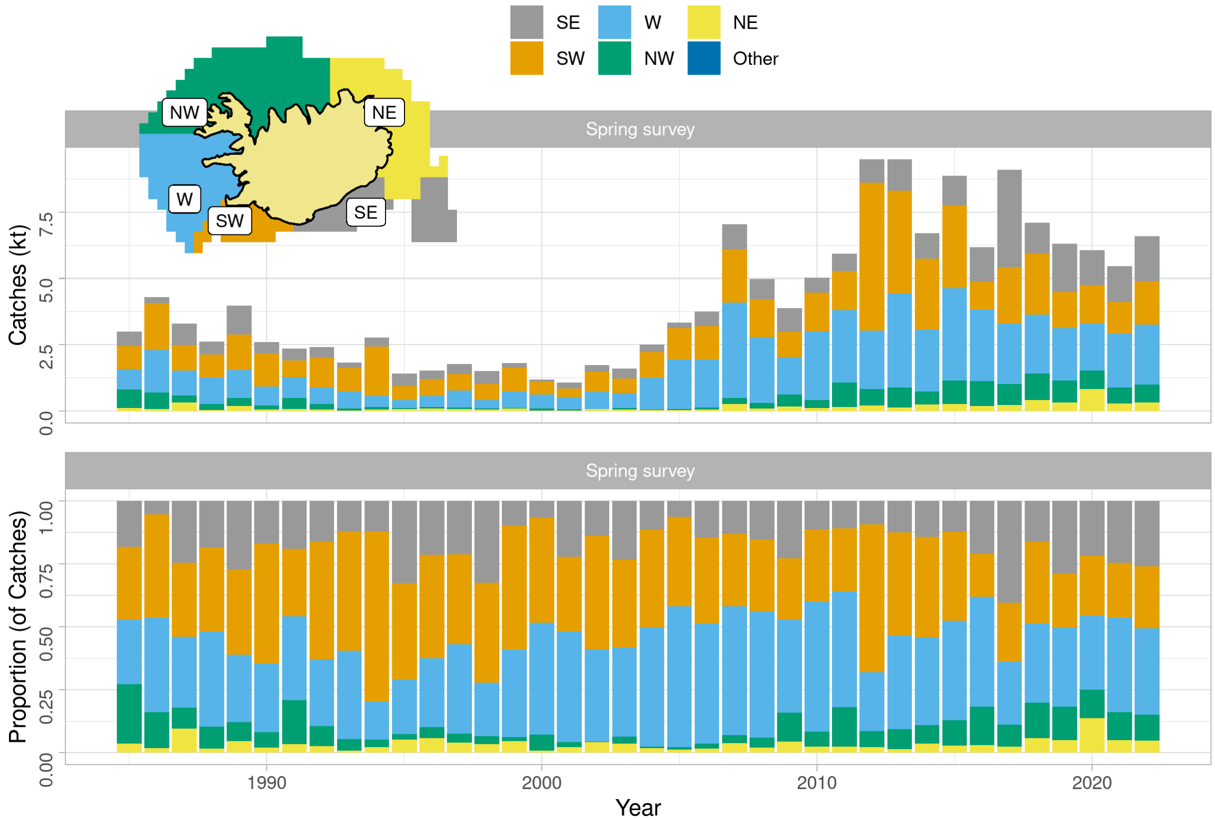

Figure 19: Ling in 5.a. Biomass by area from the spring survey.

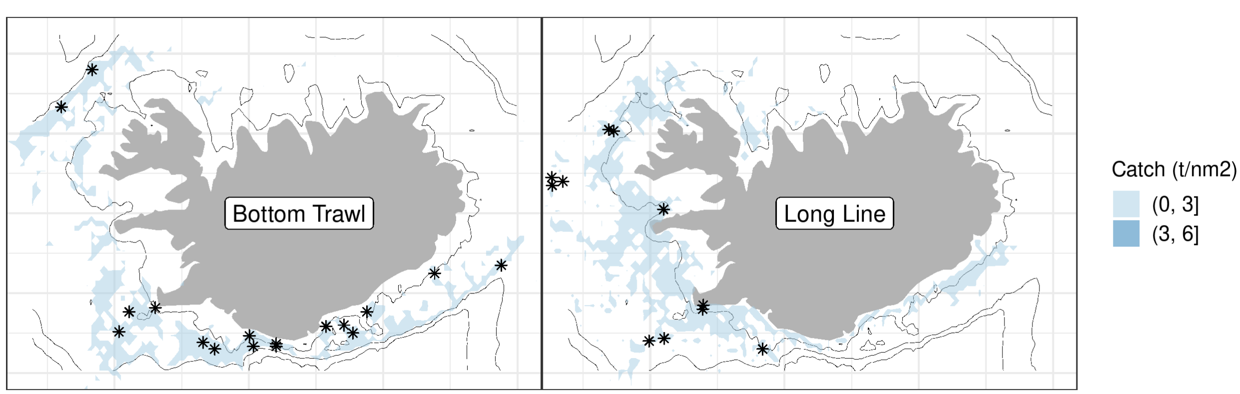

Figure 20: Ling in 5.a. Fishing grounds in 2021 as reported by catch in logbooks (tiles) and positions of samples taken from landings (asterisks) by longliners and trawlers.

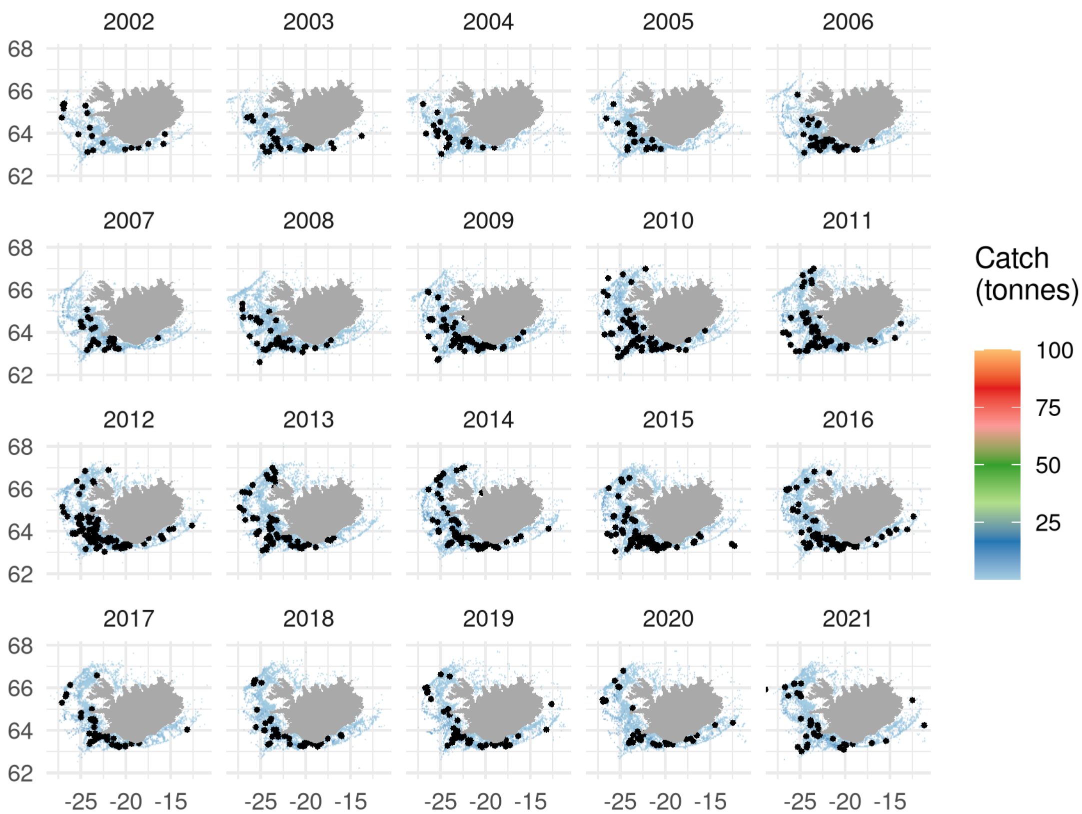

Figure 21: Ling in 5.a. Fishing grounds across years as reported by catch in logbooks (tiles) and positions of samples taken from landings (asterisks) by longliners and trawlers.

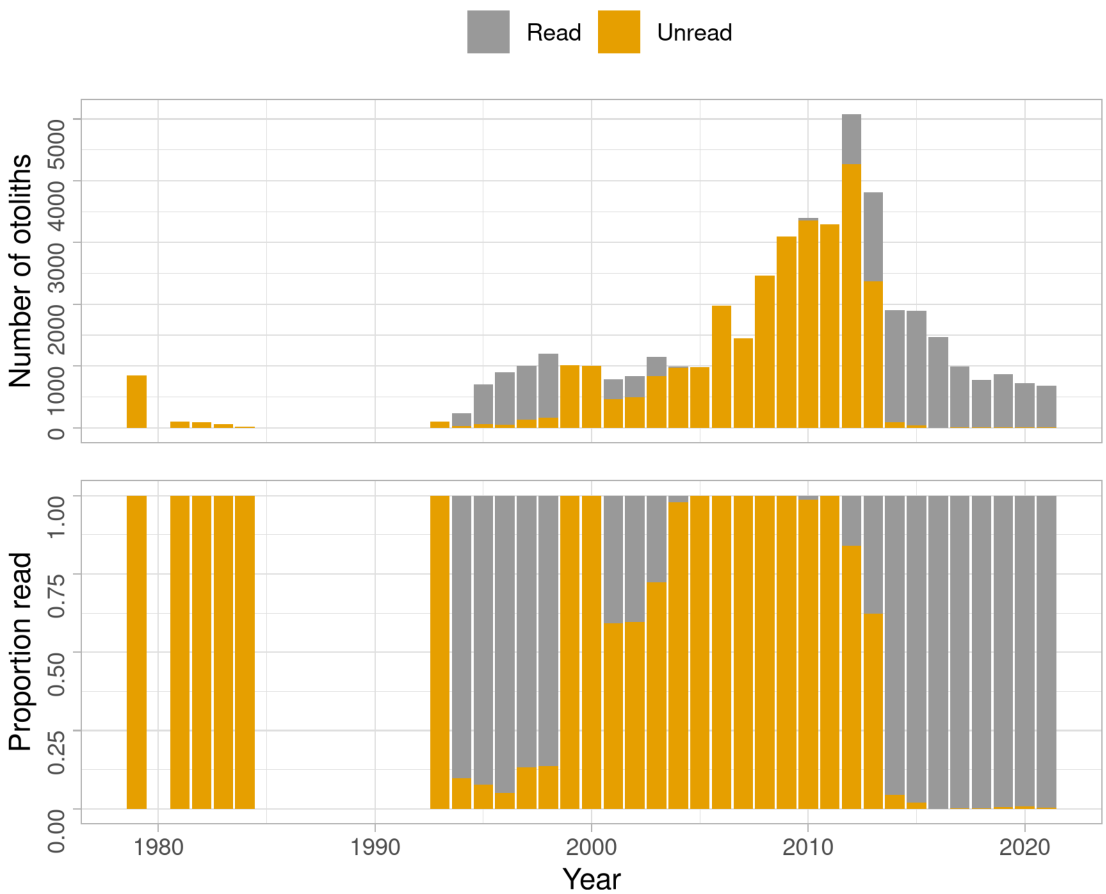

Figure 22: Ling in 5.a. Total number of otoliths read versus unread from commercial samples (upper panel) as well as their proportions (bottom panel).

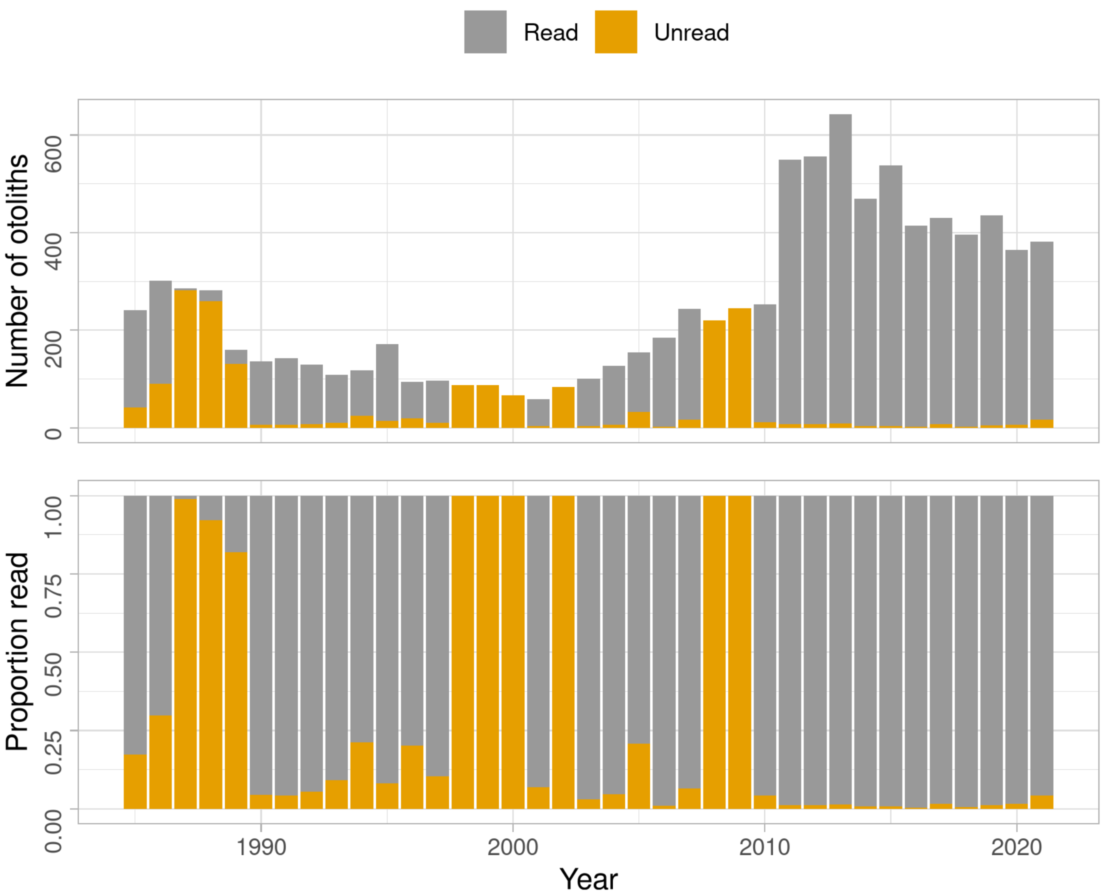

Figure 23: Ling in 5.a. Total number of otoliths read versus unread from spring survey samples (upper panel) as well as their proportions (bottom panel).

7.4 Growth

Fish weights at length are available from both surveys and commercial data (Figs. 24 and 25). Stock weights were calculated as the mean weight at age taken from the spring survey in March, after converting lengths to weights using an estimated power relationship from fish with both length and weight data collected in both survey and commercial samples. Weights are calculated as the mean weight expected from the length distribution observed for that year. Before 1985, survey data were replaced with catch weight data, which are available from 1980. Where weight at a certain age were missing which occurred only in very rare cases, data from the other data sources were used to fill the gap.

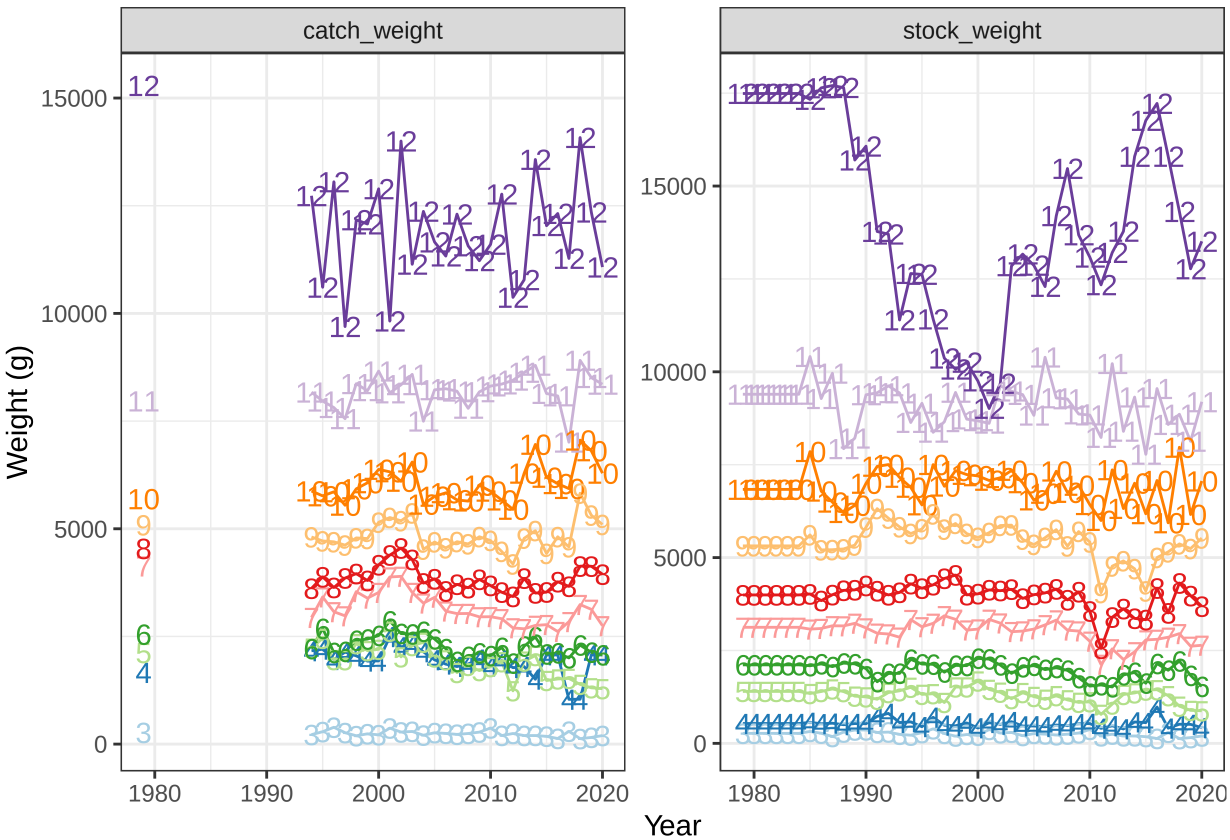

Figure 24: Ling in 5.a. Weight at age observed in the spring survey and from the commercial catches.

7.5 Maturities

Ling in Icelandic waters are mature at the age of 5-8 years and 60-80 cm total length. Females slightly grow faster and live longer than males. The main spawning area is along the edges south, southwest and west of the Icelandic continental shelf in May to June.

Maturity-at-age data are given in Figs. 26 and 27. Maturity at age data was taken from the spring groundfish survey in March, calculated based on maturity at length each year and length distributions of fish assigned to each age. This was done annually to account for annual variation in maturity ogives and growth. As maturity data are randomly sampled in surveys at the same rate across all regions of Iceland, calculating a mean maturation across all sampled fish takes into account regional differences in maturation. However, this should be compared with regionally defined maturation keys. Where no observations occurred for a specific length group (rare), predictions from a model including all years was used to fill the gap. Prior to 1985 the proportion mature is assumed fixed at 1985 levels.

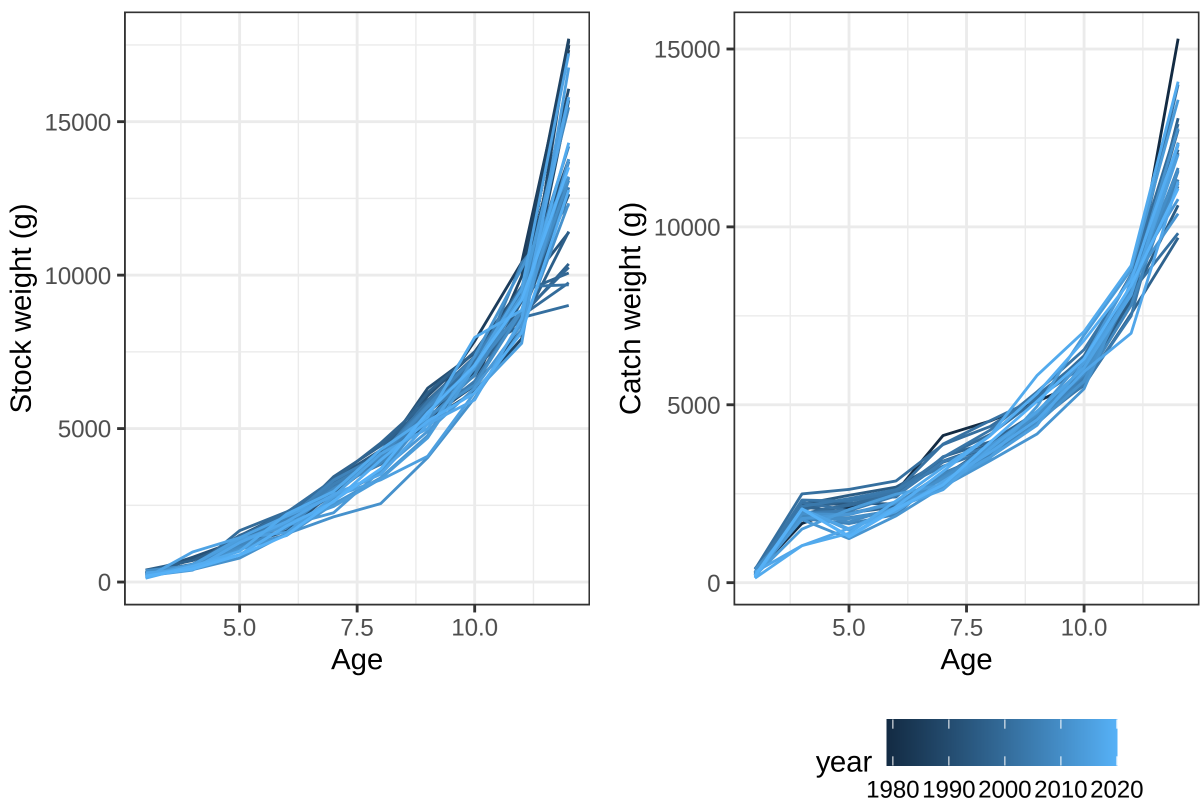

Figure 25: Ling in 5.a. Weight at age observed in the spring survey and from the commercial catches over age.

