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Report of the Workshop on Evaluation of the Adopted Harvest Control Rules for Icelandic Summer Spawning Herring, Ling and Tusk (WKICEMSE)

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Executive Summary

The Workshop on evaluation of the adopted harvest control rules for Icelandic summer spawning herring, ling and tusk (WKICEMSE), chaired by Carmen Fernández, met in Copenhagen, Denmark, during April 21–25 2017. The workshop was attended by nine participants, including two reviewers, from three countries and ICES. The aim of the workshop was to provide 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 and herring. The workshop addressed all its terms of reference, with the following main outcomes:

For ling and tusk, a review of the stock assessment methodology was conducted, which resulted in agreed data and model settings for their stock assessment. Precautionary Approach and MSY reference points were calculated. The harvest control rules proposed for ling and tusk are based on harvest rates that correspond to yield at or very close to the maximum sustainable yield, while resulting in less than 5% probability of SSB being below B_{lim}. The rules can, therefore, be considered to be precautionary and in conformity with the MSY approach.

Several harvest control rules were evaluated for herring. The occurrence of *Ichthyophonus* epidemic outbreaks in recent years, which increase natural mortality, and the uncertainty surrounding the frequency with which outbreaks may occur in future, considerably complicates the evaluation. The rules were evaluated under several scenarios of frequency of future disease outbreaks. Assessment bias (15% overestimation of stock size) was also considered in the evaluations, based on observed past patterns. All harvest control rules proposed are based on fishing mortalities or harvest rates that correspond to yield at or very close to the maximum sustainable yield. All rules resulted in less than 5% probability of SSB below B_{lim} under scenarios that assume no future *Ichthophonus* epidemics. Assuming increased mortality due to an *Ichthyophonus* epidemic in 2017–2019, and the possibility of further outbreaks in future, but no assessment bias, all rules resulted in less than 5% probability of SSB below B_{lim}, except in year 2020 for some of the rules. When this *Ichthyophonus* scenario is combined with 15% assessment bias, the behaviour of the rules differs: two of them remain precautionary, for two of them the probability of SSB being below B_{lim} slightly exceeds 5% (6%-8%) in 2019–2021, although it becomes less than 5% in the long run; finally, for one of the rules (the current advisory rule) the probability of SSB below B_{lim} exceeds 5% in most years and the rule cannot be considered precautionary under these conditions. All rules except for this one can be considered to be precautionary and in conformity with the MSY approach.

1 Introduction

The Workshop on evaluation of the adopted harvest control rules for Icelandic summer spawning herring, ling and tusk (WKICEMSE), 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 ling, tusk and herring. The request, listed in Annex 1 of this report, also included a review of input data and assessment methodology for ling and tusk. The workshop was given the following Terms of Reference:

a) Evaluate whether the proposed harvest control rules (below) are in accordance with ICES objectives, given current ICES definition of reference points for these stocks or any re-evaluation of those points that may occur in the process.

b) For ling and tusk the evaluation should also include review of input data and the applied assessment methodology (benchmark).

The generic form of the HCR is the following:

1) When the spawning–stock biomass (SSB) in the assessment year is estimated to be above SSBMGT, the TAC in the following fishing year will be set based on a FMGT.

2) When the SSB in the assessment year is estimated to be below SSBMGT, the TAC in the following fishing year will be based on FMGT * (SSBy/ SSBMGT).

The value of SSBMGT should be defined in such a way that the estimated SSB in the assessment year when fishing at FMGT has a low probability of being below SSBMGT (<5%).

The HCR could also be based on proportion of reference biomass in the assessment year instead of fishing mortality in the advisory year.

A few days before the workshop started, ICES received additional correspondence from Iceland, specifying the particular form of several harvest control rules that should be evaluated. See Annex 1 of this report for details of the request.

The workshop was successful in addressing of all its Terms of Reference. This report is organised as follows:

Section 2 covers the work and conclusions on tusk, including stock assessment, reference points, harvest control rule evaluation and the reviewers' report. Section 3 follows the same structure for ling. Section 4 covers the evaluation of harvest control rules for herring, including the reviewers' report. The annexes at the end of the report include the special request from Iceland (Annex 1), the list of working documents submitted to the workshop (Annex 2), and a list of participants (Annex 3).

2 Tusk

2.1 Summary of work during the WKICEMSE workshop

The scientific work prepared by Icelandic scientists on stock assessment, reference points and harvest control rule evaluation for tusk, which had already been discussed by correspondence with the reviewers, was presented and discussed in detail during the WKICEMSE workshop. As a result of the exchanges, several modifications were made to the document originally submitted, and the final version is included in Section 2.2 of this report. Since all technical details are included in that section, only a brief summary of main points arising from the discussion at the workshop is presented here.

Catches of tusk in Greenland, within ICES Subarea 14, were discussed. Minor catches (representing <5% of the total catch of tusk in 5.a+14) have always occurred in the Greenland area and were never included in the stock assessment of tusk. However, these catches increased in 2015 and 2016, representing around 10%–15% of the total catches in those years. None of the work presented to WKICEMSE included these catches, which seem to occur well away from the area where the catches included in the stock assessment take place (i.e. in or around ICES division 5.a). Information about these catches in the Greenland area is somewhat limited and no biological samples are available; doubts related to population structure, movement and connectivities were also noted during the discussion. It was then decided to conduct a stock assessment run incorporating those catches (just the tonnage), to gain understanding on their potential impact on stock assessment results. Their inclusion in the assessment resulted in minor revisions upwards of the estimated stock biomass (around 1%–4% revision, on average throughout the years in the stock assessment) and downwards of the estimated harvest rate (around 0%–3% revision, on average throughout the years in the stock assessment, although with an increase of the harvest rates estimated for 2015 and 2016); the results of this run are available at the end of Section 2.2. As there are some doubts in relation to these catch data and population structure of tusk in the area, WKICEMSE did not feel that a decision to include these catches in the stock assessment at this point was appropriate before conducting additional explorations and having a better understanding. It is recommended that appropriate stock experts in WGDEEP should explore this issue further.

Other main aspects discussed in detail during the presentation at WKICEMSE are covered in the reviewers' report (Section 2.3 of this report) and are not repeated here. Future work on tusk will take into account the points noted in the reviewers' report.

A new Stock Annex for tusk was prepared, in line with the new data and settings agreed for the stock assessment, and incorporating the Precautionary Approach and MSY reference points calculated as part of this process. Fishing pressure reference points can be expressed in terms of F or harvest rate, with the latter being the form generally preferred in Iceland for communication purposes. Fishing pressure reference points were therefore calculated both in terms of F and in terms of harvest rates on B(40+ cm), and both are available in Section 2.2 and Stock Annex. The workshop suggests that, in order not to make the ICES catch advice presentation unnecessarily complicated for stocks around Icelandic waters, fishing pressure in the ICES advice sheets for these stocks is presented solely in terms of harvest rates (rather than having multiple lines, one for F and another one for harvest rate, and multiple reference points, i.e. reference points both for F and for harvest rate).

The harvest control rule presented to ICES for evaluation is based on a harvest rate on the 40+ cm stock biomass in the assessment year, $B_{ref,y}$. As the annual stock assessment conducted in year y will contain data until the end of quarter 1, it seems logical to have $B_{ref,y}$ calculated at the beginning of quarter 2, i.e. with a delay of five months between assessment and fishing year (the fishing year being from September 1 of year y to August 31 of year y+1). The stock assessment model (used as operating model in the management strategy evaluation) works internally on a quarterly basis, so the five-month delay was approximated by a delay of two quarters in the management strategy evaluation. In line with this, WKICEMSE considers that $B_{ref,y}$ used in the harvest control rule should be calculated at the beginning of quarter 2 of the assessment year y.

On the other hand, the biomass reference points B_{lim} and B_{pa} were calculated based on SSB on January 1 (B_{pa} has been set to B_{loss} = SSB(2001)), and MSY $B_{trigger}$ and MGT $B_{trigger}$ have both been set equal to B_{pa}. It is therefore more appropriate that the SSB_y reported for comparison with biomass reference points and for use in the harvest control rule refers to January 1.

The workshop spent considerable time discussing the properties of the harvest control rule presented to ICES for evaluation. The evaluation is obviously based on the best information and knowledge available at this time. As is always the case, there is uncertainty associated with simulations into future years, with the possibility that non-anticipated changes may occur. The workshop considers that it would be appropriate to review the performance of the rule after some years, e.g. after approximately five years.

2.2 Stock assessment, reference points, and harvest control rule evaluation

2.2.1 A Gadget assessment of Tusk in 5.a and 14

Gadget is a shorthand for the "Globally applicable Area Dis-aggregated General Ecosystem Toolbox", which is a statistical model of marine ecosystems (previously known as BORMICON (Stefánsson and Pálsson 1997) and Fleksibest (Frøysa et al. 2002)). Gadget is an age-length structured forward-simulation modeling framework, where models can be coupled with an extensive set of data comparison and optimisation routines. Processes are generally modeled as dependent on length, but age is tracked in the models, and data can be compared on either a length and/or age scale. The framework allows for the creation of multi-area, multi-fleet models, capable of including predation and mixed fisheries issues, however it can also be used on a single species basis. Gadget models can be both very data- and computationally- intensive, with optimisation in particular taking a large amount of time. Worked examples, a detailed manual and further information on Gadget can be found on `www.github.com/hafro/gadget`. In addition the structure of the model is described in Begley and Howell (2004), and a formal mathematical description is given in Frøysa et al. (2002).

The Gadget framework is essentially three things, an **ecosystem simulator**, a **likelihood** function that takes the output from the ecosystem simulator and compares to data, and a **function mininimizer**. Gadget's **ecosytem simulator** allows for a fairly configurable ecosystem simulation. Its fundamental unit, a **stock** (or more accurately substock), represents a group of individuals that is homogenous with respect to various processes. These processes include growth, predation (including commercial fisheries) and migration. In this setup different stages of the life history of a particular species would be represented as separate stocks and individuals "moved" between stocks when required. The simulation takes place in a set number of **years** and **time-steps** within a year The time-steps within the year allow for the emulation of the annual cycles of the ecosystem, such as recruitment and stock migrations.

The stock unit within Gadget is simply a representation of the total number of individuals in a certain age range and length group range within certain areas. The stocks live in an area, or areas, where they optionally migrate to and from. In this setup processes such as fleet harvest or recruitment can be restricted to take place only in certain (or all) areas. Harvesting of the substocks is defined through fleets that fish according to harvest rate and (length–based) selection functions.

Gadget's **likelihood** module processes the output from the ecosystem simulation based on aggregate dimensions. Within the likelihood module a number of datasets can be compared to the model output. In addition to a suite of functions designed to work with different types of survey indices, length distributions, tagging data, age and length distribution and maturity data, to name a few, can be contrasted to the model output. Each data set is included at its own aggregation level, with missing data handled in a robust manner.

In contrast with Gadget, age based or stock production type stock assessments require data in a fairly processed form. For instance when using VPA one requires the total catch in numbers of individuals by age. However, apart from catches of fin whales in the North Atlantic (IWC 2015), one rarely has all catches by numbers at age. Therefore the age distribution of catches needs to be approximated using some combination of age readings, length distributions, total catches in tons and weight at age (as noted in Hirst et al. 2005). In essence using a typical VPA requires a two-step modelling process, whereas Gadget models combines these two steps.

Gadget's **function minimizer**, based on the negative log–likelihood, varies the model parameters, runs a full simulation, and calculates a new output. This process is repeated until a minimum is obtained. The total objective function to be minimised is a weighted sum of the different components. The estimation could be difficult due to groups of correlated parameters or multiple local optima. To address these issues Gadget has three alternative optimising algorithms built in, a wide area search `simulated annealing` (Corana et al. 1987), a local search `Hooke and Jeeves algorithm` (Hooke and Jeeves 1961) and finally one based on the Broyden-Fletcher-Goldfarb-Shanno algorithm, hereafter termed `BFGS`, described in Bertsekas (1999). The optimisation procedure often involves a combination of these three procedures.

2.2.1.1 Setup of a gadget run

There is a separation of model and data within Gadget. The simulation model runs with defined functional forms and parameter values, and produces a modeled population, with modeled surveys and catches. These surveys and catches are compared against the available data to produce a weighted likelihood score. Optimisation routines then attempt to find the best set of parameter values. Fig. 2.1 illustrates how this is implemented in Gadget's input file structure.

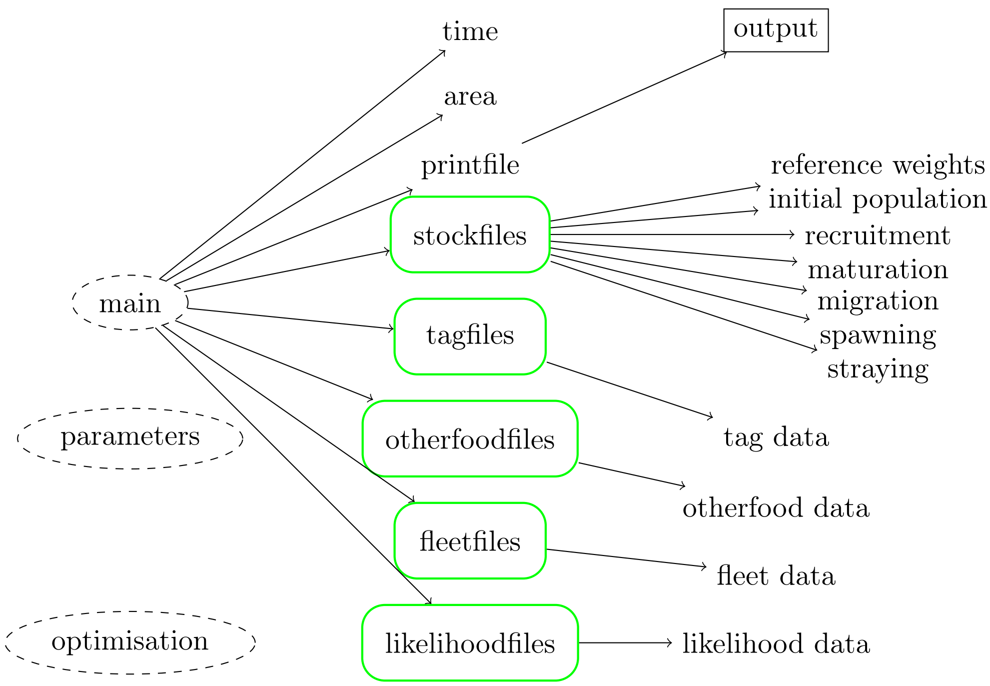

Figure 2.1: Schematic description of the file structure in a Gadget model

2.2.1.2 Simulation model

In a typical Gadget model the simulated quantity is the number of individuals, N_{alsyt}, at age $a = a_{min} \dots a_{max}$, in a length-group l, representing lengths ranging between l_{min} and l_{max} cm in Δl cm length-groups, at year y which is divided into timesteps, usually quarters, $t = 1 \dots T$. The length of the time-step is denoted Δt. The population is governed by the following equations:

$$
\begin{aligned}
N_{alsy,t+1} &= \sum_{l'} G^l_{l'} \left[(N_{al'syt} - \sum_f C_{fal'st}) e^{-M_a \Delta t} + I_{al'lsyt} \right] && \text{if } t < T \\
N_{a,ls,y+1,1} &= \sum_{l'} G^l_{l'} \left[(N_{a-1,l'sy,T} - \sum_f C_{fa-1,l's,T}) e^{-M_{a-1} \Delta t} + I_{a-1,l'lsy,T} \right] && \text{if } t = T \text{ and } a < a_{max} \\
N_{a,ls,y+1,1} &= \sum_{l'} G^l_{l'} (N_{al'sy,T} - \sum_f C_{fal'sy,T} + \\
&\qquad N_{a-1,l'sy,T} - \sum_f C_{f,a-1,l'sy,T}) e^{-M_a \Delta t} && \text{if } t = T \text{ and } a = a_{max}
\end{aligned}
\tag{2.1}
$$

where $G^l_{l'}$ is the proportion in length-group l that has grown $l - l'$ length-groups in Δt, C_{falsyt} denotes the catches by fleet $f \in \{S, C, F\}$, i.e. the survey[1], commercial and foreign[2] vessels, M_a the natural mortality at age a and $I_{al'lsyt}$ denotes the movement of fish at length l' from the immmature to the mature stock component at length l [3].

Growth

Growth in length is modeled as a two–stage process, an average length update in Δt and a growth dispersion around the mean update (as described in Stefansson 2005). Average length update is modeled by calculating the mean growth for each length group for each time step, using a parametric growth function. In the current model a simplified form of the Von Bertanlanffy function has been employed to calculate this mean length update.

$$\Delta l = (l_\infty - l)(1 - e^{-k\Delta t}) \tag{2.2}$$

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

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

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

and

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

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

$$G^{l'}_l = \frac{\Gamma(n+1)}{\Gamma((l'-l)+1)} \frac{\Gamma((l'-l)+\alpha)\Gamma(n-(l'-l)+\beta)}{\Gamma(n-(l'-l)+1)\Gamma(n+\alpha+\beta)} \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)} \tag{2.3}$$

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

[2] In the case of tusk foreign vessels are assumed to have the same suitability function as the commercial fleet, however this does however simplifies the data entry.

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

where α is subject to

$$\alpha = \frac{\beta \Delta l}{n - \Delta l} \tag{2.4}$$

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

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

$$W_{sl} = \mu_s l^{\omega_s} \tag{2.5}$$

Recruitment and initial abundance

Gadget allows for a number of relationships between stock recruitment and the size of the spawning stock to be defined. However in this model the number of recruits each year, R_y, is estimated within the model as a.

Recruitment enters the population according to:

$$N_{a_{min} l0yt'} = R_y p_l \tag{2.6}$$

where t' denotes the recruitment time-step and p_l is the proportion in length-group l that is recruited. p_l is determined by a normal density with l_0, which has a one to one mapping with t_0 used in a typical von Bertalanffy growth model, and variance σ_y^2.

A simple formulation of initial abundance in numbers is used for each age group a, of stock s and in length-group l:

$$N_{als11} = \nu_{as} q_{al} \tag{2.7}$$

where ν_{sa} is the initial number at age a in stock s in the initial year and q_l the proportion at length-group l which is determined by a normal density with a mean according to the growth model in equation 2.2 and variance σ_a^2, with a starting length, at age 1, as l_0.

Maturation

Two stage maturity is modeled and represented by the two stock components. First the movement between the two components is formulated as

$$I_{al'lsyt} = \begin{cases} N_{al'0y,t-1} \times m_{l'}^{l} & \text{if s = 1 and t > 1} \\ N_{al'0y-1,T} \times m_{l'}^{l} & \text{if s = 1 and t = 1} \\ -N_{al'0y,t-1} \times m_{l'}^{l} & \text{if s = 0 and t > 1} \\ -N_{al'0y-1,T} \times m_{l'}^{l} & \text{if s = 0 and t = 1} \end{cases} \tag{2.8}$$

where $s = 0$, as noted above, denotes the immature stock component. and $m_{l'}^{l}$ is the proportion of immatures that mature between the lengths l and l' defined as:

$$m_{l'}^{l} = \frac{\lambda(l - l')}{1 + e^{-\lambda(l - l_{50})}} \tag{2.9}$$

The second when individuals of the immature stock component reach a certain age those individuals are all moved to the mature stock component.

Fleet operations

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

$$C_{falsyt} = E_{ft} \frac{S_f(l) N_{alsyt}}{\sum_{s'} \sum_{a'} \sum_{l'} S_f(l') N_{a'l's'yt} W_{l's'}} \tag{2.10}$$

where E_{ft} is the landed biomass at time t and $S_f(l)$ is the suitability of length-group l by fleet f defined as[4]:

$$S_f(l) = \frac{1}{1 + e^{-b_f(l - l_{50,f})}} \tag{2.11}$$

The effective fishing mortality at age and at time step t is calculated according to the following equation:

$$F_{asyt} = \frac{-\log(1.0 - \frac{C_{asyt}}{N_{asyt}})}{\Delta t} \tag{2.12}$$

where $C_{asyt} = \sum_{fl} C_{falsyt}$ and $N_{asyt} = \sum_l N_{alsyt}$. For tusk the reported F_y is the average F_a for fully recruited ages, i.e. age 15 and above, for that year.

Harvest rate in terms of the reference biomass is calulated as:

$$H_y = \frac{C_y}{B_{ref,y}} \tag{2.13}$$

where $C_y = \sum_{falst} C_{falsyt} W_{s,l}$ and $B_{ref,y} = \sum_{alst} N_{alsyt} W_{s,l}$. For tusk the reported reference biomass is the biomass of fish larger than or equal to 40cm, denoted $B_{40cm^+,y}$.

2.2.1.3 Observation model

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

Importantly this ability to handle length data directly means that the model can be used for stocks such as Tusk in 5a and 14 where age data is sparse and/or are unrelible. Length data can be used directly for model comparison. The model is able to combine a wide selection of the available data by using a maximum likelihood approach to find the best fit to a weighted sum of the data-sets.

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

In formulations below it is assumed that the compositional data are sampled at random, both from the fishery and surveys, as this is how the sampling protocol is

[4] Other functional forms for the selection are defined in Gadget

Icelandic waters is set up. Other forms of likelihoods are implemented in Gadget that can be used to address other types of sampling, e.g. length stratified sampling of maturity.

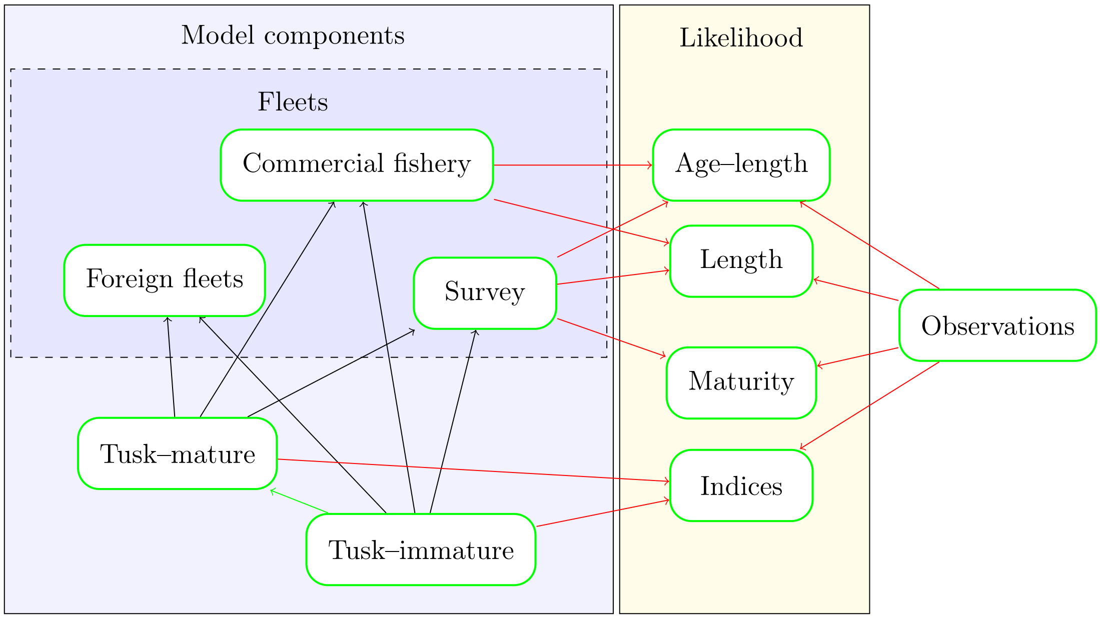

Figure 2.2: Schematic description of the Gadget model for Tusk in 5a and 14. Lines indicated flow from one model component to the other. Black lines indicate consumption by predators (fleets), red lines the modelled predictions/observations sent to the likelihood and green lines movement between stock components.

Survey indices

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

$$l_g^{\mathrm{SI}} = \sum_y \sum_t (\log I_{gy} - (\log q_g + b_g \log \widehat{N_{gyt}}))^2 \tag{2.14}$$

where

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

Fleet data

Length distributions are compared to predictions using

$$l_f^{\mathrm{LD}} = \sum_y \sum_t \sum_l (\pi_{flyt} - \hat{\pi}_{flyt})^2 \tag{2.15}$$

where f denotes the fleet where data was sampled from and

$$\pi_{flyt} = \frac{\sum_a \sum_s O_{falsyt}}{\sum_{a'} \sum_{l'} \sum_s O_{fa'l'syt}}$$

and

$$\hat{\pi}_{lyt} = \frac{\sum_a \sum_s C_{falsyt}}{\sum_{a'} \sum_{l'} \sum_s C_{fa'l'syt}}$$

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

$$l_f^{\mathrm{AL}} = \sum_y \sum_t \sum_a \sum_l (\pi_{falyt} - \hat{\pi}_{falyt})^2 \tag{2.16}$$

where

$$\pi_{falyt} = \frac{\sum_s O_{falsyt}}{\sum_a \sum_{l'} \sum_s O_{fal'syt}}$$

and

$$\hat{\pi}_{falyt} = \frac{\sum_s C_{falsyt}}{\sum_{a'} \sum_{l'} \sum_s C_{fa'l'syt}}$$

Length at maturity comparison uses the number fish of which maturity status has been assigned that are observed in a given fishery or a survey. The observed proportions are compared to the modelled proportion using sum of squares:

$$l_f^{\mathrm{M}} = \sum_y \sum_t \sum_l (\pi_{flyt} - \hat{\pi}_{flyt})^2 \tag{2.17}$$

where

$$\pi_{flyt} = \frac{\sum_a O_{fal1yt}}{\sum_{a'} \sum_{l'} \sum_s O_{fa'l'syt}}$$

and

$$\hat{\pi}_{flyt} = \frac{\sum_a C_{fal1yt}}{\sum_{a'} \sum_{l'} \sum_s C_{fa'l'syt}}$$

i.e. the observed and modelled proportions of tusk in length group l and mature, in year y and timestep t, and where the fleet f corresponds to the survey.

2.2.1.4 Order of calculations

The order of calulations is as follows:

1. **Printing**: model output at the beginning of the time-step
2. **Consumption**: mainly fleet harvesting
3. **Natural mortality**: Natural mortality is applied after consumption
4. **Growth and maturation**: length update is applied and maturing fish moved from one stock component to the other.
5. **Spawning and recruitment**: New individuals enter the immature stock component
6. **Likelihood comparison**: likelihood score is calculated here, note that the comparison is based on the modeled processes in previous steps
7. **Printing**: model output at the end of the time-step
8. **Ageing**: if this is the end of year the age is increased

2.2.1.5 Iterative re–weighting

The total objective function used the modeling process combines equations 2.14 to 2.16 using the following formula:

$$l^{\mathrm{T}} = \sum_{g} w_{gf}^{\mathrm{SI}} l_{g,S}^{\mathrm{SI}} + \sum_{f \in \{S,C\}} \left(w_f^{\mathrm{LD}} l_f^{\mathrm{LD}} + w_f^{\mathrm{AL}} l_f^{\mathrm{AL}} \right) + w^{\mathrm{M}} l^{\mathrm{M}} \tag{2.18}$$

where $f = S$ or C denotes the spring survey, commercial fleets respectively (See subsection 2.2.2.3) and w's are the weights assigned to each likelihood components.

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

Assigning likelihood weights is not a trivial matter, has in the past been the most time consuming part of a Gadget model. Commonly this has been done using some form of 'expert judgement'. General heuristics have recently been developed to estimated these weights objectively. Here the iterative re–weighting heuristic introduced by Stefansson (2003), and subsequently implemented in Taylor et al. (2007), is used.

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

1. Calculate the initial sums of squares (SS) given the initial parametrization for all likelihood components. Assign the inverse SS as the initial weight for all likelihood components, resulting in a total initial score of 1 for each component.

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

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

The number of non-zero data-points (df^*) is used as a proxy for the degrees of freedom. While this may be a satisfactory proxy for larger data-sets it could be a gross overestimate of the degrees of freedom for smaller data-sets. In particular, if the survey indices are weighed on their own while the yearly recruitment is estimated they could be over-fitted. In general problem such as these can be solved with component grouping, that is in step 2 the likelihood components that should behave similarly, such as survey indices representing similar age ranges, should be upweighted and optimized together. This kind of grouping is used in the present model (See subsection 2.2.2.4).

2.2.1.6 Optimisation

The total objective function to be minimised is a weighted sum of the different components, as described in eq. 2.18. The estimation could be difficult due to groups of correlated parameters, multiple local optima or flat surfaces of the objective function in the search neighbourhood. Therefore the optimisation procedure often involves a combination of the more robust simulated annealing, to make the results less sensitive to the initial (starting) values, and to the local search algorithms (Hooke and Jeeves and BFGS) in the neighborhood of the global optima.

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

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

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

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

The total objective function to be minimised is a weighted sum of the different components. The estimation can be difficult because of some or groups of parameters are correlated and therefore the possibility of multiple optima cannot be excluded. The optimisation was started with simulated annealing to make the results less sensitive to the initial (starting) values and then the optimisation was changed to Hooke and Jeeves when the 'optimum' was approached and then finally the BFGS was run in the end. The settings for the miniizers are listed in annex 2.2.8.2.

2.2.1.7 Bootstrap

To estimate the uncertainty in the model parameters and derived quantities a specialised boostrap for disparate datasets is used. The approach is based on spatial subdivisions that can be considered to be i.i.d. Refer to Elvarsson et al. (2014) and Lentin (2017) for further implementation details. The bootstrapping approach consists of the following:

- The base data are stored in a standardized data base:
  - Time aggregation: 3 months
  - Spatial aggregation: subdivision
  - Further dis-aggregation is based on a range of categories including fishing gear, fishing vessel class, sampling type (e.g. harbour, sea and survey). A full listing of data types used in the case study can be found in table 2.1, these data are stored subdivision dis-aggregated to allow for use in a bootstrap.
- To bootstrap the data, the list of subdivisions, depicted in fig. 2.3, required for the model is sampled (with replacement) and stored. For a multi–area model one would conduct the re-sampling of subdivisions within each area of the model.

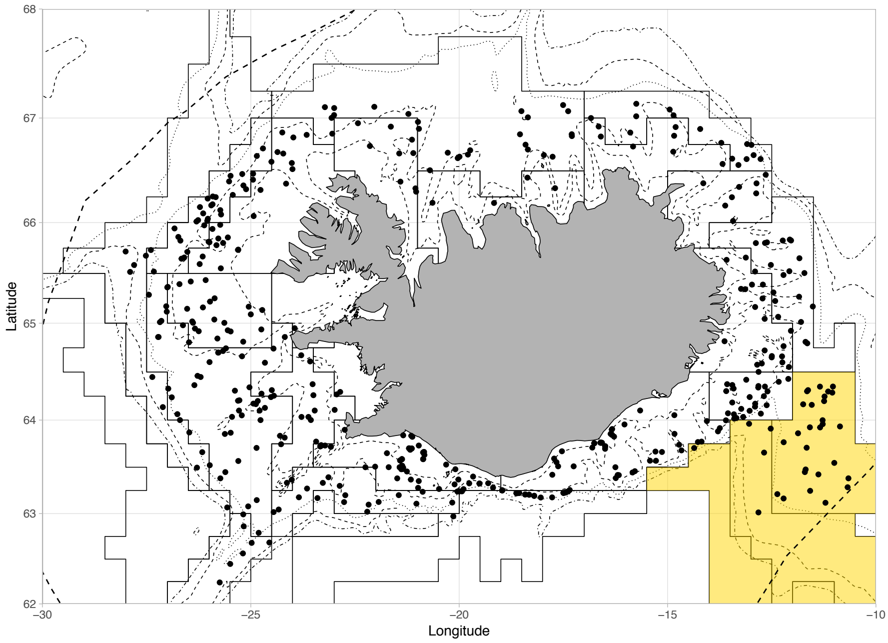

Figure 2.3: Tusk in 5a and 14. Locations of Tusk catches in 5a by commercial and survey fleets in 2015 relative to the spatial subdivision on the Icelandic continental shelf area. The yellow shaded region indicates the area that was not covered in the Iceland spring survey in between 1996 and 2005.

- The list of re-sampled subdivisions is then used to extract data (with replacement so the same data set may be repeated several times in a given bootstrap sample).
- For a single bootstrap Gadget model, the same list of re-sampled subdivisions is used to extract each likelihood data set i.e. length distributions, survey indices and age–length frequencies are extracted from the same spatial definition.
- A Gadget model is fitted to the extracted bootstrap data set using the estimation procedure described above.
- The re-sampling process is repeated until the desired number of bootstrap samples are extracted, which in this case the total sample size is 100.

When re-sampling, data are forced to remain in the correct year and time–step so re-sampling is based on sampling spatially the elementary data units within a given modeled unit of time and space. Thus, within a modeled spatial unit the bootstrap is a re-sampling of subdivisions. This implicitly assumes data contained within each area of the model to be independent and identically distributed. Independence is justified by the definition of subdivisions. Furthermore treating them as they were from the same distribution, i.e. bootstrap replicates, appears to have little negative effect when compared to more traditional methods (Taylor 2002).

The entire estimation procedure is repeated for each bootstrap sample. In particular, since the estimation procedure includes an iterative re-weighting scheme, this re-weighting is repeated for every bootstrap sample. The point of this is that the bootstrap procedure is no longer conditional on the weights. The procedure as a whole is quite computationally intensive but can easily be run in parallel, e.g. on a computer cluster.

In the few days prior to the meeting it was discovered that large parts of the maturity data had not been included in the stock assessment. Repeating the entire bootstrap process would have taken too long a time and, therefore, for the results showed here, a slightly altered approach to the bootstrap where the weighting from the previous run that did not include the additional maturity data was used to obtain the final results. This is perceived to impact the final weighting slightly, as it may emphasize the maturity more, while greatly reducing computational costs.

2.2.2 Model settings

Tusk in 5a and 14 is assumed to be fairly long lived and the maximum age is set at 18, with 18 acting also as a plus group and simulation goes back to 1982, maturing at age 15 the latest. The minimum age of the immature substock is set as 1 and the mature is set to start at age 6. The length range in the model was between 4 and 110, in 2 cm length intervals, with the mature population starting at 20 cm. Recruitment is set to occur at the end of the first time-step. An overview of the data-sets and model parameters used in the model study is shown in Tables 2.1 and 2.2 respectively.

Table 2.1: Tusk in 5a and 14. Overview of the likelihood data used in the model. Survey indices are calculated from the length distributions and are dis-aggregated ("sliced") into seven groups (Table 2.6). Number of data-points refer to aggregated data used as inputs in the Gadget model and represent the original data-set. All data can obtained from the Marine and Freshwater Research Institute, Iceland.

Origin	Time-span	Length group size	Num. data-points	Likelihood function	Weight group
	Age–length distributions:				
Commercial catches	All quarters, 1982–2016	2 cm	2187	See eq. 2.16	aldist.comm
March Survey	2^{nd}, 1985–2016	2 cm	1825	See eq. 2.16	aldist.igfs
	Length distributions:				
Commercial catches	All quarters, 1982–2016	2 cm	3329	See eq. 2.15	ldist.comm
March Survey	2^{nd}, 1985–2016	2 cm	1235	See eq. 2.15	ldist.igfs
	Ratio of immature:mature by length group:				
March Survey	2^{nd}, 1985–2016	4 cm	1404	See eq. 2.17	matp.igfs
	Survey indices:				
March Survey	1^{st}, 1985–2016	10 – 20 cm	32	See eq. 2.14	sind
March Survey	1^{st}, 1985–2016	20 – 30 cm	32	See eq. 2.14	sind
March Survey	1^{st}, 1985–2016	30 – 40 cm	32	See eq. 2.14	sind
March Survey	1^{st}, 1985–2016	40 – 50 cm	32	See eq. 2.14	sind
March Survey	1^{st}, 1985–2016	50 – 60 cm	32	See eq. 2.14	sind
March Survey	1^{st}, 1985–2016	60 – 70 cm	32	See eq. 2.14	sind
March Survey	1^{st}, 1985–2016	70 – 110 cm	32	See eq. 2.14	sind

2.2.2.1 Natural mortality

Choice of natural mortality (M) is problematic as is normally the case in stock assessments. Here M is assumed to be constant with age at 0.15.

2.2.2.2 Weight length relationship

The parameters of the weight–length relationship used in eq. 2.5 were estimate through the means of log-linear regregression. Fig. 2.4 shows the observed length-weight relation compared with the fitted values.

Table 2.2: Tusk in 5a and 14. An overview of the estimated parameters in the model.

Description	Notation	Comments	Formula
Natural mortality	M_a	Fixed at 0.15 for ages 1 to 18^+	See eq. 2.1
Growth function	k, L_∞	Estimated from age–length frequencies	See eq. 2.2
Growth implementation	β	n is fixed at 15 length-groups	See eq. 2.3
Fleet selection	b_f, $l_{50,f}$	One set for each of the fleets (Survey, Commerical and Foreign). The commercial and foreign fleet have the same selection	See eq. 2.11
Maturity ogive	λ, l_{50}		See eq. 2.8
Length at recruitment	l_0, σ_0	Mean length and std. deviation in recruitment length.	See eq. 2.6
Number of recruits by year	R_y	$y \in [1982, 2016]$. σ_0, i.e. std. deviation in recruitment length, based on length distributions obtained in the autumn survey.	See eq. 2.6
Initial abundance at ages 1 – 18 in 1982 by stock component	η_{sa}	$a \in [1, 18^+]$. σ_a^2, i.e. variance in initial length at age a, based on length distributions obtained in the spring survey.	See eq. 2.7 and table 2.3
Survey catch-ability	q_g	Intercept term in a log–linear relationship with abundance. The slope term, b_g, is assumed to be 1 for all indices.	See eq. 2.14
Length–weight relationship	μ_s, ω_s	Estimated outside of the model	See eq. 2.5
Scalars	R_c, $I_{c,s}$, F_0	Recruiment, initial numbers at age and initial fishing mortality (applied to all age groups)	

Table 2.3: Tusk in 5a and 14. Initial standard deviation in length by age, see eq. 2.7 for further details

Age	σ_a	Age	σ_a	Age	σ_a
1	5.00	7	6.45	13	7.82
2	3.34	8	6.34	14	7.40
3	3.74	9	6.26	15	7.50
4	5.70	10	6.76	16	7.50
5	6.92	11	7.44	17	7.50
6	6.73	12	7.96	18	7.50

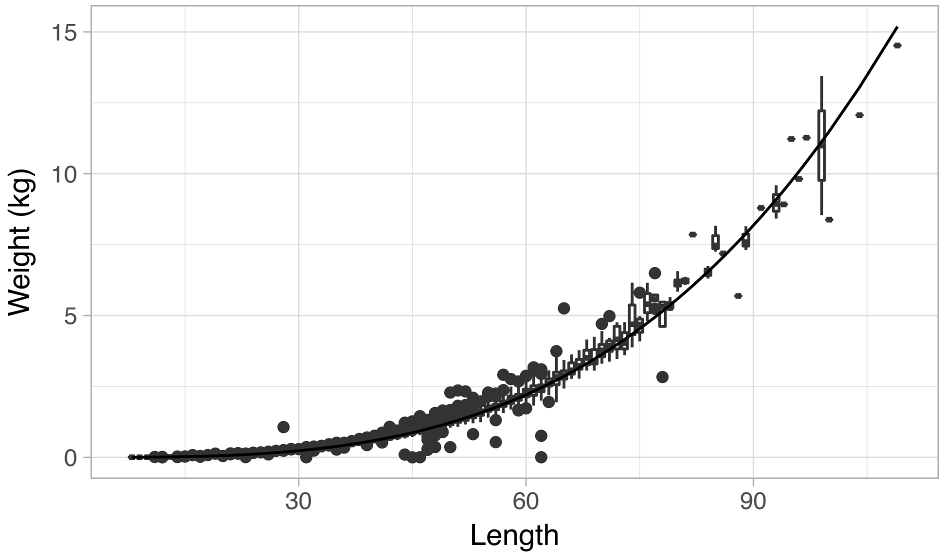

Figure 2.4: Tusk in 5a and 14. Observed length-weight relationship from the Icelandic Groundfish Survey. Estimated length weight relationship shown as a solid line.

2.2.2.3 Fleets and selection

In the model there are two commercial fleets and one survey fleet. The commercial fleets are the Icelandic longline and foreign–fleets. The selection is described by a logistic function and total catch in tonnes is specified for each time-step.

2.2.2.4 Iterative re-weighting, initial parameter- and optimisation settings

In order to assign weights to the individual likelihood components the iterative re-weighting process described in 2.2.1.5 on page 10 was used. The data-sets were grouped when over-weighting them, the rationale was that similar data-sets should contain similar information. The grouping the likelihood components, which is shown in table 2.1, was applied all survey indices together to prevent issues related to overfitting.

All runs (base and bootstrap) were started from the same initial values. The values and the boundaries are in Annex 2.2.8.1 on page 68. Settings for the optimising algorithms are shown in Annex 2.2.8.2 on page 69. All runs, both individual weighting and final runs converged.

Three types of scaling parameters were applied to the model parameters during the optimisation. First the recruitment level was scaled according to a common parameter, R_c, to allow the model to find the correct placement of the recruitment parameters. Similarly the intitial number at age for each stock component was scaled with common parameters, first a plain scalar $I_{c,s}$ and secondly by a common fishing mortality, F_0. These parameters were estimated.

2.2.3 Input data

2.2.3.1 Commercial catches

Landings

In the model there are two commercial fleets, namely commercial longlines and foreign vessels, and a survey fleet. The commercial and the foreign fleets have the same selection curve as the foreign catches, mostly from the Faroe Islands and Norway, are assumed to be caught with longlines (Table 2.4). The sources of landings of tusk in 5a and 14 are four. For the period between 1993 to the present all landings of Icelandic vessels were recorded by the Directorate of Fisheries, and all landings in 5a after 2013. Prior to 1993 landings data from Icelandic vessel were recorded by Fiskifélagið, and foreign vessel prior to 2014 were obtained from Statlant and distributed to quarters in equal proportions.

Catches from subarea 14 (Greenland) were not included here as the catches historically have been neglible until 2015 and 2016 where 1300 t and 471 t respectively were taken. In a working document presented in WGDEEP 2010 the catches of tusk in 14.b were mostly taken south of 54 N well away from the Icelandic catches. It is questionable whether these catches should be included in the assessment of tusk in 5.a due to the fact that no catches of tusk have been taken on the Iceland-Greenland ridge close to the EEZ-borders. The effects of including these catches are investigated in appendix 2.2.8.3.

Table 2.4: Tusk in 5a and 14. Commercial catches in tonnes by fleets, steps (3 month) and years.

Year	Commercial				Foreign				Total
	1	2	3	4	1	2	3	4	
1982	692.8	450.87	380.47	1277.23	769	769	769	769	5877.37
1983	1256.39	530.72	532.56	1148.75	1204.5	1204.5	1204.5	1204.5	8286.42
1984	1304.21	814.89	231.9	1079.09	565.5	565.5	565.5	565.5	5692.09
1985	1189.4	426.32	303.36	1145.38	499	499	499	499	5060.46
1986	1154.68	251.43	204.94	937.52	708	708	708	708	5380.57
1987	1052.68	180.5	237.82	1516.02	664.25	664.25	664.25	664.25	5644.02
1988	1267.94	240.19	358.99	1219.66	944.25	944.25	944.25	944.25	6863.78
1989	705.11	465.72	409.79	1577.79	979.5	979.5	979.5	979.5	7076.41
1990	1081.89	461.39	785.46	2491.99	618.75	618.75	618.75	618.75	7295.73
1991	1578.04	1108.89	1371.89	2417.13	571.5	571.5	571.5	571.5	8761.95
1992	1448.22	1102.66	1600	2281.61	391.75	391.75	391.75	391.75	7999.49
1993	1084.98	1045.75	1280.08	1334.66	332.25	332.25	332.25	332.25	6074.47
1994	856.54	937.66	960.26	1861.18	303	303	303	303	5827.64
1995	1208.71	910.37	801.5	2324.47	245.5	245.5	245.5	245.5	6227.05
1996	1237.25	1055.97	1749.87	1181.56	219.5	219.5	219.5	219.5	6102.65
1997	830.4	1359.38	1261.5	1372.58	143.75	143.75	143.75	143.75	5398.86
1998	688.96	1371.97	1034.95	1022.24	263.75	263.75	263.75	263.75	5173.12
1999	1408.82	1189.09	2116.17	1080.99	358	358	358	358	7227.07
2000	952.57	1458.34	1295.6	1004.46	93.5	93.5	93.5	93.5	5084.97
2001	1048.27	697.96	926.41	720.11	353.25	353.25	353.25	353.25	4805.75
2002	635.48	1180.9	1087.91	1003.78	410.25	410.25	410.25	410.25	5549.07
2003	925.04	974.26	944.04	1188.62	384.75	384.75	384.75	384.75	5570.96
2004	1062.59	516.75	500.8	1046.41	423.75	423.75	423.75	423.75	4821.55
2005	984.31	1162.13	420.38	969.79	367.25	367.25	367.25	367.25	5005.61
2006	1425.74	1590.41	878.64	1161.48	386	386	386	386	6600.27
2007	1509.07	1923.01	1709.05	847.68	387.5	387.5	387.5	387.5	7538.81
2008	1353.99	2636	1518.01	1426.46	423	423	423	423	8626.46
2009	1753.98	2554.5	1406.02	1239	431.5	431.5	431.5	431.5	8679.5
2010	1524.89	2468.87	1671.23	1256.22	514.25	514.25	514.25	514.25	8978.21
2011	1285.89	2162.53	1379.42	1020.38	463.25	463.25	463.25	463.25	7701.22
2012	1327.93	2377.1	1299.54	1341.34	381.75	381.75	381.75	381.75	7872.91
2013	1391.13	1904.22	906.23	778.18	321	321	321	321	6263.76
2014	1446.27	1952.46	636.81	960.07	129.45	369.76	516.61	151.87	6163.3
2015	931.53	1548.98	660.79	859.76	61.29	548.1	145.97	79.3	4835.72
2016	828.32	942.38	490.48	388.07	247.77	447.57	100.17	49.26	3494.02

Length distributions

The data available for Tusk in 5a and 14 can be seen in table 2.5 which lists the number of available length measurements from the Icelandic fleets by years and time steps. Also length distributions from the spring survey are included in the model. Length distributions for all fleets are on two cm basis.

Table 2.5: Tusk in 5a and 14:. Number of available length measurements from from the commercial fleet used as input data into the Gadget model by years and steps (3 month). Numbers in brackets indicate the number of port- or towsamples.

Year	Commercial				Survey
	1	2	3	4	2
1982	0 (0)	0 (0)	0 (0)	274 (2)	0 (0)
1983	356 (2)	0 (0)	59 (1)	52 (1)	0 (0)
1984	100 (1)	0 (0)	0 (0)	232 (2)	0 (0)
1985	556 (3)	0 (0)	0 (0)	16 (1)	1501 (298)
1986	438 (2)	0 (0)	187 (2)	288 (2)	1255 (246)
1987	346 (5)	97 (1)	0 (0)	484 (3)	1552 (287)
1988	0 (0)	0 (0)	0 (0)	159 (2)	1405 (272)
1989	0 (0)	0 (0)	0 (0)	0 (0)	1892 (306)
1990	0 (0)	0 (0)	0 (0)	0 (0)	1446 (290)
1991	212 (1)	3720 (17)	240 (1)	209 (1)	1291 (293)
1992	23 (1)	215 (1)	0 (0)	482 (2)	1400 (283)
1993	436 (2)	278 (1)	304 (1)	679 (4)	1044 (264)
1994	736 (5)	0 (0)	378 (2)	1698 (10)	1100 (261)
1995	1166 (7)	413 (3)	219 (1)	1275 (8)	818 (216)
1996	1312 (5)	856 (3)	1031 (3)	937 (3)	625 (206)
1997	901 (3)	819 (3)	666 (2)	1283 (5)	847 (227)
1998	823 (3)	900 (3)	900 (3)	954 (5)	757 (208)
1999	871 (4)	900 (6)	1434 (10)	600 (4)	768 (201)
2000	301 (2)	730 (5)	901 (6)	1063 (6)	957 (233)
2001	413 (3)	842 (4)	1494 (10)	499 (3)	786 (209)
2002	448 (3)	672 (5)	928 (7)	795 (6)	839 (210)
2003	3531 (18)	1299 (9)	1336 (7)	2278 (13)	1046 (233)
2004	1568 (12)	978 (7)	427 (3)	986 (7)	1465 (234)
2005	1147 (9)	3359 (14)	502 (4)	833 (8)	1728 (266)
2006	1493 (8)	2199 (15)	381 (3)	1260 (8)	1884 (287)
2007	2084 (15)	4141 (23)	4499 (23)	1529 (10)	1777 (294)
2008	1559 (8)	12186 (58)	4208 (26)	2857 (17)	1814 (287)
2009	4454 (18)	12369 (57)	3003 (19)	1625 (14)	1516 (286)
2010	3033 (16)	2287 (14)	2691 (18)	1051 (9)	1254 (248)
2011	1987 (9)	4278 (21)	891 (6)	1002 (7)	1354 (274)
2012	5193 (25)	3908 (26)	1165 (9)	1751 (11)	1293 (286)
2013	2433 (12)	2475 (13)	898 (6)	813 (5)	1090 (278)
2014	3433 (17)	3130 (20)	231 (2)	4954 (23)	880 (243)
2015	2071 (12)	1330 (11)	605 (5)	815 (7)	1128 (263)
2016	2218 (10)	834 (7)	484 (4)	1196 (6)	1005 (261)

2.2.3.2 Tuning data

The tuning data used here comes from the Icelandic spring survey. The spring survey abundance indices are aggregated into seven length intervals (Table 2.6, figures 2.5 and 2.6). The survey indices are defined as the total number of fish caught in a survey within a certain length interval. 10 cm intervals are used for the indices, except the smallest and the largest length intervals. The reason is to avoid getting a zero value for these length groups.

In the years between 1996 and 2006 the Icelandic spring survey did not cover the Faroe ridge (indicated in fig. 2.3) area. A considerable proportion of the catches, roughly 20%, in the survey is caught in that area, although variable between length groups. To allow for consistency within the indices the values of the indices were scaled according the median proportion caught in the area. The scaling applied is listed in table 2.6.

Table 2.6: Tusk in 5a and 14: Length aggregation of survey indices used for tuning the model and the scaling applied in the years between 1996 and 2005.

Name	min	max	Scaling
si.10-20	10	20	1.05
si.20-30	20	30	1.25
si.30-40	30	40	1.25
si.40-50	40	50	1.17
si.50-60	50	60	1.16
si.60-70	60	70	1.14
si.70-110	70	110	1.05

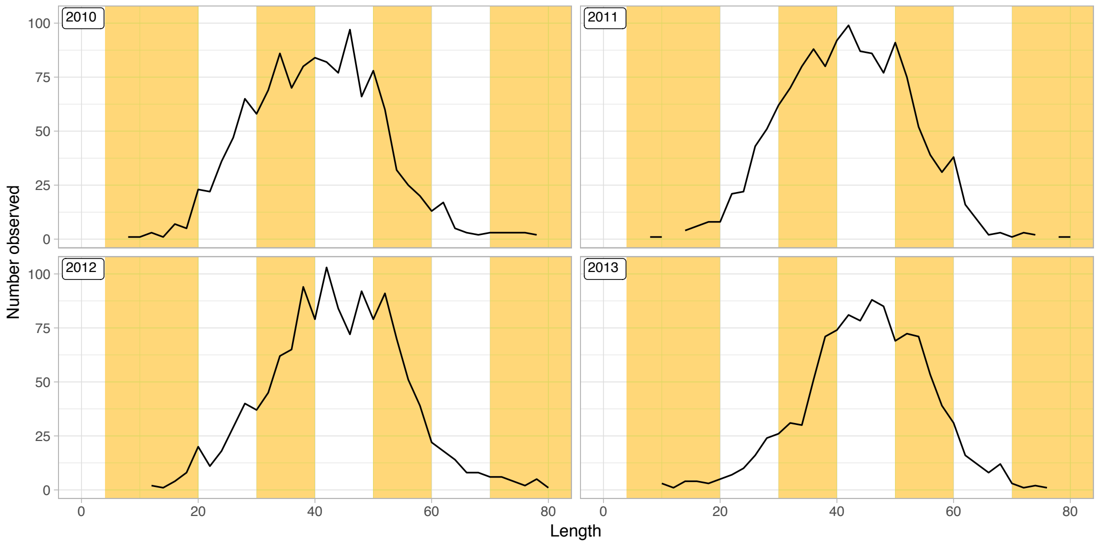

Figure 2.5: Tusk in 5a and 14. Length distributions from the Icelandic Groundfish Survey and the yellow and white polygon represent the division into length aggregated abundance indices.

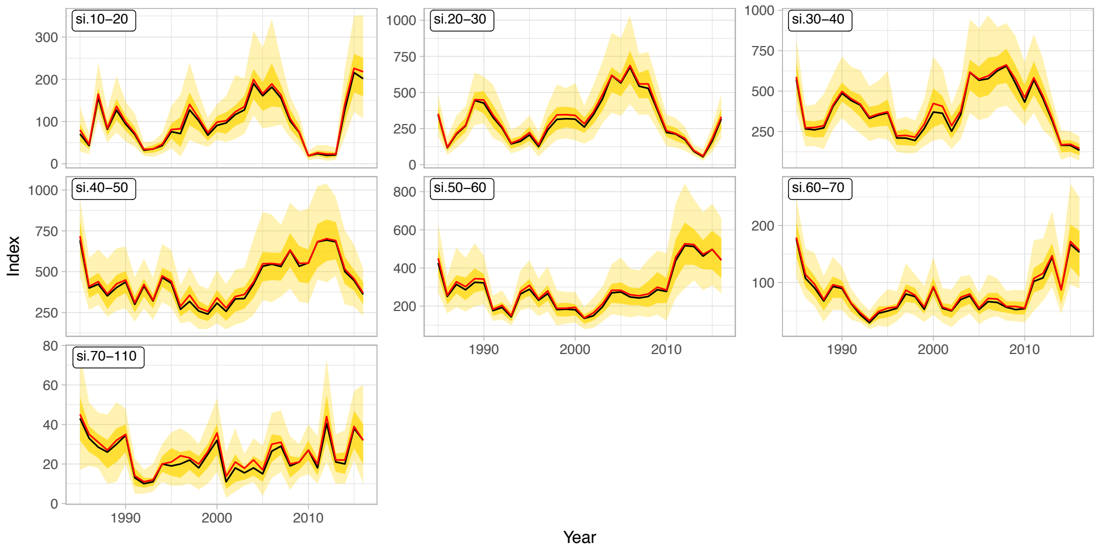

Figure 2.6: Tusk in 5a and 14. Time series of length aggregated indices used for tuning (red line), black lines and shaded regions represents bootstrap median and 90% intervals, respectively, of the indices by year.

2.2.3.3 Age data

In table 2.7 the available age data is listed by fleet, year and time-step (quarter). Due to observed difficulties in aging tusk above the age of 8, individuals that have been observed to be older that 9 are classified as 10 years and older.

Table 2.7: Tusk in 5a and 14. Number of available aged otoliths from the commercial fleet and the spring survey used as input data into the Gadget model by years and steps (3 month).

Year	Commercial 1	2	3	4	Survey 2
1982	0 (0)	0 (0)	0 (0)	100 (1)	0 (0)
1983	0 (0)	0 (0)	43 (1)	39 (1)	0 (0)
1984	91 (1)	0 (0)	0 (0)	0 (0)	0 (0)
1985	0 (0)	0 (0)	0 (0)	0 (0)	634 (130)
1995	218 (3)	22 (1)	81 (1)	187 (2)	645 (207)
2000	0 (0)	0 (0)	0 (0)	0 (0)	304 (214)
2001	0 (0)	0 (0)	0 (0)	0 (0)	271 (204)
2002	0 (0)	0 (0)	0 (0)	0 (0)	293 (201)
2003	0 (0)	0 (0)	0 (0)	0 (0)	339 (226)
2004	0 (0)	0 (0)	0 (0)	0 (0)	399 (218)
2005	0 (0)	0 (0)	0 (0)	0 (0)	148 (80)
2006	0 (0)	0 (0)	0 (0)	0 (0)	457 (268)
2007	0 (0)	0 (0)	0 (0)	0 (0)	466 (284)
2008	152 (4)	124 (3)	139 (3)	185 (4)	475 (273)
2009	235 (5)	460 (10)	395 (9)	0 (0)	434 (264)
2010	350 (7)	512 (11)	372 (8)	139 (3)	363 (233)
2011	235 (5)	533 (12)	241 (5)	297 (6)	728 (266)
2012	392 (8)	384 (12)	152 (5)	232 (9)	750 (281)
2013	178 (6)	156 (8)	117 (6)	59 (3)	536 (208)
2014	120 (5)	299 (15)	23 (1)	145 (7)	560 (234)
2015	62 (3)	206 (11)	93 (5)	144 (7)	573 (246)
2016	60 (3)	145 (7)	25 (1)	40 (2)	676 (255)

2.2.4 Results

2.2.4.1 Iterative re-weighting

Gadget allows for an extensive comparison to the fitted data-set. An overall picture of the model fit is provided in table 2.8. Overall the model is seen to fit the data relatively well, compared to the best possible fit from each step. In the final run the squared residuals are seldomly larger than an order of 2 larger than the optimal fit. In no case is the final run the worst fit to individual likelihood component. Data on maturity appears when emphasized the fit to other datasets was considerably worse than when other datasets were empasized. This has been observed in multiple settings, e.g. see Taylor et al. (2007), as the data only reflects the maturity process and hence very little information on other processes.

Fig. 2.7 shows the bootstrap distribution of contribution of individual datasets by time to the overall score, calculated using eq. 2.18. Overall few outliers can be observed from the likelihood, the fit on age length distributions in the survey appears to be higher between 2000 and 2005, which may be attributed to fewer samples in those years relative to the more recent years due to the omission of the Faroe ridge area. The survey indices representing the smallest and largest length groups appear to have worse fit relative to their optimal fits that other indices, indicating a potential conflict with other datasets.

However this is to be expected given the length groups that these indices represent. The smallest length group represents the recruitment process and as such not entirely representative to the amount of fish that enter the fishery at a later stage. The largest length group has considerably fewer samples that other indices and thus more prone to discreet jumps related to low sample size.

Table 2.8: Tusk in 5a and 14. Diagnostic from the iterative reweighing procedure. The lines denotes the likelihood component that was heavily weighted. Upper part is the value for each likelihood component, but the lower part denote the ratio of that component score to the score when it was upweighted.