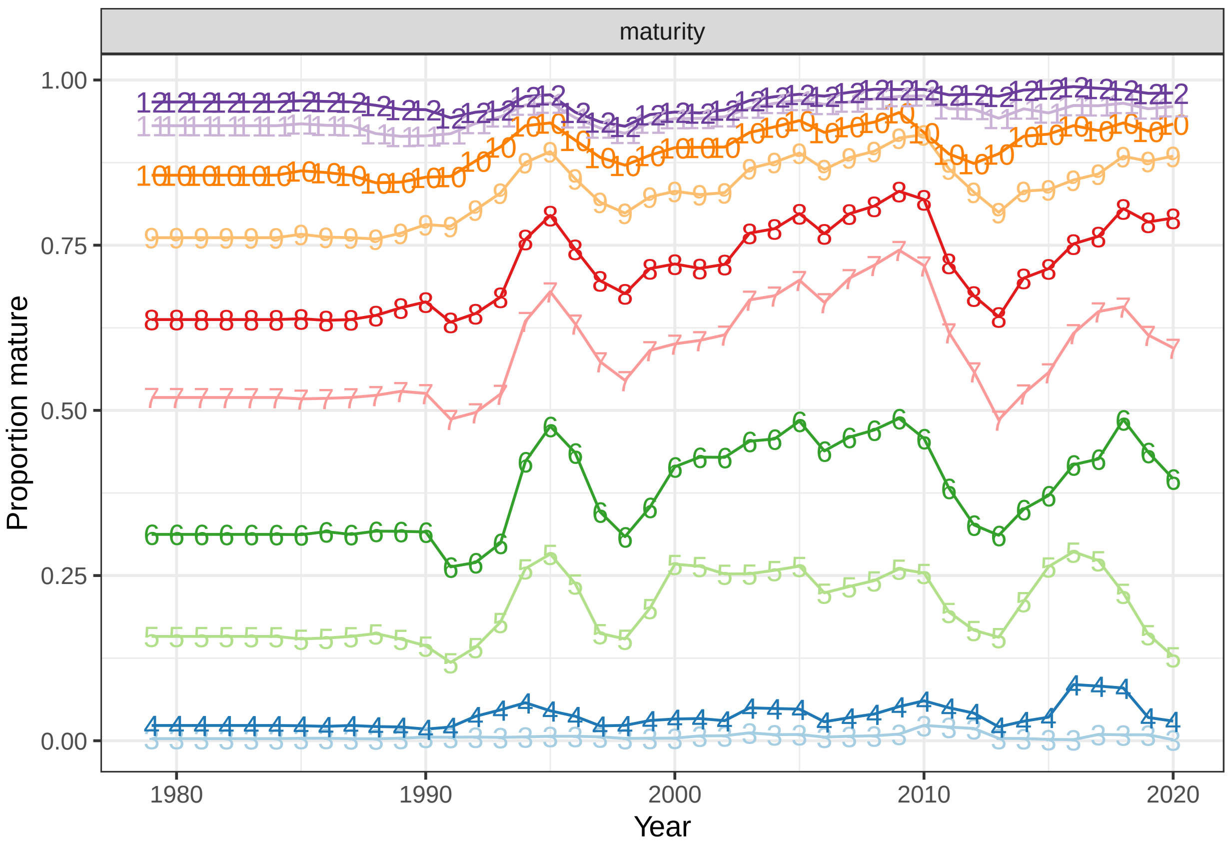

Figure 26: Ling in 5.a. Proportion mature at age from the spring survey.

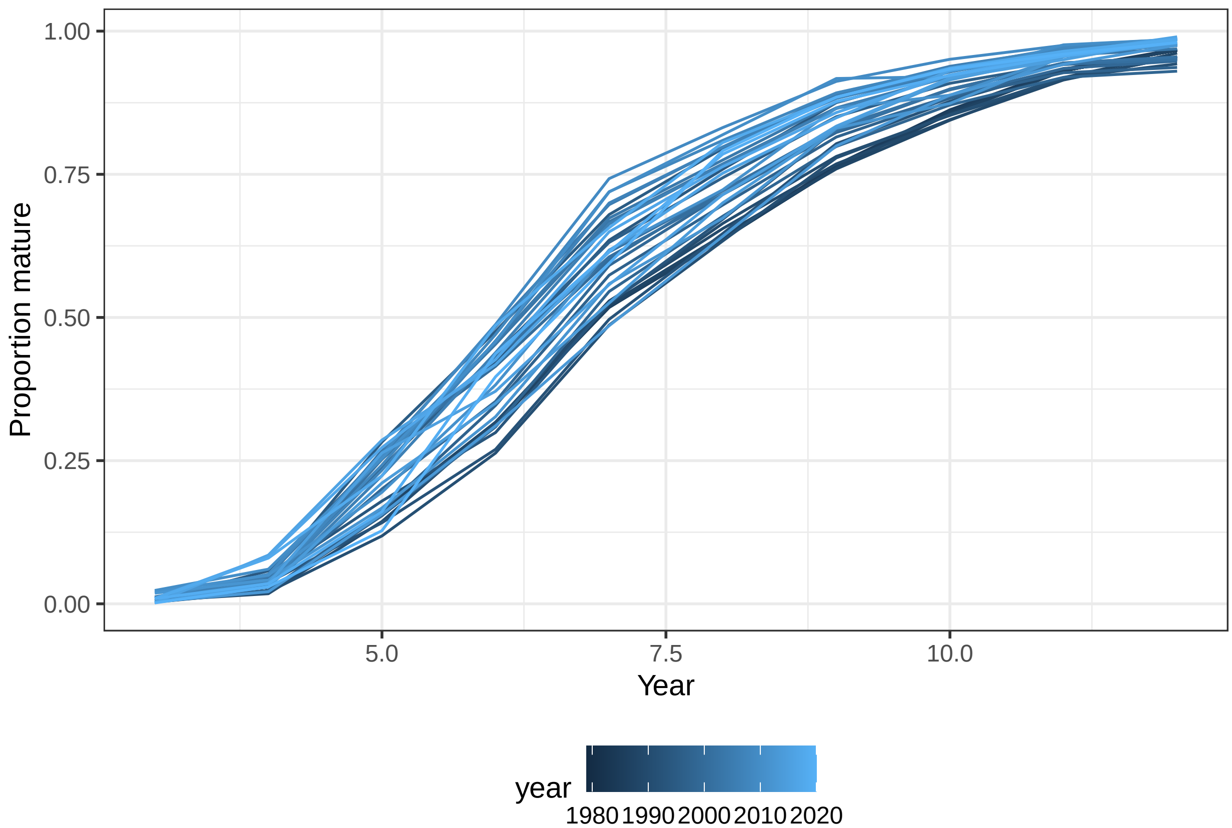

Figure 27: Ling in 5.a. Proportion mature at age from the spring survey over age.

7.5.1 Natural mortality

Natural mortality was set as 0.15 in the models presented here. Alternative formulations have been considered in the results section.

8 Assessment model

Two main modeling frameworks have been explored with ling in Iceland: the current Gadget model and the statistical catch at age State-space Assessment model (SAM, Nielsen and Berg [17], Berg and Nielsen [1]). Here we only present results from the SAM best model chosen to continue with harvest control rule evaluation. Developments in the Gadget model have begun to improve stability but we continue with the SAM modeling framework as retrospective patterns appear less at this time.

Therefore, an age-based assessment was developed using SAM (Nielsen and Berg [17], Berg and Nielsen [1]). The model runs from 1979 onwards and ages 2 to 12 are tracked by the model, treating age 12 as a plus group. Observations in SAM are assumed to arise from a multivariate normal process with an expected value derived from the model. SAM allows for the investigation of how to treat patterns in the residuals by defining different parameters by age for observation residual variances and correlations for all data sets. Furthermore, the user can define age groups for survey catchabilities, and related power relationships, and process variances for the $\log(N)$ and $\log(F)$ residuals.

SAM model development began with ALK refinement and choice of model age structure that emphasized correlations among consecutive cohort observations within catch-at-age and survey index data. Generally, the youngest ages were maintained while largest ages were grouped when correlations among consecutive ages declined, likely as a result of ageing error. The previous Gadget model used 11 as a plus group; here we have extended this to age 12. Any further extensions began to have a greater influence of sparse and more error-prone age readings (see next section).

Initial explorations were then used to find the most important configuration settings for stability in optimization and model fit. Model choice was based on minimizing AIC, while avoiding configurations for which there was little biological support. The set of models considered was created using an informed shotgun method for comparing several models with minor adjustments to configuration settings determined as those that had the greatest impact on AIC reduction. These settings included some combination of varying the pattern of linkages among ages of log observation error variances estimated, the pattern of power parameter in non-linear catchability relationships, the pattern of correlations among ages when AR(1) correlations were included in residuals, and the pattern of F variances estimated. Further parameter refinement was done through examination of residual patterns. Configurations with power relationships in catchability, correlations in catch residuals, and linkages of the recruitment process variance parameter with older ages were initially considered to marginally fit the data better, but were excluded due to a lack of theoretical reasoning supporting such configurations. In general, the best model chosen had one of the lowest AIC values, but small increases in AIC were tolerated to reduce the number of parameters when differences between estimated parameter values were unlikely to be significant. Starting values were jittered to test for stability in model outcomes.

8.1 Input data

Spring survey length and age data ranged from 1985 through 2021, ranging from age 1. The spring survey indices at length are converted to age using age-length keys (ALKs). Survey indices at age were generated from the spring survey data using standard stratification procedures (ICES [10], Fig. 30). Age-length keys (ALKs) were created and applied within regions to account for regional growth differences. All ALKs were created using 5 cm length bins from 20 - 155 cm, with longer bins at length 0 –10 and 155+. Length data are available from 1985, and reliable age data are available from roughly 2005, but are sparse before then. Annual age-length keys were applied from 2010 onwards to account for annual differences in growth, but before this period, a single ALK was created from all age data available through 2009 due to constraints in age data availability. In addition, to counter sparse age readings at the largest and smallest sizes, ALKs for fish length 110 cm and greater or less than 40 cm were based on all years of data combined. ALKs were created and applied within regions to account for regional differences. Lagged correlations among adjacent ages in the spring survey indices indicate that the indices are highly informative for tracking cohorts (Fig. 31).

Autumn survey indices at length and age were available from 2000 using a standard stratification procedure. Extensions to the survey were added in 2000 so 1996 - 1999 data were excluded (Fig. 32). Most ages are not read from this survey, so ALKs from the spring survey were used, but adjusted to apply to the previous year and age group after preliminary analyses indicated better alignment with commercial age samples taken at the same time as the autumn survey was conducted. Lagged correlations among adjacent ages in both the autumn indices indicate that the indices are highly informative for tracking cohorts (Figs. 33).

April (gillnet) survey indices at length and age were available from 2002. Northern extensions to the survey were added in 2002 so 1998 - 2001 data were excluded. ALKs from the spring survey were used directly as this survey occurs directly after that spring survey.

Catch at age and total landings are available from the 1970s, but only those from 1979 are used. Annual ALKs were created from 2012 onwards, but age readings were sparse before 2012. Although survey indices are available from age 2, catch data ranged from age 4. ALKs applied to this period were based on all age data combined from 1999 - 2012. ALKs are gear- and season-specific (January - June vs. July - December), and applied to the approximate catch amount caught by the same gear in the same season. Gear groups included 1) trawls and seines, 2) long-lines, handlines, and gillnets, and 3) other gears. Gillnets were included with the long-line group as there were few instances of gillnet age samples. Within year- and gear-specific fishing segments, seasonal groups split the calendar year between January-June and July-December. To avoid overly sparse ALKs, the final ALKs used were a weighted combination of ALKs based on fleet segments (gear- , year- and time-specific groupings, with weight 0.9), and progressively less-segmented ALKs (gear- and year-specific groupings, with weight 0.09, and year-only-specific ALKs, with weight 1 - 0.9 - 0.09). This procedure was done within years (post-2011) or year group (through 2011). Exploratory analysis indicated that ALKs changed very little with its inclusion, but was included to ensure that no data were lost (samples from length bins with no corresponding age data). ALKs were rescaled if necessary to ensure sums to 1 within a length bin.

Catch at age by season-specific fishing segment was then calculated by applying a segment-specific ALK to the length distributions caught by that segment, scaled by their segment-specific catches. Segment-specific catch at ages were then summed across segments to generate a single catch at age per year. This total catch-at-age was used as input (Fig. 28). Due to poor quality data in earlier periods, catch at age data were replaced with a series of total landings (1980 - 1993). Lagged correlations among adjacent ages in the catch at age data indicate that they are highly informative for tracking cohorts (Fig. 29). Age readings from 2021 catch data were not complete at the time of analysis, so this year was excluded.

8.2 Results

8.2.1 Proposed model

Years 1979 - 2021, ages 2 - 12+ (catch data mostly >4). The final model configuration included AR(1) residual correlations estimated (between ages surrounding '/') as two spring survey parameters for ages 2/3–5/6, and 6/7–11/12+ estimated separately, four autumn survey parameters for ages 4/5–5/6, 6/7–7/8, and 8/9–9/10, and 10/11–11/12+ estimated separately, and two gillnet April survey parameters for ages 5/6–6/7 and 7/8–11/12+. Inclusion of the spring survey autocorrelation parameters also increased retrospective patterns but not by a large degree. The maximal age fishing mortality parameter, which is by default fixed to the the same value as next-oldest age, was instead estimated separately. Observation variance parameters were estimated for age groupings $2-5$, $6-10$, and $11-12+$ for catch at age data, $2-3$ and $4-12+$ for spring survey data, 3, and 4 - 12+ for autumn survey data, and all ages with a single variance for April gillnet survey data. Including power parameters in the catchability relationships was explored, and improved the fit to the data very slightly for ages 2 - 6, but were in the end not included due to a lack of biological support for the parameterisation. Instead it was deemed better to maintain a simpler model structure, especially as the improvement to the model fit was very minimal. All other default settings were used.

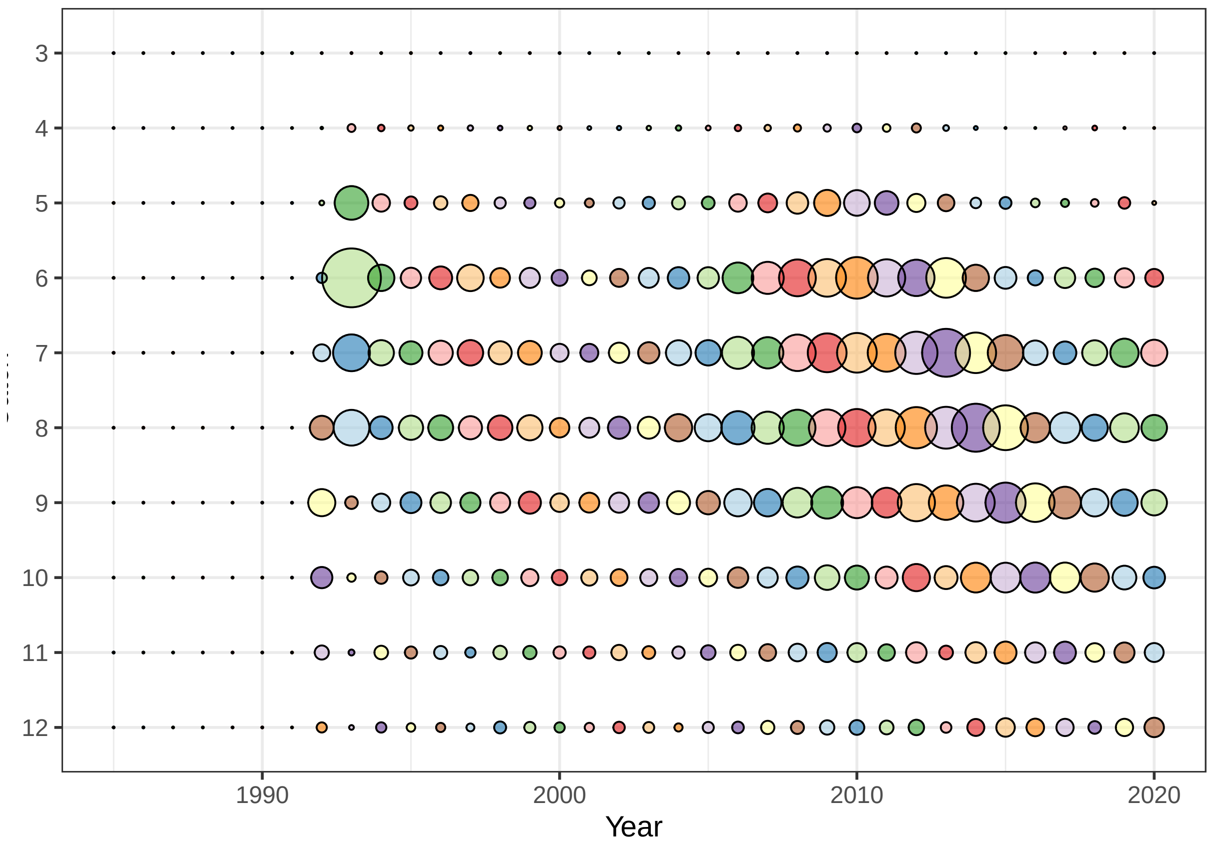

Figure 28: Ling in 5a. Catch at age, point sizes indicate the numbers by age. Points are colored by year class.

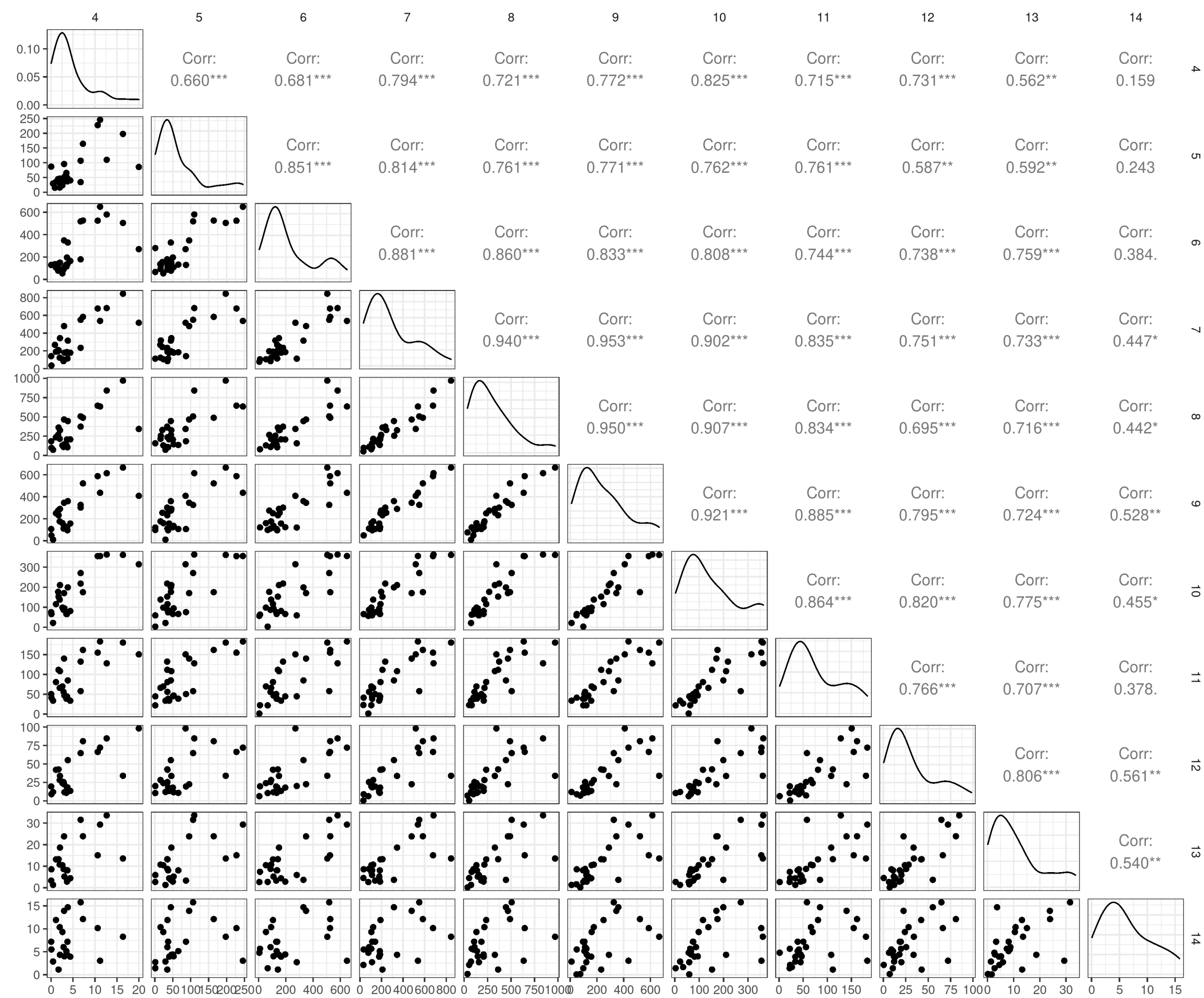

Figure 29: Ling in 5.a. Correlations among observations with a cohort observed at each age in catch at age data.