Component	matp.-igfs	aldist.-comm	aldist.-igfs	ldist.-comm	ldist.-igfs	si.10-20	si.20-30	si.30-40	si.40-50	si.50-60	si.60-70	si.70-110
aldist.comm	231.4	0.793	0.148	1.651	0.175	9.006	7.269	4.853	5.332	7.558	11.86	20.14
aldist.igfs	234.7	1.208	0.098	4.338	0.144	10.37	5.322	2.92	1.853	2.549	5.928	15.46
ldist.comm	262.3	2	0.397	1.063	0.165	9.526	7.429	5.578	3.652	2.614	5.067	8.606
ldist.igfs	232.7	1.503	0.232	2.382	0.041	5.271	1.388	1.173	0.818	1.17	2.976	6.652
matp.igfs	146.2	1.343	0.35	2.931	1.074	18.46	12.81	6.803	2.267	3.957	6.716	7.896
sind	248.1	2.062	0.281	5.969	0.09	1.454	1.43	0.967	0.799	1.424	2.416	3.112
final	235.6	0.885	0.118	1.193	0.072	5.26	1.756	1.085	1.476	1.435	3.108	7.209
aldist.comm	1.583	1	1.512	1.553	4.27	6.194	5.083	5.018	6.672	5.308	4.909	6.472
aldist.igfs	1.605	1.523	1	4.081	3.511	7.132	3.722	3.019	2.319	1.79	2.454	4.968
ldist.comm	1.794	2.521	4.049	1	4.033	6.552	5.195	5.768	4.57	1.836	2.097	2.765
ldist.igfs	1.592	1.895	2.368	2.241	1	3.625	0.971	1.213	1.023	0.822	1.232	2.138
matp.igfs	1	1.693	3.576	2.757	26.221	12.696	8.958	7.034	2.837	2.779	2.78	2.537
sind	1.697	2.6	2.872	5.615	2.187	1	1	1	1	1	1	1
final	1.611	1.115	1.206	1.122	1.746	3.618	1.228	1.122	1.847	1.008	1.286	2.317

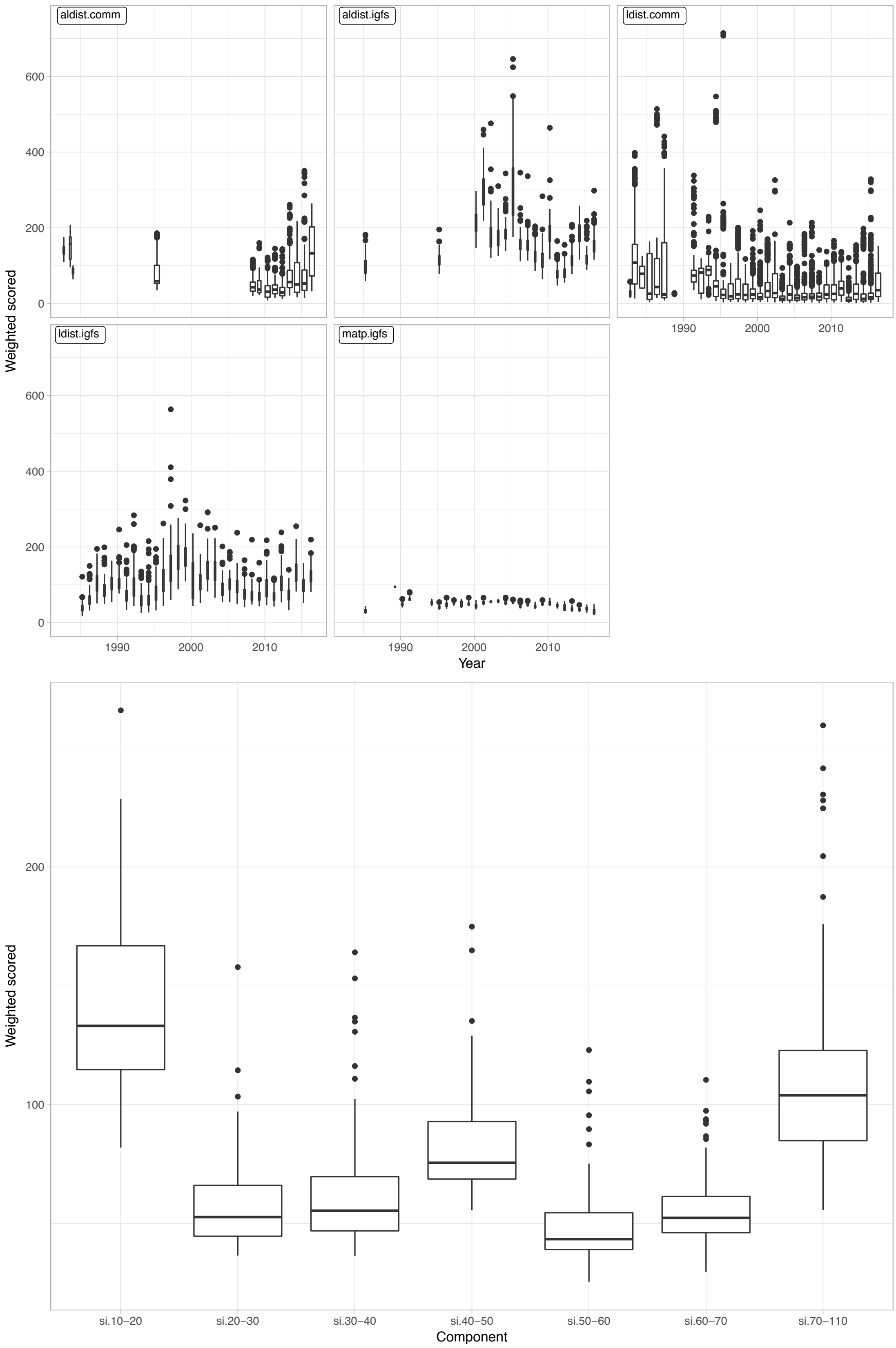

Figure 2.7: Tusk in 5a and 14. Boxplot of the bootstrap distribution of the weighted likelihood component scores by time and component from the final model fits.

2.2.4.2 Parameter estimates

In the base and bootstrap runs the estimates rarely hit the boundaries. In figure 2.8 the distributions of the bootstrap estimates for the growth, maturity and selection parameters is shown. For most of them the histogram indicates a nice spread of the estimates. Two parameters, β and σ_0 which are related to the estimated growth, were estimated at the boundary in a substantial portion of the bootstrap trials, suggesting that these are illdetermined. The effect of this can be considered minimal as these have little effect on the estimated biomass and fishing mortality. Other growth parameters appear to be fairly biased, but as illustrated in fig. 2.9 these are positively correlated. Although the positive correlation is surprising, the range of the bootstrap estimates for k is fairly narrow. In addition there is strong correlation between l_0 and both k and L_∞. Further, the maturity l_{50} parameter was estimated at the boundary for most cases, which is considered to be related to both the overlap in length distributions of the mature and immature components, and the relatively low sample size of fish from length ranges where one would expect to see fully recruited fish (as illustrated in fig. 2.26).

Estimates of recruitment parameters are shown in figure 2.11. In no cases did they hit the boundaries and the estimates show a fairly symmetric spread. The spread in after 2013 exhibits a large uncertainty, as is to be expected given the data available than can inform on recruitment. Similarly the uncertainty in the initial years of the model is higher, as less data is available on the age structure in those years. The base run follows the median of the bootstrap estimates closely. The estimated initial population is illustrated in fig. 2.12. As in the case of the estimated recruitment little concernable bias was observed in the based compared with the bootstrap medians.

The bootstrap distribution of the catchability estimates, described in eq. 2.14, is illustrated in fig. 2.13. The figure illustrates that the mode of the catchability is centred around the 60 to 70 cm length group and starts to taper off for larger fish.

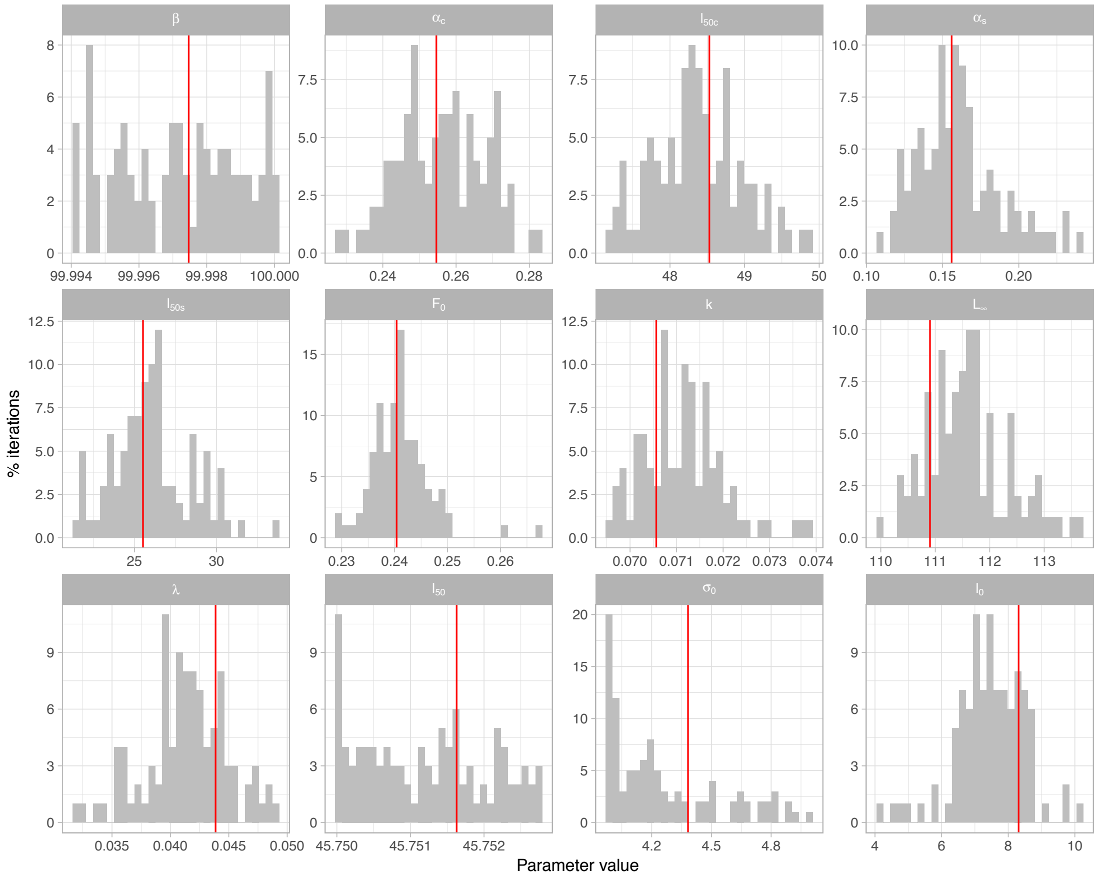

Figure 2.8: Tusk in 5a and 14. Histogram of parameter estimates from 100 bootstrap samples, the red line indicates the estimate from the base run

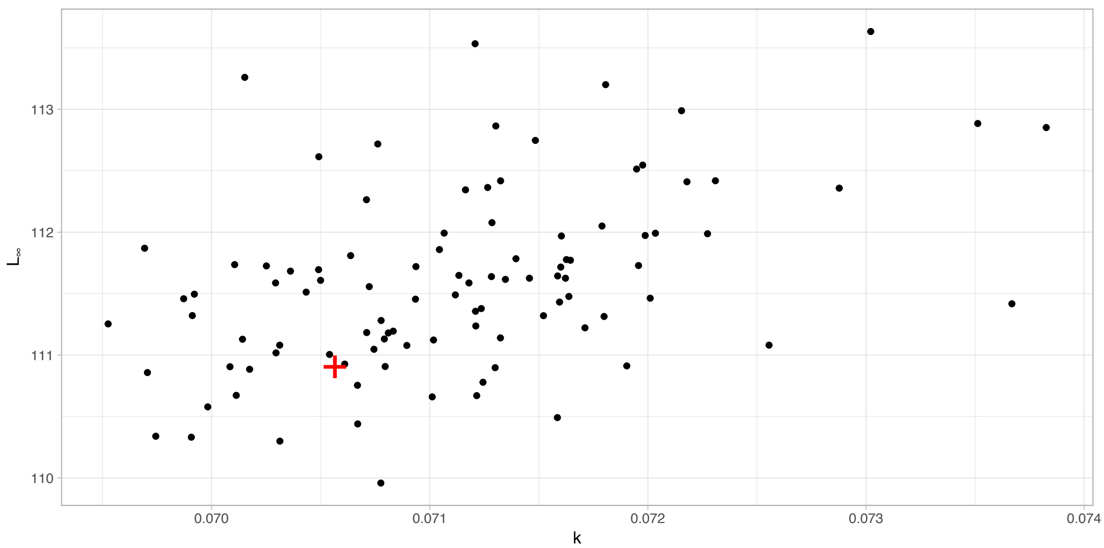

Figure 2.9: Tusk in 5a and 14. X-Y scatterplot of the bootstrap estimates of L_∞ and k. The red cross indicates the base run estimate.

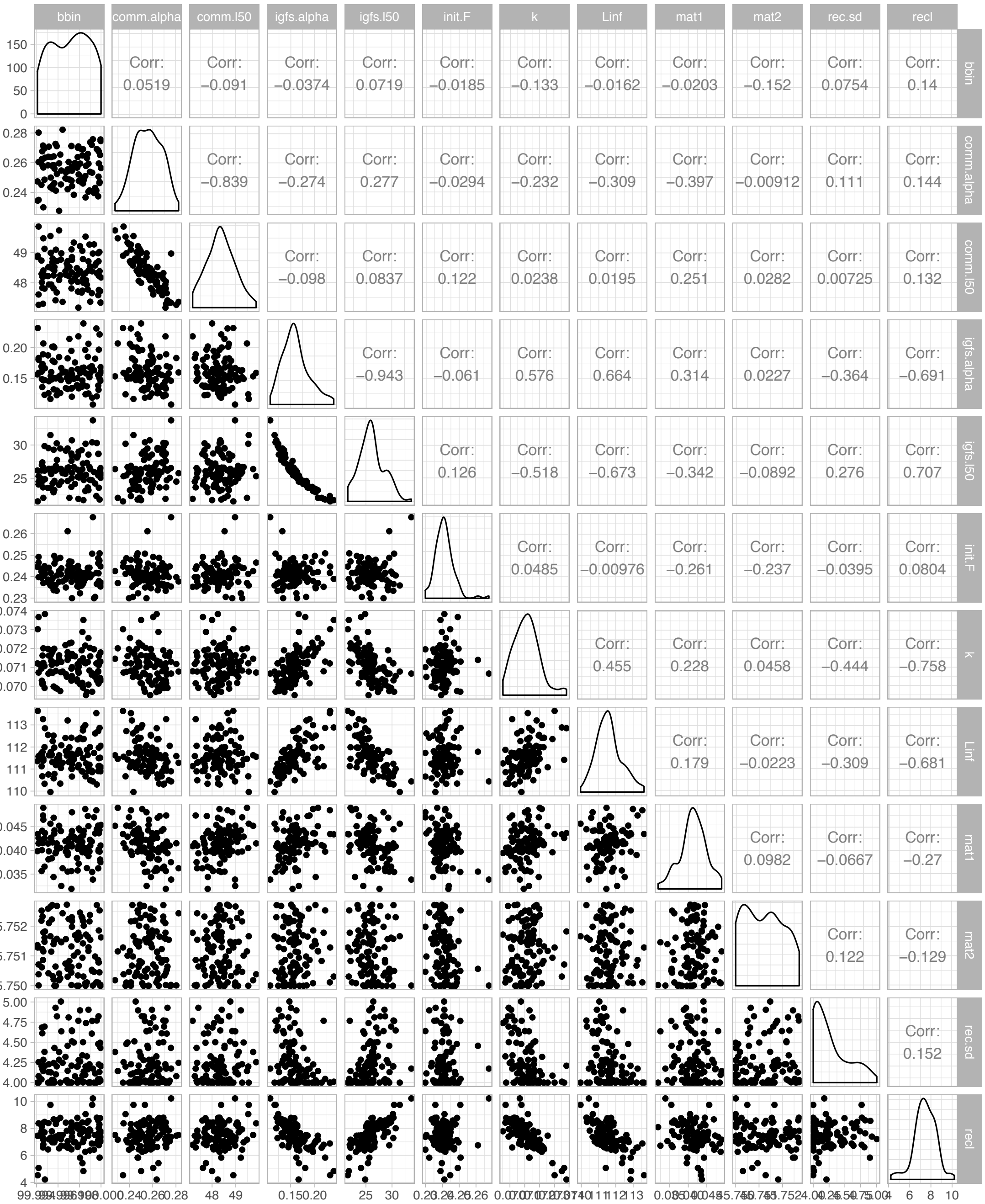

Figure 2.10: Tusk in 5a and 14. Pairs-plot of all parameters except those related to the number of recruits and initial number at age.

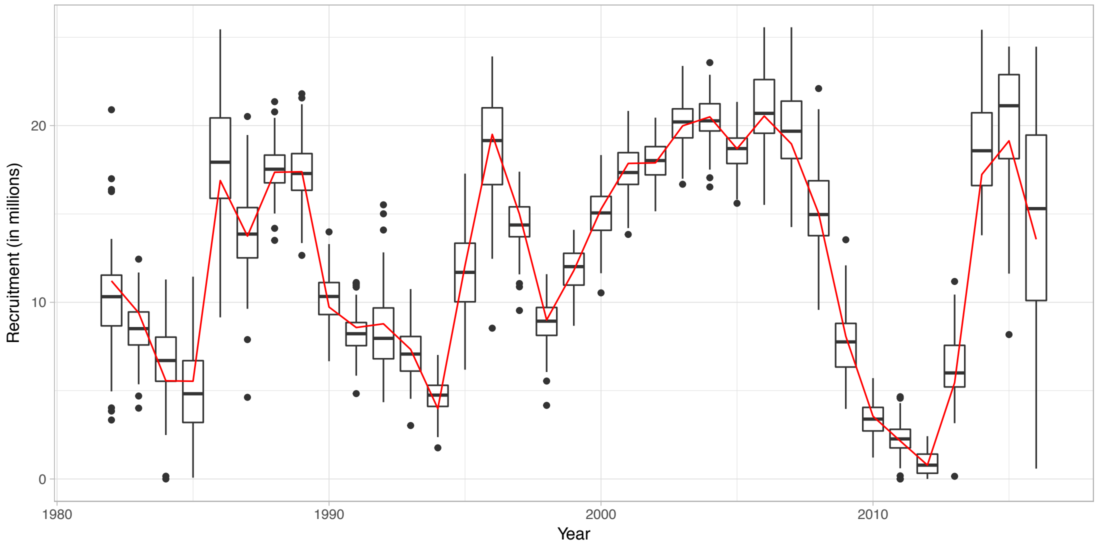

Figure 2.11: Tusk in 5a and 14. Boxplots of annual recruitment bootstrap estimates, the red line indicates the estimate from the base run.

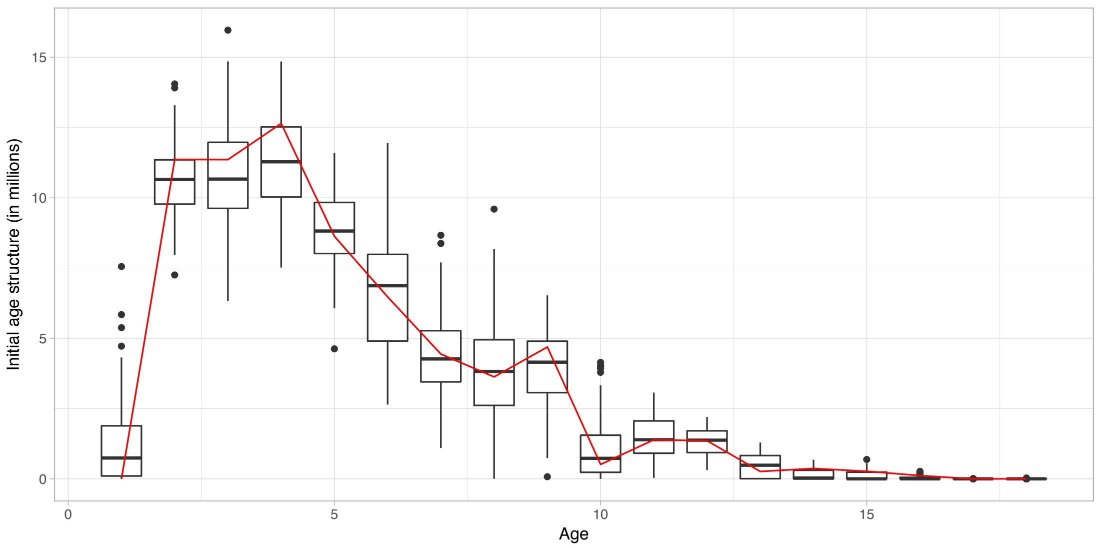

Figure 2.12: Tusk in 5a and 14. Boxplots of initial age structure bootstrap estimates, the red line indicates the estimate from the base run.

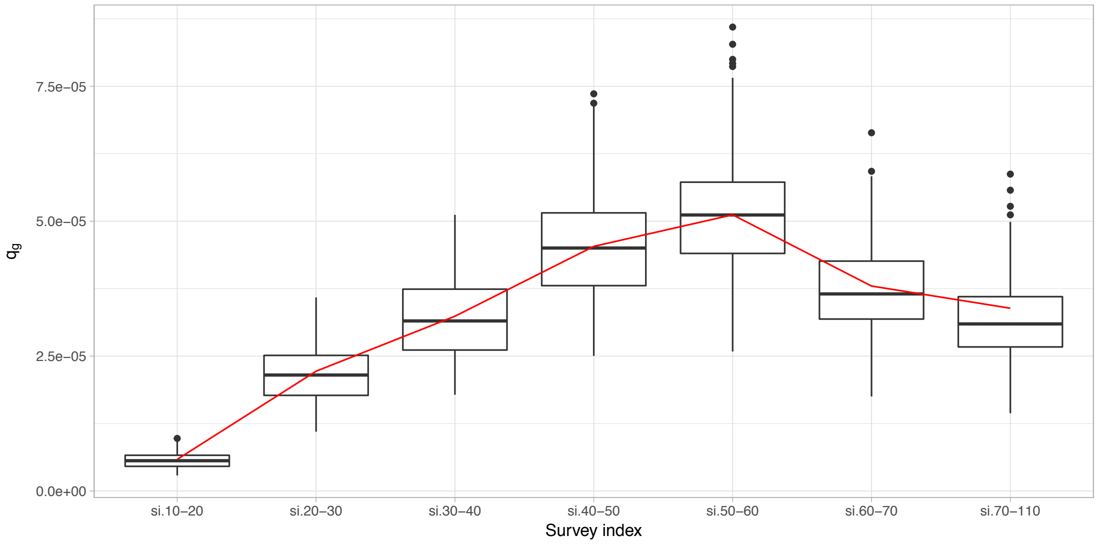

Figure 2.13: Tusk in 5a and 14. Boxplot of estimated catchability parameters, q_g, as a function of the survey index length group.

2.2.4.3 Fit to individual data sets

Abundance indices

The fit to the abundance indices is shown in fig. 2.14 and as X-Y scatter plot on a log-scale in fig. 2.15. For all but the largest length-group the fit is fairly good, as the model appears to follow the trends of the survey indices. When looking at the X-Y scatter plot the assumption of a slope of 1 (i.e. a linear relationship between index and abundance) appears to be fair.

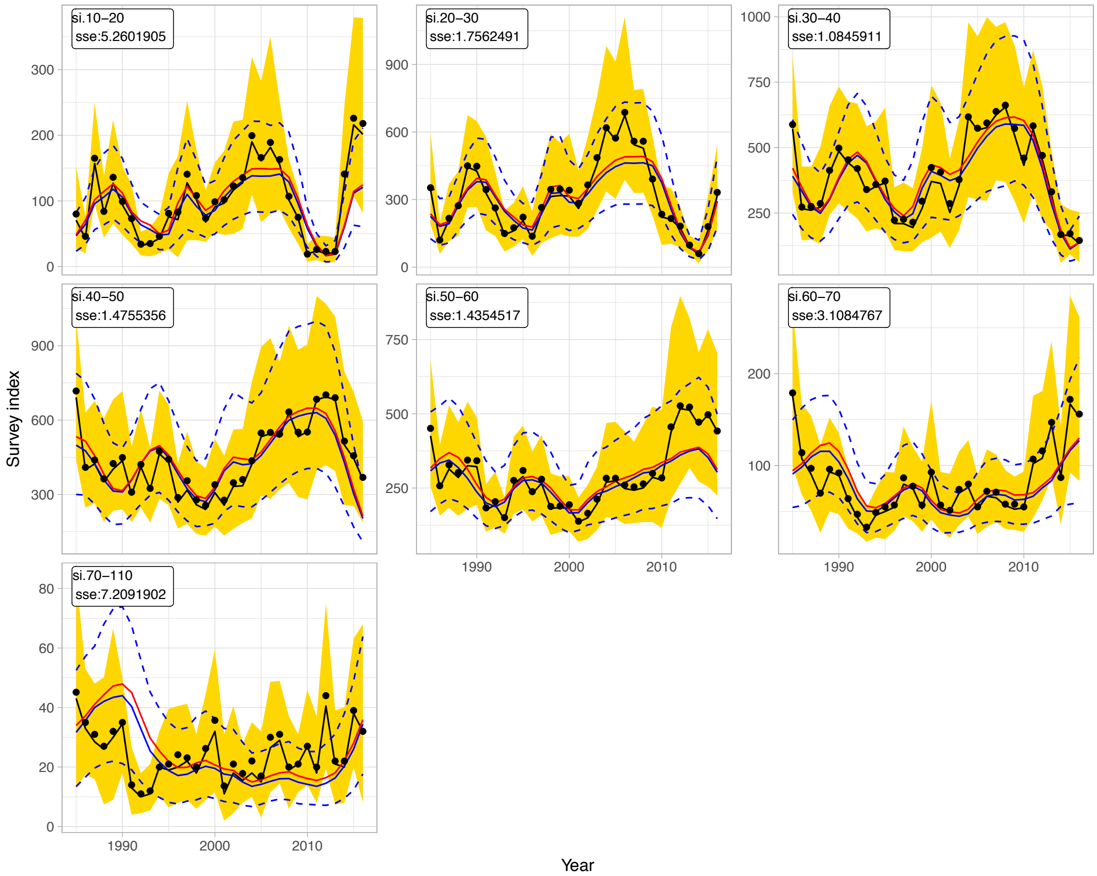

Figure 2.14: Tusk in 5a and 14. Bootstrap distribution of the length aggregated abundance indices from the spring survey compared with the predicted survey indices. The black line is the bootstrap median and the yellow area is the 90% quantile of the bootstrapped indices, while the black points indicate the survey index. The blue solid line is the median of the predicted indices from the bootstrap runs and the blue dotted line the 90% quantile. The red line is the predicted indices from the base model.

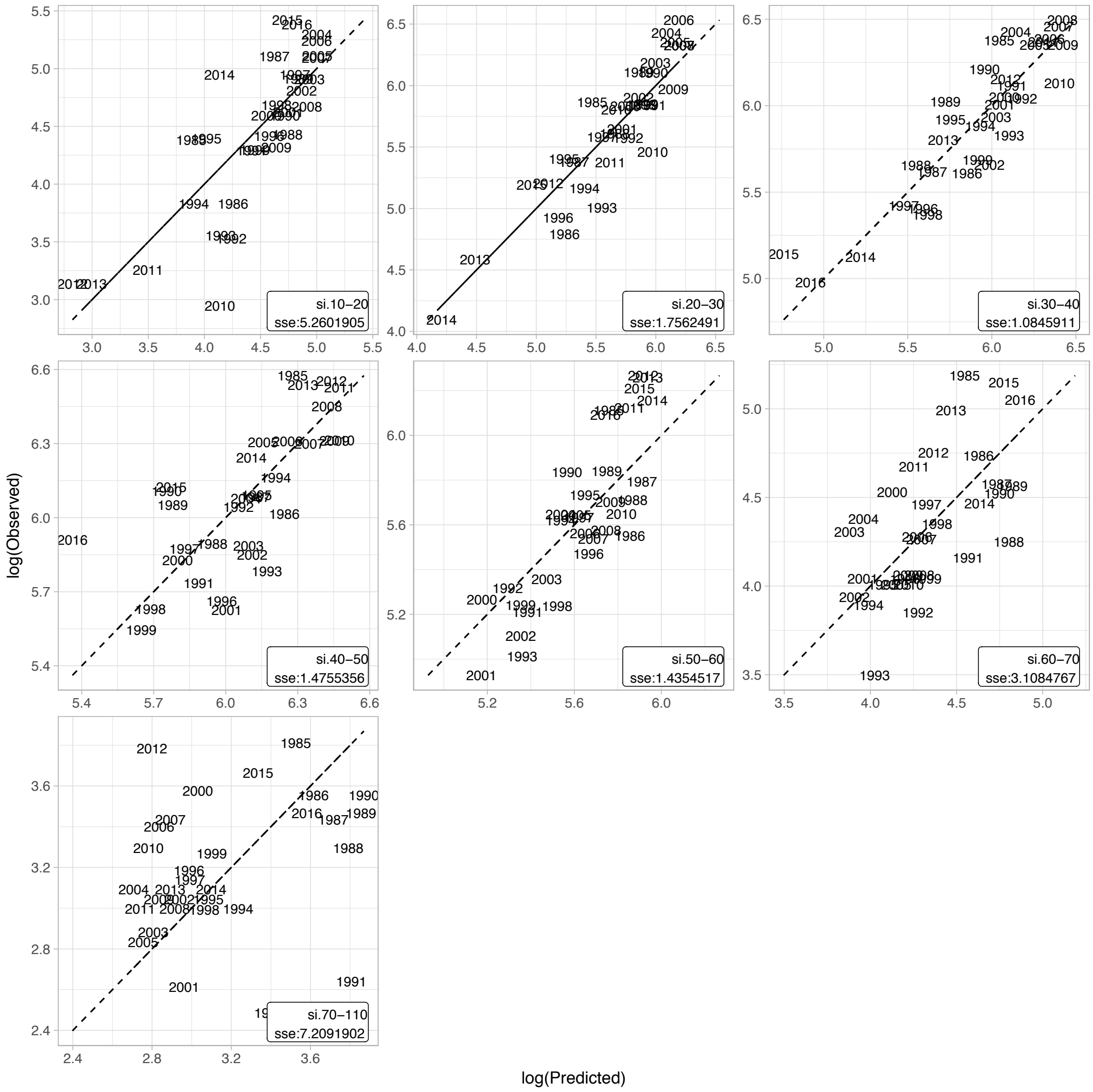

Figure 2.15: Tusk 5a. Observed survey index from the base model run as a function of the predicted values on the log-scale. The panels indicate the index length group, the dashed line denotes a line with slope 1 and the labels denote the year.

Length distributions

In general it is observed that the fit to the length distributions is good. In figure 2.16 examples of the bootstrapped data and their fits from the spring survey and commercial samples in the second quarter of 1996 and 2015 are shown. The examples from 2016 contain cells that have a lot of samples/measurements. However the 1996 samples from the commercial samples, where there are only 856 measurements (3 samples) are available, the model fit appears to underpredict the size range of the catches. However note that the sampling effort from commercial catches in years prior to 2003 was substantially lower than in latter days (table 2.5). This is also apparent in the fit to the length distributions, both from the spring survey and commercial catches that are illustrated in figures 2.17 to 2.18, (base model and all data). The fit to samples from the commercial fishery is seen vary in the older sample and is seen to improve in the terminal years, as data becomes more readily available. In comparison the fit to the survey length distributions is good.