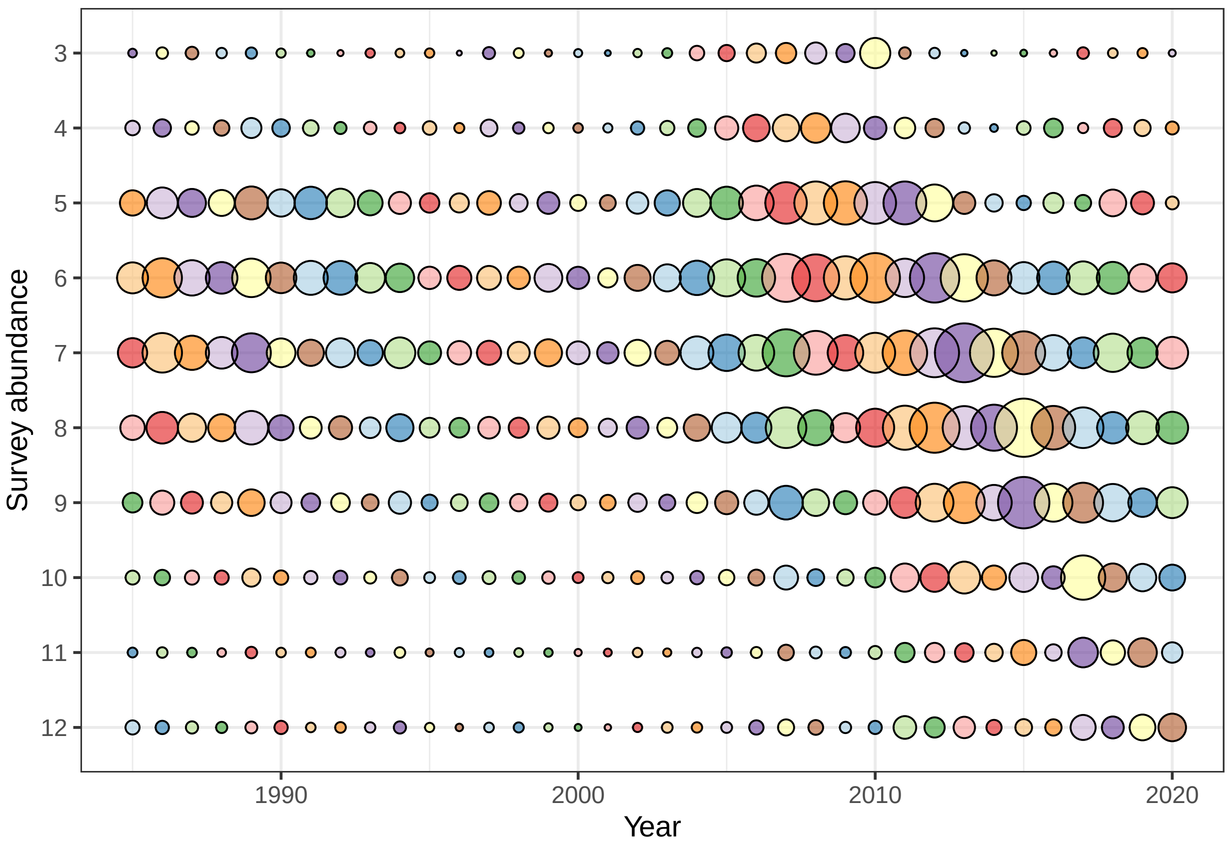

Figure 30: Ling in 5a. Survey numbers at age from the spring survey, point sizes indicate the estimated swept area abundance by age. Points are colored by year class.

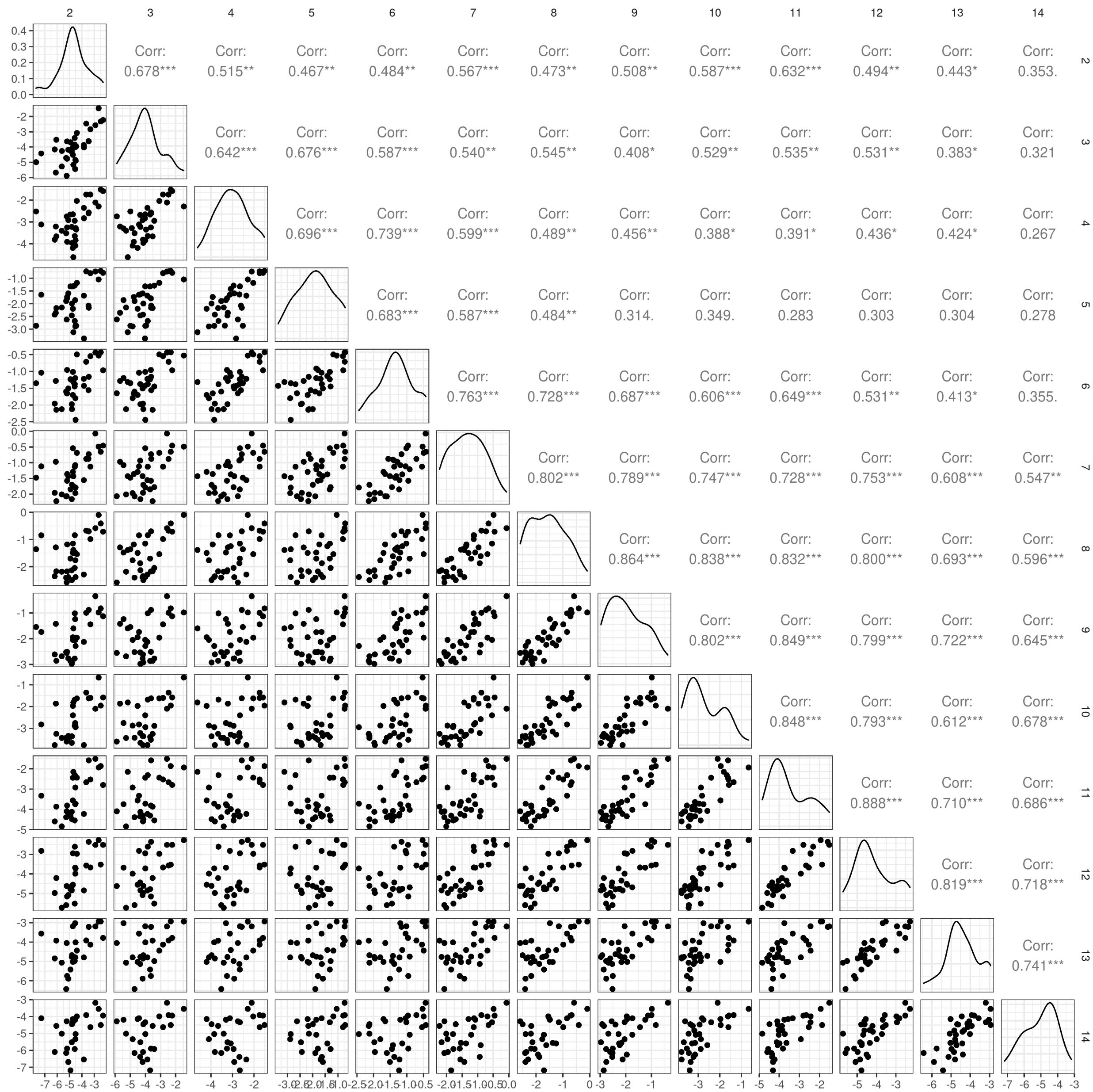

Figure 31: Ling in 5.a. Correlations among observations with a cohort observed at each age in spring survey indices.

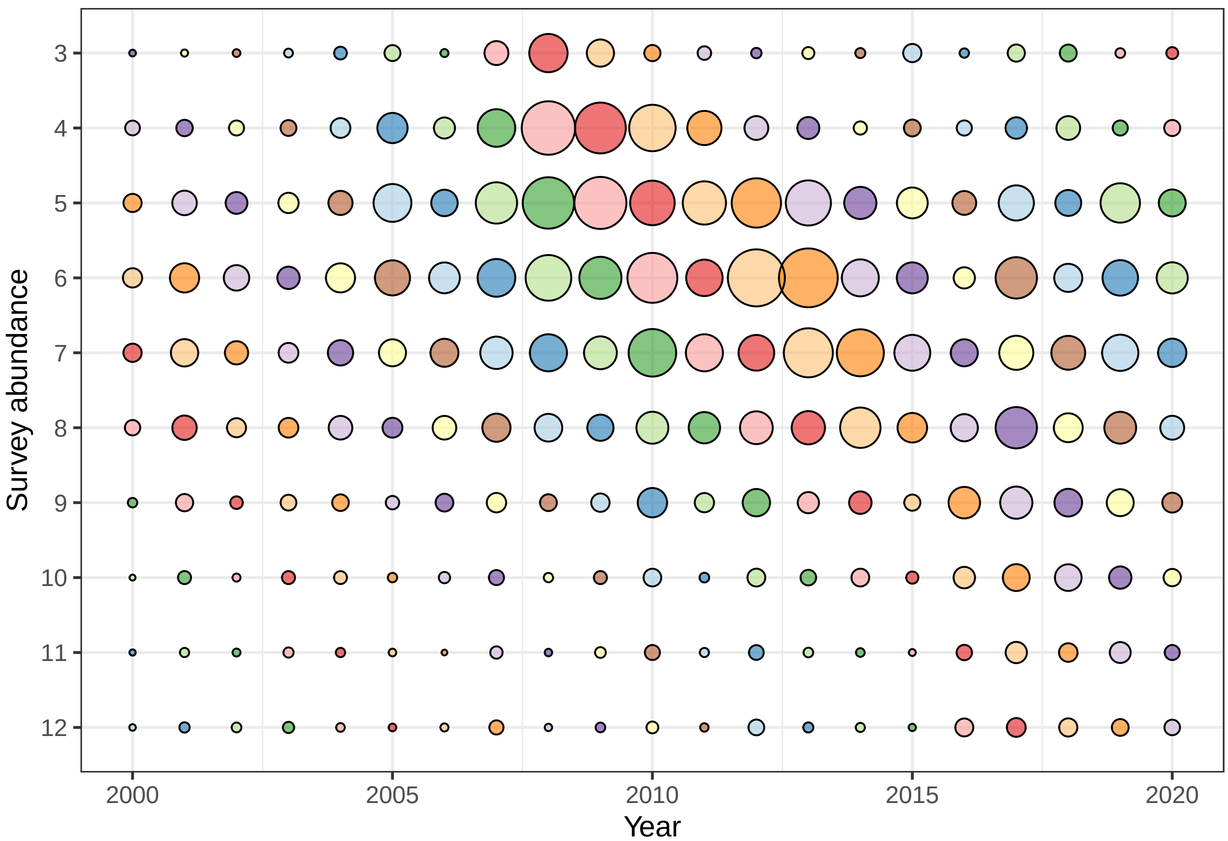

Figure 32: Ling in 5a. Survey numbers at age from the autumn survey, point sizes indicate the estimated swept area abundance by age. Points are colored by year class.

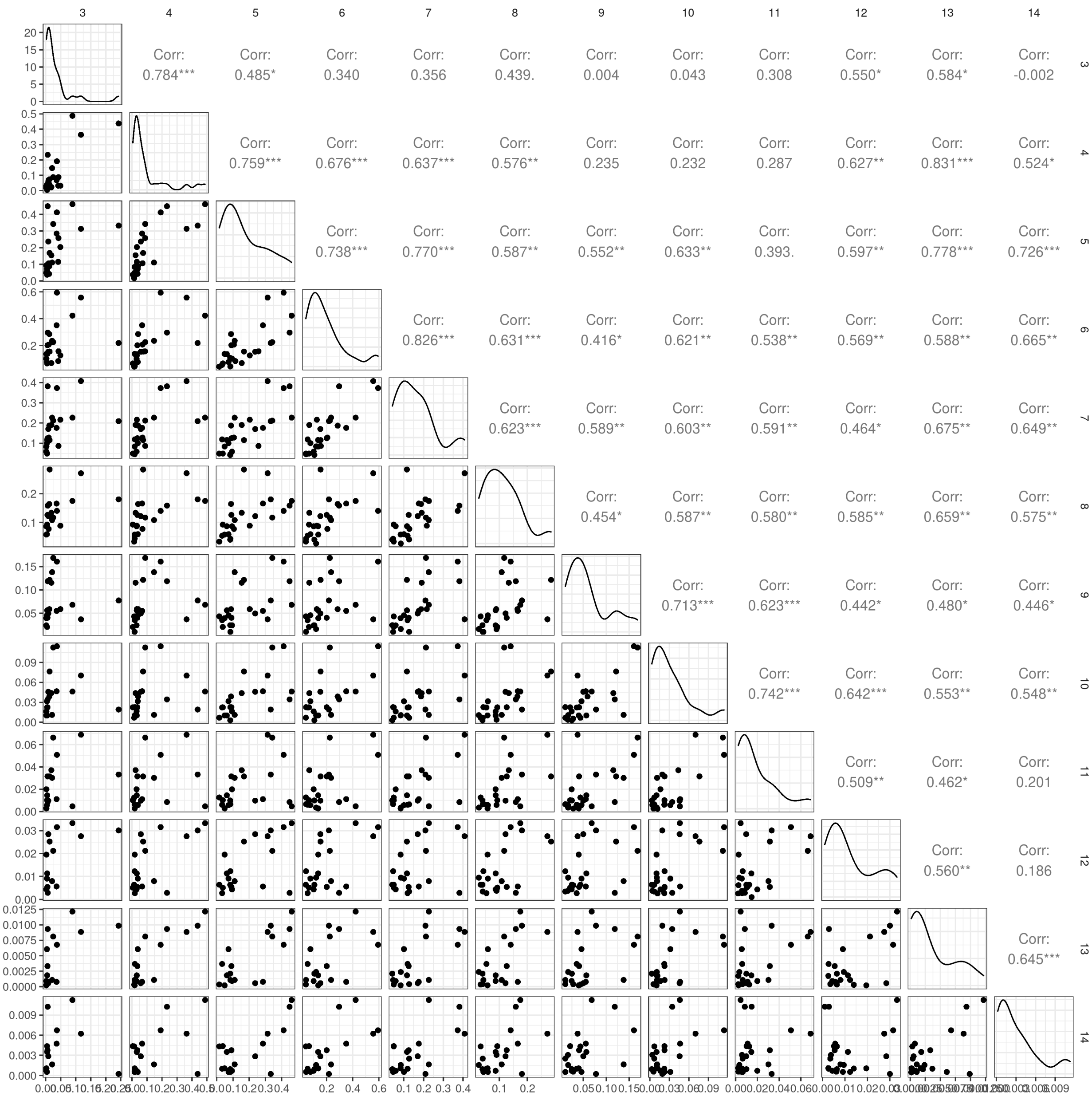

Figure 33: Ling in 5.a. Correlations among observations with a cohort observed at each age in autumn survey indices.

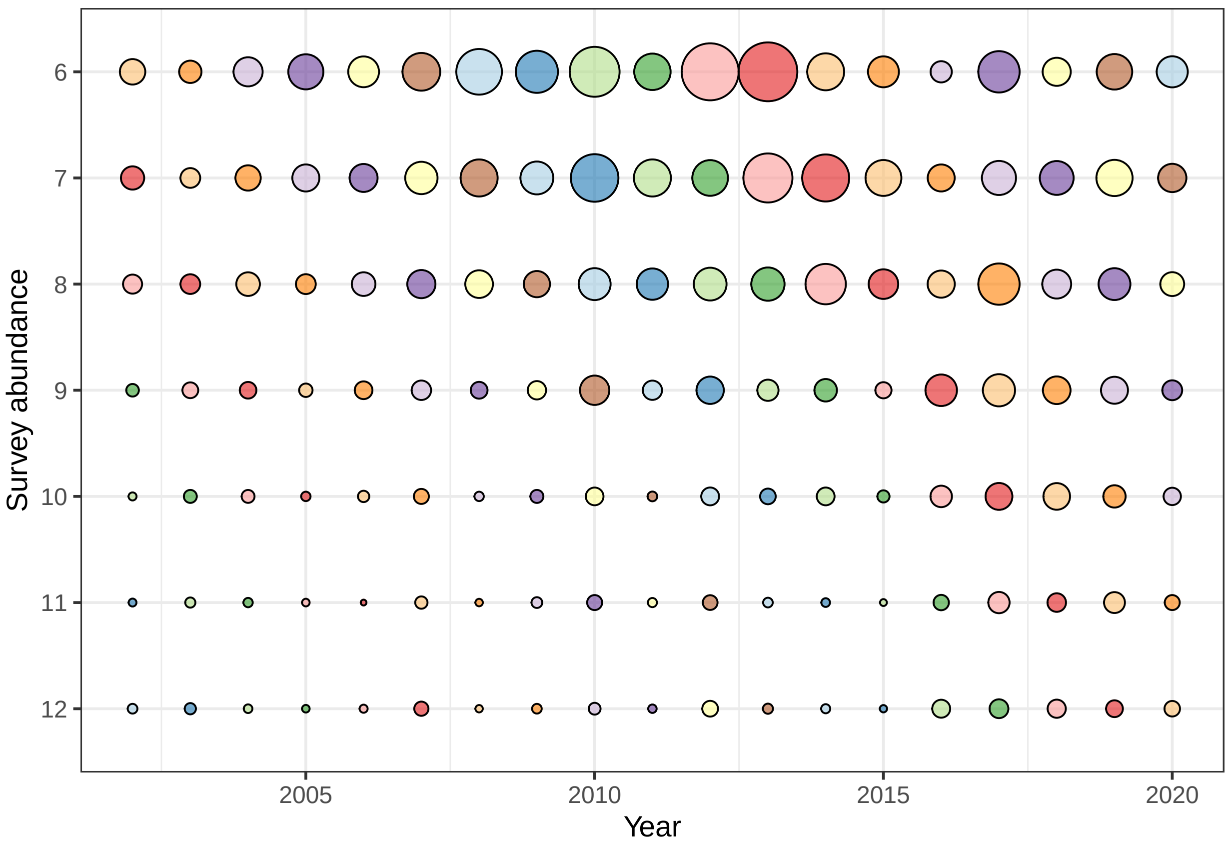

Figure 34: Ling in 5a. Survey numbers at age from the April gillnet survey, point sizes indicate the estimated swept area abundance by age. Points are colored by year class.

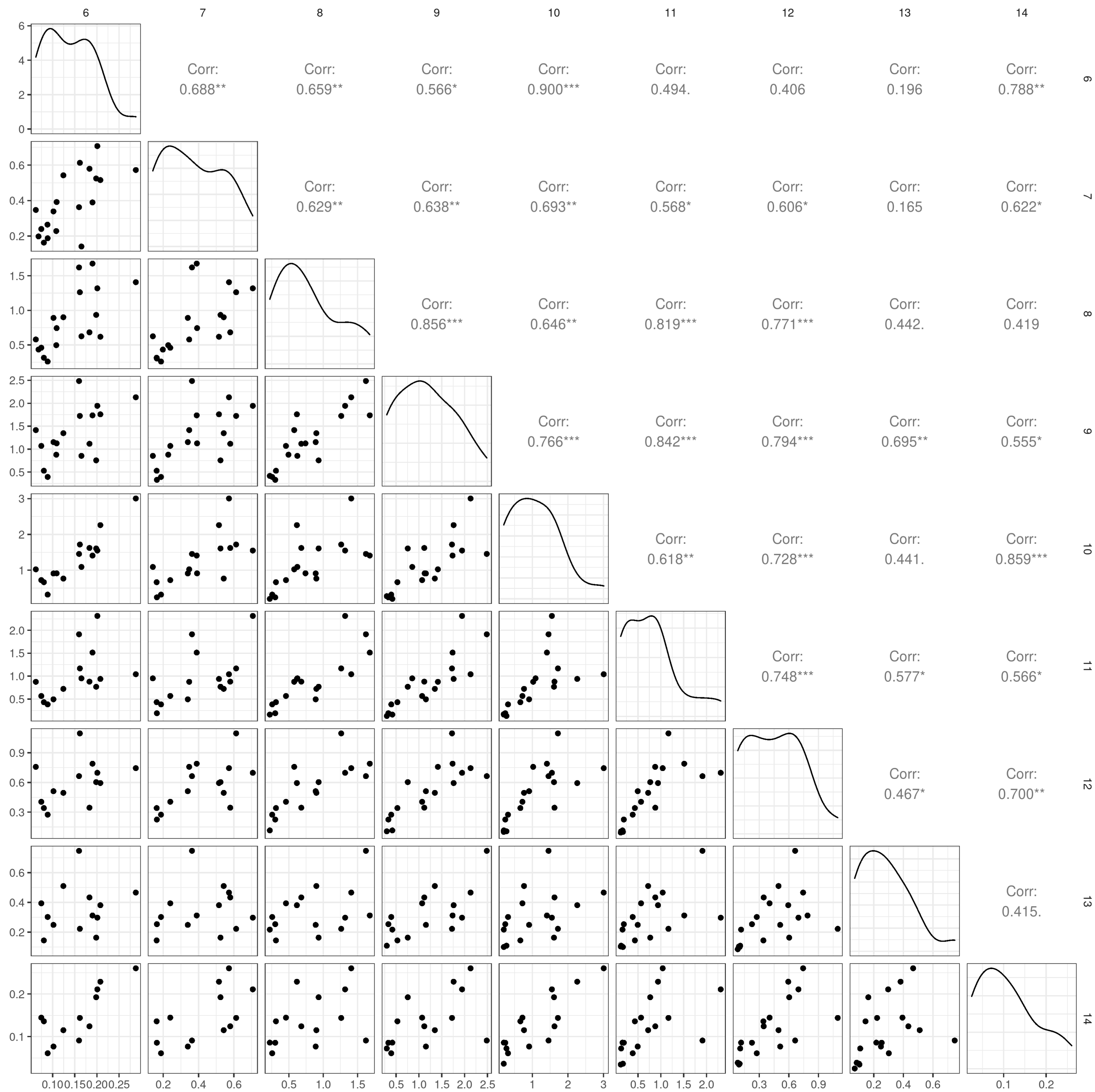

Figure 35: Ling in 5.a. Correlations among observations with a cohort observed at each age in April gillnet survey indices.

8.2.2 Diagnostics

Fits to the catch-at-age data and survey numbers-at-age indices can be found in Fig. 36. The fit to total catch and landings data can be found in Figs. 37 and 38. Note that age 2 and 3 can be found in the bottom two panel rows of Fig. 36 as they are absent from catch data. All data support the presence of a large peak in recruitment during 2005 - 2010, as all data sources have a good fit to these peak cohorts are easily tracked with good fits as they travel through time at into higher age classes. Earlier data on recruitment is only informed by the spring survey data, which are highly variable. Fits to landings data are quite variable, but more recent fits catch at age data are better.

Neither observation nor process residuals show obvious trends (Figs. 39 and 40).

An overview of model parameter estimates can be seen in Fig. 41. Parameters with similar values were joined across ages within data sources if estimates overlapped substantially; therefore those left show appreciable differentiation.

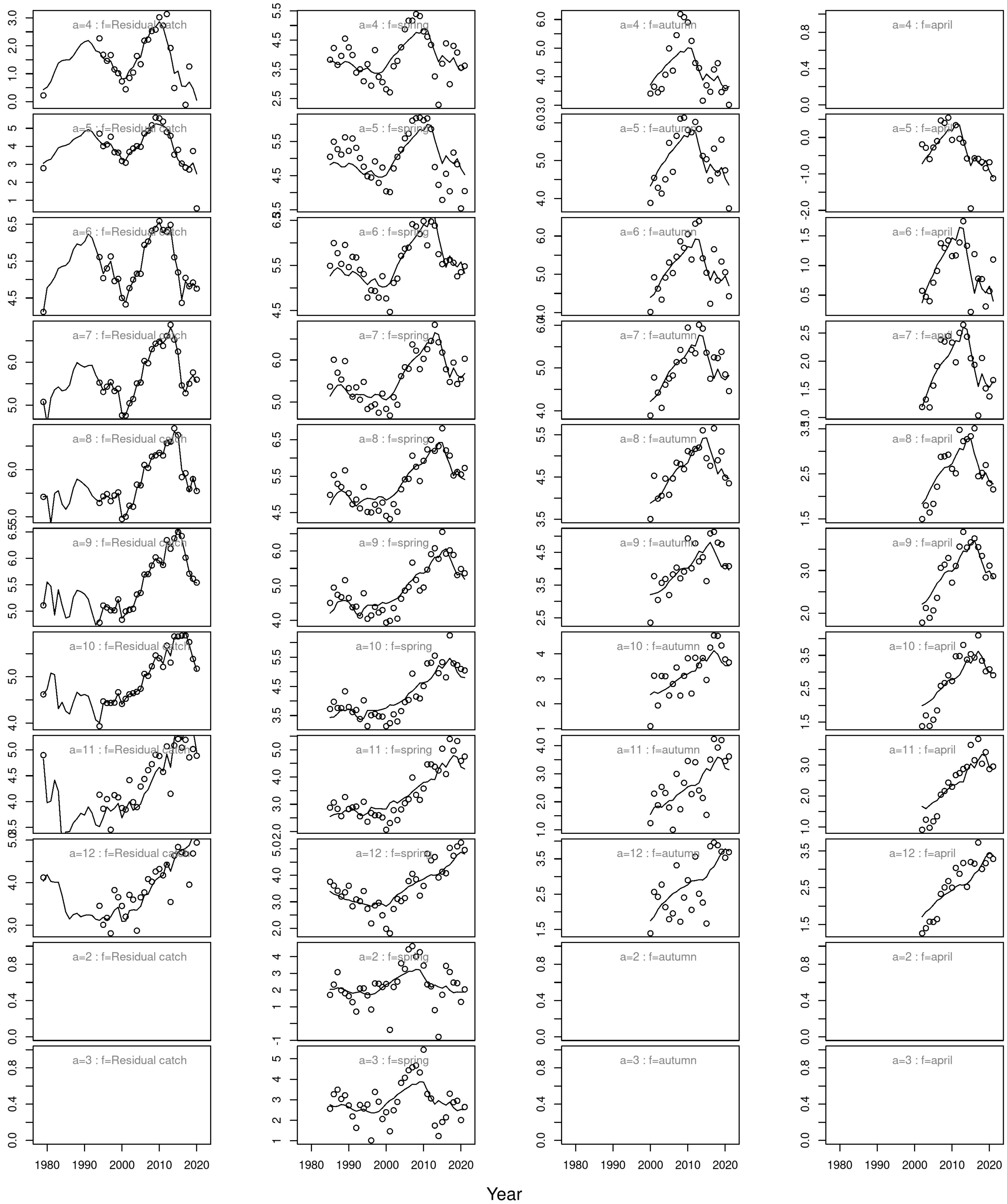

Figure 36: Ling in 5.a. Fit to the numbers at age input data to the proposed SAM model (columns left to right: catch, spring survey, autumn survey, and gillnet (April) survey.

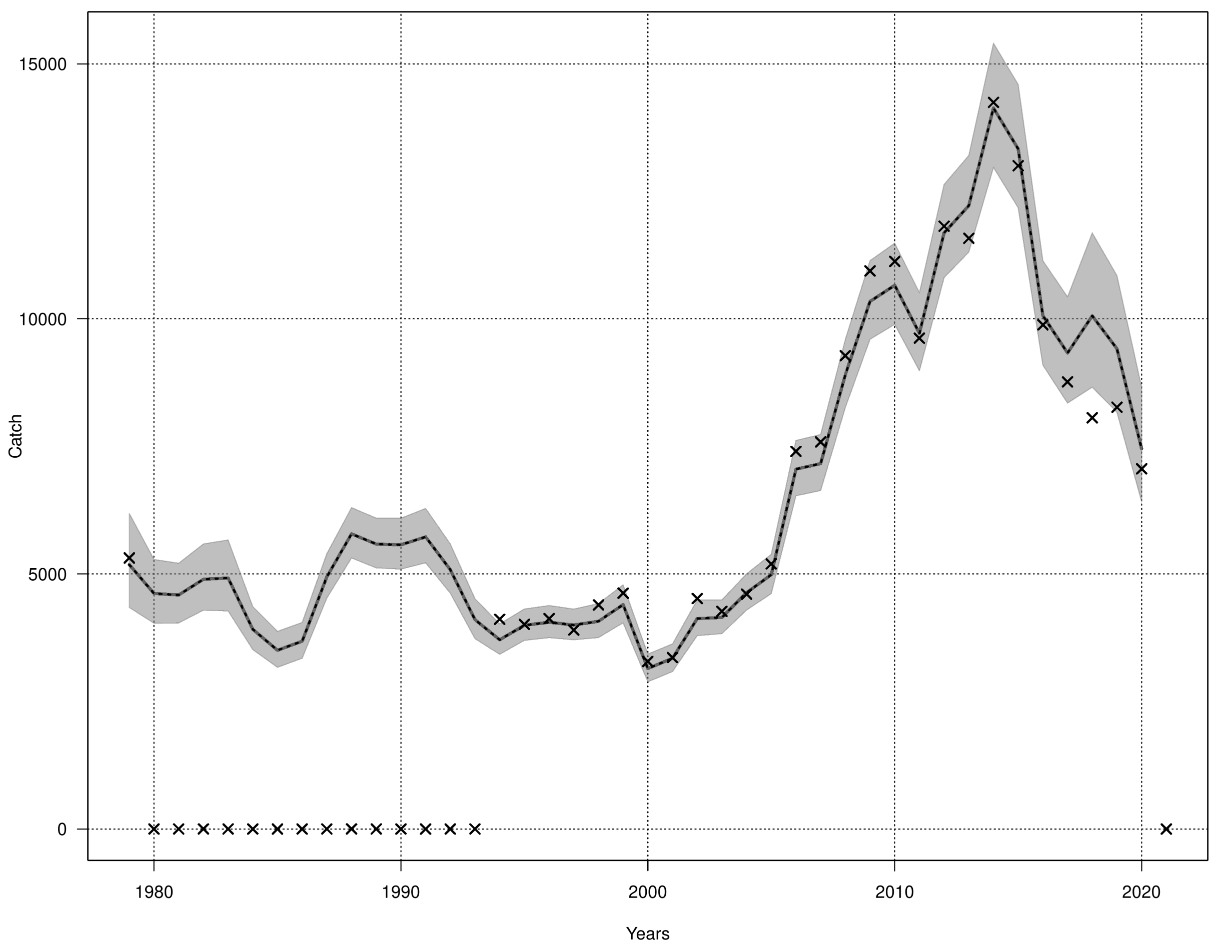

Figure 37: Ling in 5.a. Fit to the total catch in the proposed SAM model.

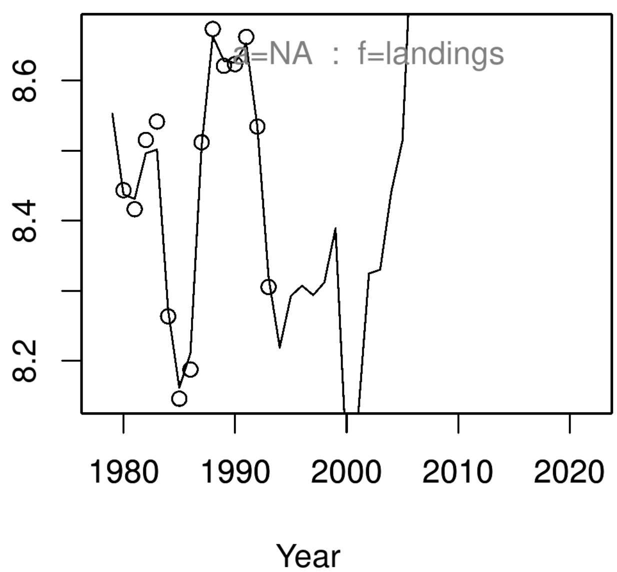

Figure 38: Ling in 5.a. Fit to the landings input data to the proposed SAM model.

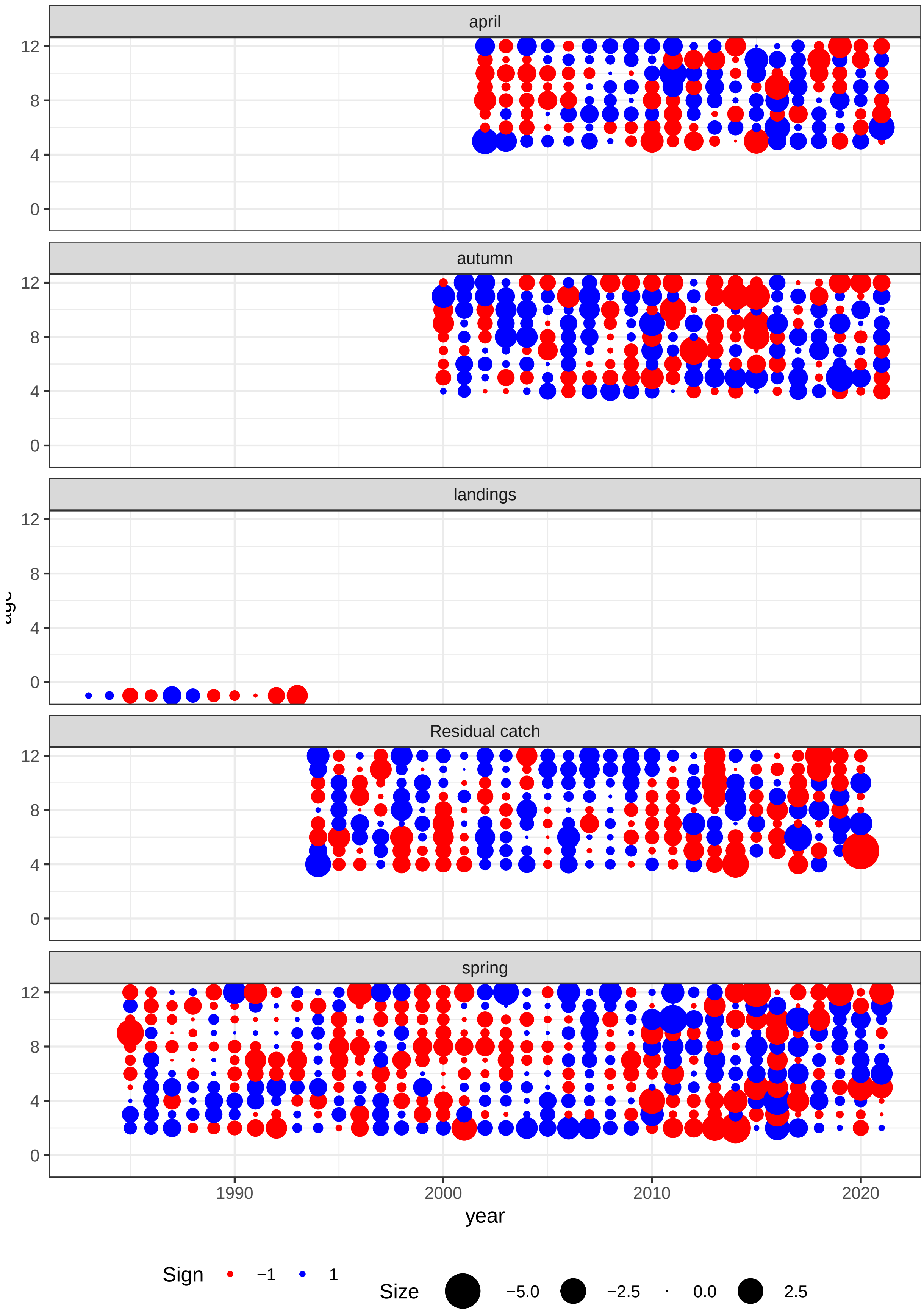

Figure 39: Ling in 5.a. Observation error residuals of the proposed SAM model.

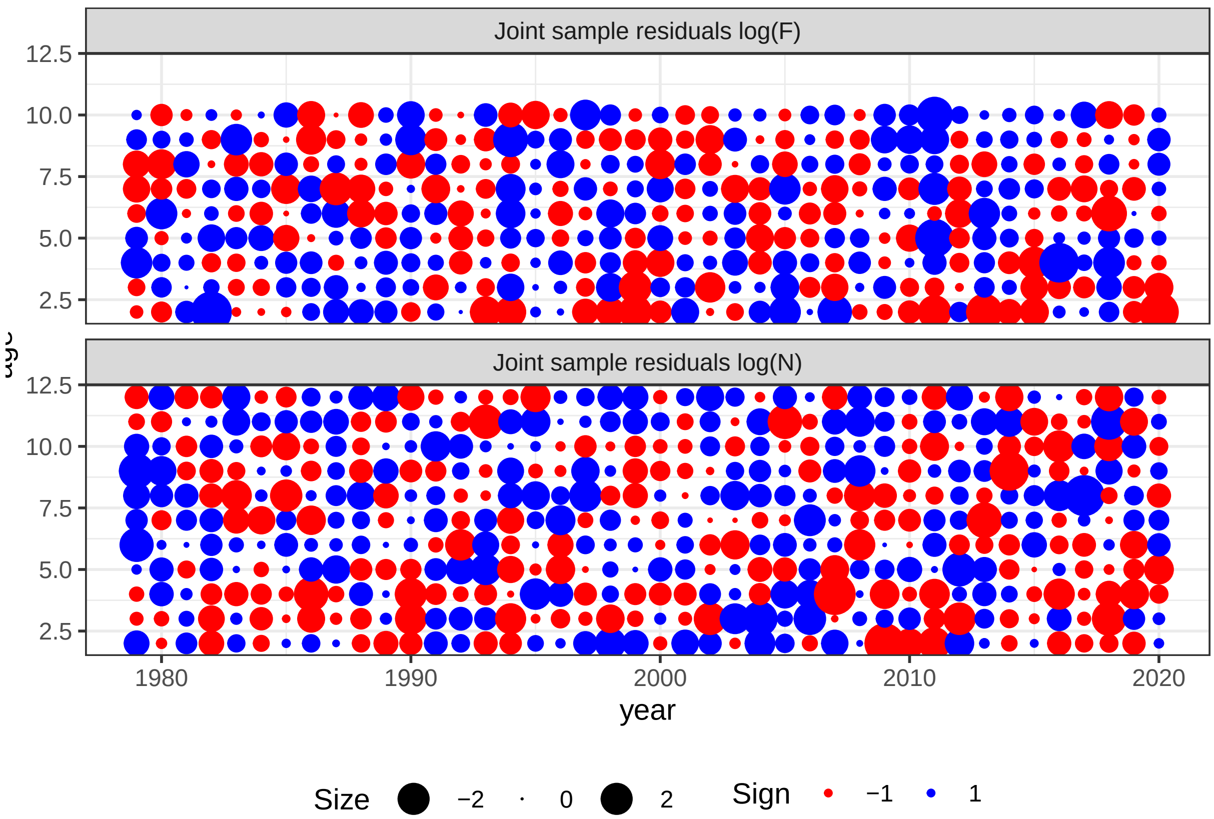

Figure 40: Ling in 5.a. Process error residuals of the proposed SAM model.

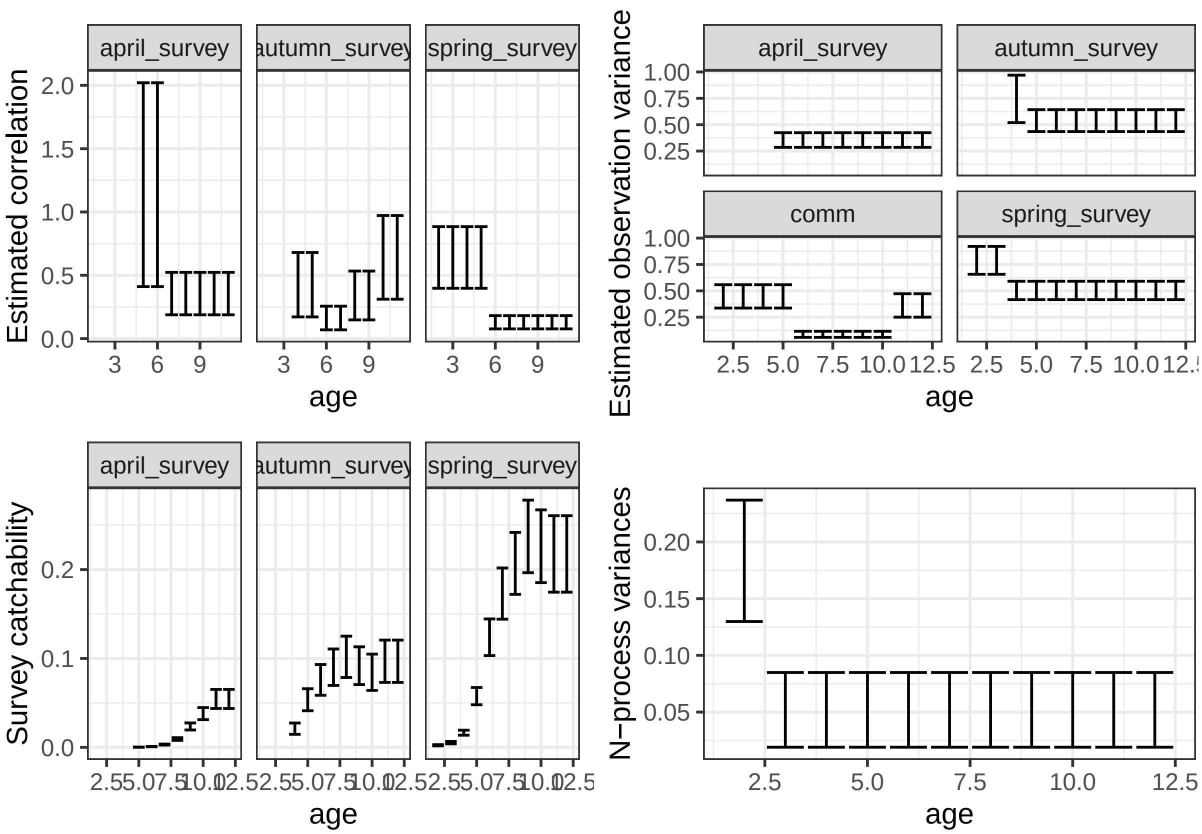

Figure 41: Ling in 5.a. Overview of the proposed SAM model parameter estimates.