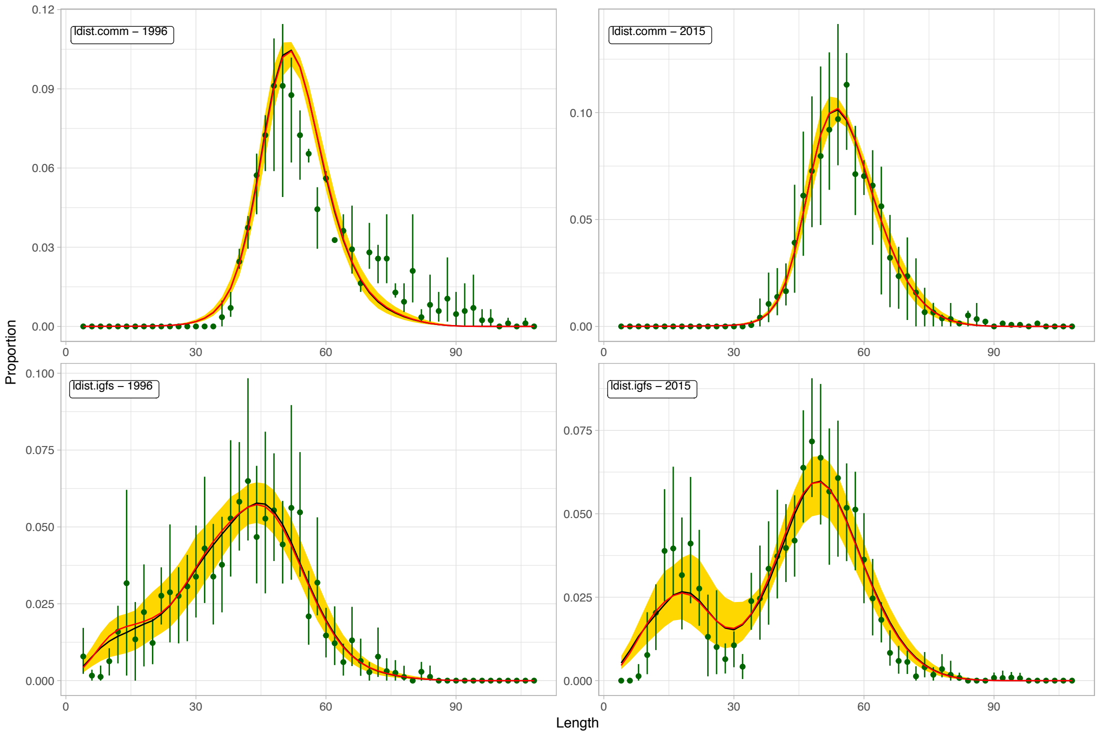

Figure 2.16: Bootstrap length distribution from both survey and commercial samples compared with model estimates. Green points and vertical bars denote the median and 90% interval of the bootsrap distribution of observed values, while the solid lines and golden ribbon the median and 90% intevals of the bootstrapped estimates by the model. The solid red line indicates the fit from the baseline model.

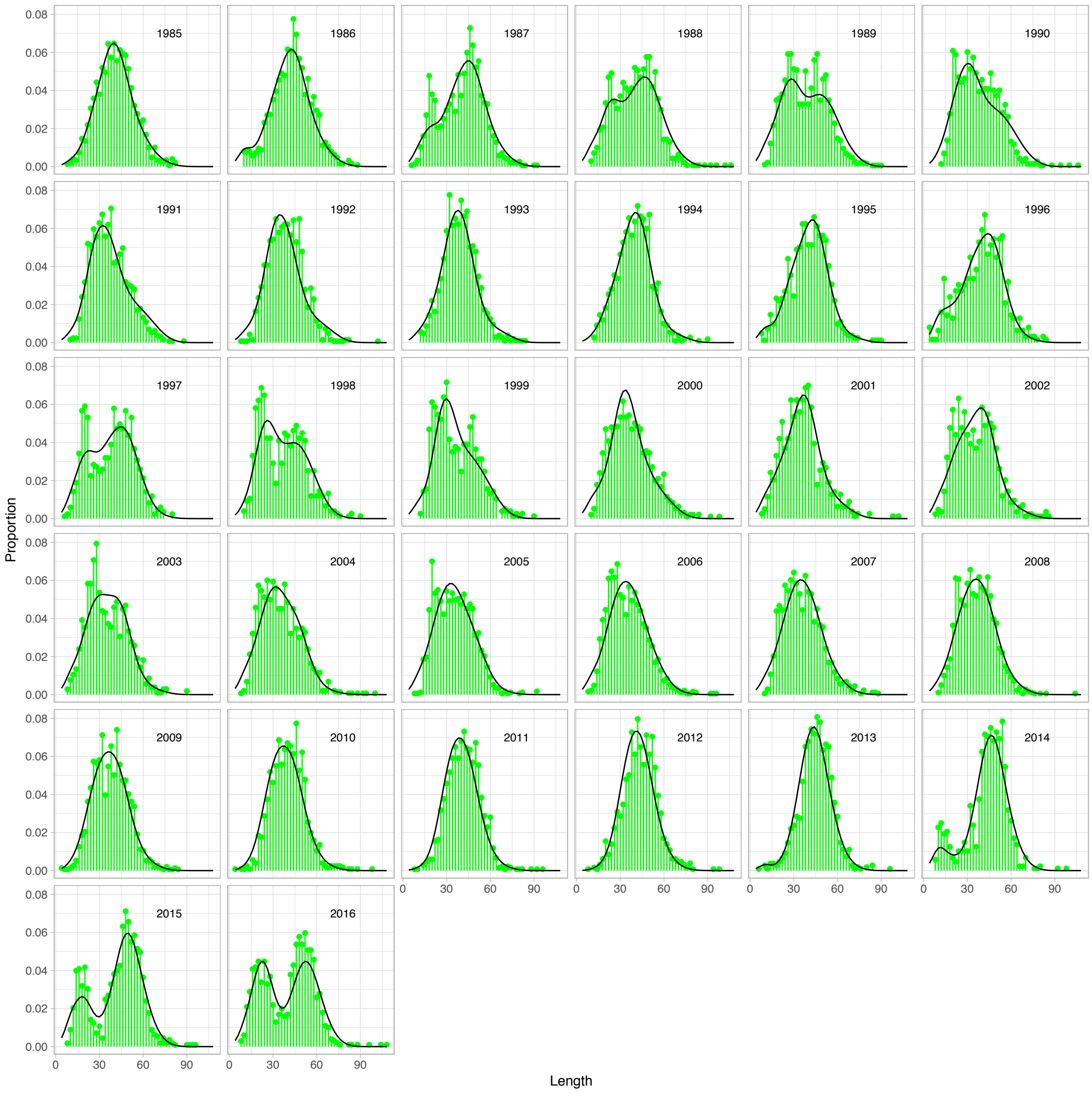

Figure 2.17: Length distribution from survey. Points denote the observed values, solid lines the predictions by the base model.

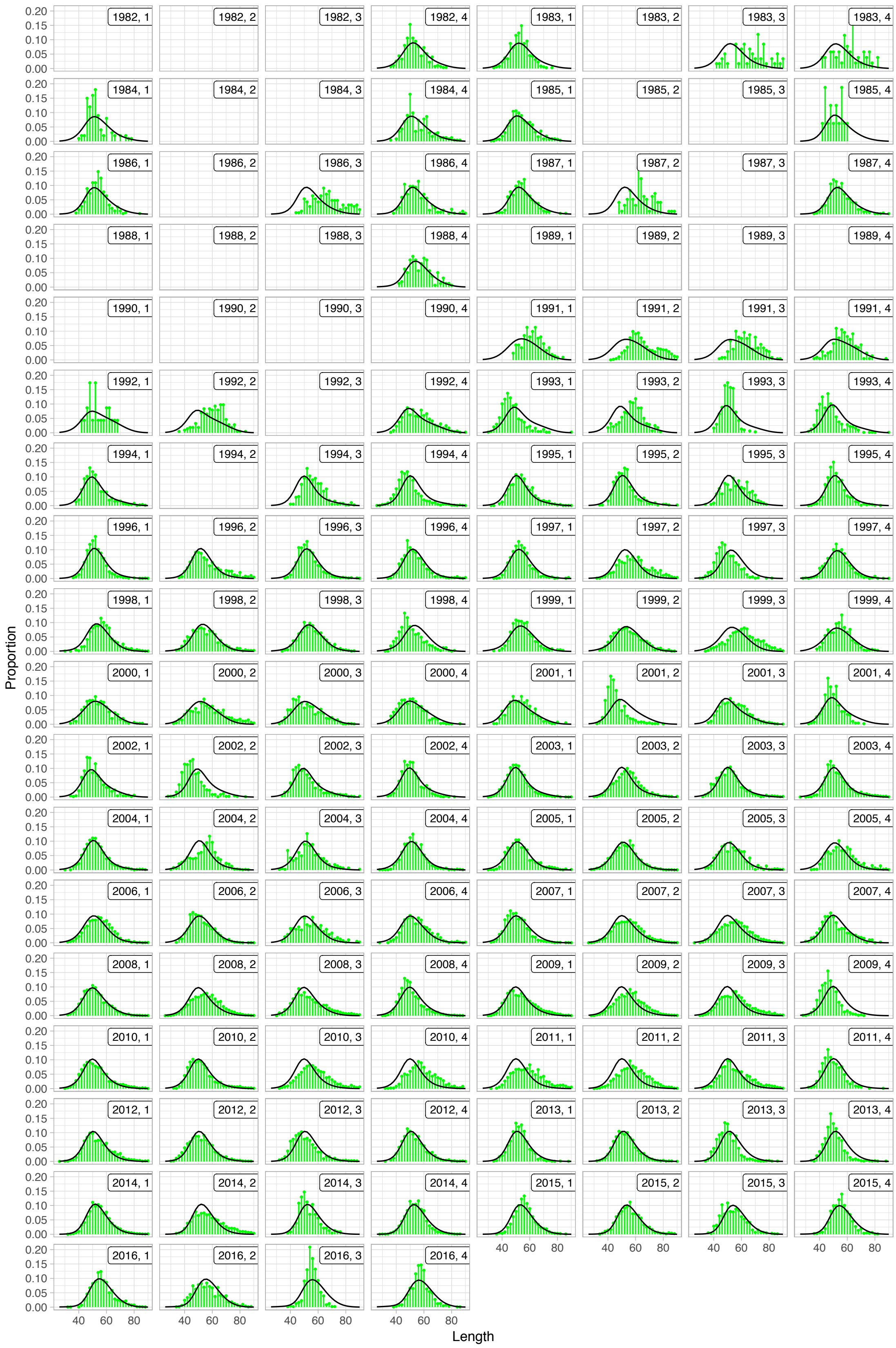

Figure 2.18: Tusk in 5.a. Length distribution from the commercial fleet. Points denote the observed values, solid lines the predictions by the base model.

Figure 2.19: Tusk in 5.a. Standardised residual plots for the fitted length distribution from the commercial and survey fleets. Red points denot a model underestimate and blue points an overestimated. The size of the points denote the scale of the standardised residual.

2.2.4.4 Age–length distributions

In fig. 2.20 examples of the bootstraped proportions at age compared with model estimates from commercial and survey age samples. In general the model appears to capture the proportions in the commercial catches (fig. 2.21), whereas the fit to the survey proportion appears to overpredict the proportion of fish younger that 5 in the years prior to 2011 (as seen further evident in fig. 2.22) to be able to fit the proportion of fish older that 5 in the years following.

Growth in the model estimated based on the age-length distribution. The model fit to the available information on growth can be observed from figures 2.23 and 2.24 from survey and commercial samples respectively. In general the model appears to fit the observed growth quite well. However some variations can be observed, e.g. the grow was slightly overestimate compared to the 2001 survey sample, but these are considered within limits.

Figure 2.20: Bootstrap age distribution from both survey and commercial samples compared with model estimates from 2008 onwards in quarter 2. Green points and vertical bars denote the median and 90% interval of the bootstrap distribution of observed values, while the solid lines and golden ribbon the median and 5 and 95% percentiles of the bootstrapped estimates by the model. The solid red line indicates the fit from the baseline model. Note that age 10 is a plus group.

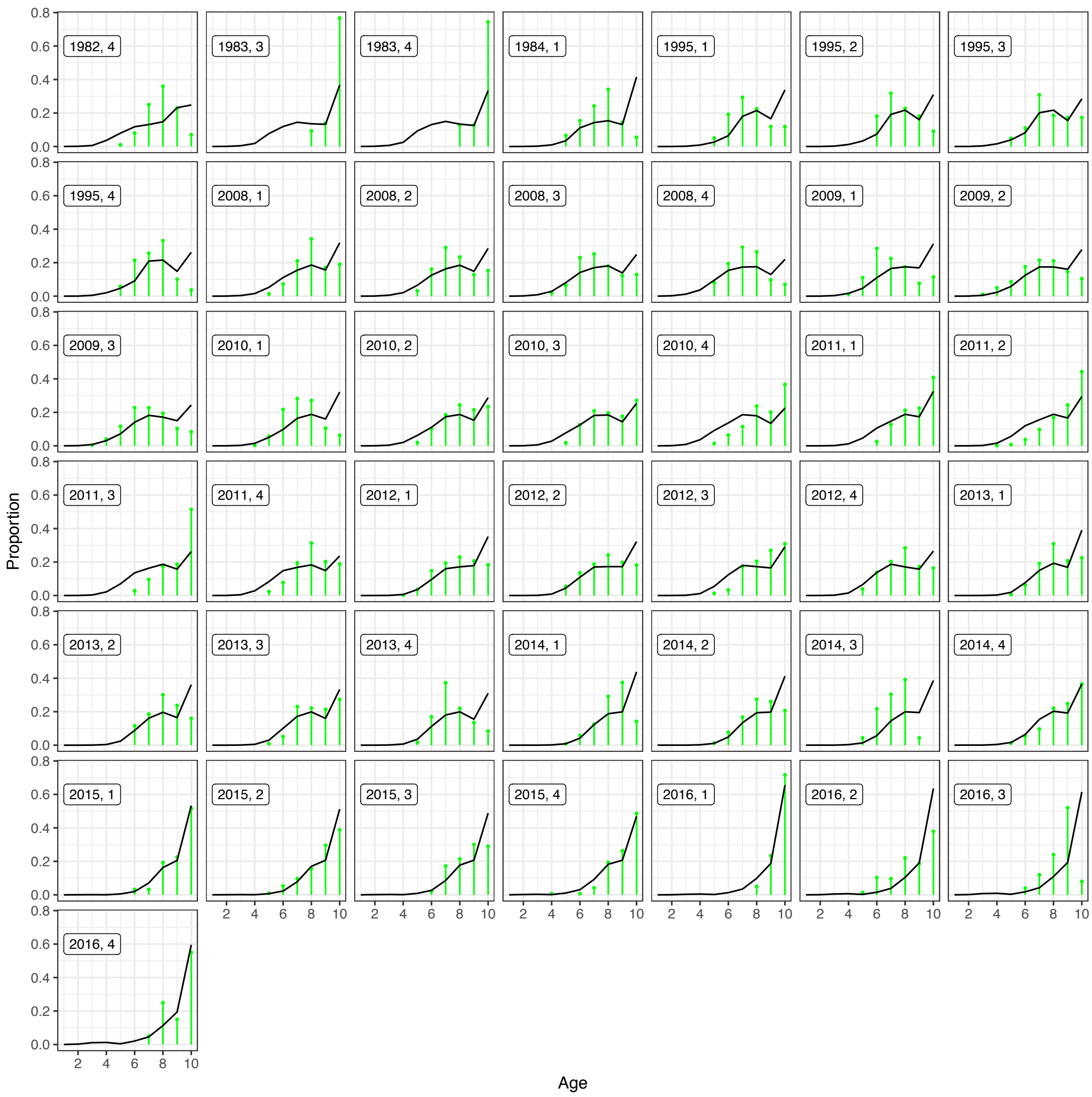

Figure 2.21: Age distribution from the commercial fleet. Points denote the observed values, solid lines the predictions by the base model. Note that age 10 is a plus group.

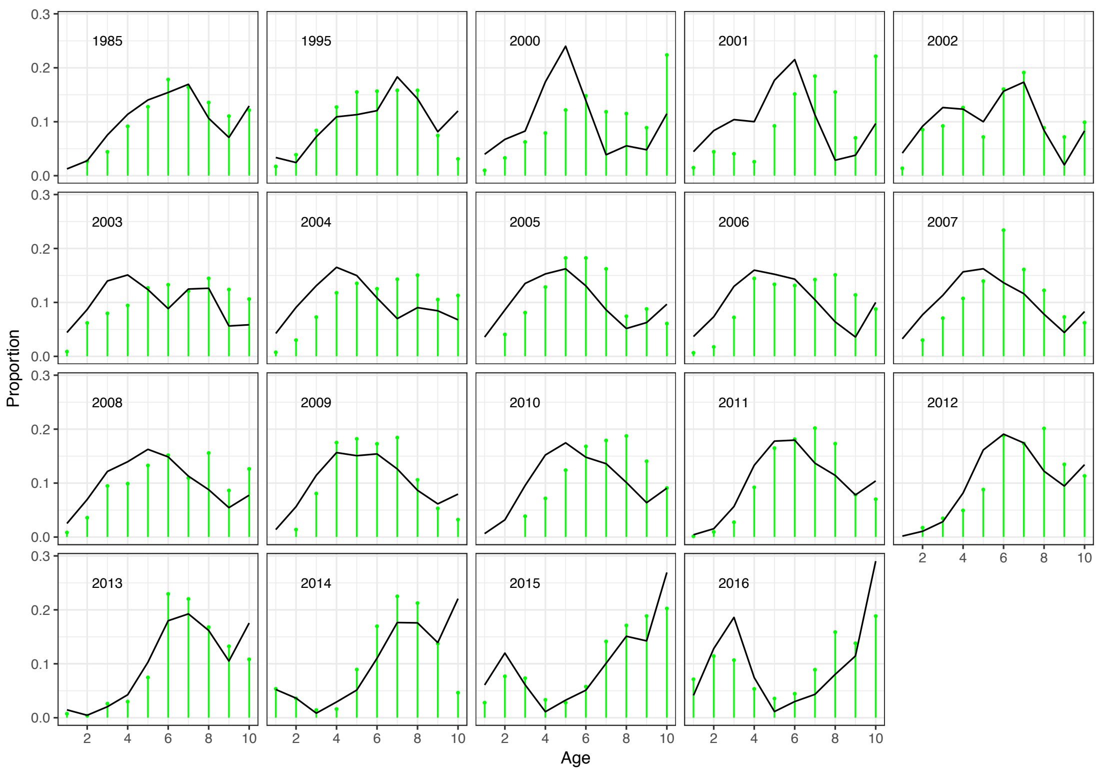

Figure 2.22: Age distribution from the March survey. Points denote the observed values, solid lines the predictions by the base model. Note that age 10 is a plus group.

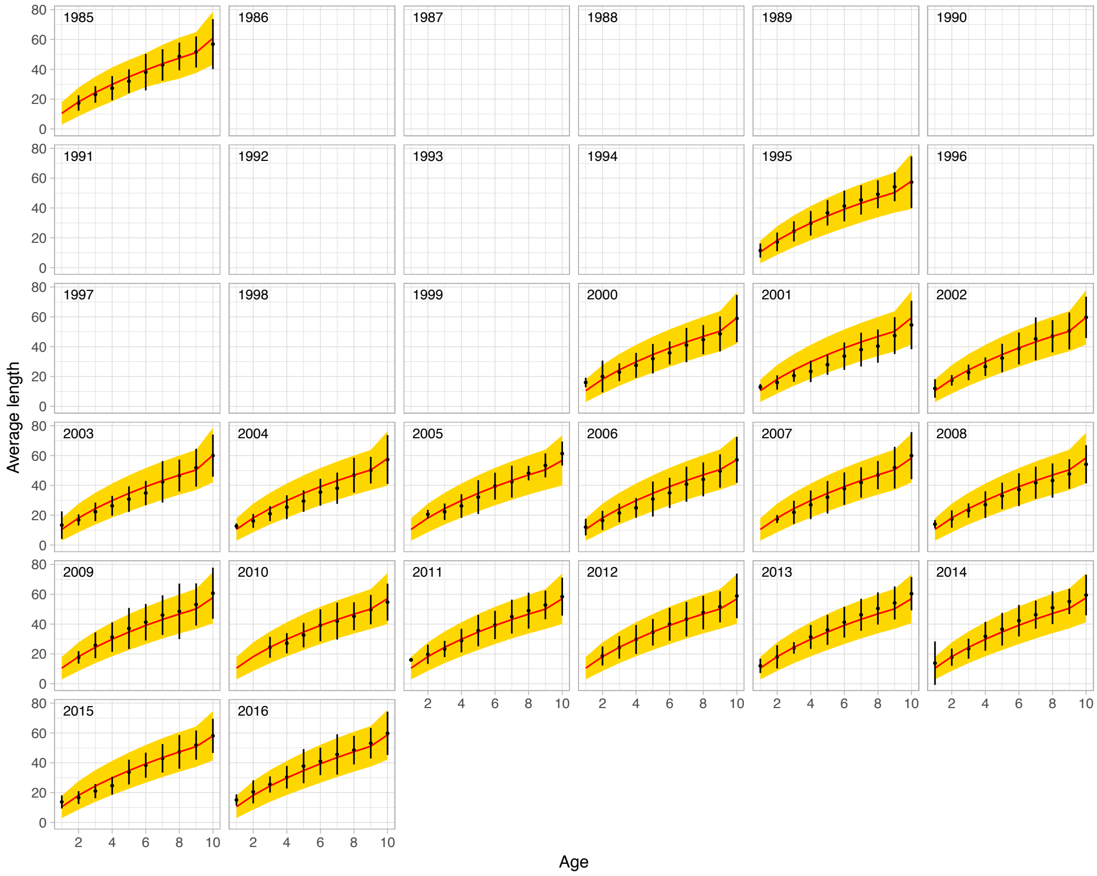

Figure 2.23: Tusk in 5a and 14. Fitted length at age by year compared to observed values from the Icelandic spring survey. The black point and vertical bar denotes the observed mean and 95% confidence intervals of length at age, while the golden ribbon and red line indicates the model estimates.

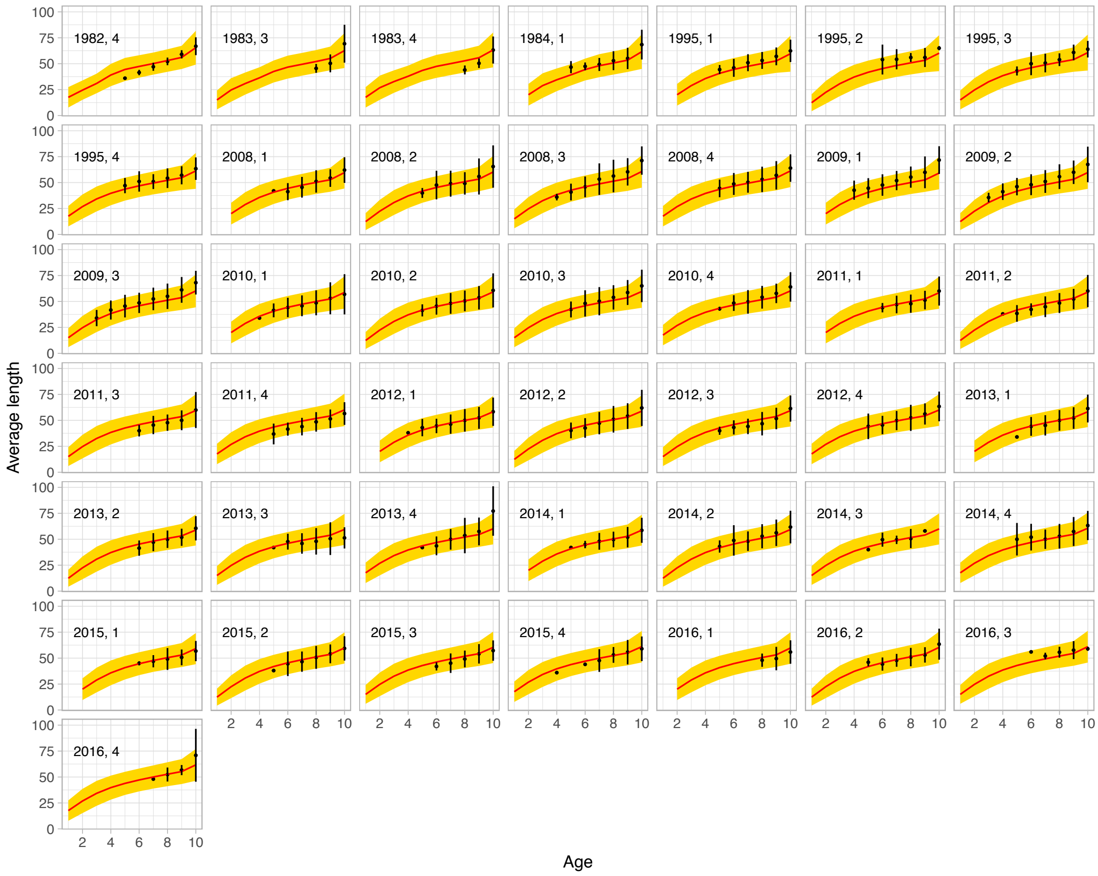

Figure 2.24: Tusk in 5a and 14. Fitted length at age by year compared to observed values from the commercial samples. The black point and vertical bar denotes the observed mean and 95% confidence intervals of length at age, while the golden ribbon and red line indicates the model estimates.

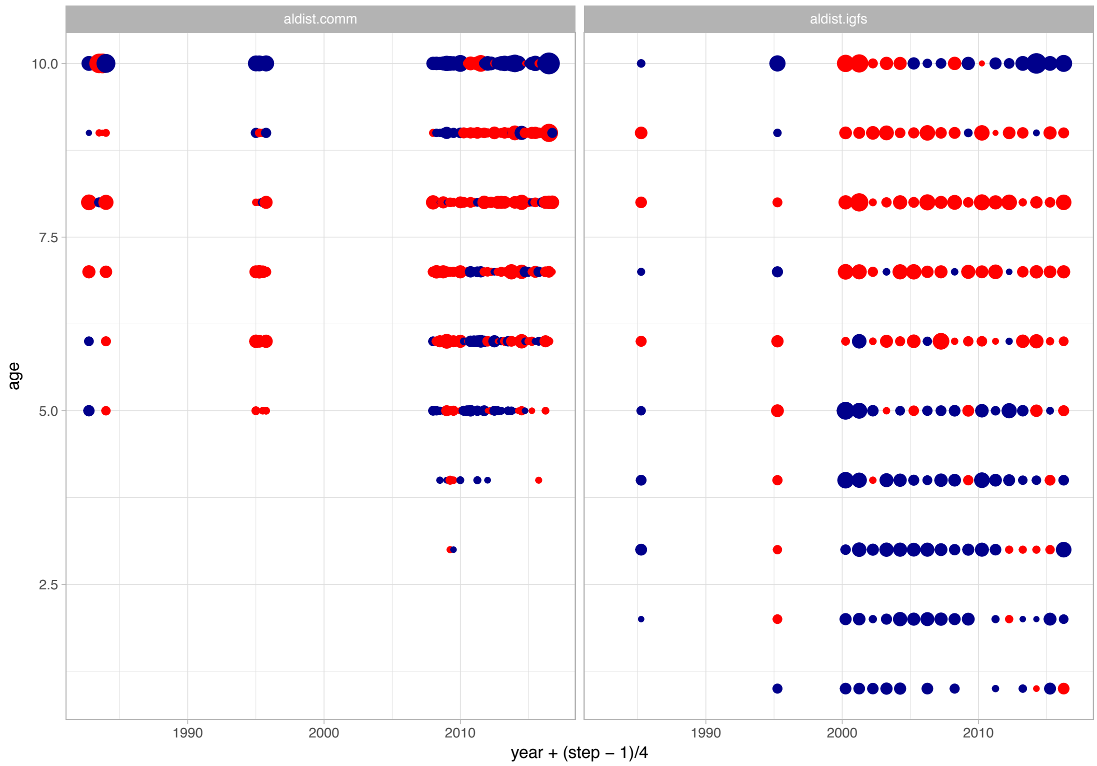

Figure 2.25: Tusk in 5.a. Standardised residual plots for the fitted age distribution from the commercial and survey fleets. Red points denot a model underestimate and blue points an overestimated. The size of the points denote the scale of the standardised residual.

2.2.4.5 Maturity

The estimated maturity at length and the observed values from the spring survey are contrasted in fig. 2.26, along with bootstrap estimates. Some discrepancy can be observed from from the figure, notably in the years 2001 and 2002 and in the upper length ranges where the model predicts lower proportion mature than observed.

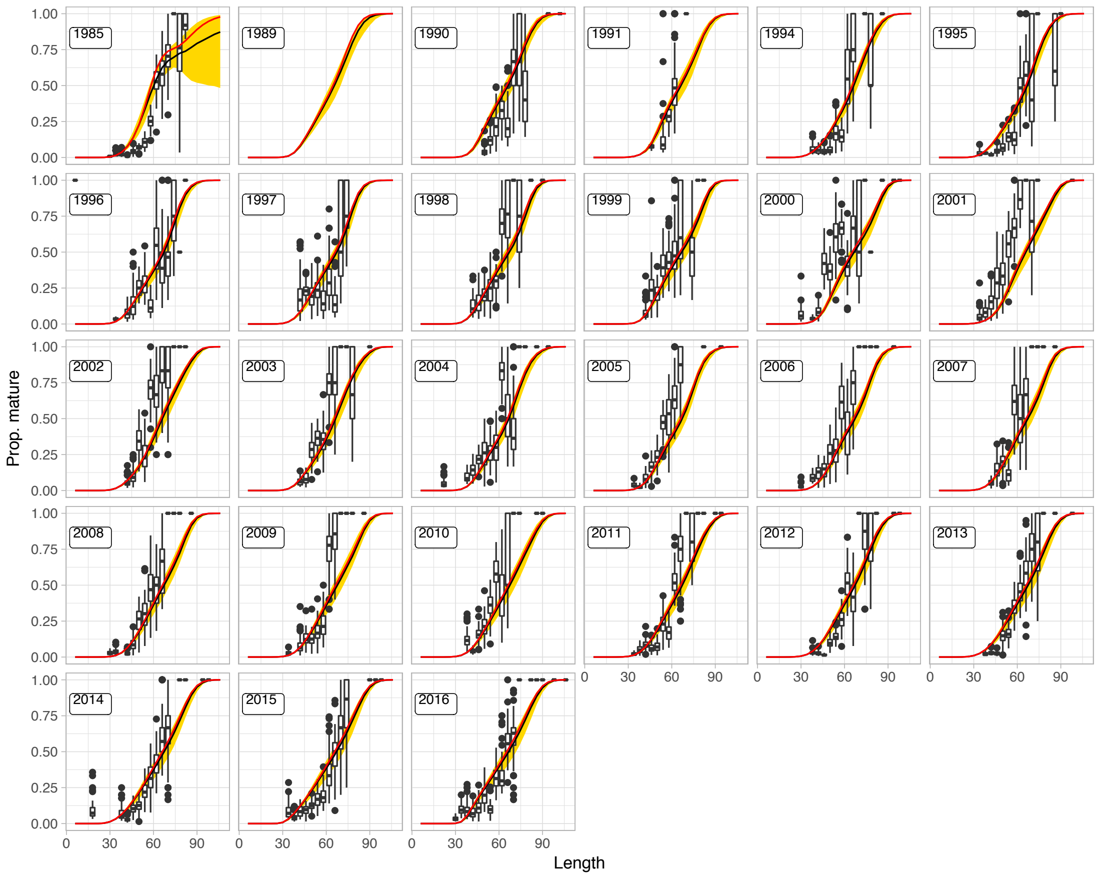

Figure 2.26: Tusk in 5a and 14. A boxplot of the bootstrap distribution of the maturity at length from the Icelandic spring survey compared to the bootstrap confidence and median of model estimates, indicated by a gold ribbon and a solid black line. Base model estimates are shown as a red line.