8.2.3 Stock overview

Population dynamics of the ling estimated in this model show a clear trend of a high recruitment period from 2004 - 2010, corresponding with increased spawning stock biomass (SSB) and catches during the 2010 - 2019 period. Despite this trend, fishing mortality has remained rather steady or slightly declined (Fig. 42). Any trends prior to the spring survey data (1985) should be taken with caution due to a lack of data supporting the model during this period.

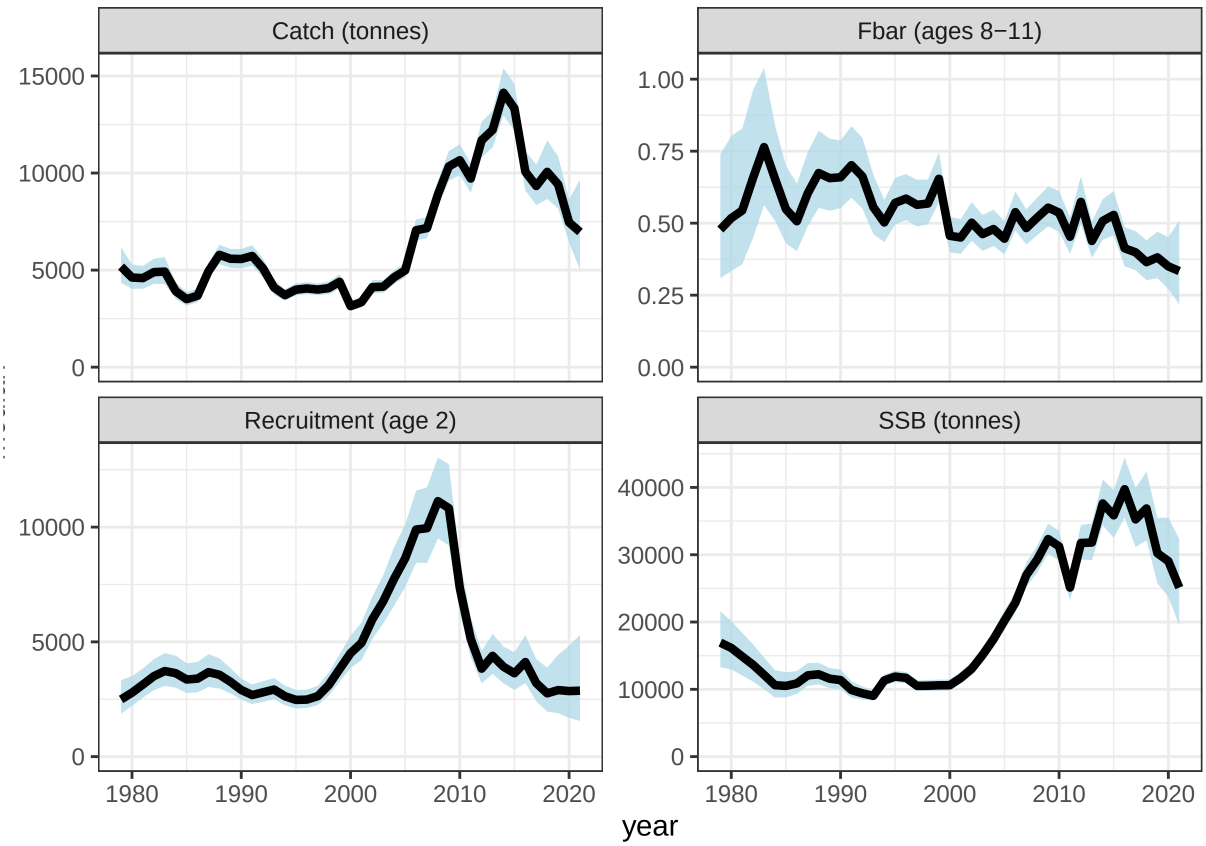

Figure 42: Ling in 5.a. Model results of population dynamics overview: estimated catch, average fishing mortality over ages 8 - 11 (Fbar), recruitment (age 2), and spawning stock biomass (SSB).

The scale of model results generaed by the SAM model are on a similar scale as the previously benchmarked assessment, although the previous assessment does not follow that steeper bends in the population dynamics series upwards and downwards (Fig. 43).

8.2.4 Retrospective analyses

The proposed model had Mohn's ρ statistic values for spawning stock biomass, fishing mortality, and recruitment that were not substantial, fall within the range recommended by Carvalho et al. [4], and were less than those exhibited by the previously benchmarked model (Table 2). Retrospective patterns are not considered for recruitment because uncertainty in estimation of age 2 is extremely high, as ling do not enter the fishery until age 4 - 5. Analytical retrospective plots indicate that the values are mainly due to the oldest peels which showed the steepest decline in biomass after the effect of the recruitment peak passed (Fig. 44).

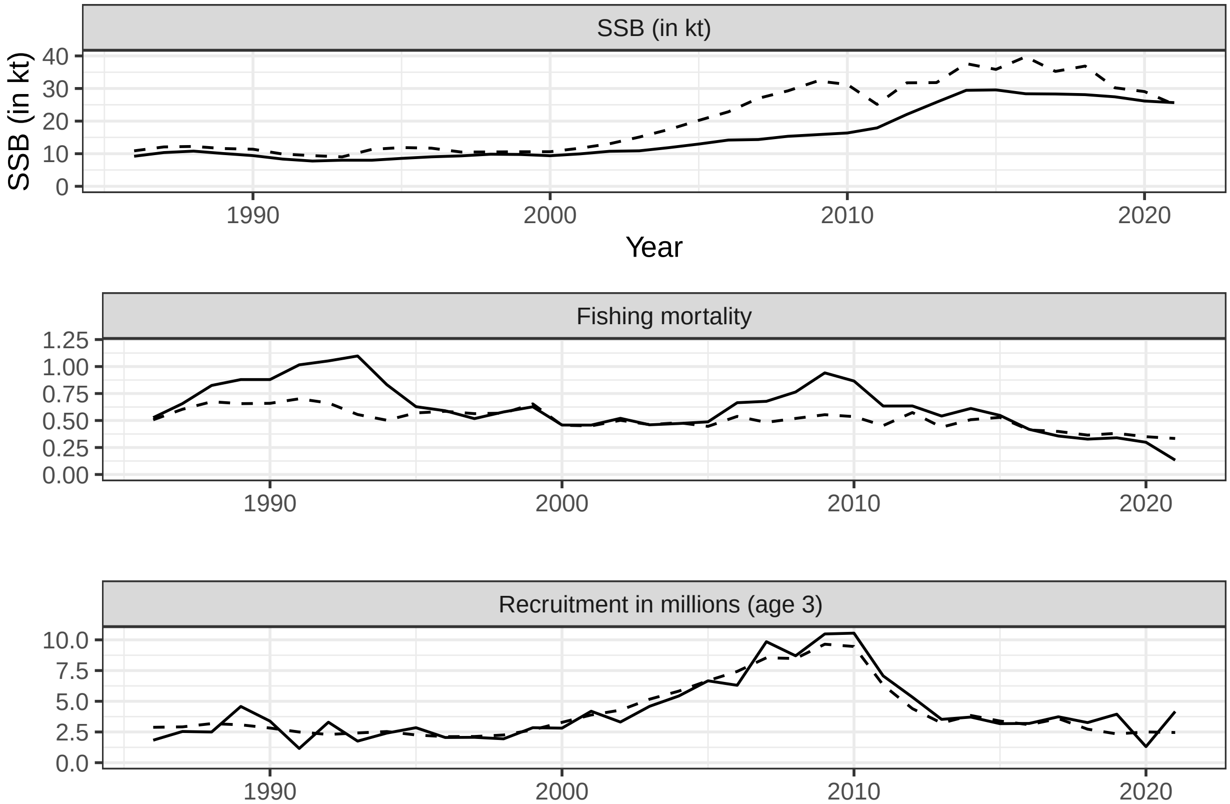

Figure 43: Ling in 5.a. Comparison of proposed SAM assessment results (dashed) with the previous Gadget assessment results (solid).

Table 2: Ling in 5.a. Mohn's *ho* calculated from analytical retrospective analyses of the proposed model.

R(age 2)	SSB	Fbar(8-11)
0.266	0.068	-0.058

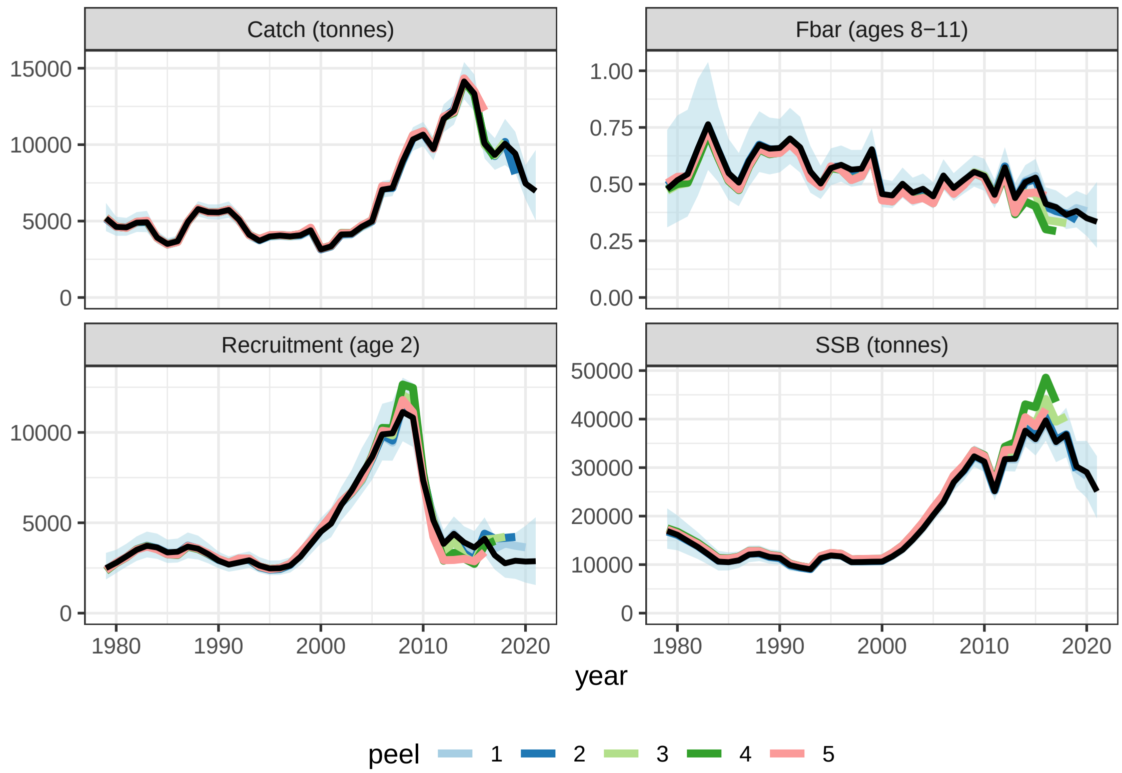

Figure 44: Ling in 5.a. Analytical retrospective analysis.

8.3 Leave-out analysis

Fig. 45 shows the results comparing the full model estimates with estimates where a certain data time series has been omitted from the observation likelihood. The results show good agreement between model estimates with and with out most survey data, except the spring survey, suggesting high influence of the spring survey and catch data to the final model.

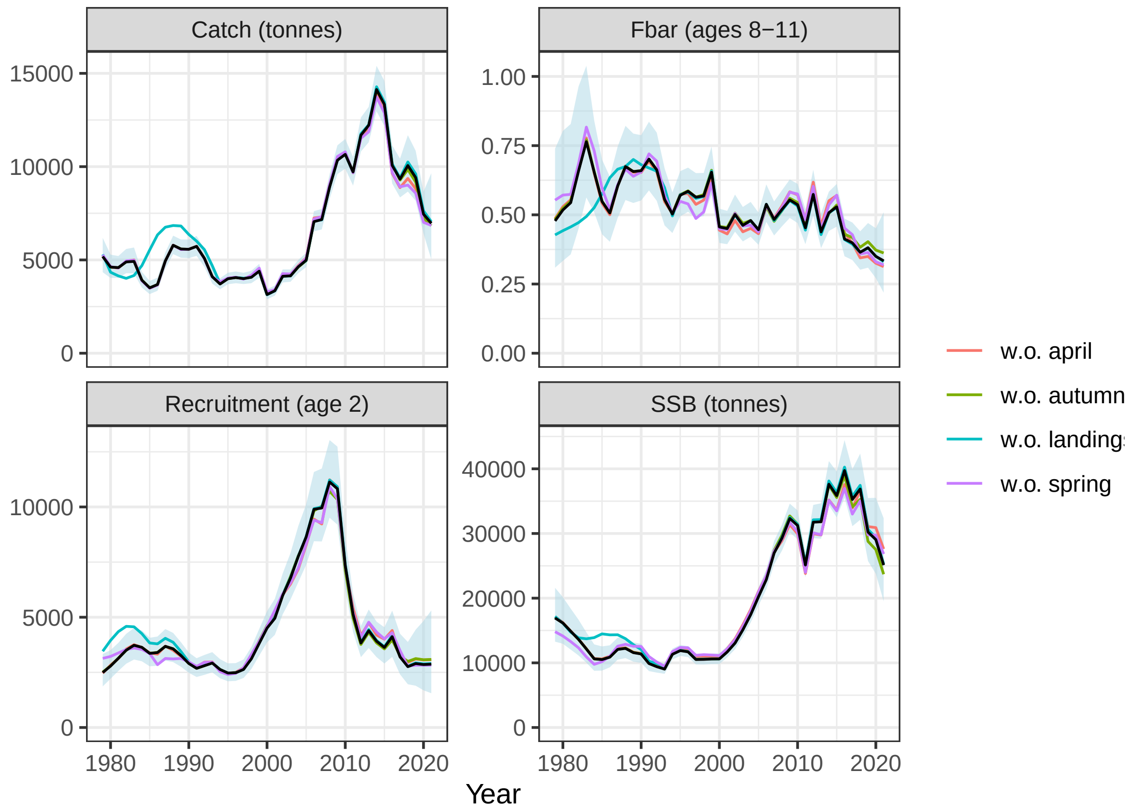

Figure 45: Ling in 5.a. Leave-out estimates of SSB, catch, F and recruitment.

8.4 Ranges of natural mortality

A range of Ms was investigated (see Fig. 46) along with size dependent M using both the Gislason and Chernov method. The profile likelihood shows a minimum close to 0 and no other indicator based on life history attributes showed a clear indication of M. Therefore the assumption of natural mortality as 0.15 for all ages was maintained. See Appendix I for more detail.

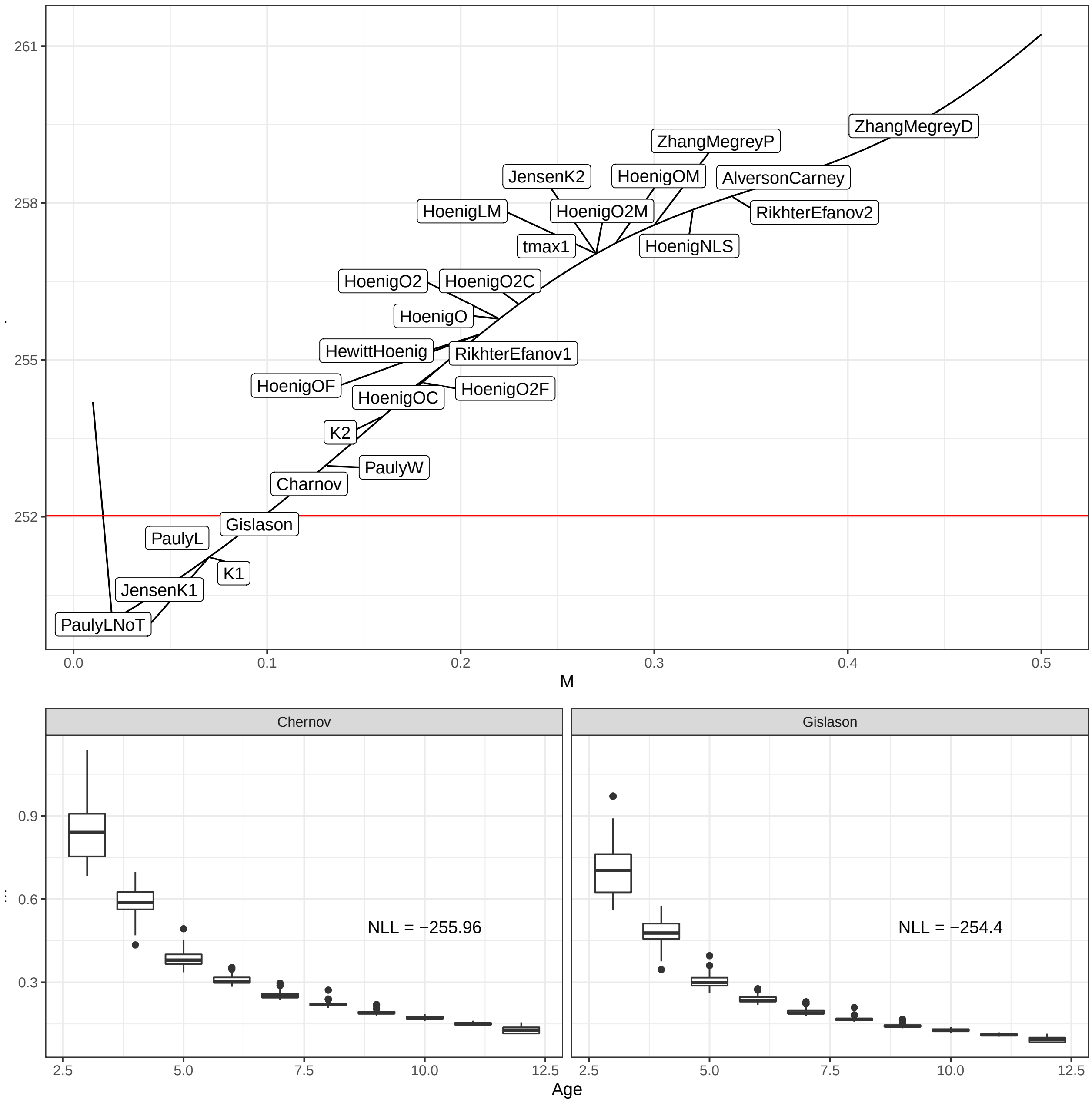

Figure 46: Ling in 5a. Left panel shows a profile likelihood plot (negative log likelihood) for different values of fixed M. Results from different M derivations based on life-history parameters are overlayed. Red line indicates 95% confidence regions. Bottom panels show boxplots of size based M values along with the negative log-likelihood values from the fitted SAM model.

9 Short term projections

Short term projections are performed using the standard procedure in SAM using the `forecast` function. Three year averages are used for stock and catch weights, and maturity. From this projection the advice is derived. The advice is based on the Icelandic fishing year starting in September each year. This causes a mismatch between the assessment model, which is based on the calendar year. So in order to provide advice for the fishing year, the standard projection procedure in SAM will need to be adapted to accommodate these differences. So given the assessment in year y the interim year catches are based on the following fishing mortality:

$$F_y = \left(\frac{8}{12}F_{sq} + \frac{4}{12}F_{mgt}\right)$$

and therefore the total catches for year y will be:

$$C_y = \frac{F_y}{F_y + M}\left(1 - e^{-(F_y+M)}\right)B_y$$

and the part of the catch in the fishing year y-1/y will be

$$\frac{\frac{8}{12}F_{sq}}{\left(\frac{8}{12}F_{sq} + \frac{4}{12}F_{mgt}\right)}C_y$$

and the catch in fishing year y/y+1 will be:

$$C_{y/y+1} = \frac{\frac{4}{12}F_{mgt}}{\left(\frac{8}{12}F_{sq} + \frac{4}{12}F_{mgt}\right)}C_y + \frac{8}{12}C_{y+1}$$

where

$$C_{y+1} = \frac{F_{mgt}}{F_{mgt} + M}\left(1 - e^{-(F_{mgt}+M)}\right)B_y$$

10 Appropriate Reference Points (MSY)

According ICES technical guidelines (ICES [8]), two types of reference points are referred to when giving advice for category 1 stocks:

precautionary approach (PA) reference points and *maximum sustainable yield* (MSY) reference points. The PA reference points are used when assessing the state of stocks and their exploitation rate relative to the precautionary approach objectives. The MSY reference points are used in the advice rule applied by ICES to give advice consistent with the objective of achieving MSY.

Generally ICES derives these reference points based on the level of the spawning stock biomass and fishing mortality. The following sections describe the derivation of the management reference points in terms of fishing mortality (F) and SSB (B). It further describes the model for stock–recruitment, weight and maturity at age, and assessment error which is used to project the stock stochastically in order to derive the PA and MSY reference points.

10.0.1 Setting B_{lim} and B_{pa}

B_{lim} was considered from examination of the SSB–Recruitment (at age 2) scatterplot based on the estimates from the stock assessment, as illustrated in Fig. 47. The figure shows that the recruitment is fairly independent of the size of SSB. In this situation there is no clear guidance from the ICES technical guidelines. The stock appears to have gone through a large upward shift in productivity and returned to low values. The minimum SSB estimate occurred several years before this shift, however, and therefore could reflect an upper boundary of impaired recruitment. Therefore, this stock best fits the Type 5 Stock Category description in ICES Category 1 & 2 Guidelines (ICES [8]), and thus B_{lim} is derived from the lowest observed SSB during that period high productivity (i.e. $B_{loss} = \text{SSB}(1993) = 9032$). In line with ICES technical guidelines B_{pa} is then calculated based on multiplying B_{lim} with the standard factor, $e^{\sigma * 1.645}$ where σ is the CV in the assessment year of SSB or 0.14, used for calculating B_{pa} from B_{lim}. However this CV estimate is not considered to be reflective of the true assessment error of the SSB as the retrospective analysis shows that terminal estimates commonly fluctuate on the outer edge of the model CV limits, and thus the CV used here to determine B_{pa} is 0.2, which is the default ICES value for assessment error. Default values were taken because estimates derived from the the model as listed in Table 2 are likely to be underestimates given the uncertainty in age data. Therefore B_{pa} should be set at $B_{lim}e^{1.645*0.2} = 9032kt \times 1.4 = 11125kt$.

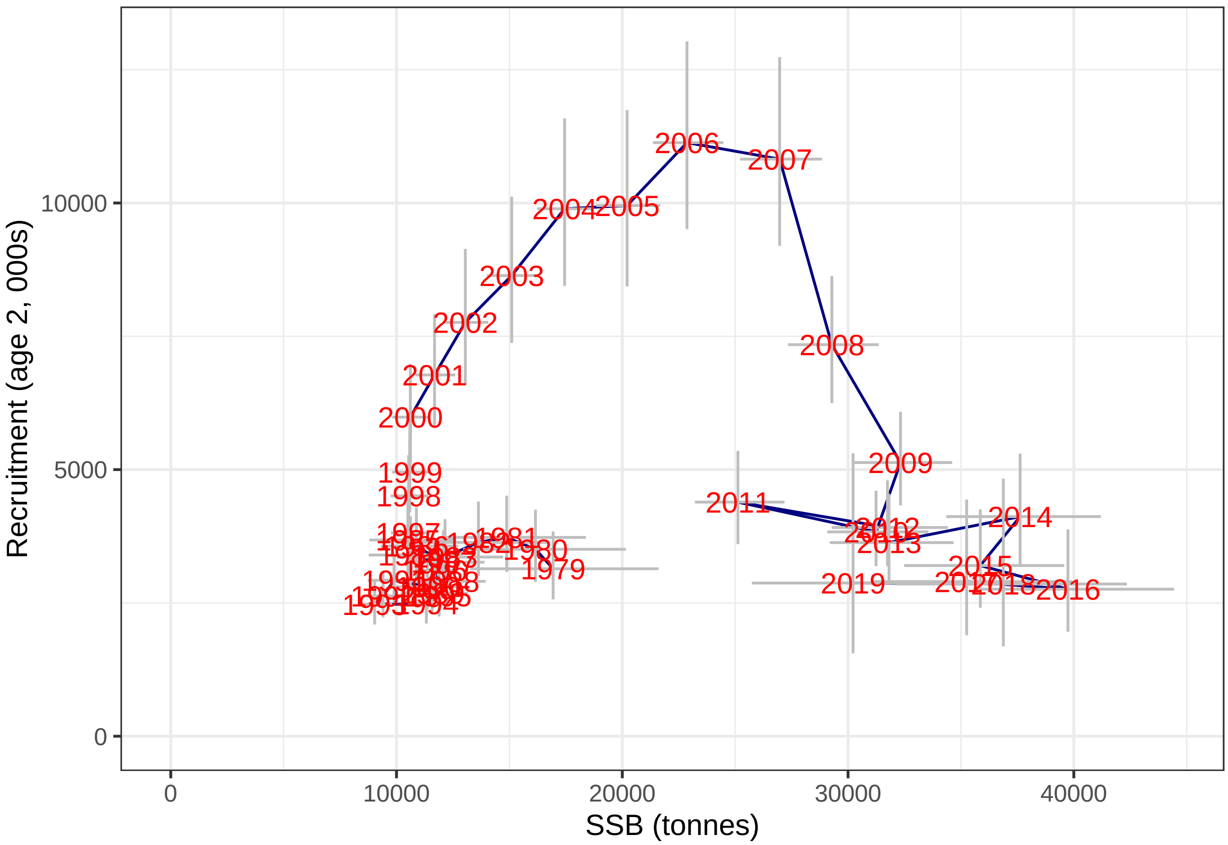

Figure 47: Ling in 5.a. Estimated stock recruitment plot. Grey crossed indicate uncertainty, red text point estimate with the associated year and black lines show the progression of the stock recruitment relationship. Years correspond with SSB year.

Table 3: Ling in 5.a. Listing of the CV for key model outputs.

variable	cv
SSB (tonnes)	0.144
Fbar (ages 8-11)	0.145
Recruitment (age 2)	0.424
Catch (tonnes)	0.081

10.0.2 Management procedure in forward projections

Illegal landings and discards by Icelandic fishing vessels are considered to be negligible (as noted above). Current knowledge of ling in 5.a, discussed above, suggests that it should be assessed as a single stock unit. The currently proposed assessment model is more stable than historical assessments. In the projections described below the effect of assessment model is modeled as auto correlated log-normal variable with the mean as the true state of the stock. The values for the CV and correlation in the assessment error are based on the default values from the ICES guidelines of 0.212 and 0.423, as deriving such estimates from historical retros would be problematic due to the shift in modeling framework and large retrospective pattern exhibited by the Gadget plot used previously.

10.0.3 Stock recruitment relationship

A variety of approaches are common when estimating a stock–recruitment relationship. In the absence of a stock-recruitment signal from the available historical data (Fig. 47, the ICES guidelines suggest that the "hockey-stick' ' recruitment function is used, i.e.

$$R_y = \bar{R}_y \min(1, S_y/B_{break})$$

where R_y is annual recruitment, S_y the spawning stock biomass, B_{break} the break point in hockey stick function and $\bar{R}_y$ is the recruitment when not impaired due to low levels of SSB. Here $\bar{R}_y$ is considered to be drawn from an auto–correlated log–normal distribution with a mean, CV and ρ estimated based on the estimated recruits. This is done to account for possible auto-correlation in the recruitment time–series. As the stock appears to no longer be exhibiting high recruitment and instead returned to recruitment values prior to this period, recruitment values from the years 2004 - 2010 were excluded when fitting the relationship (years 2002 - 2008 in SSB years in Fig. 47, corresponding with a cut-off > 7 million). Fig. 48 shows the fit to a segmented regression setting B_{lim} to B_{loss}, used to generate the hockey–stick relationship used in forward simulations.

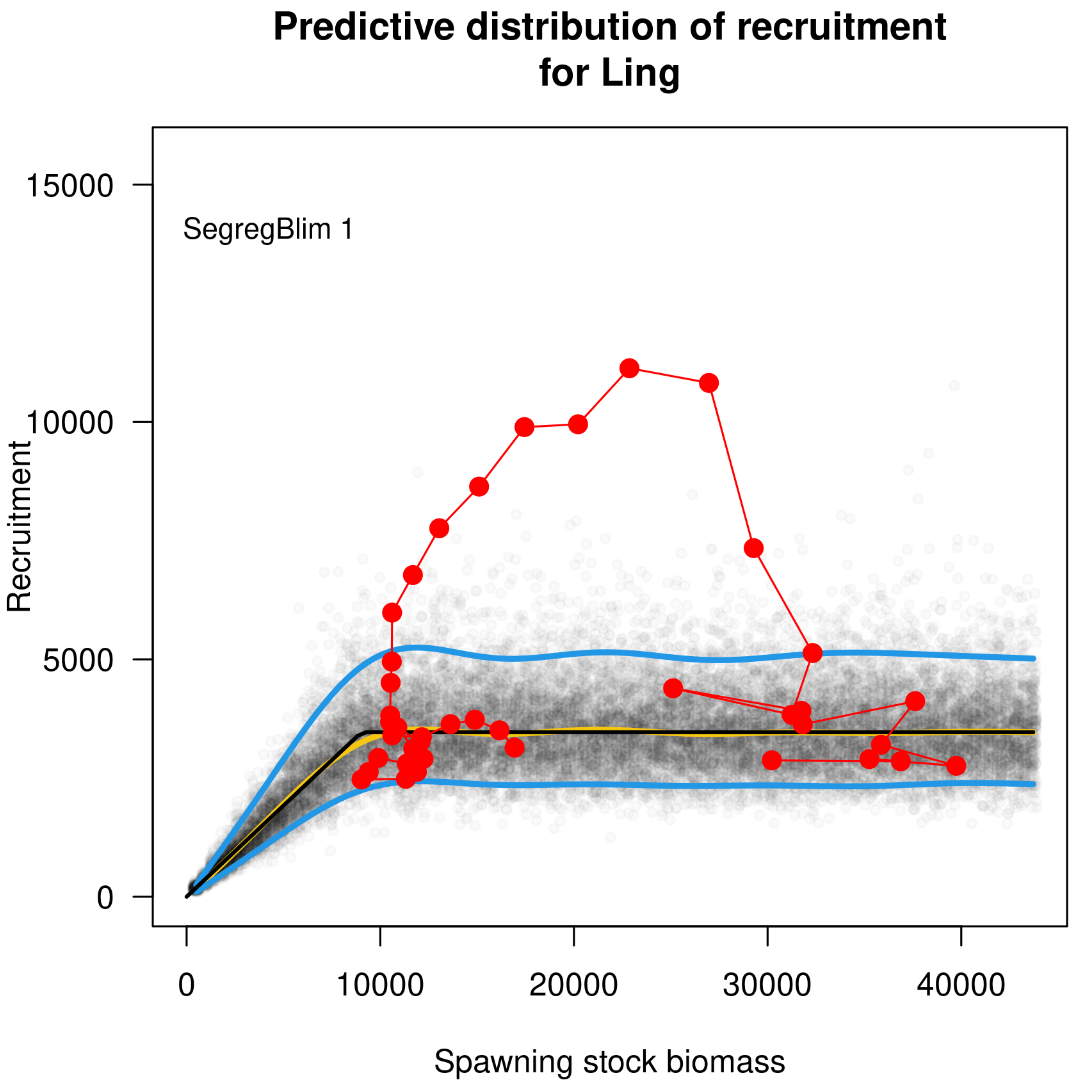

Figure 48: Ling in 5a. Fit segmented regression to spawning stock biomass and recruitment (age 2) relationship.

10.0.4 Stock– and catch–weights

Prediction of weight at age in the stock, selectivity and the maturity at age follow the traditional process from the ICES guidelines, that is the average of the last 10 years of values for weight, selectivity and maturity at age used in the projections. These values are illustrated in Figures 49 to 51.

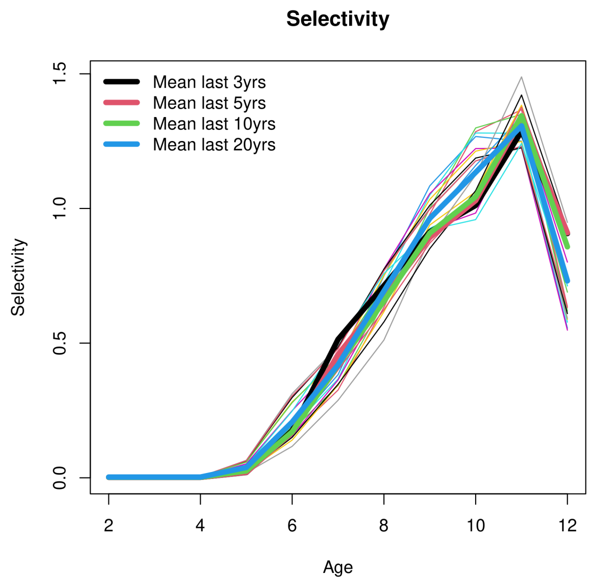

Figure 49: Ling in 5a. Settings for the projections. Estimated selectivity at age by year (narrow coloured lines) illustrated with 3, 5, 10 and 20 year averages (thick lines).

10.0.5 Setting $\mathbf{F}_{lim}$ and $\mathbf{F}_{pa}$

According to the ICES guidelines, the precautionary reference points are set by simulating the stock using the stock-recruitment, growth and maturity relationship described above, based on a wide range of harvest rates, ranging from 0 to 1 and setting F_{lim} as the F that, in equilibrium, gives a 50% probability of SSB $> B_{lim}$ without assessment error.

For each replicate the stock status was projected forward 50 years as simulations, and average of those projected values used to estimate the MSY reference points.

The results from the long–term simulations estimate the value of F, F_{lim}, resulting in 50% long–term probability of SSB $> B_{lim}$ to be at 0.95.

10.0.6 MSY reference points

As an additional simulation experiment where, in addition to recruitment and growth variations, assessment error was added. The harvest rate that would lead to the maximum sustainable yield, F_{msy}, was then estimated. Average annual landings and 90% quantiles were used to determine the yield by F. Fig. 54 shows the evolution of catches, SSB and fishing mortality for select values of F. The equilibrium yield curve is shown in fig. 52, and with the $B_{trigger}$ implemented in an HCR in 53, where the maximum median yield, under the recruitment assumptions, is around 6 thousand tons.

In line with ICES technical guidelines, the MSY $B_{trigger}$ is set as B_{pa} as this is the first time the reference points are evaluated. Maximum yield is estimated to be obtained at a F of 0.3. F_{p05}, i.e. the maximum F that has less than 5% chance of going below B_{lim} when the advice rule is applied, is 0.62, thus not limiting the estimate of F_{msy}. The evolution of the spawning stock biomass is shown in Figure 54 for select F values in the HCR (0.20, F_{msy} 0.30, F_{sq} 0.37, and 0.5). F_{sq} was calculated as the mean F over the three most recent

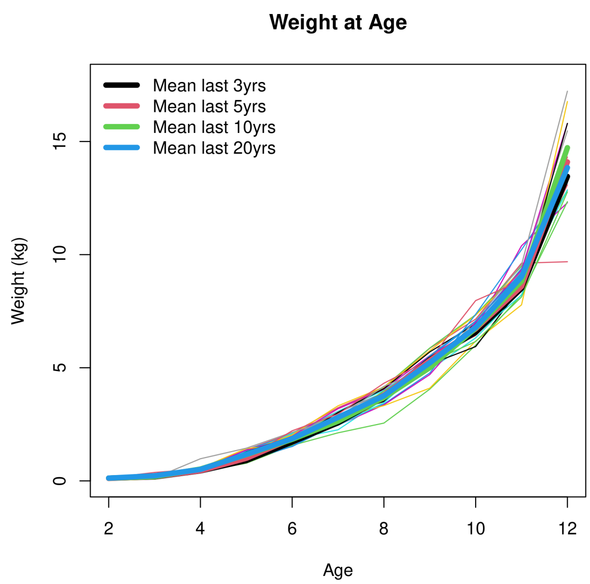

Figure 50: Ling in 5a. Settings for the projections. Estimated weight at age by year (narrow coloured lines) illustrated with 3, 5, 10 and 20 year averages (thick lines)

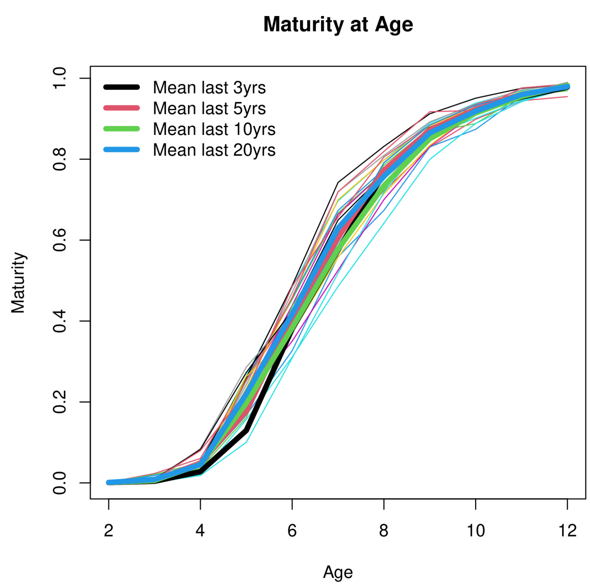

Figure 51: Ling in 5a. Settings for the projections. Estimated maturity at age by year (narrow coloured lines) illustrated with 3, 5, 10 and 20 year averages (thick lines)

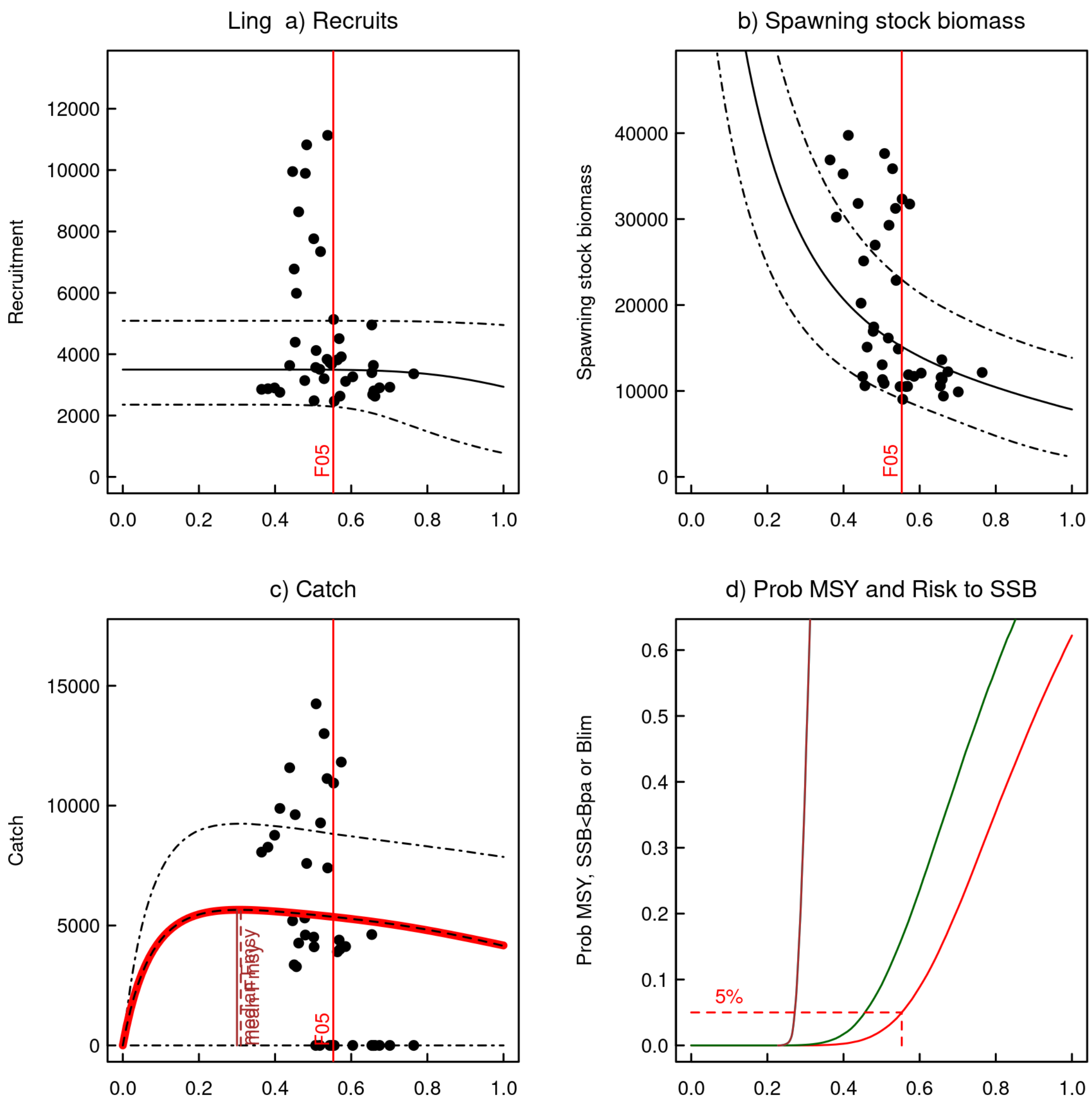

Figure 52: Ling in 5.a. Equilibrium catch, recruitment, SSB and risk from forward projections, generated from Eqsim. No trigger values used.