2.2.5 Estimates

2.2.5.1 Growth

In the model, information on growth of tusk is obtained from the aged otoliths (see subsection 2.2.3.3). In figure 2.27 examples of the growth estimates are presented. In the model L_∞ and k are estimated. In figure 2.27a predictions of the growth curve using the bootstrap estimates of of the growth process pre-exploitation are plotted (black solid line and blue area). On top of that the bootstrap estimates of mean length at age in 2016 are plotted (black dashed line and yellow area). There is some difference between these two growth curves which can be attributed to fishing mortality (size selective). The growth curves in figure 2.27a look plausible. In figure 2.27b the bootstrap estimates of the standard deviation (s) of mean length at age in the population in 2016 are presented. The estimates of s increase rapidly from the age of 1 to age 6 or 7, after that the increase is slower. For the oldest age groups the estimates of s decrease again slightly, due to the size selectivity in the model.

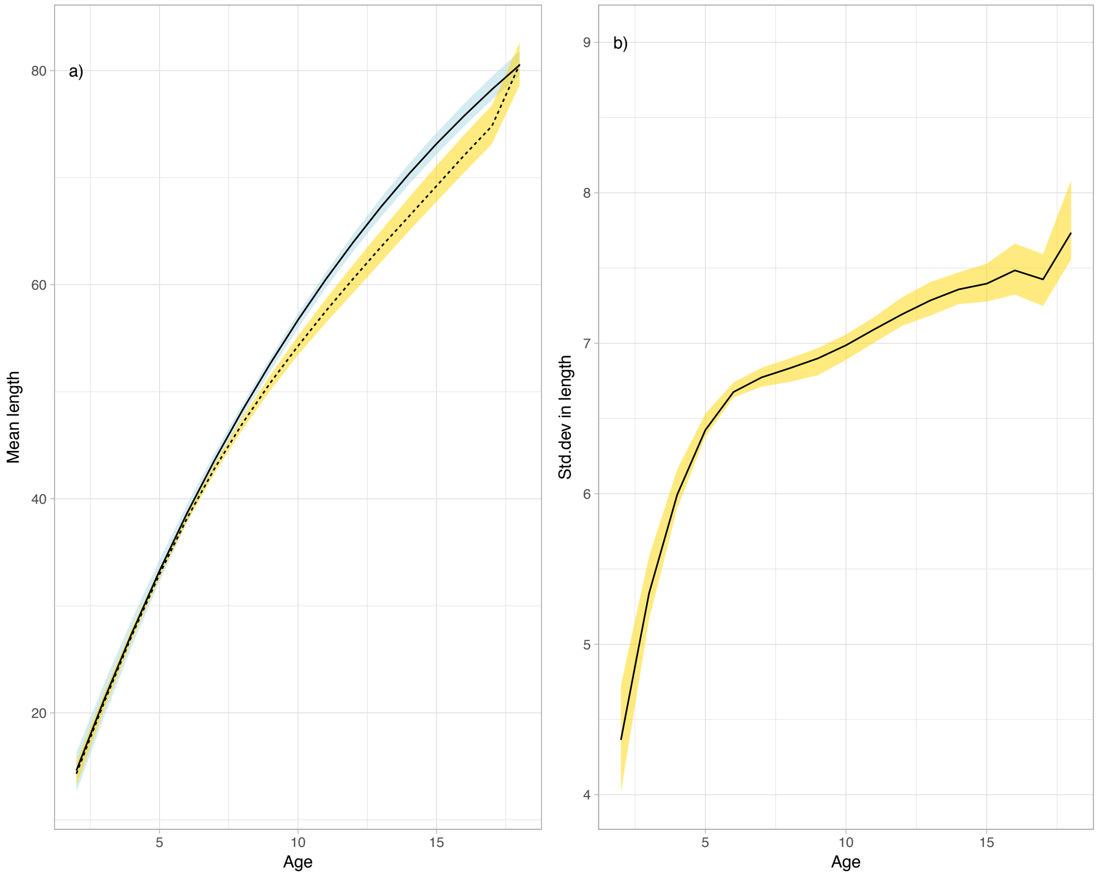

Figure 2.27: Tusk in 5a and 14: Estimates of growth from the gadget model for age 2 and above. Note that the recruitment length and standard deviation are estimated and constant for all model years. The figures show a) Predicted growth from bootstrap estimates of von Bertalanffy parameters (median: black solid line) and 5-95% inter quantile range (blue area) and predicted length in stock in 2016 from the bootstrap estimates (median: black dashed line) and 5-95% inter quantile range (yellow area). b) Bootstrap estimates of standard deviation of length at age in 2016 (black line: median, yellow area 5-95% quantiles).

2.2.5.2 Predicted age-structure

Having a large plus group in the model can indicate either low natural mortality or to slow growth rate, or a combination of both. The predicted catch in numbers (Figure 2.28) shows that the main age groups in the catches according to the model are ages 5 to 14 and hardly any tusk older than age 16 is caught. Similarly, stock abundance declines rapidly after the age of 15 and the plus group (18^{+}) is very close to zero in most cases (Figure 2.29). Uncertainty in rectruitment in the terminal years of the model appears to have an effect on the most recent estimates of the age structure. From 2013 the is a notable spike in uncertainty at age 1 that continues the following year and ages.

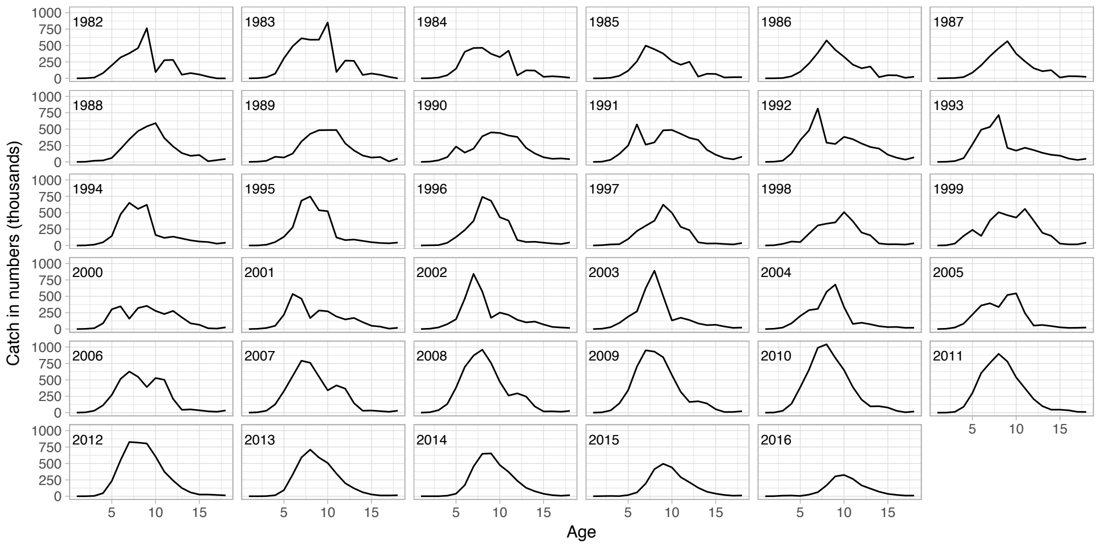

Figure 2.28: Tusk in 5a and 14. Estimates of catch in numbers from the base-run.

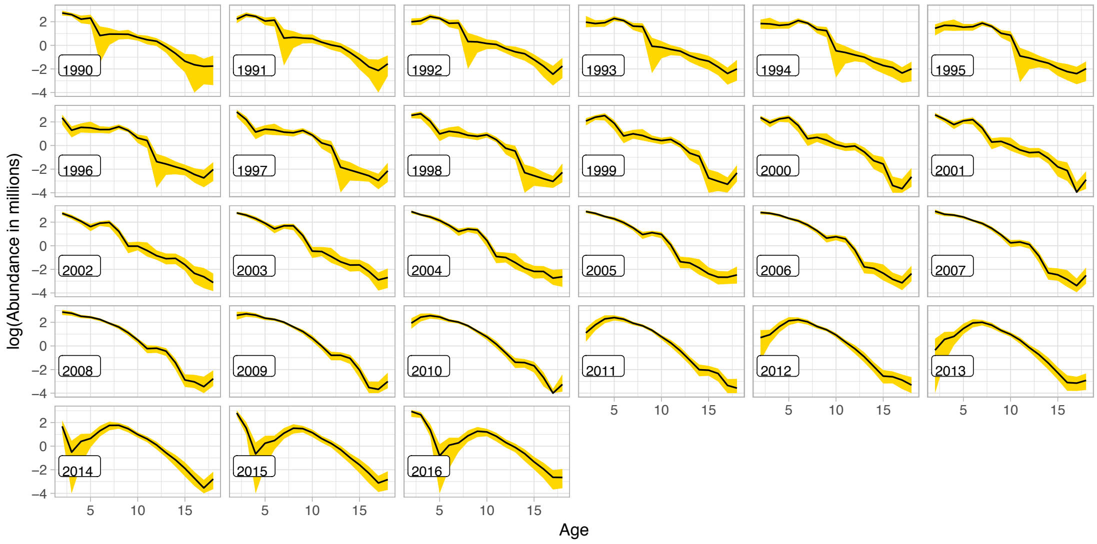

Figure 2.29: Tusk in 5a and 14. Estimates of abundance by age and year, log transformed. Black solid line and golden ribbon indicate the bootstrap median and 90% inter-quantile range.

2.2.5.3 Selectivity

The estimated selection curves for commercial and survey fleets are shown in fig. 2.30 along with the respective bootstrap 90% interquantile range. L_{50} in the survey is considerably lower than the commercial fleet, while more uncertain due noisier data. The estimated survey and commercial l_{50} were estimated at 26.96 (22.76 – 34.41) and 48.49 (47.24 – 49.72) respectively.

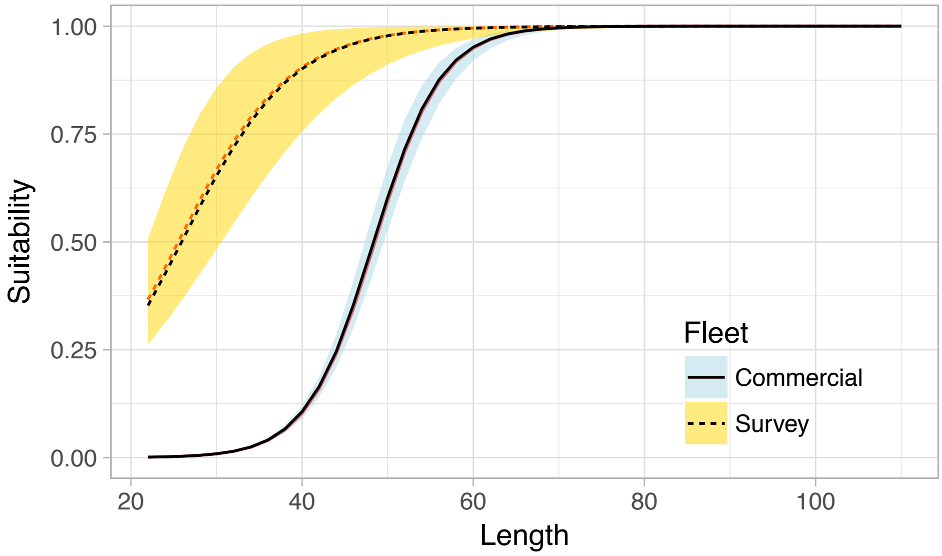

Figure 2.30: Tusk in 5a and 14. Bootstrap estimates of selection curves from the fleets in the model. Black lines is the median and shaded area the 5-95% interquantile range. Red lines indicates estimate from the base model.

2.2.5.4 Population estimates

The model predicts that total biomass is decreasing after having peaked to its highest level since 1982 in 2009. Reference biomass is still increasing since its lowest point in 2000. Similarly the spawning stock biomass is rising from its lowest point of 5.3 kt in 2000. (Fig. 2.31). The bootstrap runs indicate that uncertainty about population estimates has been increasing in recent years, which in accordance with fewer cohorts with data available for all ages. A similar effect is observed in the inital years of the model.

The coefficient of variation (CV) of the population estimates in the years before 2010 estimated from the bootstrap runs is slightly above 0.2 for the SSB, 0.08 for the reference biomass (>40 cm) and 0.22 for recruitment. However in the terminal years the CV of SSB and reference biomass is around 0.25 and 0.21 respectively, the range for these two metrics is between 0.15 to 0.25 and 0.06 to 0.21. For recruitment the range is 6 to 76%. The CV of fishing mortality has similarly fluctuated around 0.12, while increasing towards 0.24 in the last year.

Catches of immature fish, in terms of total biomass caught, is estimated to have varied between 51 % in 1985 to 70% in 2010 and in 2016 the estimated proportion is 58%.

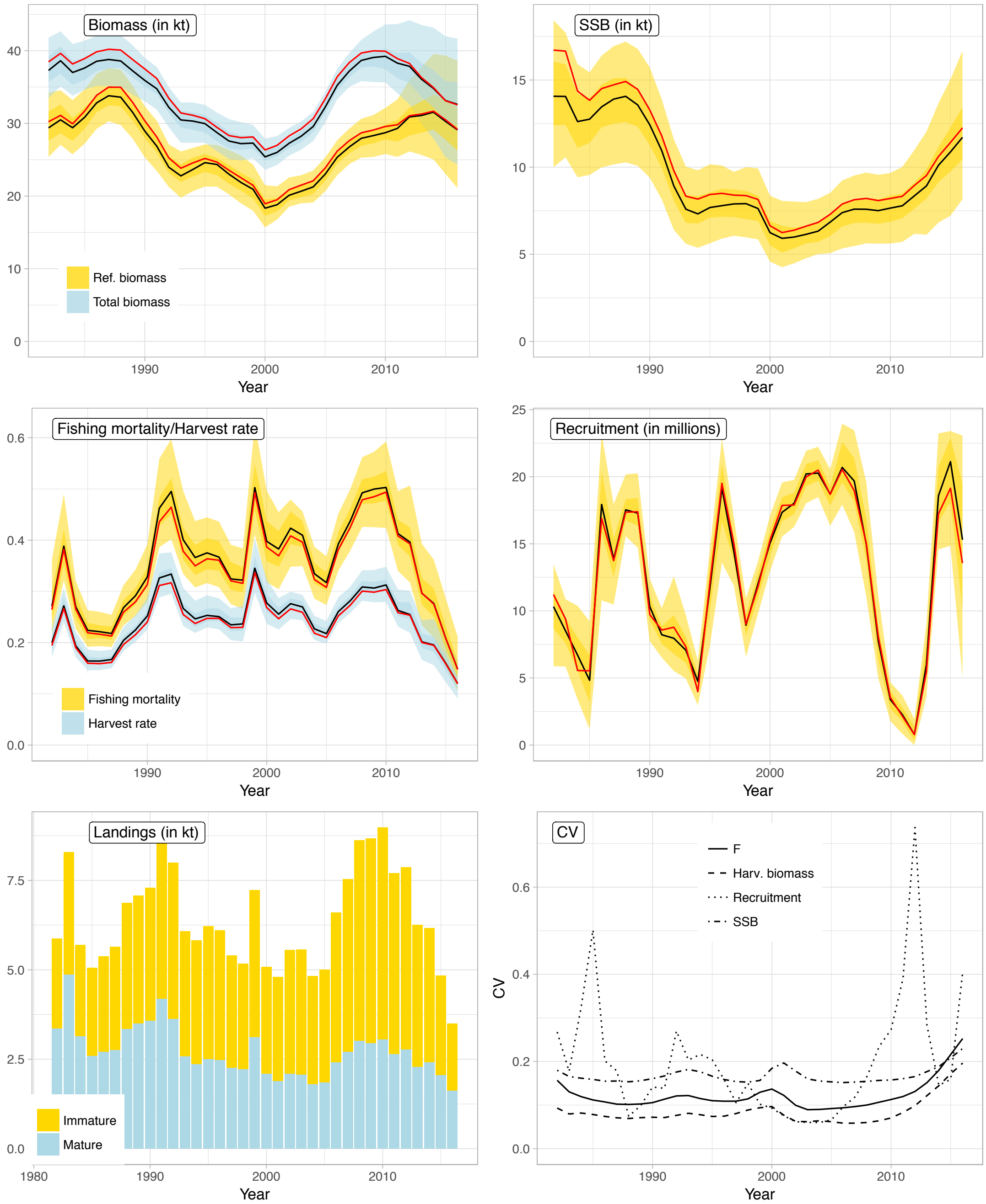

Figure 2.31: Tusk in 5a and 14. Estimates of biomass, reference biomass (tusk larger than 40 cm, knife-edge) and spawning stock biomass. Estimates of recruitment at age 1 in millions and fishing mortality (age 15^{+}). Black line is the median of bootstrap estimates, yellow area is the range between the 5-95% quantiles of the bootstrap estimates and the red line is the results of the base-run. Estimates of coefficient of variation (CV) for reference biomass, recruitment and spawning stock biomass from the bootstrap runs.

2.2.5.5 Analytic retrospective analysis

In figure 2.32 the results of an analytical retrospective analysis are presented. The analysis indicates that there is a downward revision of biomass (SSB and reference) in 2012 to 2016 and subsequently an upward revision of F. Terminal estimates of recruitment fluctuate considerably.

Two things have to be considered when looking at figure 2.32. First is that these fluctuations are roughly within the 90% bootstrap interquantile range, although there appears to be a one way correction each consecutive year. This is appears to be related to the discounting of peak value of the si.20-30 and si.30-40 indices in the latter half of the first decade of this century (See figure 2.33) when more data on the subsequent decrease emerged. Therefore as the increase in the indices is discounted each year, as the signal (increase) does not transfer to the larger length groups, the biomass estimates are reduced.

The second thing is that the bulk of the age structured data is in the terminal years and therefore a very informative data is being omitted, this specially affects the recruitment estimates. Also the lack of age data back in time, in contrast with traditional age based assessments appears to result in greater variation in historical estimates.

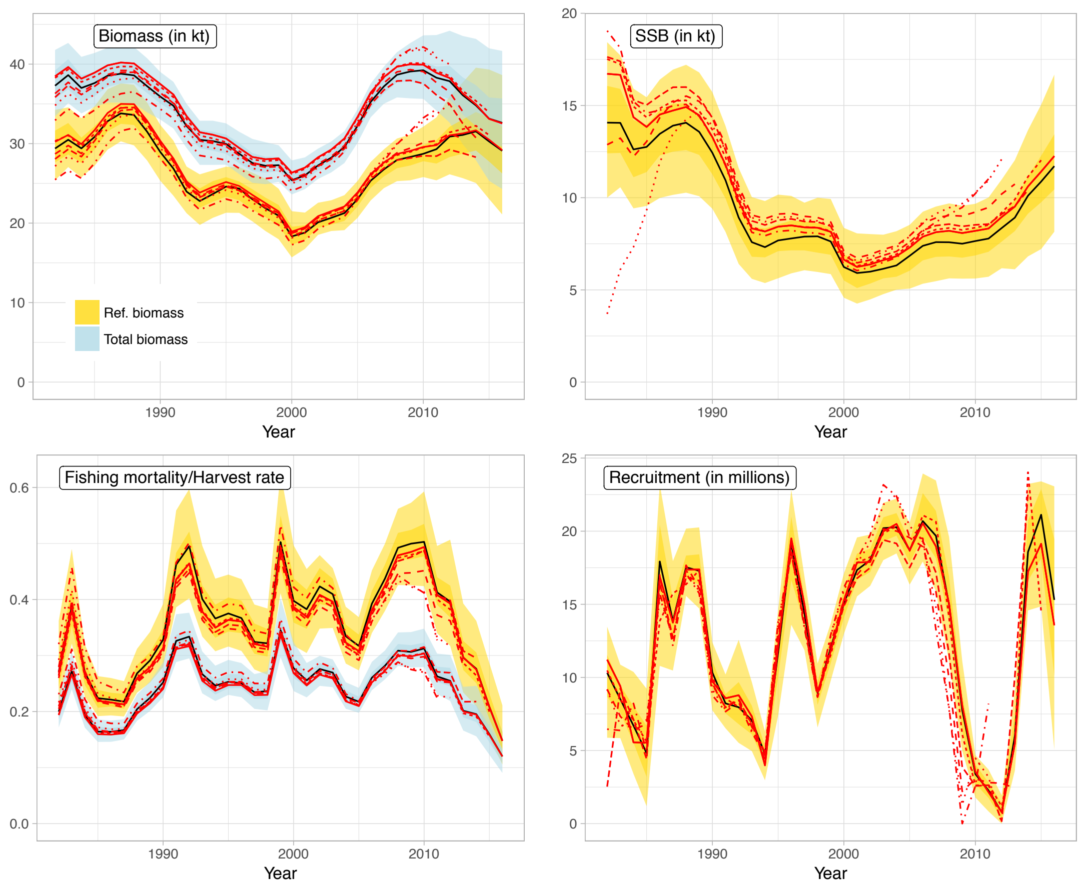

Figure 2.32: Tusk in 5a and 14. Analytical retrospective analysis from the Gadget model

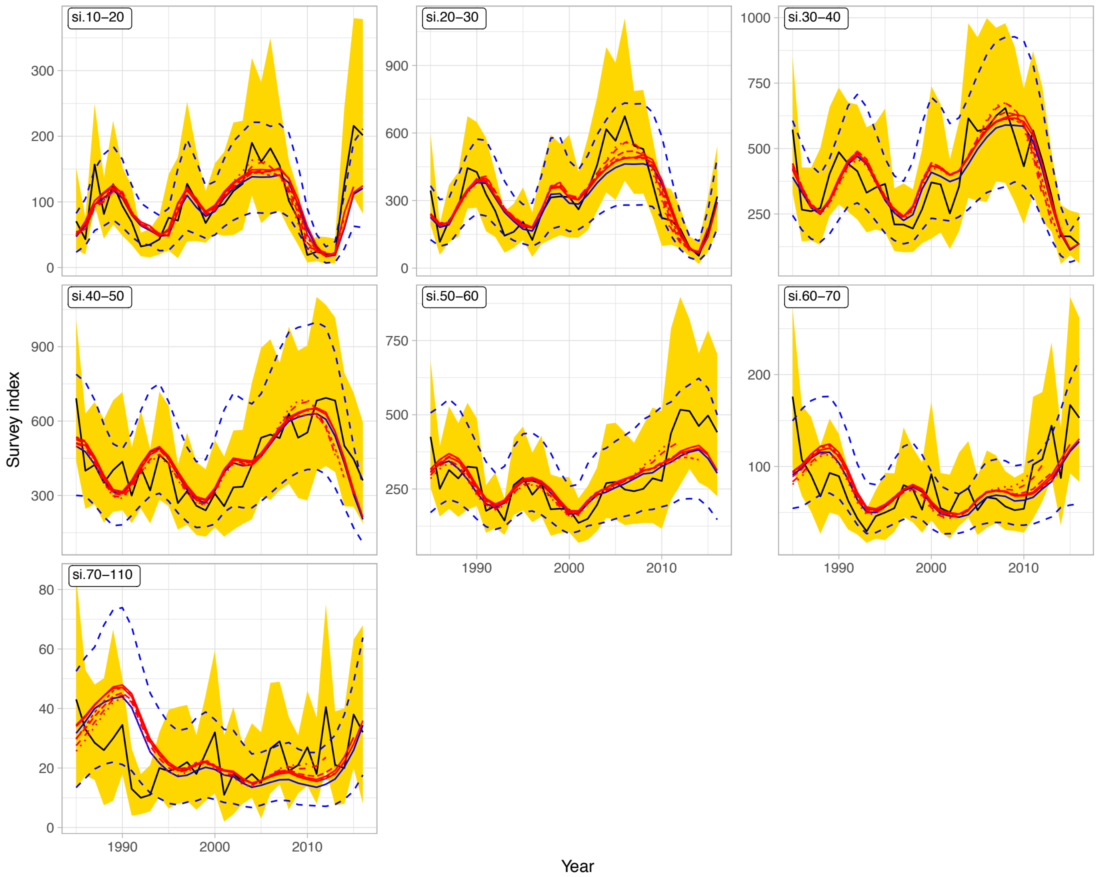

Figure 2.33: Tusk in 5a and 14. Analytical retrospective analysis of the fit to the survey indices.

2.2.5.6 Changes since the last benchmark

At WGDEEP in 2009 an exploratory stock assessment of tusk in 5a and 14 using the Gadget model was presented and subsequently tusk in 5a and 14 was benchmarked in 2010. At the Benchmark Meeting for Deep-sea Species in 2010 (WKDEEP) the Group concluded that the results of the Gadget model for tusk in 5a were indicative of trends. The Gadget setup presented at WKDEEP-2010 was preliminary and has been im-proved vastly since then. WGDEEP-2010, followed by RGDEEP-2010 and ADGDEEP-2010, proposed that advice should be based on the estimates and projections from Gadget. Following this recommendation ACOM decided that the ICES advice for tusk in 5a and 14 should be based on Gadget. At the WGDEEP-2011 meeting improvements to the settings of the model were presented (WGDEEP-2011:WD-03 and WGDEEP-2011:WD-04). These improvements were:

- Iterative reweighting of likelihood components following the procedure described by Taylor et al. (2007). This replaced the ad hoc weighing of likelihood components used in 2010.
- Inclusion of the Iceland-Faroe ridge in the survey series. Considerable part of the tusk caught in the Icelandic Spring survey is caught in this area, however the area was not covered in 1996 to 2004. In line with other stocks in 5a that use the survey in their assessment, the Ridge is now included. The trend in the series is similar.
- Additional ageing material, from commercial catches (1984, 1995, 2008-2010) and from surveys (1985, 1995, 2009-2010).
- Extension of the survey length-distribution from 20 cm down to 10 cm. This resulted in a more realistic estimation of the survey selection curve.
- Reduction of survey likelihood components from 5 to 3.

These improvements, though quite substantial, did not alter the perception of the stock in a significant way. The assessment presented this at WGDEEP-2012 was the same as in 2011, except that the value of natural mortality was decreased from 0.2 to 0.15. The rationale for the changes were:

- Lower value gives a better fit to the available data as it allows the fishery to impact the stock.
- The assumption of constant motality for all ages and sizes of fish through time commonly used in stock assessments is an oversimplification of the natural order of things. Therefore natural mortality in these assessments can at best be viewed as scaling parameter.
- Assuming lower value of natural mortality gives more conservative estimates of sustainable harvest levels of stocks through lower estimates of reference points and a better definition of them (in Y/R analysis).
- It is unlikely that tusk being a slow growing and late maturing species has the same natural mortality as haddock (0.2). the change in natural mortality was subsequently adopted by the RG, ADG and ACOM in 2012. Since then the model has been run in the same manner each year.

For the 2017 benchmark the main changes to the assessment model are:

- The model building process is built up from scratch such that it would allow for it to be reproducible. The scripts that generate the assessment are currently available from github.com/fishvice/mfdb-hafro-etl and github.com/fishvice/gadget-models

- The model now estimates explicitly the maturity process by setting up two sub-stocks, immmature and mature, allowing for the direct estimate of the spawning stock biomass. In comparison, in previous iterations of the assessment model, the spawning stock biomass was estimated based on the maturity at length ogive and proportion mature at age calculated based on mean length at age. The overall SSB was then calculated as the biomass at age times the proportion mature at age. This lead to a lower estimate of SSB than that obtained from the biomass at length, while having the same trends.

- Age readings where fish have been assigned an age of 10 or older are now grouped together before comparing with the model output. This is done as age of tusk is harder to determine after the age of 8 and number samples of old fish are fairly low, and potentially result in biases in estimated mortality rates.

- The indices of abundance are now defined in terms of number of fish caught in the Icelandic groundfish survey in certain length bins, instead of being derived from swept area biomass. This change has a minimal impact on the trends observed in these indices, as this effectively results in a scale change.

- The grouping of survey indices was changed. Previously the model grouped together survey indices in lumps of three and the weight assigned to each survey group was the inverse of the total variance of the group. In the proposed assessment the inverse variance of each lengthgroup index is used as the weight to allow for more appropriate weighting.

- Age–length and length distributions are now compared using sums of squares rather than a multinomial distribution. While neither of those likelihood functions are considered representative of the truth, it is known that the sums of squares tolerates considerable deviations while giving reasonable point estimates.

- Bootstrap is used to estimate the uncertainty in the assessment output and to derive management reference points.

- Initial conditions in the model were loosened. The previous assement model the weight length relationship was set incorrectly. In addition the abundance of fish older that 8 had been fixed at a low number to prevent problems relating to little data on age. The weight at length is now estimated from the spring survey and initial abundance at age is estimated freely as more data has come available.

- Timing of the recruitment and age of first recruits is modelled differently. The revised model is now set up such that the recruitment occurs prior to the survey on the first time-step and the age of first recruits is now 1. Previously the recruitment occurred at age 2 after the survey which may have resulted in a skewed growth rate.