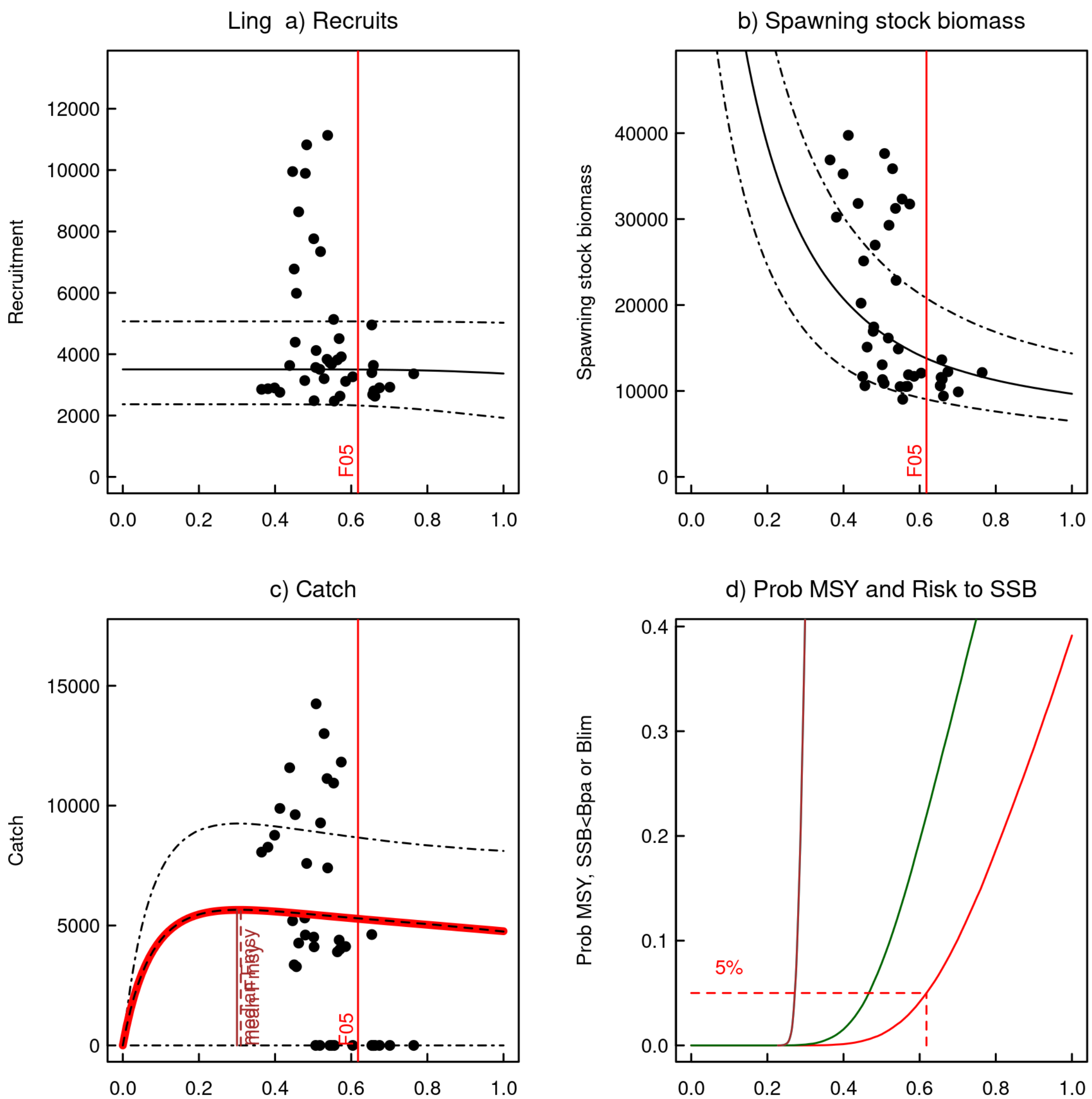

Figure 53: Ling in 5.a. Equilibrium catch, recruitment, SSB and risk from forward projections, generated from Eqsim. The trigger was implemented in these projections, used to derive F_{p05}.

years. All levels considered maintain a probability less than 5% of SSB falling below B_{lim}, but a target F of 0.30 maximises long-term yield.

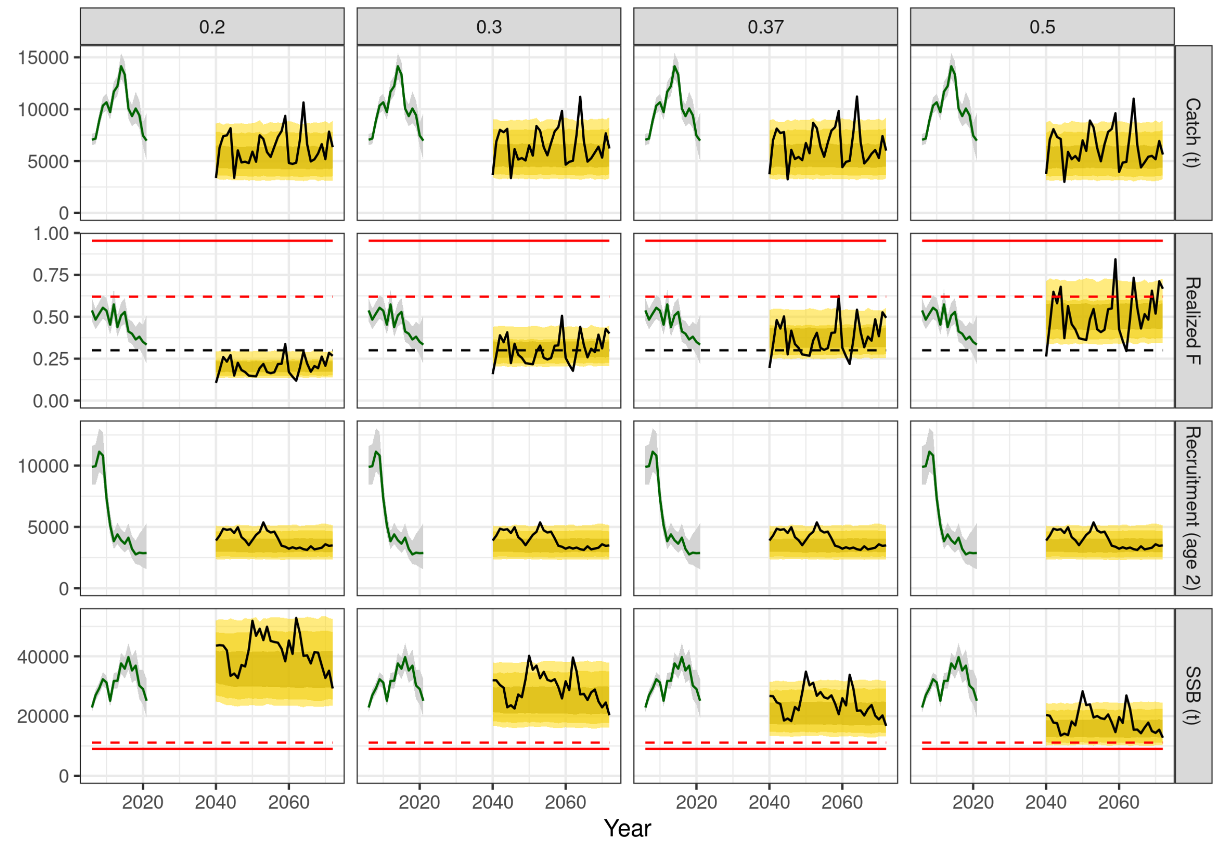

Figure 54: Atlantic wolffish in 5a. Assessment (from 2006 onwards) and projections of recruitment (thousands at age 4), realized F, catch (in t) and SSB (in t) for different F values in the HCR. The different shades of yellow indicate 90%, 80%, and 50% distribution ranges of projections, the black line one iteration. Grey shading indicates 95% confidence intervals on the assessment model results (green line). The red solid and dashed horizontal lines refer to B_{lim} or F_{lim} and $B_{trigger}$, respectively. The black dashed horizontal line refers to F_{msy}.

Ling in 5a. Overview of estimated reference points

Reference point	Value	Basis
MSYBtrigger	11100	Bpa
5thPerc_SSBmsy	18500	5th quantile of SSB when fishing at Fmsy
Bpa	11100	Blim x exp(1.645 sigma_SSB)
Blim	9000	Lowest SSB (1993) (Type 5)
Flim	0.95	F leading to P(SSB < Blim) = 0.5
Fp05	0.62	F, when ICES AR is applied, leading to P(SSB > Blim) = 0.05
Fmsy_unconstr	0.30	Unconstrained F leading to MSY
Fmsy	0.30	F leading to MSY

11 Future Research and data requirements

The most important information lacking in the assessment of ling is reliable age readings for older fish. It would be best to include ling in workshops that cross-validate age reading methods.

Tagging data would also be useful to understand movements around Iceland, and whether the recruitment high influx of biomass resulted from reduced fishing alongside high recruitment, leading to greater survival of large ling, or if large ling appear to have congregated from deeper offshore waters.

12 Model configuration

```
## # Configuration saved: Tue Apr 19 01:03:11 2022
## #
## # Where a matrix is specified rows corresponds to fleets and columns to ages.
## # Same number indicates same parameter used
## # Numbers (integers) starts from zero and must be consecutive
## # Negative numbers indicate that the parameter is not included in the model
## #
## $minAge
## # The minimium age class in the assessment
##  2
##
## $maxAge
## # The maximum age class in the assessment
##  12
##
## $maxAgePlusGroup
## # Is last age group considered a plus group for each fleet (1 yes, or 0 no).
##  1 1 1 1 1
##
## $keyLogFsta
## # Coupling of the fishing mortality states processes for each age (normally only
## # the first row (= fleet) is used).
## # Sequential numbers indicate that the fishing mortality is estimated individually
## # for those ages; if the same number is used for two or more ages, F is bound for
## # those ages (assumed to be the same). Binding fully selected ages will result in a
## # flat selection pattern for those ages.
##   -1  -1   0   1   2   3   4   5   6   7   8
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##
## $corFlag
## # Correlation of fishing mortality across ages (0 independent, 1 compound symmetry,
## # 2 AR(1), 3 separable AR(1).
## # 0: independent means there is no correlation between F across age
## # 1: compound symmetry means that all ages are equally correlated;
## # 2: AR(1) first order autoregressive - similar ages are more highly correlated than
## # ages that are further apart, so similar ages have similar F patterns over time.
## # if the estimated correlation is high, then the F pattern over time for each age
## # varies in a similar way. E.g if almost one, then they are parallel (like a
## # separable model) and if almost zero then they are independent.
## # 3: Separable AR - Included for historic reasons . . .  more later
```

```
##  2
##
## $keyLogFpar
## # Coupling of the survey catchability parameters (nomally first row is
## # not used, as that is covered by fishing mortality).
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##    0   1   2   3   4   5   6   7   8   9   9
##   -1  -1  10  11  12  13  14  15  16  17  17
##   -1  -1  -1  18  19  20  21  22  23  24  24
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##
## $keyQpow
## # Density dependent catchability power parameters (if any).
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##
## $keyVarF
## # Coupling of process variance parameters for log(F)-process (Fishing mortality
## # normally applies to the first (fishing) fleet; therefore only first row is used)
##    0   0   0   0   0   0   0   0   0   0   0
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##
## $keyVarLogN
## # Coupling of the recruitment and survival process variance parameters for the
## # log(N)-process at the different ages. It is advisable to have at least the first age
## # class (recruitment) separate, because recruitment is a different process than
## # survival.
##  0 1 1 1 1 1 1 1 1 1 1
##
## $keyVarObs
## # Coupling of the variance parameters for the observations.
## # First row refers to the coupling of the variance parameters for the catch data
## # observations by age
## # Second and further rows refers to coupling of the variance parameters for the
## # index data observations by age
##    6   6   6   6   0   0   0   0   0   7   7
##    4   4   1   1   1   1   1   1   1   1   1
##   -1  -1   5   2   2   2   2   2   2   2   2
##   -1  -1  -1   3   3   3   3   3   3   3   3
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##
## $obsCorStruct
## # Covariance structure for each fleet ("ID" independent, "AR" AR(1), or "US" for unstructured). | Pos
##  "ID" "AR" "AR" "AR" "ID"
##
## $keyCorObs
## # Coupling of correlation parameters can only be specified if the AR(1) structure is chosen above.
## # NA's indicate where correlation parameters can be specified (-1 where they cannot).
```

```
## #2-3 3-4 4-5 5-6 6-7 7-8 8-9 9-10 10-11 11-12
##   NA  NA  NA  NA  NA  NA  NA  NA  NA  NA
##    6   6   6   6   7   7   7   7   7   7
##   -1  -1   0   0   1   1   2   2   3   3
##   -1  -1  -1   4   4   5   5   5   5   5
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##
## $stockRecruitmentModelCode
## # Stock recruitment code (0 for plain random walk, 1 for Ricker, 2 for Beverton-Holt, 3 piece-wise co
##  0
##
## $noScaledYears
## # Number of years where catch scaling is applied.
##  0
##
## $keyScaledYears
## # A vector of the years where catch scaling is applied.
##
##
## $keyParScaledYA
## # A matrix specifying the couplings of scale parameters (nrow = no scaled years, ncols = no ages).
##
## $fbarRange
## # lowest and higest age included in Fbar
##  8 11
##
## $keyBiomassTreat
## # To be defined only if a biomass survey is used (0 SSB index, 1 catch index, 2 FSB index, 3 total ca
##  -1 -1 -1 -1 4
##
## $obsLikelihoodFlag
## # Option for observational likelihood | Possible values are: "LN" "ALN"
##  "LN" "LN" "LN" "LN" "LN"
##
## $fixVarToWeight
## # If weight attribute is supplied for observations this option sets the treatment (0 relative weight
##  0
##
## $fracMixF
## # The fraction of t(3) distribution used in logF increment distribution
##  0
##
## $fracMixN
## # The fraction of t(3) distribution used in logN increment distribution (for each age group)
##  0 0 0 0 0 0 0 0 0 0 0
##
## $fracMixObs
## # A vector with same length as number of fleets, where each element is the fraction of t(3) distribut
##  0 0 0 0 0
##
## $constRecBreaks
## # Vector of break years between which recruitment is at constant level. The break year is included in
##
##
```

```
## $predVarObsLink
## # Coupling of parameters used in a prediction-variance link for observations.
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##   -1  -1  -1  -1  -1  -1  -1  -1  -1  -1  -1
##   NA  NA  -1  -1  -1  -1  -1  -1  -1  -1  -1
##   NA  NA  NA  -1  -1  -1  -1  -1  -1  -1  -1
##   NA  NA  NA  NA  NA  NA  NA  NA  NA  NA  NA
##
## $hockeyStickCurve
## #
##  20
##
## $stockWeightModel
## # Integer code describing the treatment of stock weights in the model (0 use as known, 1 use as obse
##  0
##
## $keyStockWeightMean
## # Coupling of stock-weight process mean parameters (not used if stockWeightModel==0)
##  NA NA NA NA NA NA NA NA NA NA NA
##
## $keyStockWeightObsVar
## # Coupling of stock-weight observation variance parameters (not used if stockWeightModel==0)
##  NA NA NA NA NA NA NA NA NA NA NA
##
## $catchWeightModel
## # Integer code describing the treatment of catch weights in the model (0 use as known, 1 use as obse
##  0
##
## $keyCatchWeightMean
## # Coupling of catch-weight process mean parameters (not used if catchWeightModel==0)
##  NA NA NA NA NA NA NA NA NA NA NA
##
## $keyCatchWeightObsVar
## # Coupling of catch-weight observation variance parameters (not used if catchWeightModel==0)
##  NA NA NA NA NA NA NA NA NA NA NA
##
## $matureModel
## # Integer code describing the treatment of proportion mature in the model (0 use as known, 1 use as o
##  0
##
## $keyMatureMean
## # Coupling of mature process mean parameters (not used if matureModel==0)
##  NA NA NA NA NA NA NA NA NA NA NA
##
## $mortalityModel
## # Integer code describing the treatment of natural mortality in the model (0 use as known, 1 use as o
##  0
##
## $keyMortalityMean
## #
##  NA NA NA NA NA NA NA NA NA NA NA
##
## $keyMortalityObsVar
## # Coupling of natural mortality observation variance parameters (not used if mortalityModel==0)
```

```
##  NA NA NA NA NA NA NA NA NA NA NA
##
## $keyXtraSd
## # An integer matrix with 4 columns (fleet year age coupling), which allows additional uncertainty to
```

13 Input data

13.1 Spring survey at age

year	2	3	4	5	6	7	8	9	10	11	12
1985	0.006	0.013	0.046	0.156	0.242	0.215	0.146	0.090	0.041	0.018	0.043
1986	0.010	0.026	0.069	0.242	0.401	0.406	0.253	0.141	0.053	0.021	0.037
1987	0.022	0.033	0.039	0.195	0.321	0.298	0.199	0.114	0.043	0.017	0.031
1988	0.007	0.021	0.052	0.167	0.252	0.254	0.182	0.107	0.043	0.013	0.024
1989	0.006	0.025	0.095	0.276	0.385	0.393	0.287	0.174	0.076	0.026	0.029
1990	0.005	0.015	0.070	0.185	0.235	0.207	0.153	0.104	0.044	0.017	0.037
1991	0.004	0.009	0.054	0.267	0.295	0.169	0.114	0.080	0.037	0.018	0.017
1992	0.002	0.005	0.030	0.203	0.291	0.211	0.129	0.081	0.040	0.018	0.022
1993	0.008	0.016	0.033	0.150	0.221	0.157	0.101	0.063	0.029	0.013	0.021
1994	0.008	0.013	0.022	0.117	0.202	0.240	0.182	0.119	0.056	0.022	0.030
1995	0.005	0.016	0.040	0.088	0.120	0.126	0.092	0.057	0.023	0.011	0.015
1996	0.002	0.003	0.019	0.085	0.141	0.134	0.090	0.063	0.033	0.015	0.009
1997	0.011	0.029	0.064	0.136	0.139	0.141	0.112	0.080	0.035	0.013	0.017
1998	0.011	0.018	0.026	0.073	0.120	0.115	0.095	0.068	0.032	0.013	0.019
1999	0.009	0.008	0.021	0.114	0.192	0.182	0.119	0.074	0.032	0.012	0.012
2000	0.011	0.011	0.017	0.057	0.117	0.126	0.082	0.051	0.023	0.008	0.007
2001	0.001	0.004	0.015	0.055	0.087	0.108	0.075	0.054	0.025	0.010	0.006
2002	0.009	0.012	0.037	0.111	0.166	0.167	0.114	0.078	0.034	0.016	0.015
2003	0.012	0.018	0.044	0.156	0.182	0.140	0.092	0.057	0.027	0.011	0.022
2004	0.037	0.046	0.070	0.193	0.302	0.274	0.171	0.102	0.039	0.017	0.021
2005	0.026	0.059	0.130	0.268	0.354	0.340	0.224	0.129	0.052	0.021	0.023
2006	0.084	0.085	0.175	0.307	0.363	0.327	0.228	0.143	0.056	0.024	0.044
2007	0.102	0.098	0.175	0.449	0.610	0.583	0.429	0.289	0.139	0.054	0.058
2008	0.055	0.107	0.219	0.482	0.580	0.503	0.317	0.176	0.063	0.028	0.047
2009	0.071	0.076	0.205	0.491	0.490	0.325	0.214	0.129	0.059	0.024	0.025
2010	0.032	0.231	0.121	0.455	0.651	0.415	0.374	0.141	0.091	0.036	0.037
2011	0.010	0.027	0.101	0.480	0.381	0.521	0.510	0.236	0.198	0.087	0.124
2012	0.009	0.021	0.077	0.351	0.646	0.634	0.664	0.369	0.202	0.087	0.096
2013	0.002	0.006	0.026	0.116	0.590	0.930	0.490	0.438	0.258	0.080	0.109
2014	0.000	0.003	0.010	0.069	0.313	0.614	0.558	0.323	0.141	0.070	0.050
2015	0.006	0.007	0.040	0.044	0.252	0.482	0.910	0.702	0.206	0.154	0.063
2016	0.031	0.009	0.081	0.095	0.268	0.323	0.498	0.374	0.122	0.061	0.059
2017	0.022	0.027	0.020	0.057	0.277	0.239	0.431	0.413	0.515	0.220	0.154
2018	0.012	0.018	0.074	0.176	0.259	0.379	0.250	0.361	0.198	0.144	0.115
2019	0.011	0.019	0.059	0.125	0.192	0.228	0.275	0.202	0.187	0.204	0.163
2020	0.004	0.007	0.035	0.034	0.211	0.256	0.257	0.241	0.164	0.099	0.189
2021	0.008	0.014	0.038	0.057	0.239	0.415	0.307	0.213	0.155	0.116	0.142

13.2 Autumn survey at age

year	2	3	4	5	6	7	8	9	10	11	12
2000	0.001	0.004	0.030	0.048	0.055	0.049	0.033	0.010	0.003	0.003	0.004
2001	0.000	0.005	0.038	0.094	0.137	0.119	0.093	0.044	0.023	0.010	0.013
2002	0.002	0.006	0.032	0.072	0.102	0.084	0.054	0.021	0.007	0.007	0.011
2003	0.002	0.009	0.036	0.062	0.077	0.058	0.058	0.035	0.022	0.013	0.016
2004	0.018	0.021	0.059	0.090	0.136	0.100	0.087	0.040	0.022	0.010	0.008
2005	0.008	0.036	0.147	0.237	0.202	0.116	0.059	0.024	0.010	0.006	0.006
2006	0.000	0.007	0.067	0.110	0.153	0.125	0.087	0.046	0.016	0.003	0.007
2007	0.018	0.089	0.233	0.285	0.235	0.170	0.126	0.057	0.032	0.020	0.028
2008	0.053	0.243	0.487	0.449	0.351	0.226	0.122	0.041	0.010	0.006	0.006
2009	0.033	0.117	0.438	0.461	0.296	0.176	0.108	0.050	0.023	0.014	0.011
2010	0.013	0.037	0.364	0.333	0.423	0.382	0.166	0.138	0.046	0.031	0.018
2011	0.003	0.025	0.191	0.313	0.218	0.227	0.159	0.055	0.011	0.010	0.008
2012	0.001	0.013	0.088	0.412	0.557	0.209	0.175	0.119	0.047	0.030	0.035
2013	0.005	0.019	0.074	0.342	0.594	0.408	0.180	0.068	0.034	0.011	0.012
2014	0.000	0.012	0.024	0.168	0.225	0.373	0.271	0.078	0.046	0.008	0.010
2015	0.000	0.049	0.040	0.154	0.155	0.212	0.140	0.037	0.019	0.005	0.005
2016	0.008	0.010	0.032	0.088	0.069	0.115	0.117	0.161	0.070	0.033	0.047
2017	0.009	0.043	0.070	0.203	0.285	0.190	0.284	0.168	0.114	0.069	0.052
2018	0.006	0.042	0.088	0.106	0.126	0.187	0.134	0.122	0.112	0.051	0.049
2019	0.000	0.011	0.032	0.258	0.207	0.216	0.164	0.115	0.076	0.066	0.041
2020	0.001	0.018	0.037	0.115	0.157	0.128	0.089	0.059	0.044	0.031	0.034
2021	0.000	0.008	0.020	0.042	0.084	0.086	0.077	0.059	0.039	0.037	0.040

13.3 Catch at age

year	2	3	4	5	6	7	8	9	10	11	12
1979	0	0	1	16	62	160	226	165	101	134	62
1980	0	0	0	0	0	0	0	0	0	0	0
1981	0	0	1	3	16	86	94	116	75	133	74
1982	0	0	0	76	173	200	138	194	153	69	51
1983	0	0	0	0	0	0	0	0	0	0	0
1984	0	0	0	0	0	0	0	0	0	0	0
1985	0	0	0	0	0	0	0	0	0	0	0
1986	0	0	0	0	0	0	0	0	0	0	0
1987	0	0	0	0	0	0	0	0	0	0	0
1988	0	0	0	0	0	0	0	0	0	0	0
1989	0	0	0	0	0	0	0	0	0	0	0
1990	0	0	0	0	0	0	0	0	0	0	0
1991	0	0	0	0	0	0	0	0	0	0	0
1992	0	0	0	4	32	103	220	291	170	68	31
1993	0	0	16	459	1483	556	524	52	19	7	4
1994	0	0	10	110	273	251	199	119	51	62	32
1995	0	0	5	55	154	202	228	165	87	48	20
1996	0	0	4	61	200	228	240	159	84	57	24
1997	0	0	5	93	277	253	206	150	84	32	17
1998	0	0	3	39	142	206	233	150	85	62	46
1999	0	0	3	38	151	218	249	186	106	59	39
2000	0	0	2	24	90	117	141	126	83	48	32
2001	0	0	2	22	75	117	148	147	92	47	25
2002	0	0	2	40	118	155	188	152	102	83	41
2003	0	0	3	48	148	171	183	155	104	54	37
2004	0	0	5	55	174	247	294	203	107	49	18
2005	0	0	4	53	173	252	289	209	115	73	39
2006	0	0	9	111	379	415	446	297	158	84	44
2007	0	0	9	129	416	394	419	299	151	100	59
2008	0	0	13	176	555	548	533	352	186	113	56
2009	0	0	13	268	583	622	547	411	235	135	71
2010	0	0	20	258	720	652	576	387	222	132	75
2011	0	0	15	215	569	590	545	355	184	97	65
2012	0	0	23	120	542	744	708	570	291	159	83
2013	0	0	7	98	652	967	729	484	202	63	35
2014	0	0	2	34	271	683	971	588	355	162	103
2015	0	0	0	45	180	518	842	665	355	183	126
2016	0	0	0	21	79	235	344	615	361	155	112
2017	0	0	1	17	155	196	374	408	363	180	108
2018	0	0	4	15	124	245	268	301	314	128	52
2019	0	0	0	42	137	318	330	274	218	151	108
2020	0	0	0	2	116	269	256	255	177	132	140

13.4 Catch weights

year	2	3	4	5	6	7	8	9	10	11	12
1979	132	269	1663	2126	2550	4135	4542	5089	5696	7966	15289
1980	132	269	2071	2056	2398	3435	3964	4871	5983	8164	11738
1981	132	269	1653	1727	2480	6235	6064	5725	6956	9052	13204
1982	132	269	1852	1540	2726	2821	4321	5253	6692	9598	10523
1983	132	269	2071	2056	2398	3435	3964	4871	5983	8164	11738
1984	132	269	2071	2056	2398	3435	3964	4871	5983	8164	11738
1985	129	321	2071	2056	2398	3435	3964	4871	5983	8164	11738
1986	132	273	2071	2056	2398	3435	3964	4871	5983	8164	11738
1987	128	182	2071	2056	2398	3435	3964	4871	5983	8164	11738
1988	137	302	2071	2056	2398	3435	3964	4871	5983	8164	11738
1989	204	358	2071	2056	2398	3435	3964	4871	5983	8164	11738
1990	102	361	2071	2056	2398	3435	3964	4871	5983	8164	11738
1991	138	294	2071	2056	2398	3435	3964	4871	5983	8164	11738
1992	148	303	3343	2942	3626	4363	4802	5363	6170	7910	9751
1993	137	243	1932	1070	1120	1647	1096	3562	5259	6969	9101
1994	143	220	2166	2229	2214	2939	3616	4809	5876	8172	12731
1995	177	288	2204	2455	2685	3417	3882	4717	5763	7964	10607
1996	88	390	1963	1963	2127	3074	3636	4697	5858	7814	13055
1997	145	266	2137	1960	2151	2978	3856	4619	5546	7555	9695
1998	113	194	2048	2332	2409	3541	3958	4787	5927	8368	12172
1999	110	239	1927	2170	2439	3389	3798	4772	6067	8205	12076
2000	95	216	1932	2200	2521	3521	4162	5150	6378	8660	12892
2001	247	371	2494	2621	2859	3880	4388	5260	6321	8154	9822
2002	138	280	2257	2025	2567	3895	4551	5185	6100	8343	14001
2003	117	294	2323	2288	2555	3521	4285	5365	6549	8585	11141
2004	106	206	2142	2362	2615	3273	3738	4524	5568	7497	12369
2005	149	263	1956	2022	2439	3408	3835	4692	5752	8225	11657
2006	105	249	1857	1956	2215	3088	3553	4555	5834	8252	11331
2007	105	225	1801	1661	1916	3030	3709	4699	5669	8194	12304
2008	141	247	1862	1827	2034	3033	3630	4647	5642	7795	11566
2009	104	278	1970	1706	2115	2955	3823	4814	6010	8178	11222
2010	135	373	1808	1798	2051	2958	3681	4725	5870	8312	11602
2011	143	199	1942	1911	2243	2911	3525	4471	5665	8359	12769
2012	114	246	1774	1237	1877	2698	3426	4179	5449	8447	10372
2013	165	199	1800	1925	2273	2678	3849	4778	6287	8629	10780
2014	199	199	1506	2055	2487	2756	3507	4955	6958	8794	13573
2015	94	181	2071	1476	2090	2773	3528	4424	6193	8140	12036
2016	95	130	2071	1512	2116	2613	3769	4814	6046	8084	12319
2017	91	297	1040	1525	2001	2842	3662	4578	5932	7010	11276
2018	90	126	1041	1386	2298	3240	4131	5825	7058	8910	14082
2019	95	155	2071	1307	2132	3130	4130	5315	6809	8509	12351
2020	166	198	2071	1287	2070	2749	3944	5099	6289	8356	11076

13.5 Stock weights

year	2	3	4	5	6	7	8	9	10	11	12
1979	132	269	534	1399	2113	3123	3995	5315	6836	9396	17491
1980	132	269	534	1399	2113	3123	3995	5315	6836	9396	17491
1981	132	269	534	1399	2113	3123	3995	5315	6836	9396	17491
1982	132	269	534	1399	2113	3123	3995	5315	6836	9396	17491
1983	132	269	534	1399	2113	3123	3995	5315	6836	9396	17491
1984	132	269	534	1399	2113	3123	3995	5315	6836	9396	17491
1985	129	321	565	1341	2089	3075	4020	5610	7853	10412	17332
1986	132	273	528	1396	2139	3092	3841	5206	6788	9280	17642
1987	128	182	542	1465	2065	3165	4000	5212	6491	9962	17704
1988	137	302	502	1393	2160	3162	4118	5233	6211	7931	17650
1989	204	358	533	1271	2140	3231	4131	5335	6407	8215	15699
1990	102	361	528	1251	2013	3107	4247	5818	6998	9381	16073
1991	138	294	727	1187	1658	2964	4105	6317	7455	9435	13776
1992	148	303	807	1367	1881	2944	3995	6060	7503	9623	13705
1993	137	243	560	1414	1883	2857	4062	5825	7157	9430	11395
1994	143	220	578	1508	2261	3331	4295	5645	6890	8636	12645
1995	177	288	448	1318	2136	3137	4174	5771	6417	9153	12621
1996	88	390	702	1336	2127	3230	4266	6172	7502	8372	11420
1997	145	266	487	1099	1916	3434	4438	5759	6920	8654	10366
1998	113	194	473	1516	2099	3338	4528	5917	7340	9446	10070
1999	110	239	549	1516	2091	3048	3997	5645	7235	8727	10252
2000	95	216	414	1675	2286	3075	4024	5540	7198	8679	9751
2001	247	371	556	1450	2268	3337	4129	5669	7076	8614	9013
2002	138	280	510	1375	2107	3237	4109	5863	7148	9621	9686
2003	117	294	583	1202	1884	3004	4145	5873	7343	9478	12850
2004	106	206	465	1363	2055	3022	3902	5490	7010	9386	13167
2005	149	263	468	1258	2094	3076	4002	5349	6546	8829	12862
2006	105	249	446	1183	1985	3188	4049	5535	6725	10392	12294
2007	105	225	493	1280	2035	3318	4151	5752	7324	9294	14198
2008	141	247	477	1169	1965	3045	3859	5307	6750	9268	15471
2009	104	278	527	1103	1764	3023	4076	5701	6942	8864	13683
2010	135	373	533	1118	1541	2746	3557	5417	6423	8836	13084
2011	143	199	404	780	1573	2124	2555	4055	5997	8232	12341
2012	114	246	473	1056	1518	2544	3395	4770	7361	10220	13210
2013	165	199	388	1315	1841	2258	3623	4911	6320	8397	13779
2014	199	199	575	1357	1909	2463	3363	4698	7002	9320	15797
2015	94	181	558	1433	1619	2783	3328	4099	6179	7779	16765
2016	95	130	979	1445	2146	2801	4179	5001	7075	9549	17223
2017	91	297	409	1283	1967	2857	3510	5154	5936	8582	15799
2018	90	126	515	1002	2215	2954	4316	5369	7969	8858	14314
2019	95	155	511	889	1829	2615	3975	5243	6160	8130	12772
2020	166	198	422	877	1532	2640	3690	5526	7061	9194	13512

13.6 Maturity

year	2	3	4	5	6	7	8	9	10	11	12
1979	0.001	0.003	0.023	0.158	0.312	0.520	0.637	0.761	0.856	0.931	0.967
1980	0.001	0.003	0.023	0.158	0.312	0.520	0.637	0.761	0.856	0.931	0.967
1981	0.001	0.003	0.023	0.158	0.312	0.520	0.637	0.761	0.856	0.931	0.967
1982	0.001	0.003	0.023	0.158	0.312	0.520	0.637	0.761	0.856	0.931	0.967
1983	0.001	0.003	0.023	0.158	0.312	0.520	0.637	0.761	0.856	0.931	0.967
1984	0.001	0.003	0.023	0.158	0.312	0.520	0.637	0.761	0.856	0.931	0.967
1985	0.001	0.004	0.023	0.154	0.312	0.517	0.639	0.767	0.863	0.934	0.969
1986	0.001	0.004	0.022	0.155	0.316	0.518	0.636	0.762	0.860	0.931	0.968
1987	0.001	0.003	0.023	0.158	0.312	0.520	0.637	0.761	0.856	0.931	0.967
1988	0.001	0.003	0.021	0.162	0.317	0.523	0.644	0.759	0.844	0.919	0.962
1989	0.001	0.004	0.021	0.154	0.317	0.529	0.655	0.768	0.845	0.915	0.956
1990	0.001	0.005	0.018	0.144	0.316	0.526	0.664	0.781	0.853	0.915	0.955
1991	0.001	0.005	0.021	0.118	0.263	0.487	0.634	0.779	0.854	0.919	0.943
1992	0.001	0.006	0.037	0.141	0.270	0.497	0.647	0.803	0.877	0.934	0.951
1993	0.001	0.005	0.047	0.179	0.299	0.525	0.671	0.829	0.899	0.944	0.955
1994	0.001	0.006	0.058	0.261	0.422	0.635	0.759	0.875	0.931	0.962	0.975
1995	0.002	0.007	0.045	0.283	0.476	0.680	0.795	0.892	0.935	0.965	0.978
1996	0.001	0.007	0.037	0.238	0.436	0.631	0.744	0.851	0.909	0.943	0.951
1997	0.001	0.006	0.023	0.162	0.346	0.574	0.696	0.815	0.883	0.927	0.937
1998	0.001	0.004	0.023	0.154	0.309	0.545	0.677	0.799	0.871	0.919	0.930
1999	0.001	0.004	0.031	0.201	0.353	0.591	0.715	0.823	0.886	0.935	0.948
2000	0.001	0.004	0.033	0.267	0.415	0.601	0.722	0.832	0.898	0.942	0.952
2001	0.001	0.007	0.034	0.264	0.429	0.606	0.715	0.827	0.898	0.942	0.950
2002	0.001	0.008	0.030	0.252	0.429	0.614	0.721	0.829	0.899	0.944	0.955
2003	0.002	0.012	0.050	0.253	0.453	0.667	0.768	0.866	0.921	0.958	0.969
2004	0.001	0.009	0.049	0.258	0.457	0.673	0.775	0.876	0.929	0.965	0.975
2005	0.001	0.009	0.048	0.264	0.484	0.697	0.798	0.890	0.939	0.969	0.978
2006	0.001	0.006	0.029	0.224	0.439	0.663	0.767	0.865	0.921	0.963	0.976
2007	0.001	0.007	0.035	0.233	0.459	0.700	0.797	0.883	0.930	0.967	0.981
2008	0.001	0.008	0.040	0.242	0.470	0.720	0.809	0.892	0.936	0.971	0.986
2009	0.001	0.010	0.052	0.260	0.488	0.742	0.832	0.912	0.951	0.975	0.986
2010	0.001	0.023	0.060	0.254	0.458	0.719	0.819	0.917	0.921	0.976	0.986
2011	0.001	0.021	0.050	0.195	0.382	0.618	0.723	0.866	0.888	0.957	0.978
2012	0.001	0.019	0.042	0.167	0.327	0.559	0.673	0.830	0.874	0.956	0.978
2013	0.001	0.004	0.021	0.157	0.311	0.486	0.642	0.800	0.888	0.942	0.976
2014	0.001	0.003	0.030	0.211	0.350	0.525	0.700	0.832	0.915	0.956	0.985
2015	0.001	0.002	0.036	0.264	0.371	0.557	0.714	0.834	0.918	0.950	0.987
2016	0.001	0.002	0.085	0.286	0.418	0.617	0.752	0.849	0.931	0.961	0.990
2017	0.001	0.010	0.083	0.273	0.426	0.649	0.763	0.858	0.924	0.961	0.988
2018	0.001	0.009	0.080	0.224	0.486	0.657	0.805	0.885	0.935	0.965	0.985
2019	0.000	0.009	0.035	0.161	0.437	0.614	0.785	0.877	0.923	0.956	0.980
2020	0.001	0.002	0.030	0.128	0.396	0.595	0.791	0.885	0.934	0.960	0.980

13.7 Landings

Year	Landings
1979	5315
1980	4645
1981	4520
1982	4990
1983	5123
1984	3880
1985	3450
1986	3596
1987	4974
1988	5846
1989	5547
1990	5560
1991	5780
1992	5086
1993	4046
1994	4115
1995	4015
1996	4125
1997	3906
1998	4394
1999	4625
2000	3284
2001	3362
2002	4519
2003	4270
2004	4606
2005	5198
2006	7405
2007	7591
2008	9283
2009	10945
2010	11131
2011	9626
2012	11817
2013	11581
2014	14246
2015	13035
2016	9884
2017	8766
2018	8062
2019	8269
2020	7061
2021	7128

14 Appendix I. Exploration of possible natural mortality values for ling (*Molva molva*) in 5.a

14.1 Data-limited M estimators

The R package Fisheries Stock Analysis (FSA, Ogle et al. [18]) was used to explore a variety of M estimators using life history information estimated from the spring survey length and age data. Growth is relatively linear in ling (see Appendix I), so Von Bertalanffy growth parameters were estimated as $L_\infty = 273$ cm, $K = 0.04$ and $t_0 = -0.18$. Replacement of L_∞ with a reasonable max length (the 99.95th percentile, 169 cm, from Icelandic spring survey data) resulted in no appreciable change in M estimations. Max age of the population was taken to be the oldest ling in the survey data (20), and the temperature experienced was taken to be the mean of 1) the mean of all spring survey bottom temperature records where ling were caught, 2) the mean of all autumn survey bottom temperature records where ling were caught, and 3) the mean of all commercial records of ling. The mean of means was taken to reduce the influence of the number of records as well as seasonality of each data source (7°C). Maturation data from the spring survey was used to estimated L_50 as 75.5 cm (length at 50% mature from a maturation ogive), which was then translated into $t_50 = 7.9$ (age at 50% mature) using the Von Bertalanffy growth parameters. The weight-length power parameter b was estimated to be 3.2 using all ling caught in the spring survey, and this relationship was also used to set W_∞ as 32 kg, calculated from the the 99.95th percentile ling length in the spring survey (169 cm). Weights calculated for ling longer than this were heavier than any ling recorded in survey data, so were not used.

The **metaM** function in the FSA package calculates a variety of M estimates based on different life history information, two of which vary with length (“Gislason” and “Charnov” methods). Results of using these methods (with length set to 87 cm, the mean length of commercial samples, for the length-variable methods), indicated that M estimates varied widely, ranging 0.06 - 0.45 with both the mean and median of 0.21. Methods that relied on K estimates gave the lowest estimates. Methods that relied on max age were widely distributed, while methods that relied mainly on L_∞ or b were generally high (Fig. 55.

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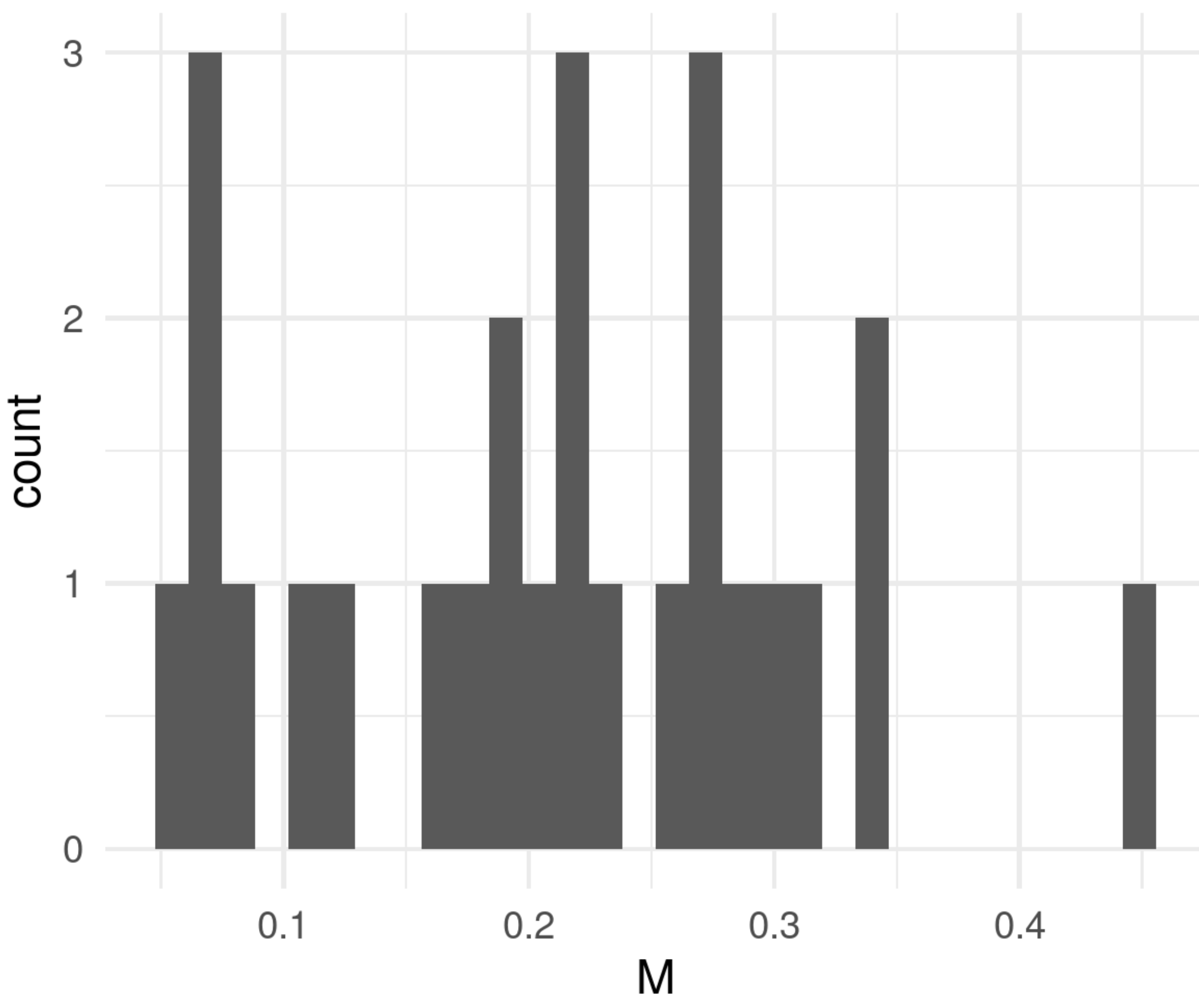

Figure 55: Ling in 5a. Histogram of life-history based natural mortality (M) estimates.

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