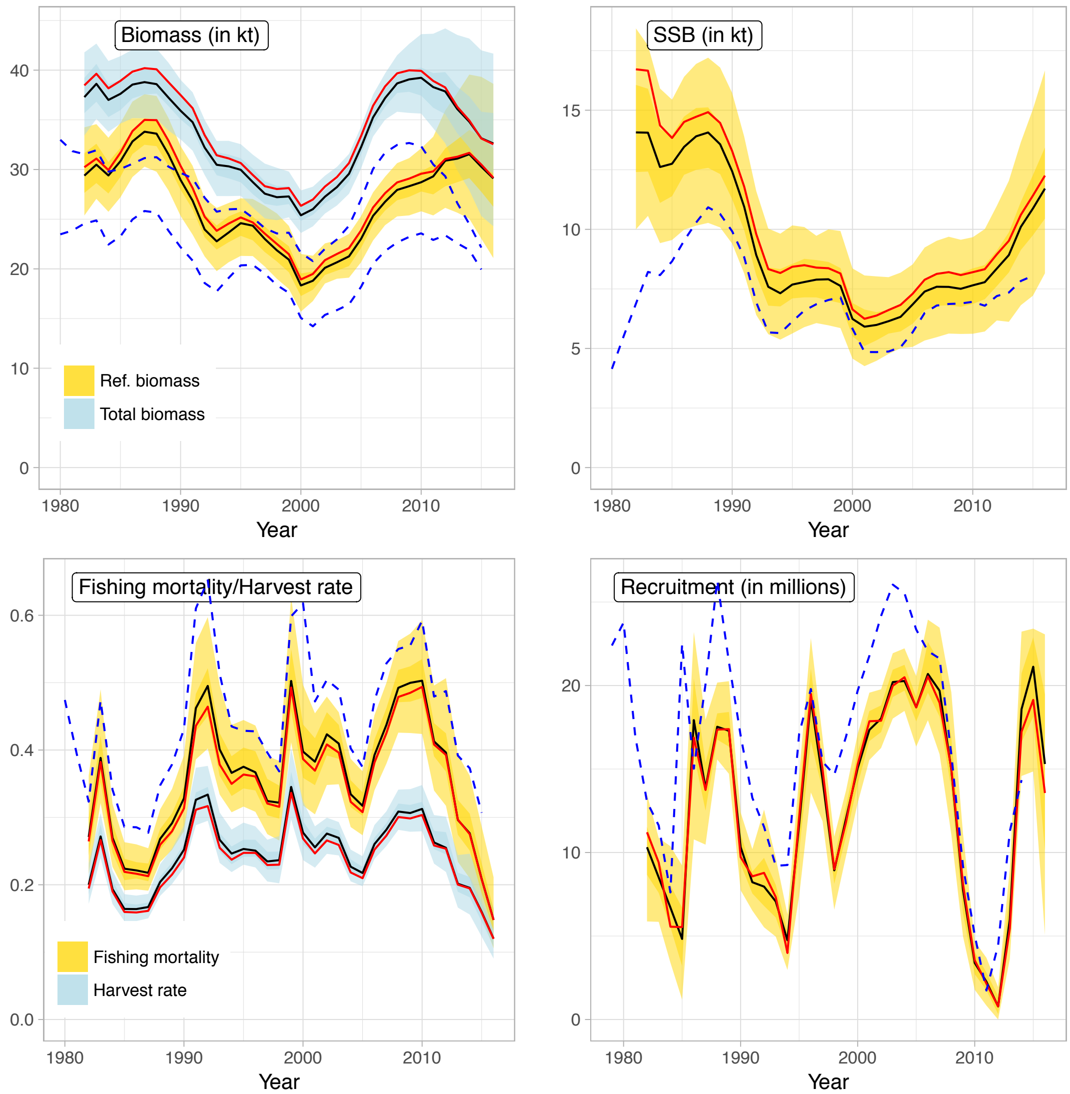

Figure 2.34: Tusk in 5a and 14. Comparison with last year assessment results. Estimates of biomass, reference biomass (tusk larger than 40 cm, knife-edge) and spawning stock biomass. Estimates of recruitment (age 1) in millions and fishing mortality (age 15^+). Black line is the median of bootstrap estimates, yellow area is the range between the 5-95% quantiles of the bootstrap estimates and the red line is the results of the base-run. The blue dashed lines denote results from last years (2016) assessment reported on comparable metrics to the results of this benchmark assessment.

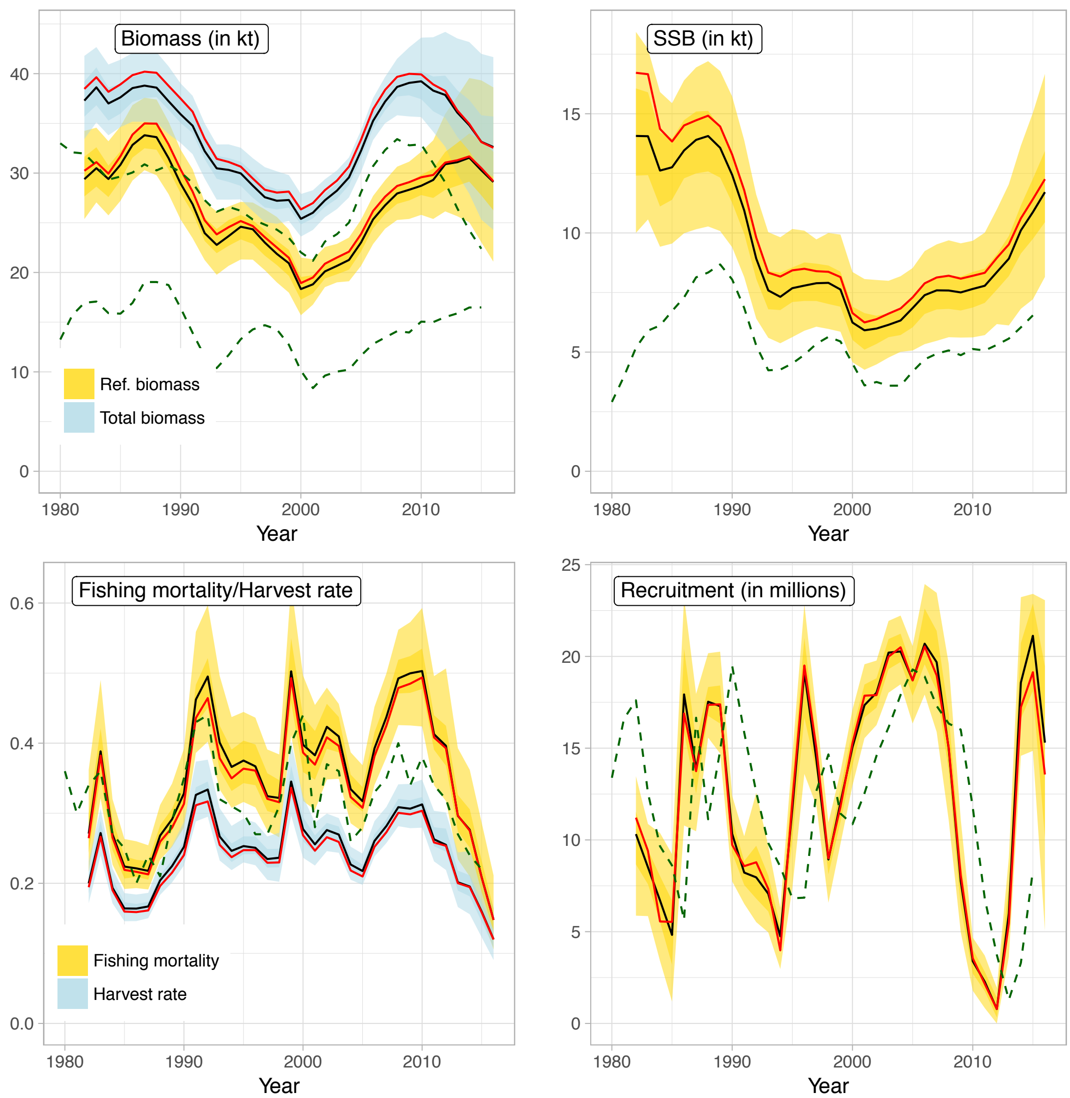

Figure 2.35: Tusk in 5a and 14. Comparison with last year assement results. Estimates of biomass, reference biomass (tusk larger than 40 cm, knife-edge) and spawning stock biomass. Estimates of recruitment (age 1 for benchmark assessment, and age 3 for last years assessment) in millions and fishing mortality (age 15^{+} for benchmark assessment, and average of ages 7-10 for last years assessment). Black line is the median of bootstrap estimates, yellow area is the range between the 5-95% quantiles of the bootstrap estimates and the red line is the results of the base-run. The green dashed lines denote results from last years (2016) assessment, reported as they were presented by ICES last year (i.e. SSB calculated with external maturity ogive, ages of F and Recruitment as indicated above).

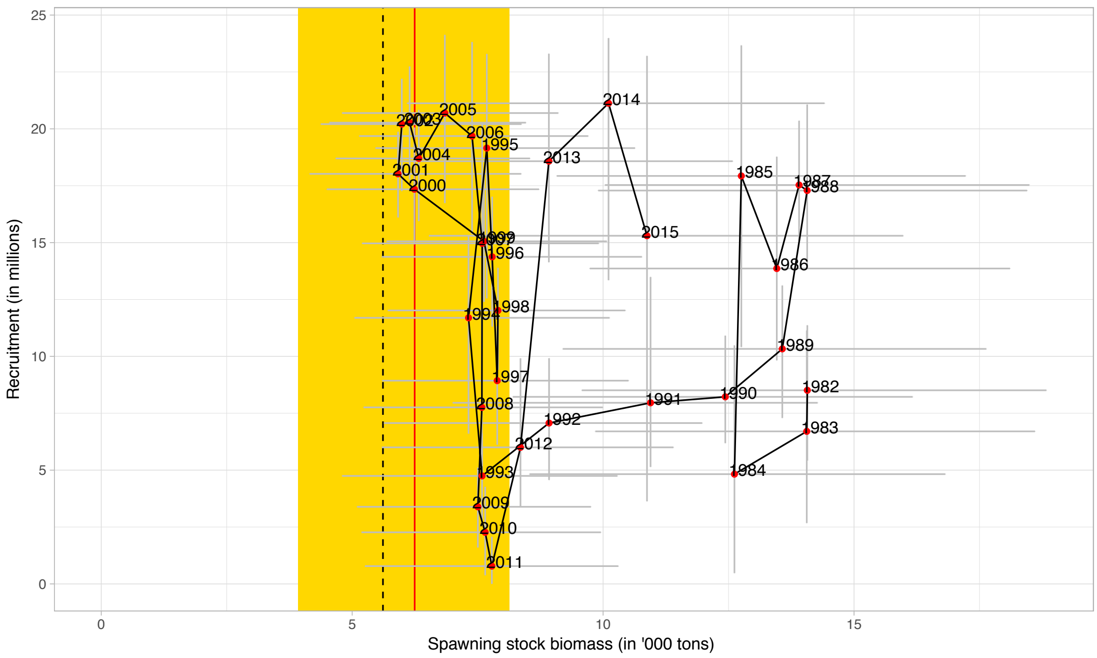

Figure 2.36: Spawning stock biomass recruitment relationship for tusk in 5a. Uncertainty in recruitment and SSB is indicated with 90% quantile intervals as grey bars. Red point indicate the median estimate and black solid line the chronological order. The yellow the vertical bar represents the distribution of B_{loss}, also shown in fig. 2.37.

2.2.6 Derivation of reference points

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 fishing mortality, but for some stocks the reference points are determine in terms of harvest rate, i.e. the amount of catches relative to a reference biomass (s.a. spawning stock biomass, or biomass of fish larger than a minimum size or older than a minimum age). For Tusk in 5a and 14 the suggested management plan will be determined in terms of the harvest rate of the total biomass above 40 cm.

The following sections describe the derivation of the management reference points both in terms of harvest rate (H) and fishing mortality (F). The model for the stock recruitment and assessment error which in combination with the bootstrap results is used to project the stock status stochastically in order to derive the PA and MSY reference points.

2.2.6.1 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. 2.36. The figure shows a relatively narrow dynamic range of SSB and no evidence of impaired recruitment. In this situation, according to the ICES technical guidelines, B_{lim} can not be estimated

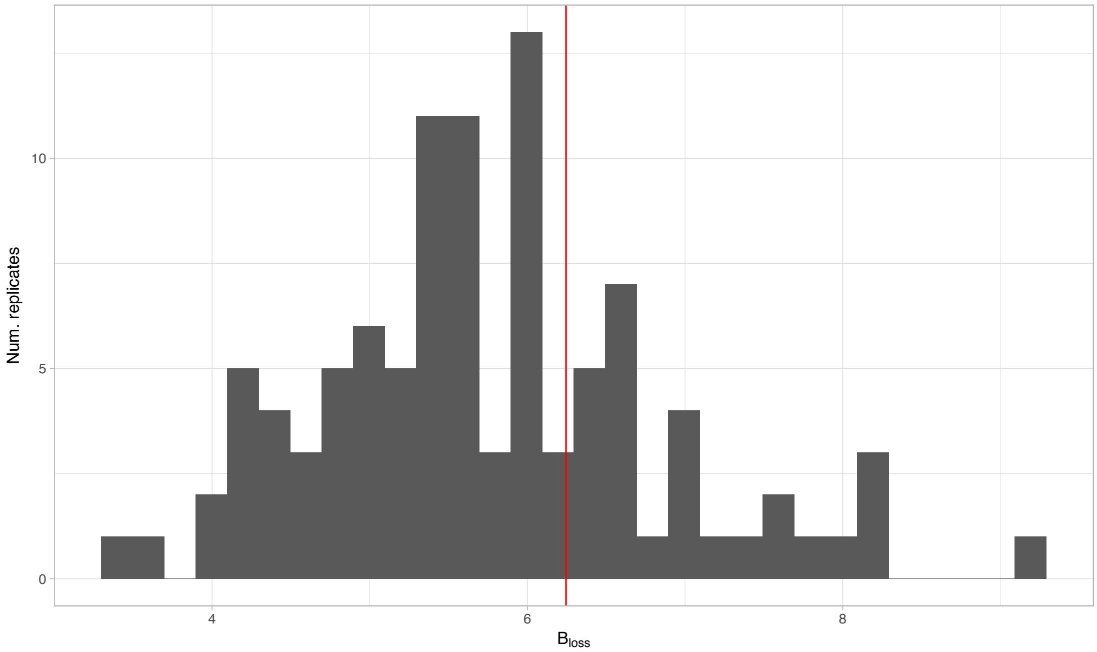

Figure 2.37: Tusk in 5a and 14. Histogram of the bootstrap distribution of B_{loss} where the red line indicates the base model estimate.

from these data and that the lowest observed SSB during that period (i.e. B_{loss} = SSB(2001) = 6.24 kt), which is the lowest observed biomass from the base–line model, is a potential candidate for either B_{pa} or B_{lim}. Historically fishing pressure toward tusk in 5.a and 14 has been low, with an estimated apical F ranging between 0.2 and 0.6, and there large areas where tusk is available but not fished, in the south east in particular. Therefore B_{loss} is considered an appropriate estimate of B_{pa} at this point in time.

In line with ICES technical guidelines, since B_{pa} but not B_{lim} can be estimated, a proxy for B_{lim} can be calculated based on the inverse of the standard factor, $e^{\sigma*1.645}$ using $\sigma = 0.2$, used for calculating B_{pa} from B_{lim}. Therefore, a proxy for B_{lim} could be set at $B_{pa}/e^{1.645*0.2} = 6.24/1.4 = 4.46kt$.

2.2.6.2 Stock recruitment relationship

A variety of approaches are common when estimating a stock–recruitment relationship. Under a lack of stock-recruitment signals in the available data, the ICES guidelines suggest using "hockey-stick" recruitment function is suggested, i.e. the recruitment at year y is calculated from the using the following equation:

$$R_y = \bar{R}_y \min(1, S_y/B_{loss}) \tag{2.19}$$

where R_y is annual recruitment, S_y the spawning stock biomass, B_{loss} 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 the historical distribution using a block-bootstrap, randomly drawn block starting years and including 6 consecutive years in the blocks. This is done to account for intra-correlation in the recruitment time–series, as illustrated in fig. 2.38. The timing of the recruitment in the model occurs at the end of the 1^{st} time-step, using the projected spawning stock biomass at the same time.

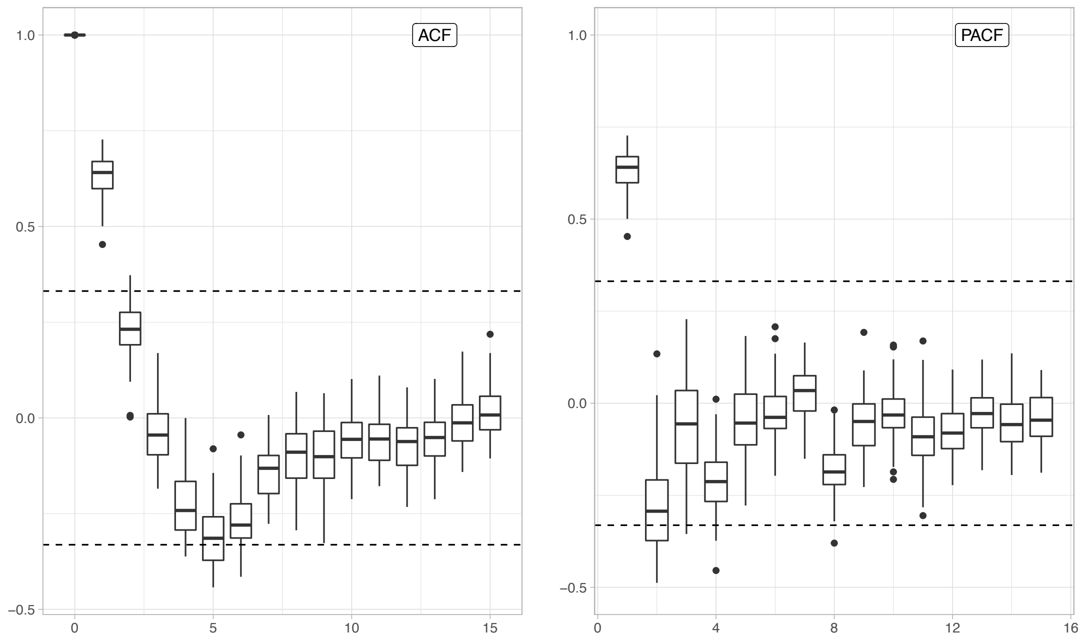

Figure 2.38: Tusk in 5a and 14. Boxplot of the bootstrap distribution of estimates of autocorrelation (left panel) and partial autocorrelation (right) in recruitment.

2.2.6.3 Management procedure in forward projections

Observation error and to some degree model error are addressed by the bootstrap approach employed in here. Issues related to the stock structure have been discussed in WGDEEP-2007, which suggested that tusk in 5a and 14 should be assessed as single stock unit. Analytical retrospetive analysis indicates some degree autocorrelation in observation error, while this is a concern it assumed that this is caused by inconsistencies in the survey indices.

Illegal landings and discards by Icelandic fishing vessels are considered to be neglible and it is assumed that foreign vessel catches are a part of the management plan when implemented. It is assumed therefore implementation error would be virtually none. The largest source of error outstanding is the extent of process error, in particular variation in the stock recruitment relationship.

The descision rule evaluated follows the methodology set out in AGICOD2009. The rule evaluation framework can be classified as simulation without an assessment feedback (ICES 2006), i.e. it is thus assumed that the simulation within the operating model represents the true stock dynamics. Errors in the assessment procedure that relate to harvest advice model are emulated as:

$$\hat{B}_y^{ref} = e^{E_y} B_y^{ref} \tag{2.20}$$

where B_y^{ref} is the reference biomass, $E_y = \sigma(\rho\epsilon_{y-1} + \sqrt{1-\rho^2}\epsilon_y)$ is the assessment error and σ is CV of the reference biomass, ρ the autocorrelation between assement years and $\epsilon_y \sim N(0,1)$. Then the decision which allocates catches to the fleets is simply a scalar applied to the estimate of the reference biomasss:

$$TAC_{y+1} = H\hat{B}_y^{ref} \tag{2.21}$$

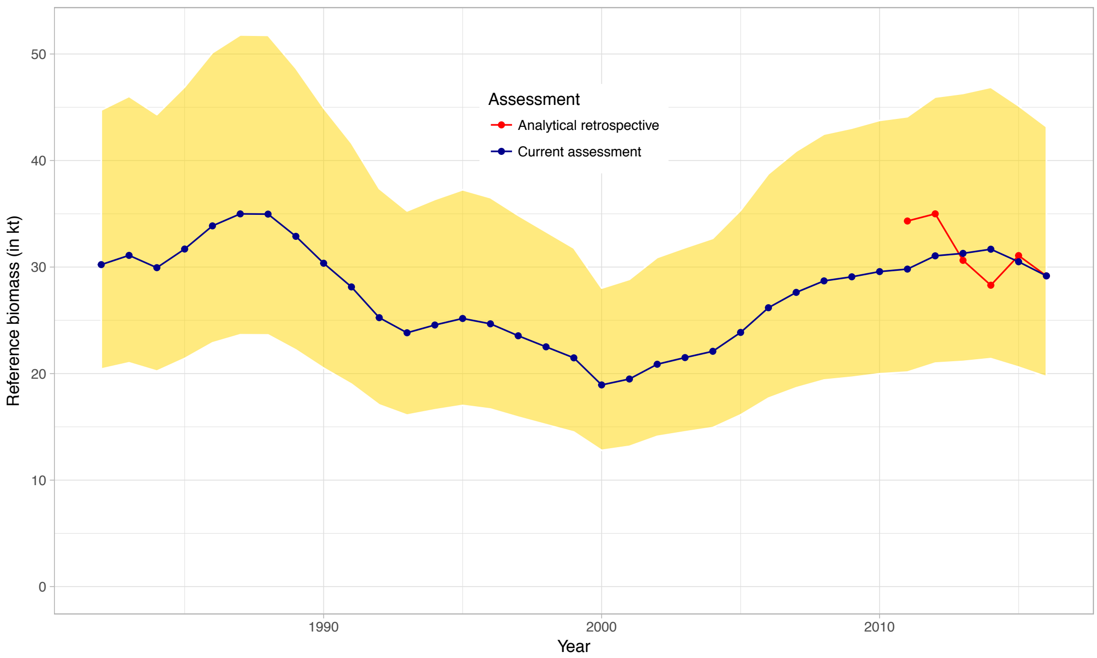

Figure 2.39: Tusk in 5a and 14. Current assement of the reference biomass of tusk ($>$ 40 cm) compared with assessment from the analytical retrospective estimate of the terminal biomass. The shaded yellow ribbon represents the uncertainty (CV $= 0.2$) at the terminal year.

where the evaluation assumes that 2 quarters elapse between the time at which the reference biomass is estimated and the beginning of the fishing year to which the TAC applies. This is to approximate the situation that will normally be encountered when providing advice in practice, where the stock assessment will cover until the end of quarter 1 and the fishing year goes from September 1 to August 31[5].

For Tusk in 5a and 14 B_y^{ref} is the biomass of fish larger than 40 cm at the assessment step, the corresponding CV set at 0.2 i.e the CV of the reference biomass. The autocorrelation in assessment error ρ is set to 0.8 which is perceived as the upper limit to potential correlation. Figure 2.39 illustrates the deviation of the reference biomass as estimated in the last year of the analytical retrospective compared with the most recent assement.

[5]In real applications the harvest rate will be scaled when SSB is below $B_{trigger}$ according to the ratio between SSB and $B_{trigger}$

2.2.6.4 Setting H_{lim} and H_{pa}

According to the ICES guidelines, the precautionary reference points are set by simulating the stock using the stock-recruitment relationship described in section 2.2.6.2, based on a wide range of harvest rates, (see eq. 2.21), ranging from 0 to 1 and setting H_{lim} as the H that, in equilibrium, gives a 50% probability of SSB $> B_{lim}$ without assessment error, described in eq. 2.20. From this F_{lim} is set as the equilibrium fishing mortality when H_{lim} is applied. H_{pa} is then set as the harvest rate that would lead to the equilibrium fishing mortality of F_{pa}. F_{pa} is defined as the $F_{lim}/e^{1.645\sigma}$ where σ is the CV of the estimated fishing mortality in the assessment year.

The simulation predicted the stock status was projected forward 300 years. For each bootstrap model estimate the stock status was projected 10 times, resulting in a total of 1000 samples. The spawning stock biomass was calculated based on model output after 2060. This is done to ensure that the stock had reached an equilibrium under the new fishing mortality regime.

The results from the long term simulations are shown in the top panels of fig. 2.40; the value of H, H_{lim}, resulting in 50% long–term probability of SSB $> B_{lim}$ was estimated at 0.27 (an equivalent F of 0.41). As the CV of F in 2016 is 0.25, F_{pa} is estimated as $0.41/1.5 = 0.27$. The equivalent harvest rate is then $H_{pa} = 0.2$.

2.2.6.5 Maximum sustainable yield

An additional simulation experiment where, in addition to recruitment variations, assessment error was added the harvest rate that would lead to the maximum sustainable yield, H_{msy}, was estimated. From the simulation annual total landings c_y were calculated after 2060. Average annual landings and 90% quantiles were used to determine the yield by H. Figure 2.41 shows the evolution of catches, SSB and fishing mortality for select values of H are shown. The equilibrium yield curve with assessment error is shown in the bottom left figure 2.40, where the maximum average yield is obtained for a harvest rate of 0.17; under the recruitment assumptions used in the evaluation, the maximum average yield is 6.21 thousand tons with a 90% interval of 3.78 and 9.00 thousand tons. Table 2.9 shows the equilibrium results by harvest rate for select statistics.

H_{msy} is estimated to be 0.17. Equilibrium spawning stock biomass is shown in figure 2.40. The spawning stock biomass obtained at H_{msy} is estimated at 15.22 thousand tons with an upper quantile of 22.61 thousand tons and lower quantile of 8.93 thousand tons.

In-line with ICES technical guidelines the MSY $B_{trigger}$ is set as B_{pa}, as the stock has not been managed according to F_{msy}, or equivalents thereof, for more than 5 years.

2.2.6.6 Proposed target harvest rate

When considering the candidate harvest rate for Tusk in 5a and 14 a few point are worth consideration: First the is marginal gain of increasing the harvest rate in terms of equilibrium yields. Even with catch rates as low as 0.1 the equilibrium yields are roughly comparable with that of the H_{msy}. In addition short term forward projections illustrated in fig. 2.41 indicate that for harvest rates above 0.1 the average catches will all increase from the 2016 level, although the 2016 catches are the lowest levels on record.

Second the fisheries is fairly targeted towards immature fish, as illustrated in fig. 2.31, and as illustrated in fig. 2.40 slight decreases in fishing rate would substantially increase the SSB. Notably when applying a harvest rate of 0.1 this would lead to an average decrease in catches of 10% while approximately doubling the SSB relative, to applying $H_{msy} = 0.17$.

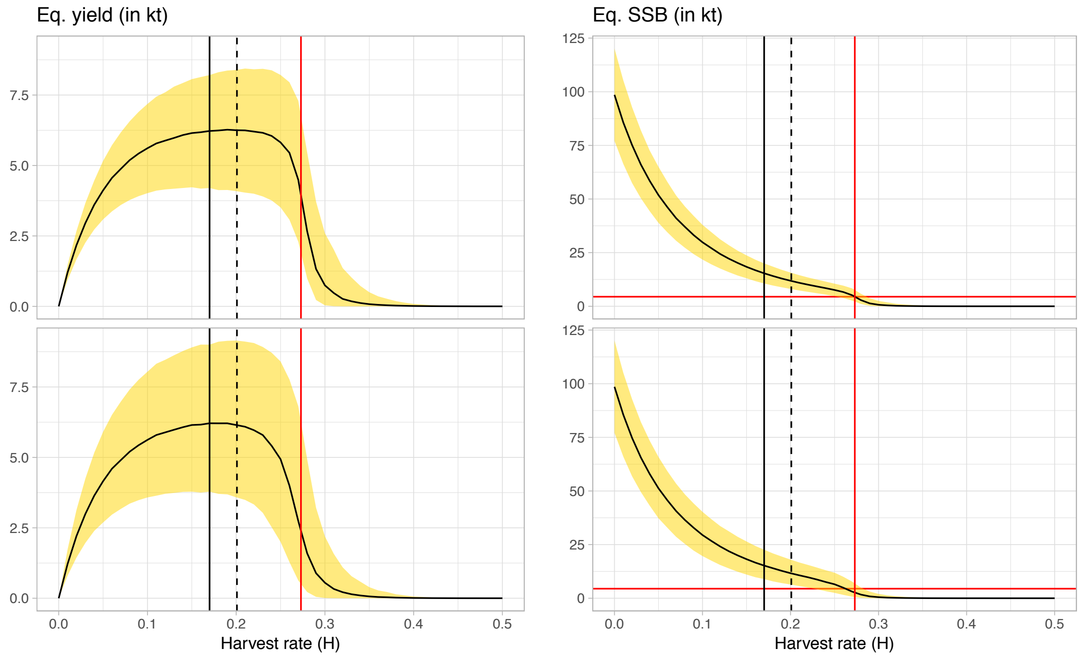

Figure 2.40: Tusk in 5a and 14. Equilibrium catch (left) and SSB (right) curves as a function of H. Top panels show the results with process error while the bottom panels have furter added assessment uncertainty. The black solid curves indicate the median projected catch and SSB and the shaded yellow region the 5% – 95% percentiles. Vertical lines indicate H_{lim} (red), H_{pa} (dashed) and H_{msy}. The horizontal red line indicates B_{lim}.

Taking these points into consideration the proposed target havest rate, of 0.13 with a $B_{trigger} = B_{pa}$, is considered safe and precautionary and in line with ICES MSY approach. The expected 5% and 95% percentiles of true harvest rates, when setting catches according 0.13, are 0.09 and 0.18 respectively, and the entire distribution is illustrated in figure 2.42.

2.2.7 Conclusions

Overall the Gadget model for Tusk in 5a and 14 presented is considered to give a satisfactory description of the stock trends. It synthesizes information on the stock development based on the available biological data, both from scientific surveys conducted in 5a and samples obtained from the commercial fishery as well as indices of abundance from the spring survey. In spite of minor mis-fits the results presented here suggest that the model is usable for assessing the stock and to be used as the basis for the ICES advice. The model for Tusk in 5a and 14 is also used as the basis for determining the advisory reference points according to ICES technical guidelines. These reference points, which are shown in table 2.10.

In a complicated model such as Gadget that has many parameters and many datasets of varying quality it is to be expected that there may be problems with some parameters and fit to some data-sets. Notably the proportion at age from the spring survey exhibited conflicting signals when compared accross years, resulting in poor model fit to these data. This suggests that observation error alone can not account for this variability. On the other hand predicted proportion at age from the commercial fishery

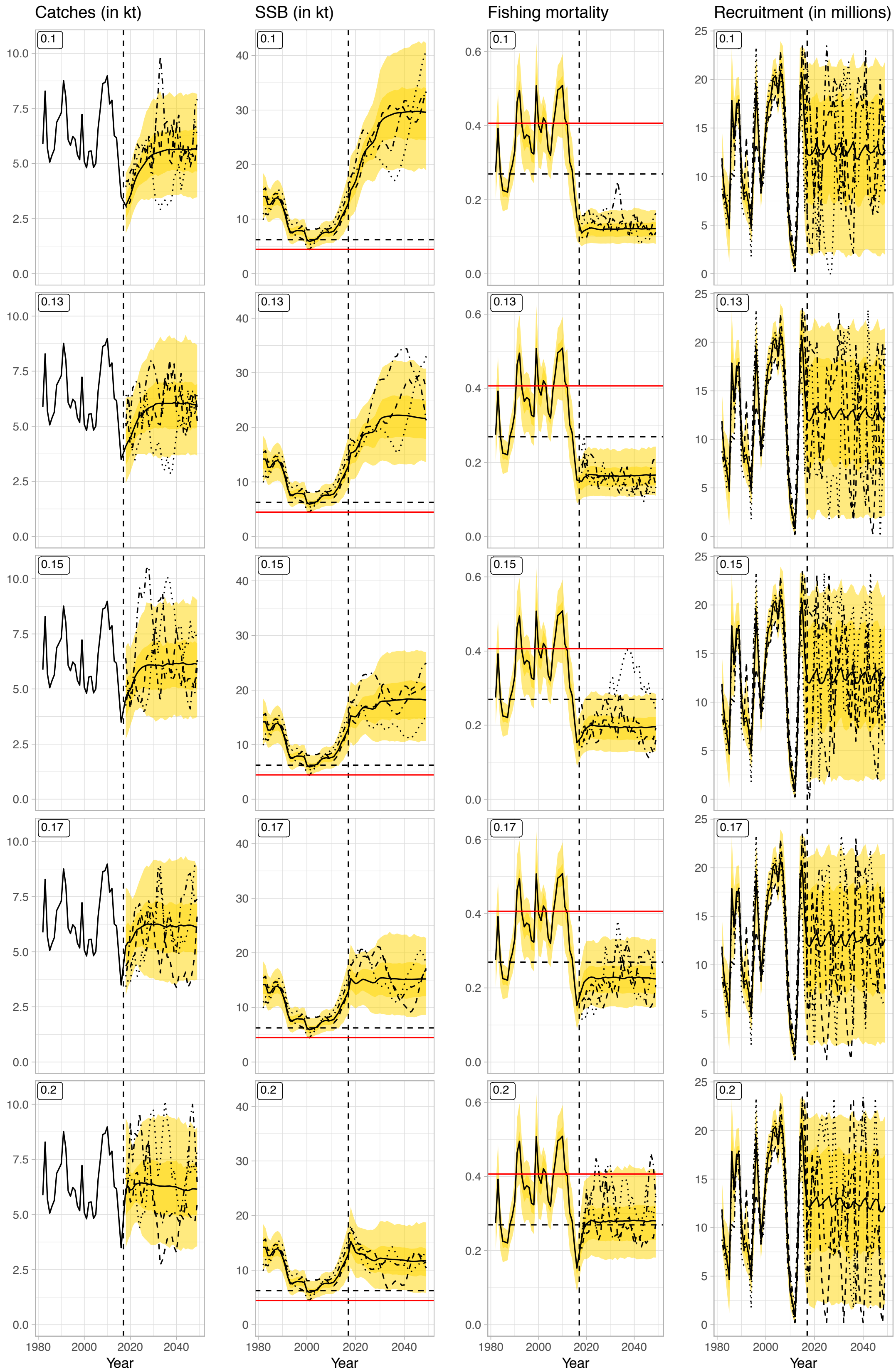

Figure 2.41: Tusk in 5a and 14. Projected catches, spawning stock biomass and fishing mortality for select target harvest rates. Red and black dashed horizontal lines represent the limit and pa reference points respectively for SSB and F.

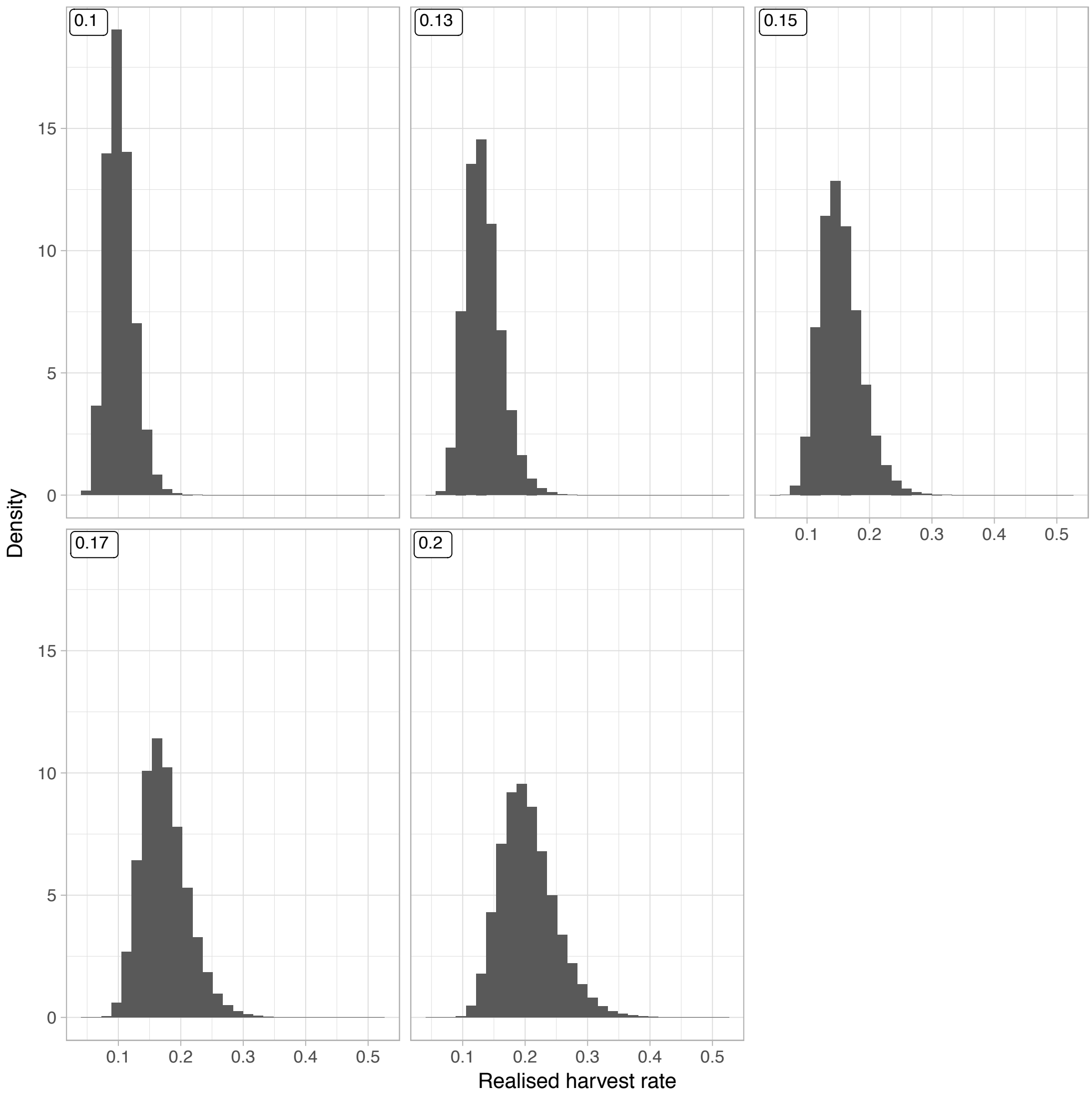

Figure 2.42: Tusk in 5a and 14. Distribution realised harvest rates as a function target harvest rates

Table 2.9: Tusk in 5a and 14. Equilibrium median, 5% and 95% percentiles of yield, fishing mortality (F at age 12^{+}) spawning stock biomass (SSB), recruitment and probability that SSB falls below either B_{pa} or B_{pa} at at least once in the 300 years included in the forward projections of the stock status of tusk. These results are based on projections where assessment error is applied.

Harvest rate	Eq. yield	F	SSB	Recruitment	$P(\exists y \vert SSB_y < B_{pa})$	$P(\exists y \vert SSB_y < B_{lim})$
0.06	4.60 (2.97,6.51)	0.069 (0.048,0.097)	45.70 (32.89,59.29)	12.65 (2.05,21.58)	0.00	0.00
0.07	4.90 (3.17,6.98)	0.082 (0.056,0.114)	40.65 (28.63,53.43)	12.59 (2.05,21.58)	0.00	0.00
0.08	5.20 (3.36,7.41)	0.095 (0.065,0.133)	36.47 (25.32,48.42)	12.58 (2.06,21.60)	0.00	0.00
0.09	5.43 (3.48,7.75)	0.108 (0.074,0.152)	32.82 (22.19,44.17)	12.62 (2.09,21.61)	0.00	0.00
0.1	5.62 (3.58,8.04)	0.121 (0.082,0.172)	29.46 (19.66,40.26)	12.62 (2.05,21.58)	0.00	0.00
0.11	5.79 (3.64,8.32)	0.136 (0.091,0.192)	26.73 (17.52,36.88)	12.64 (2.10,21.59)	0.00	0.00
0.12	5.89 (3.71,8.46)	0.149 (0.101,0.213)	24.14 (15.52,33.67)	12.58 (2.08,21.59)	0.00	0.00
0.13	5.98 (3.74,8.63)	0.164 (0.110,0.236)	21.89 (13.89,31.17)	12.57 (2.06,21.58)	0.01	0.00
0.14	6.07 (3.77,8.78)	0.179 (0.119,0.259)	19.95 (12.34,28.62)	12.64 (2.05,21.59)	0.04	0.01
0.15	6.15 (3.78,8.90)	0.195 (0.129,0.282)	18.21 (11.04,26.46)	12.63 (2.06,21.60)	0.10	0.01
0.16	6.16 (3.75,9.00)	0.210 (0.139,0.307)	16.60 (9.80,24.38)	12.56 (2.03,21.58)	0.23	0.04
0.17	6.21 (3.78,9.00)	0.227 (0.149,0.331)	15.22 (8.93,22.61)	12.59 (2.08,21.58)	0.36	0.06
0.18	6.21 (3.70,9.11)	0.243 (0.159,0.358)	13.98 (7.86,20.90)	12.59 (2.04,21.56)	0.60	0.16
0.19	6.21 (3.69,9.14)	0.262 (0.170,0.387)	12.77 (7.06,19.43)	12.55 (2.03,21.52)	0.78	0.28
0.2	6.15 (3.58,9.15)	0.279 (0.180,0.415)	11.67 (6.41,18.02)	12.47 (2.00,21.49)	0.91	0.45
0.21	6.09 (3.49,9.11)	0.298 (0.191,0.446)	10.68 (5.66,16.66)	12.30 (1.96,21.38)	0.97	0.66
0.22	5.96 (3.33,9.06)	0.315 (0.201,0.477)	9.75 (5.00,15.50)	12.07 (1.87,21.20)	0.99	0.80
0.23	5.79 (3.03,8.92)	0.336 (0.213,0.510)	8.72 (4.16,14.30)	11.68 (1.69,21.00)	1.00	0.91
0.24	5.41 (2.52,8.71)	0.357 (0.224,0.550)	7.56 (3.29,13.04)	10.95 (1.28,20.64)	1.00	0.96
0.25	4.93 (2.00,8.40)	0.376 (0.235,0.581)	6.51 (2.50,11.91)	9.99 (0.78,20.05)	1.00	0.99
0.26	4.00 (1.28,7.77)	0.400 (0.247,0.622)	4.88 (1.56,10.00)	8.13 (0.39,19.20)	1.00	1.00
0.27	2.74 (0.63,6.81)	0.424 (0.261,0.666)	3.09 (0.72,7.73)	5.42 (0.20,17.47)	1.00	1.00
0.28	1.59 (0.22,4.93)	0.446 (0.272,0.706)	1.69 (0.24,4.97)	3.08 (0.11,14.82)	1.00	1.00
0.29	0.89 (0.05,3.21)	0.469 (0.285,0.748)	0.86 (0.05,3.10)	1.58 (0.08,9.70)	1.00	1.00
0.3	0.55 (0.01,2.19)	0.496 (0.298,0.798)	0.51 (0.01,2.01)	0.95 (0.04,6.06)	1.00	1.00
0.31	0.33 (0.00,1.58)	0.524 (0.312,0.850)	0.29 (0.00,1.36)	0.54 (0.02,3.60)	1.00	1.00
0.32	0.22 (0.00,1.10)	0.552 (0.325,0.915)	0.18 (0.00,0.94)	0.34 (0.01,2.37)	1.00	1.00
0.33	0.14 (0.00,0.78)	0.584 (0.338,0.972)	0.11 (0.00,0.65)	0.21 (0.01,1.55)	1.00	1.00
0.34	0.10 (0.00,0.59)	0.612 (0.352,1.031)	0.08 (0.00,0.45)	0.14 (0.01,1.03)	1.00	1.00
0.35	0.06 (0.00,0.39)	0.646 (0.367,1.098)	0.05 (0.00,0.29)	0.09 (0.00,0.67)	1.00	1.00
0.36	0.04 (0.00,0.28)	0.686 (0.383,1.176)	0.03 (0.00,0.19)	0.06 (0.00,0.43)	1.00	1.00
0.37	0.03 (0.00,0.22)	0.715 (0.395,1.247)	0.02 (0.00,0.15)	0.04 (0.00,0.32)	1.00	1.00
0.38	0.02 (0.00,0.14)	0.750 (0.391,1.322)	0.01 (0.00,0.10)	0.03 (0.00,0.23)	1.00	1.00
0.39	0.02 (0.00,0.10)	0.786 (0.359,1.409)	0.01 (0.00,0.06)	0.02 (0.00,0.16)	1.00	1.00
0.4	0.01 (0.00,0.06)	0.807 (0.343,1.484)	0.01 (0.00,0.04)	0.01 (0.00,0.10)	1.00	1.00
0.41	0.01 (0.00,0.05)	0.820 (0.317,1.558)	0.00 (0.00,0.02)	0.01 (0.00,0.08)	1.00	1.00
0.42	0.01 (0.00,0.03)	0.815 (0.299,1.619)	0.00 (0.00,0.02)	0.01 (0.00,0.05)	1.00	1.00
0.43	0.00 (0.00,0.02)	0.805 (0.277,1.668)	0.00 (0.00,0.01)	0.00 (0.00,0.04)	1.00	1.00
0.44	0.00 (0.00,0.02)	0.777 (0.258,1.688)	0.00 (0.00,0.01)	0.00 (0.00,0.03)	1.00	1.00
0.45	0.00 (0.00,0.01)	0.749 (0.241,1.669)	0.00 (0.00,0.00)	0.00 (0.00,0.02)	1.00	1.00
0.46	0.00 (0.00,0.01)	0.727 (0.215,1.640)	0.00 (0.00,0.00)	0.00 (0.00,0.01)	1.00	1.00
0.47	0.00 (0.00,0.00)	0.709 (0.208,1.614)	0.00 (0.00,0.00)	0.00 (0.00,0.01)	1.00	1.00
0.48	0.00 (0.00,0.00)	0.683 (0.177,1.621)	0.00 (0.00,0.00)	0.00 (0.00,0.01)	1.00	1.00
0.49	0.00 (0.00,0.00)	0.667 (0.164,1.603)	0.00 (0.00,0.00)	0.00 (0.00,0.00)	1.00	1.00
0.5	0.00 (0.00,0.00)	0.645 (0.133,1.615)	0.00 (0.00,0.00)	0.00 (0.00,0.00)	1.00	1.00
0.51	0.00 (0.00,0.00)	0.626 (0.108,1.630)	0.00 (0.00,0.00)	0.00 (0.00,0.00)	1.00	1.00
0.52	0.00 (0.00,0.00)	0.600 (0.091,1.614)	0.00 (0.00,0.00)	0.00 (0.00,0.00)	1.00	1.00
0.53	0.00 (0.00,0.00)	0.588 (0.065,1.642)	0.00 (0.00,0.00)	0.00 (0.00,0.00)	1.00	1.00
0.54	0.00 (0.00,0.00)	0.563 (0.045,1.676)	0.00 (0.00,0.00)	0.00 (0.00,0.00)	1.00	1.00
0.55	0.00 (0.00,0.00)	0.541 (0.028,1.701)	0.00 (0.00,0.00)	0.00 (0.00,0.00)	1.00	1.00
0.56	0.00 (0.00,0.00)	0.520 (0.018,1.735)	0.00 (0.00,0.00)	0.00 (0.00,0.00)	1.00	1.00
0.57	0.00 (0.00,0.00)	0.498 (0.008,1.713)	0.00 (0.00,0.00)	0.00 (0.00,0.00)	1.00	1.00
0.58	0.00 (0.00,0.00)	0.482 (0.005,1.732)	0.00 (0.00,0.00)	0.00 (0.00,0.00)	1.00	1.00
0.59	0.00 (0.00,0.00)	0.463 (0.002,1.724)	0.00 (0.00,0.00)	0.00 (0.00,0.00)	1.00	1.00

and growth from both the survey and the fishery fit well with the observations.

Table 2.10: Tusk in 5a and 14. Summary of reference point proposed. The fishing mortality is relative to ages 15^+ and harvest rates correspond to the reference biomass of B_{40cm^+}.

Framework	Reference point	Value	Technical basis
MSY approach	MSY $B_{trigger}$	6.24 kt	B_{pa}
	H_{msy}	0.17	The harvest rate that maximises the median long-term catch in stochastic simulations with recruitment drawn from a block bootstrap, with block size of 6, of historical recruitment scaled ccording to a hockey stick recruitment function with a breakpoint at B_{loss}.
	F_{msy}	0.23	The median fishing mortality when an harvest rate of H_{msy} is applied.
Precautionary approach	B_{lim}	4.46 kt	$B_{pa}/e^{1.645\sigma}$ where $\sigma = 0.2$
	B_{pa}	6.24 kt	SSB(2001), corresponding to B_{loss}
	H_{lim}	0.27	H corresponding to 50% long-term probability of SSB $> B_{lim}$
	F_{lim}	0.41	F corresponding to H_{lim}
	F_{pa}	0.27	$F_{lim}/e^{1.645\sigma}$ where $\sigma = 0.25$
	H_{pa}	0.20	H corresponding to F_{pa}
Proposed HCR	H_{mp}	0.13	H such that $F \leq F_{msy}$, long-term yield is consistent with MSY while leading to high stock biomass
	$B_{trigger}$	6.24 kt	Set as B_{pa} as the stock has not been harvested at F_{msy}, or equivalents thereof

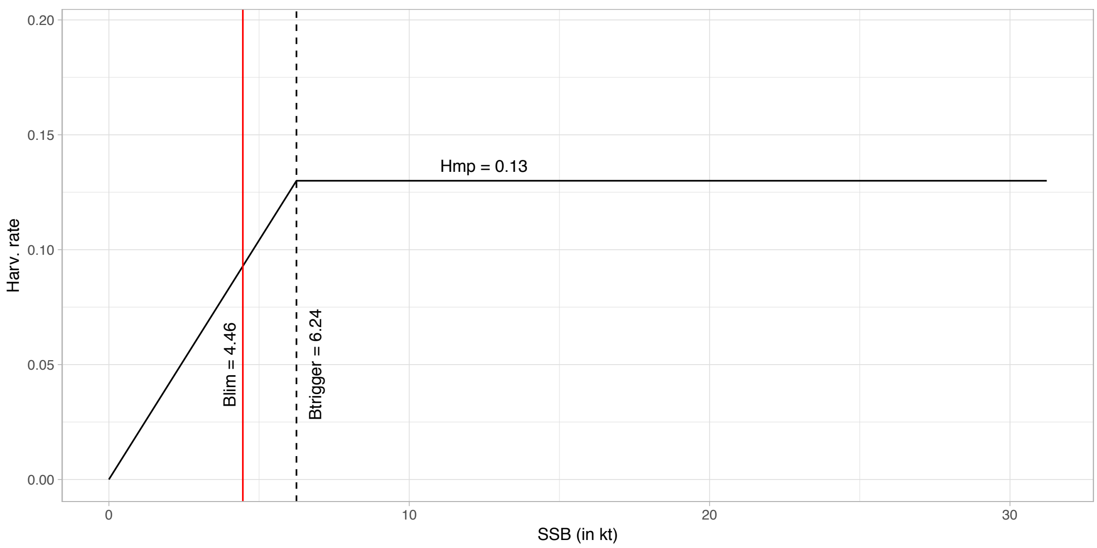

Figure 2.43: Tusk in 5.a and 1. Graphical presention of the proposed managment rule. The black solid line indicates the harvest rate relative to the >40cm biomass as a function of the SSB

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2.2.8 Annex

2.2.8.1 Initial parameter values and boundaries

```
; input file for the gadget model
; created automatically from Rgadget
; 08-tusk/03-fixes/params.in - Mon Feb 27 10:40:30 2017
switch value lower upper optimise
tusk.Linf 110 100 160 1
tusk.k 90 40 100 1
tuskimm.walpha 3.97359087638933e-06 1e-10 1 0
tuskimm.wbeta 3.23039633553992 2 4 0
tusk.bbin 6 1e-08 100 1
tuskimm.M 0.15 0.001 1 0
tuskimm.init.scalar 200 1 300 1
tusk.init.F 0.4 0.1 1 1
tuskimm.init.1 1 0.001 100 1
tuskimm.init.2 1 0.001 100 1
tuskimm.init.3 1 0.001 100 1
tuskimm.init.4 1 0.001 100 1
tuskimm.init.5 1 0.001 100 1
tuskimm.init.6 1 0.001 100 1
tuskimm.init.7 1 0.001 100 1
tuskimm.init.8 1 0.001 100 1
tuskimm.init.9 1 0.001 100 1
tuskimm.init.10 1 0.001 100 1
tuskimm.init.11 1 0.001 100 1
tuskimm.init.12 1 0.001 100 1
tuskimm.init.13 1 0.001 100 1
tuskimm.init.14 1 0.001 100 1
tuskimm.init.15 1 0.001 100 1
tusk.recl 12 4 20 1
tusk.mat1 70 10 200 1
tusk.mat2 61 45.75 76.25 1
tusk.rec.scalar 400 1 500 1
tusk.rec.1982 1 0.001 100 1
tusk.rec.sd 5 4 20 1
tusk.rec.1983 1 0.001 100 1
tusk.rec.1984 1 0.001 100 1
tusk.rec.1985 1 0.001 100 1
tusk.rec.1986 1 0.001 100 1
tusk.rec.1987 1 0.001 100 1
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tusk.rec.2010 1 0.001 100 1
tusk.rec.2011 1 0.001 100 1
tusk.rec.2012 1 0.001 100 1
tusk.rec.2013 1 0.001 100 1
tusk.rec.2014 1 0.001 100 1
tusk.rec.2015 1 0.001 100 1
tusk.rec.2016 1 0.001 100 1
tuskmat.walpha 3.97359087638933e-06 1e-10 1 0
tuskmat.wbeta 3.23039633553992 2 4 0
tuskmat.M 0.15 0.001 1 0
tuskmat.init.scalar 200 1 300 1
tuskmat.init.6 1 0.001 100 1
tuskmat.init.7 1 0.001 100 1
tuskmat.init.8 1 0.001 100 1
tuskmat.init.9 1 0.001 100 1
tuskmat.init.10 1 0.001 100 1
tuskmat.init.11 1 0.001 100 1
tuskmat.init.12 1 0.001 100 1
tuskmat.init.13 1 0.001 100 1
tuskmat.init.14 1 0.001 100 1
tuskmat.init.15 1 0.001 100 1
tuskmat.init.16 1 0.001 100 1
tuskmat.init.17 1 0.001 100 1
tuskmat.init.18 1 0.001 100 1
tusk.igfs.alpha 0.5 0.01 3 1
tusk.igfs.l50 50 10 100 1
tusk.comm.alpha 0.5 0.01 3 1
tusk.comm.l50 50 10 100 1
```

2.2.8.2 Settings of optimisation routines

```
[simann]
simanniter 100000 ; number of simulated annealing iterations
simanneps 1e-03 ; minimum epsilon, simann halt criteria
t         30000000   ; simulated annealing initial temperature
rt        0.85  ; temperature reduction factor
nt        2     ; number of loops before temperature adjusted
ns        5     ; number of loops before step length adjusted
vm        1     ; initial value for the maximum step length
cstep     2     ; step length adjustment factor
lratio    0.3   ; lower limit for ratio when adjusting step length
uratio    0.7   ; upper limit for ratio when adjusting step length
check     4     ; number of temperature loops to check
[hooke]
hookeiter 40000  ; number of hooke & jeeves iterations
hookeeps  1e-04 ; minimum epsilon, hooke & jeeves halt criteria
rho       0.5   ; value for the resizing multiplier
lambda    0     ; initial value for the step length
[bfgs]
bfgsiter  10000 ; number of bfgs iterations
bfgseps   0.01  ; minimum epsilon, bfgs halt criteria
sigma     0.01  ; armijo convergence criteria
beta      0.3   ; armijo adjustment factor
```

2.2.8.3 Effects of the inclusion of catches from the Greenland area in ICES subarea 14

To test the effects of the omission of the catches in the Greenland area in ICES subarea 14, that have historically been negliable but in the last two years the catches were 898 and 471 in 2015 and 2016 respectively. To test the effects of these catches a model assessment that includes these catches was conducted. The results of this excercise is illustrated in fig. 2.44, where this assessment is compared with the assessment described in the sections above. Overall the difference between the two assessments is perceived to be neglible. The increase in reference biomass is estimated to range from 1.2% to 4.1%, with similar effects observed for other biomass estimates. At the same time the estimated harvest rate was reduced by 0% to 3.4% in most years, while it increased by 12% and 10% is the last two years of the assessment respectively.

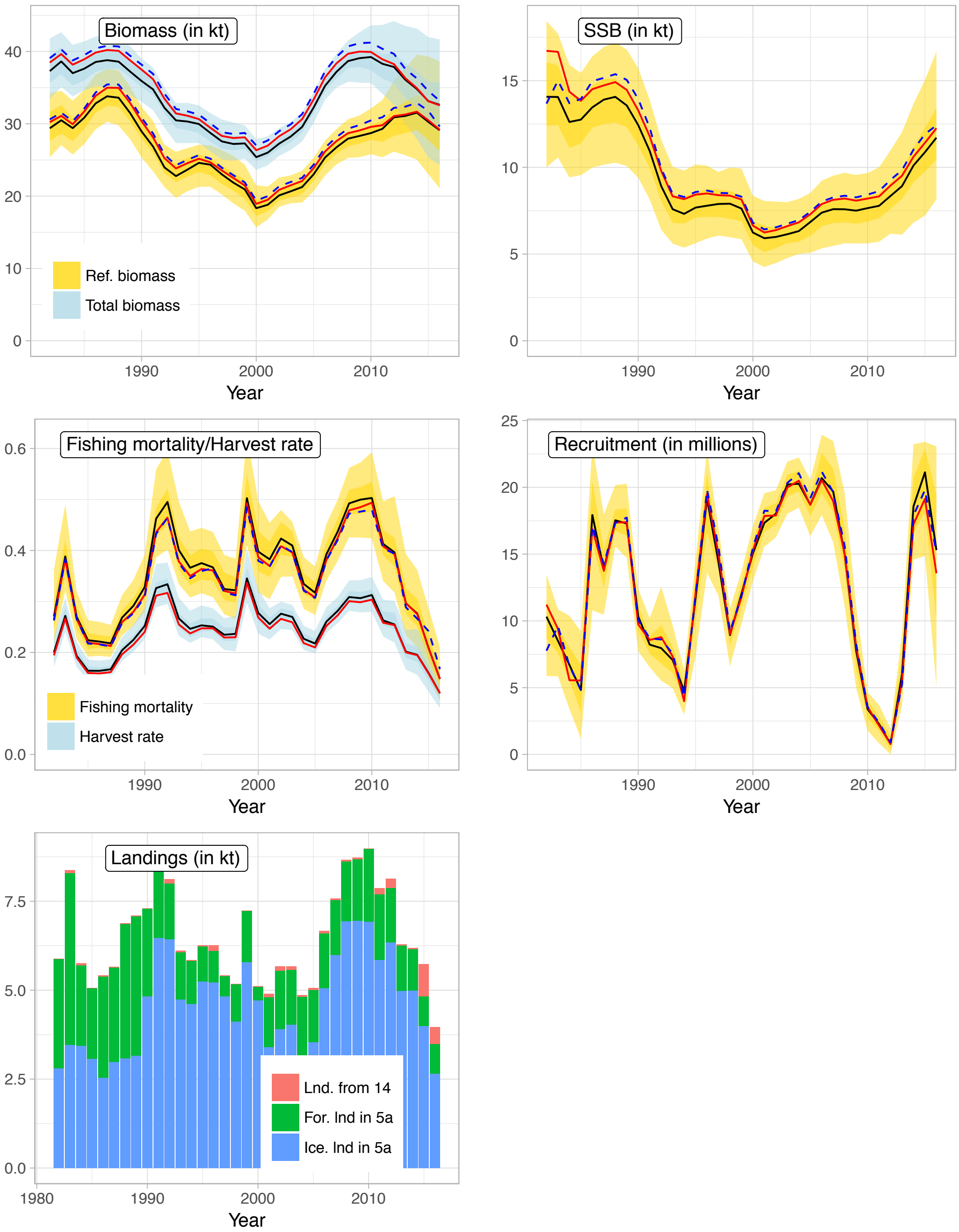

Figure 2.44: Tusk in 5a and 14. Comparison of assement results where catches from the Greenlandic area of ICES subarea were included with the proposed assessment, where these were not included. Top panels illustrate the comparison of estimates of biomass, reference biomass (tusk larger than 40 cm, knife-edge) and spawning stock biomass. Mid panels show estimates of recruitment in millions and fishing mortality (age 15^+) and the bootom panel the landings. Black line is the median of bootstrap estimates, yellow area is the range between the 5-95% quantiles of the bootstrap estimates and the red line is the results of the base-run. The blue dashed lines denotes results from the model that includes these catches..

2.3 Reviewers' report

Carmen Fernández (Spain) and Alfonso Pérez (the Netherlands)

The reviewers examined the stock assessment and Management Strategy Evaluation (MSE) document submitted by Icelandic scientists in advance of the WKICEMSE workshop and provided comments by correspondence. Some of the aspects raised by the reviewers were addressed by correspondence and an updated document was prepared by Icelandic scientists. The workshop then provided a further opportunity to discuss the work in detail. This led to some additional updates of the scientific document. The final version appears in Section 2.2 of the WKICEMSE report. Many of the reviewers' comments were clarifications or referred to aspects that could be explored in future work rather than urgent matters that needed to be resolved or changed immediately.

2.3.1 Overall conclusion

The overall conclusion from the reviewers is that the stock assessment model and settings proposed for the assessment of tusk (see Section 2.2 of WKICEMSE report) are appropriate and that results generated by the assessment model can be used for providing fisheries advice as an ICES Category 1 stock (stocks with quantitative assessments). Aspects identified for additional future consideration are noted below, under "Comments on stock assessment".

The Precautionary Approach and MSY reference points have been calculated in line with ICES guidelines.

The MSE work conducted to examine the performance of the proposed harvest control rule was also of high quality and provides an appropriate technical basis to respond to the harvest control rule evaluation ICES has been requested to undertake. This harvest control rule has a harvest rate HR_{MGT}=0.13 on B(40+ cm) and a trigger SSB point at MGT $B_{trigger}$ = 6.24 kt = B_{pa} (with the harvest rate being reduced proportionally when SSB is estimated to be below the trigger). This rule is precautionary (it leads to less than 5% probability of SSB < B_{lim} in all years) and, while based on a harvest rate which is below HR_{MSY}=0.17, the simulations indicate a similar level of long-term catch as with HR_{MSY}; this is because the resulting curve of average catch in equilibrium versus harvest rate is flat-topped, with the average long-term catch at HR_{MGT}=0.13 being only 4% below that corresponding to HR_{MSY}=0.17. Therefore, the proposed harvest control rule can be considered to be in conformity with the MSY approach.

2.3.2 Comments on stock assessment

The stock assessment is performed with Gadget, which is considered to be an appropriate tool for a stock such as this, with sparse information, particularly on age structure.

Main questions raised by the reviewers were:

- Selection pattern (at length) of fishery and survey. There is some suggestion in the length frequency data and residuals from model fitting, that the survey selection pattern could have some dome-shaping for the large lengths. This was discussed during the workshop and an exploratory run conducted with these settings was seen to result in a slight reduction of stock biomass (approximately 7%). There are however other aspects of the model that could be influencing the results, such as the Gadget treatment of the L_{∞} parameter. At this point, the workshop considered this to be a relatively minor issue. The reviewers suggest that this is further explored in future benchmarks of this stock.

- Maturity. Substantial time was taken during the workshop to try to understand the way maturity has been modelled and its possible implications on stock assessment results. In the new assessment model, maturation has been modelled internally (as opposed to e.g. using a simple length-based ogive outside Gadget). It was recognized that modelling internally the maturation process would be advantageous if differences between mature and immature tusk in any of the processes affecting productivity were considered explicitly in the model. However, the current assessment model does not include any such differences. In addition, the fits to the available maturity-at-length data are not good for the large lengths (Figure 26 in Section 2.2). This issue was raised by the reviewers and discussed by the workshop. It was concluded that the effect of the misfits on stock assessment results is likely not large at present, given that they occur mostly for lengths with low abundance of fish. However, if those large lengths become more frequent in the population in the future, the issue could become more relevant. At the same time, it was argued that an increase in the proportion of large fish in the population would also be associated with more maturity data for those lengths and a likely improvement in the model fits to the maturity data at those lengths. The reviewers recommend that this aspect continues to be monitored and examined again in future benchmarks, especially due to the influence it could have on the perception of the stock–recruitment relationship.
- The stock assessment which forms the basis of all work presented to WKICEMSE, including the retrospective plots in Figure 32 of Section 2.2, used data until the end of 2016. In similar future work, it will be better if the stock assessment replicates as closely as possible the data situation most likely encountered when annual assessments are conducted for the stock, i.e. the data included in the stock assessment go to the end of quarter 1 rather than to the end of the year.

2.3.3 Comments on reference points

The Precautionary Approach and MSY reference points were calculated in line with ICES guidelines.

There seems to be an overall preference in Iceland for characterising fishing pressure in terms of harvest rates rather than F. For this stock, the harvest rates are calculated relative to the B(40+ cm) biomass. In response to a question by the reviewers, scientists explained that the choice of 40+ cm is because this is a length just below the selectivity of the fishery, so that when the fleet starts fishing the advised catches, taking into account the delay between the end of the assessment and the start of the fishing year, the tusk will have grown a bit so the B(40+ cm) will refer to tusk slightly larger than 40cm+, and hence correspond well with the harvestable biomass. In line with this, the fishing pressure reference points were calculated as harvest rates on B(40+ cm) biomass, and equivalent values of F were obtained. The fishing pressure reference points were expressed both in terms of harvest rates (HR_{lim}, HR_{pa}, HR_{MSY}) and F (F_{lim}, F_{pa}, F_{MSY}). The reviewers consider that both ways of characterising fishing pressure reference points are valid.

B_{pa} was set equal to B_{loss} mainly because the range of estimated SSB values by the stock assessment (starting in the early 1980s) is relative narrow and there is no sign of reduced recruitment when SSB is at the low end of the estimated values (Figure 36 of Section 2.2), in combination with the fact that historical harvest rates are not considered to have been overly high. This was discussed during the workshop, and accepted by both workshop participants and reviewers.

2.3.4 Comments on harvest control rule evaluation

The evaluation uses the Gadget stock assessment to provide an Operating Model. Key uncertainties are taken into account in the MSE. In particular, a bootstrap for disparate datasets, based on resampling spatial subdivisions, was used to run assessments with alternative (bootstrapped) datasets. The magnitude of the assessment error in the final assessment year was inferred from these runs and used to characterise assessment error in the MSE. A time autocorrelation of 0.8 in assessment error was also included in the MSE, so that long periods of stock over or under estimation will be generated in the simulations. Simulated future recruitment incorporates both uncertainty and time autocorrelation via random resampling of blocks of six consecutive past years. These settings were discussed before and during the workshop and considered appropriate by the reviewers.

Because of the timing of the annual assessments of this stock, in practice the harvest control rule will be applied based on the B(40+ cm) biomass at the beginning of quarter 2 (the stock assessment will include data until the end of quarter 1). It was noted during the workshop that this timing was not perfectly taken into account in the MSE, but this is not perceived to be a major problem, although it should be amended in future evaluations. The fishing year in Iceland is September 1–August 31, so there is close to a six month delay between assessment and start of the fishing year, which was taken into account in the MSE.

The range of simulation outputs provided to examine the performance of fishing at different harvest rates (graphs showing the development of the stock, fishing pressure and catch over the next 30 years, as well as in long-term equilibrium) is appropriate. As noted above, the harvest control rule that ICES has been requested to evaluate is based on a harvest rate $HR_{MGT}=0.13$ and a trigger point at MGT $B_{trigger}$ = 6.24 kt = B_{pa} (with the harvest rate being reduced proportionally when SSB is estimated to be below MGT $B_{trigger}$). This rule is precautionary (it leads to less than 5% probability of SSB < B_{lim} in all years) and the simulations indicate a flat-topped equilibrium catch curve. According to this curve, although HR_{MGT} is below $HR_{MSY}=0.17$, the resulting average long-term catch at $HR_{MGT}=0.13$ is only 4% below that corresponding to $HR_{MSY}=0.17$.

As with all work where simulations into the future are conducted, it must be kept in mind that there is uncertainty associated with results. The workshop suggested that the performance of the harvest control rule should be reviewed after some years, e.g. after about five years, and this is considered appropriate by the reviewers.

3 Ling

3.1 Summary of work during the WKICEMSE workshop

The scientific work prepared by Icelandic scientists on stock assessment, reference points and harvest control rule evaluation for ling, which had already been discussed by correspondence with the reviewers, was presented and discussed in detail during the WKICEMSE workshop. As a result of the exchanges by correspondence and the workshop discussions, several modifications were made to the document originally submitted, and the final version is included in Section 3.2 of this report. Since all technical details are included in that section, only a brief summary of main points arising from the discussion at the workshop, many of which are common with tusk (Section 2 of this report), is presented here.

Most of the main aspects discussed in detail during the presentation at WKICEMSE are covered in the reviewers' report (Section 3.3) and are not repeated here. Future work on ling will take into account the points noted by the reviewers.

A new Stock Annex for ling was prepared, in line with the new data and settings agreed for the stock assessment, and incorporating the Precautionary Approach and MSY reference points calculated as part of this process. Fishing pressure reference points can be expressed in terms of F or harvest rate, with the latter being the form generally preferred in Iceland for communication purposes. Fishing pressure reference points were therefore calculated both in terms of F and in terms of harvest rates on B(75+ cm), and both are available in Section 3.2 and Stock Annex. The workshop suggests that, in order not to make the ICES catch advice presentation unnecessarily complicated for stocks around Icelandic waters, fishing pressure in the ICES advice sheets for these stocks is presented solely in terms of harvest rates (rather than having multiple lines, one for F and another one for harvest rate, and multiple reference points, i.e. reference points both for F and for harvest rate).

The harvest control rule presented to ICES for evaluation is based on applying a harvest rate on the 75+ cm stock biomass in the assessment year y, $B_{ref,y}$. As the annual stock assessment conducted in year y will contain data until the end of quarter 1, it seems logical to calculate $B_{ref,y}$ at the beginning of quarter 2, i.e. with a delay of five months between assessment and fishing year (the fishing year being from September 1 of year y to August 31 of year y+1). A delay of two quarters (as the stock assessment model works internally on a quarterly basis) between assessment and start of fishing year was taken into account in the management strategy evaluation. Therefore, WKICEMSE considers that $B_{ref,y}$ used in the harvest control rule should be calculated at the beginning of quarter 2 of the assessment year y.

On the other hand, as the biomass reference points B_{lim} and B_{pa} were calculated based on SSB on January 1 (B_{pa} has been set to B_{loss} = SSB(1992)), and MSY $B_{trigger}$ and MGT $B_{trigger}$ have both been set equal to B_{pa}, it is more appropriate that the SSB_y reported for comparison with biomass reference points and for use in the harvest control rule refers to January 1.

The workshop spent considerable time discussing the properties of the harvest control rule presented to ICES for evaluation. The evaluation is obviously based on the best information and knowledge available at this time. As is always the case, there is uncertainty associated with simulations into future years, with the possibility that non-anticipated changes occur. The workshop considers that it would be appropriate to review the performance of the rule after some years, e.g. after approximately five years.

3.2 Stock assessment, reference points, and harvest control rule evaluation

3.2.1 A Gadget assessment of Ling in 5a

Gadget is a shorthand for the "Globally applicable Area Dis-aggregated General Ecosystem Toolbox", which is a statistical model of marine ecosystems (previously known as BORMICON (Stefánsson and Pálsson 1997) and Fleksibest Frøysa et al. (2002)). Gadget is an age-length structured forward-simulation modeling framework, where models can be coupled with an extensive set of data comparison and optimisation routines. Processes are generally modeled as dependent on length, but age is tracked in the models, and data can be compared on either a length and/or age scale. The framework allows for the creation of multi-area, multi-fleet models, capable of including predation and mixed fisheries issues, however it can also be used on a single species basis. Gadget models can be both very data- and computationally- intensive, with optimisation in particular taking a large amount of time. Worked examples, a detailed manual and further information on Gadget can be found on `www.github.com/hafro/gadget`. In addition the structure of the model is described in Begley and Howell (2004), and a formal mathematical description is given in Frøysa et al. (2002).

The Gadget framework is essentially three things, an **ecosystem simulator**, a **likelihood** function that takes the output from the ecosystem simulator and compares to data, and a **function mininimizer**. Gadget's **ecosytem simulator** allows for a fairly configurable ecosystem simulation. Its fundamental unit, a **stock** (or more accurately substock), represents a group of individuals that is homogenous with respect to various processes. These processes include growth, predation (including commercial fisheries) and migration. In this setup different stages of the life history of a particular species would be represented as separate stocks and individuals "moved" between stocks when required. The simulation takes place in a set number of **years** and **time-steps** within a year. The time-steps within the year allow for the emulation of the annual cycles of the ecosystem, such as recruitment and stock migrations.

The stock unit within Gadget is simply a representation of the total number of individuals in a certain age range and length group range within certain areas. The stocks live in an area, or areas, where they optionally migrate to and from. In this setup processes such as fleet harvest or recruitment can be restricted to take place only in certain (or all) areas. Harvesting of the substocks is defined through fleets that fish according to harvest rate and (length–based) selection functions.

Gadget's **likelihood** module processes the output from the ecosystem simulation based on aggregate dimensions. Within the likelihood module a number of datasets can be compared to the model output. In addition to a suite of functions designed to work with different types of survey indices, length distributions, tagging data, age and length distribution and maturity data, to name a few, can be contrasted to the model output. Each data set is included at its own aggregation level, with missing data handled in a robust manner.

In contrast with Gadget, age based or stock production type stock assessments require data in a fairly processed form. For instance when using VPA one requires the total catch in numbers of individuals by age. However, apart from catches of fin whales in the North Atlantic (IWC 2015), one rarely has all catches by numbers at age. Therefore the age distribution of catches needs to be approximated using some combination of age readings, length distributions, total catches in tons and weight at age (as noted in Hirst et al. 2005). In essence using a typical VPA requires a two-step modelling process, whereas Gadget models combines these two steps.

Gadget's **function minimizer**, based on the negative log–likelihood, varies the model parameters, runs a full simulation, and calculates a new output. This process is repeated until a minimum is obtained. The total objective function to be minimised is a weighted sum of the different components. The estimation could be difficult due to groups of correlated parameters or multiple local optima. To address these issues Gadget has three alternative optimising algorithms built in, a wide area search `simulated annealing` (Corana et al. 1987), a local search `Hooke and Jeeves algorithm` (Hooke and Jeeves 1961) and finally one based on the Broyden-Fletcher-Goldfarb-Shanno algorithm, hereafter termed `BFGS`, described in Bertsekas (1999). The optimisation procedure often involves a combination of these three procedures.

3.2.1.1 Setup of a gadget run

There is a separation of model and data within Gadget. The simulation model runs with defined functional forms and parameter values, and produces a modeled population, with modeled surveys and catches. These surveys and catches are compared against the available data to produce a weighted likelihood score. Optimisation routines then attempt to find the best set of parameter values. Fig. 2.1 illustrates how this is implemented in Gadget's input file structure.

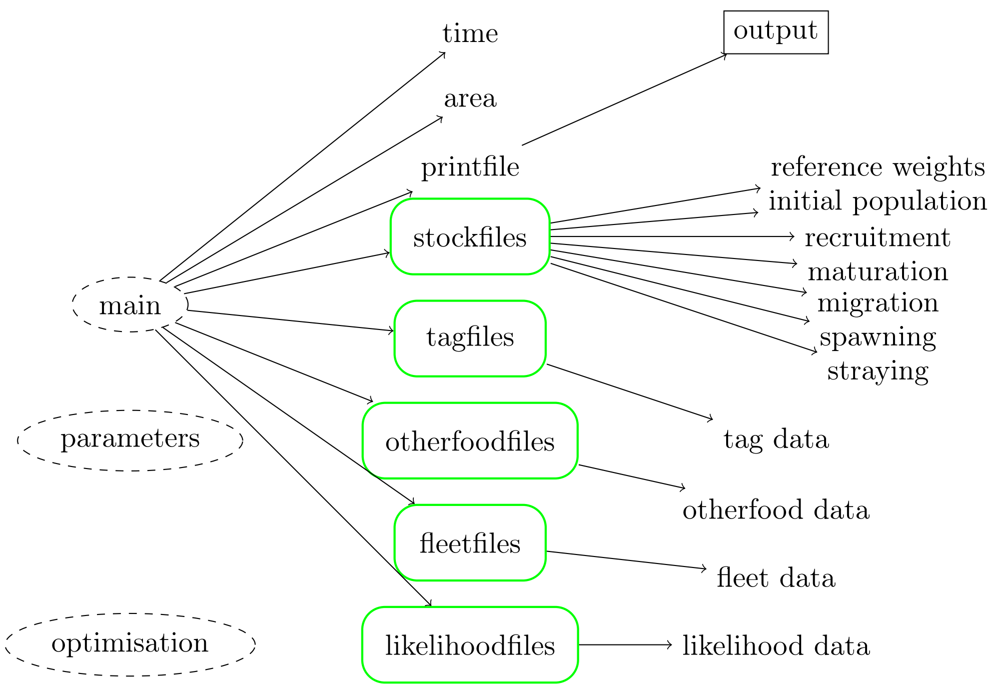

Figure 2.1: Schematic description of the file structure in a Gadget model

3.2.1.2 Simulation model

In a typical Gadget model the simulated quantity is the number of individuals, N_{alsyt}, at age $a = a_{min} \dots a_{max}$, in a length-group l, representing lengths ranging between l_{min} and l_{max} cm in Δl cm length-groups, at year y which is divided into timesteps, usually quarters, $t = 1 \dots T$. The length of the time-step is denoted Δt. The population is governed by the following equations:

$$
\begin{aligned}
N_{alsy,t+1} &= \sum_{l'} G^l_{l'} \left[(N_{al'syt} - \sum_f C_{fal'st}) e^{-M_a \Delta t} + I_{al'lsyt} \right] && \text{if } t < T \\
N_{a,ls,y+1,1} &= \sum_{l'} G^l_{l'} \left[(N_{a-1,l'sy,T} - \sum_f C_{fa-1,l's,T}) e^{-M_{a-1} \Delta t} + I_{a-1,l'lsy,T} \right] && \text{if } t = T \text{ and } a < a_{max} \\
N_{a,ls,y+1,1} &= \sum_{l'} G^l_{l'} (N_{al'sy,T} - \sum_f C_{fal'sy,T} + \\
&\qquad N_{a-1,l'sy,T} - \sum_f C_{f,a-1,l'sy,T}) e^{-M_a \Delta t} && \text{if } t = T \text{ and } a = a_{max}
\end{aligned}
\tag{2.1}
$$

where $G^l_{l'}$ is the proportion in length-group l that has grown $l - l'$ length-groups in Δt, C_{falsyt} denotes the catches by fleet $f \in \{S, L, G, T, F\}$, i.e. the survey[1], longliner, gillnetters, trawlers and foreign vessels[2], M_a the natural mortality at age a and $I_{al'lsyt}$ denotes the movement of fish at length l' from the immmature to the mature stock component at length l [3].

Growth

Growth in length is modeled as a two–stage process, an average length update in Δt and a growth dispersion around the mean update (as described in Stefansson 2005). Average length update is modeled by calculating the mean growth for each length group for each time step, using a parametric growth function. In the current model a simplified form of the Von Bertanlanffy function has been employed to calculate this mean length update.

$$\Delta l = (l_\infty - l)(1 - e^{-k\Delta t}) \tag{2.2}$$

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

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

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

and

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

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

$$G^{l'}_l = \frac{\Gamma(n+1)}{\Gamma((l'-l)+1)} \frac{\Gamma((l'-l)+\alpha)\Gamma(n-(l'-l)+\beta)}{\Gamma(n-(l'-l)+1)\Gamma(n+\alpha+\beta)} \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)} \tag{2.3}$$

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

[2] In the case of ling foreign vessels are assumed to have the same suitability function as the commercial fleet, however this does however simplifies the data entry.

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

where α is subject to

$$\alpha = \frac{\beta \Delta l}{n - \Delta l} \tag{2.4}$$

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

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

$$W_{sl} = \mu_s l^{\omega_s} \tag{2.5}$$

Recruitment and initial abundance

Gadget allows for a number of relationships between stock recruitment and the size of the spawning stock to be defined. However in this model the number of recruits each year, R_y, is estimated within the model as a.

Recruitment enters the population according to:

$$N_{a_{min} l 0 y t'} = R_y p_l \tag{2.6}$$

where t' denotes the recruitment time-step and p_l is the proportion in length-group l that is recruited. p_l is determined by a normal density with mean length set according to eq. 2.2 where the initial length l_0 at age 1 [4] and variance σ_3^2.

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

$$N_{als11} = \nu_{as} q_{al} \tag{2.7}$$

where ν_{as} is the initial number at age a in the initial year of stock s and q_l the proportion at length-group l which is determined by a normal density with a mean according to the growth model in equation 2.2 and variance σ_a^2, with a starting length according as l_0 (length at age 1).

Maturation

Two stage maturity is modeled and represented by the two stock components. First the movement between the two components is formulated as

$$I_{al'lsyt} = \begin{cases} N_{al'0y,t-1} \times m_{l'}^{l} & \text{if s = 1 and t > 1} \\ N_{al'0y-1,T} \times m_{l'}^{l} & \text{if s = 1 and t = 1} \\ -N_{al'0y,t-1} \times m_{l'}^{l} & \text{if s = 0 and t > 1} \\ -N_{al'0y-1,T} \times m_{l'}^{l} & \text{if s = 0 and t = 1} \end{cases} \tag{2.8}$$

where $s = 0$, as noted above, denotes the immature stock component. and $m_{l'}^{l}$ is the proportion of immatures that mature between the lengths l and l' defined as:

$$m_{l'}^{l} = \frac{\lambda(l - l')}{1 + e^{-\lambda(l - l_{50})}} \tag{2.9}$$

The second when individuals of the immature stock component reach a certain age those individuals are all moved to the mature stock component.

[4] l_0 as a one to one mapping with t_0 used in a typical von Bertalanffy growth model

Fleet operations

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

$$C_{falsyt} = E_{ft} \frac{S_f(l) N_{alsyt} W_{ls}}{\sum_{s'} \sum_{l'} \sum_{a'} S_f(l') N_{al's'yt} W_{l's'}} \tag{2.10}$$

where E_{ft} is the landed biomass at time t and $S_f(l)$ is the suitability of length-group l by fleet f defined as[5]:

$$S_f(l) = \frac{1}{1 + e^{(-b_f(l - l_{50,f})}} \tag{2.11}$$

The effective fishing mortality at age and at time step t is calculated according to the following equation:

$$F_{asyt} = \frac{-\log(1.0 - \frac{C_{asyt}}{N_{asyt}})}{\Delta t} \tag{2.12}$$

where $C_{asyt} = \sum_{fl} C_{falsyt}$ and $N_{asyt} = \sum_l N_{alsyt}$. For ling the reported F_y is the average F_a for fully recruited ages, i.e. age 12 and above, for that year.

Harvest rate in terms of the reference biomass is calulated as:

$$H_y = \frac{C_y}{B_{ref,y}} \tag{2.13}$$

where $C_y = \sum_{falst} C_{falsyt} W_{s,l}$ and $B_{ref,y} = \sum_{alst} N_{alsyt} W_{s,l}$. For ling the reported reference biomass is the biomass of fish larger than or equal to 75cm, denoted $B_{75cm^+,y}$.

3.2.1.3 Observation model

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

Importantly this ability to handle length data directly means that the model can be used for stocks such as ling in 5a where age data is sparse and/or are unrelible. Length data can be used directly for model comparison. The model is able to combine a wide selection of the available data by using a maximum likelihood approach to find the best fit to a weighted sum of the data-sets.

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

In formulations below it is assumed that the compositional data are sampled at random, both from the fishery and surveys, as this is how the sampling protocol is

[5] Other functional forms for the selection are defined in Gadget

Icelandic waters is set up. Other forms of likelihoods are implemented in Gadget that can be used to address other types of sampling, e.g. length stratified sampling of maturity.

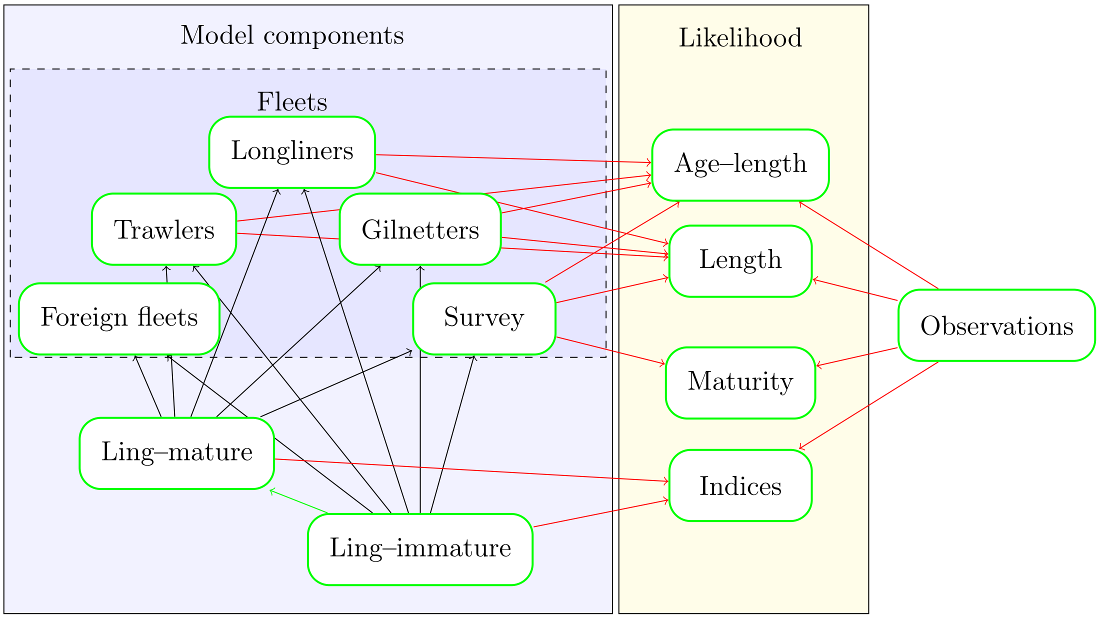

Figure 2.2: Schematic description of the Gadget model for Ling in 5a. Lines indicated flow from one model component to the other. Black lines indicate consumption by predators (fleets), red lines the modelled predictions/observations sent to the likelihood and green lines movement between stock components.

Survey indices

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

$$l_g^{\mathrm{SI}} = \sum_y \sum_t (\log I_{gy} - (\log q_g + b_g \log \widehat{N_{gyt}}))^2 \tag{2.14}$$

where

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

Fleet data

Length distributions are compared to predictions using

$$l_f^{\mathrm{LD}} = \sum_y \sum_t \sum_l (\pi_{flyt} - \hat{\pi}_{flyt})^2 \tag{2.15}$$

where f denotes the fleet where data was sampled from and

$$\pi_{flyt} = \frac{\sum_a \sum_s O_{falsyt}}{\sum_{a'} \sum_{l'} \sum_s O_{fa'l'syt}}$$

and

$$\hat{\pi}_{lyt} = \frac{\sum_a \sum_s C_{falsyt}}{\sum_{a'} \sum_{l'} \sum_s C_{fa'l'syt}}$$

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

$$l_f^{\mathrm{AL}} = \sum_y \sum_t \sum_a \sum_l (\pi_{falyt} - \hat{\pi}_{falyt})^2 \tag{2.16}$$

where

$$\pi_{falyt} = \frac{\sum_s O_{falsyt}}{\sum_a \sum_{l'} \sum_s O_{fal'syt}}$$

and

$$\hat{\pi}_{falyt} = \frac{\sum_s C_{falsyt}}{\sum_{a'} \sum_{l'} \sum_s C_{fa'l'syt}}$$

Length at maturity comparison uses the number fish of which maturity status has been assigned that are observed in a given fishery or a survey. The observed proportions are compared to the modelled proportion using sum of squares:

$$l_f^{\mathrm{M}} = \sum_y \sum_t \sum_l (\pi_{flyt} - \hat{\pi}_{flyt})^2 \tag{2.17}$$

where

$$\pi_{flyt} = \frac{\sum_a O_{fal1yt}}{\sum_{a'} \sum_{l'} \sum_s O_{fa'l'syt}}$$

and

$$\hat{\pi}_{flyt} = \frac{\sum_a C_{fal1yt}}{\sum_{a'} \sum_{l'} \sum_s C_{fa'l'syt}}$$

i.e. the observed and modelled proportions of ling in length group l and and mature, in year y and timestep t, and where the fleet f corresponds to the survey.

3.2.1.4 Order of calculations

The order of calulations is as follows:

1. **Printing**: model output at the beginning of the time-step
2. **Consumption**: mainly fleet harvesting
3. **Natural mortality**: Natural mortality is applied after consumption
4. **Growth and maturation**: length update is applied and maturing fish moved from one stock component to the other.
5. **Spawning and recruitment**: New individuals enter the immature stock component
6. **Likelihood comparison**: likelihood score is calculated here, note that the comparison is based on the modeled processes in previous steps
7. **Printing**: model output at the end of the time-step
8. **Ageing**: if this is the end of year the age is increased

3.2.1.5 Iterative re–weighting

The total objective function used the modeling process combines equations 2.14 to 2.16 using the following formula:

$$l^{\mathrm{T}} = \sum_{g} w^{\mathrm{SI}}_{gf} l^{\mathrm{SI}}_{g,S} + \sum_{f \in \{S,T,G,L\}} \left(w^{\mathrm{LD}}_{f} l^{\mathrm{LD}}_{f} + w^{\mathrm{AL}}_{f} l^{\mathrm{AL}}_{f} \right) + w^{\mathrm{M}} l^{\mathrm{M}} \tag{2.18}$$

where $f = S, T, G, L$ or C denotes the spring survey, trawl, gillnet and longline fleets respectively (See subsection 3.2.2.3) and w's are the weights assigned to each likelihood components.

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

Assigning likelihood weights is not a trivial matter, has in the past been the most time consuming part of a Gadget model. Commonly this has been done using some form of 'expert judgement'. General heuristics have recently been developed to estimated these weights objectively. Here the iterative re–weighting heuristic introduced by Stefansson (2003), and subsequently implemented in Taylor et al. (2007), is used.

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

1. Calculate the initial sums of squares (SS) given the initial parametrization for all likelihood components. Assign the inverse SS as the initial weight for all likelihood components, resulting in a total initial score of 1 for each component.

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

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

The number of non-zero data-points (df^*) is used as a proxy for the degrees of freedom. While this may be a satisfactory proxy for larger data-sets it could be a gross overestimate of the degrees of freedom for smaller data-sets. In particular, if the survey indices are weighed on their own while the yearly recruitment is estimated they could be over-fitted. In general problem such as these can be solved with component grouping, that is in step 2 the likelihood components that should behave similarly, such as survey indices representing similar age ranges, should be upweighted and optimized together. This kind of grouping is used in the present model (See subsection 3.2.2.4).

3.2.1.6 Optimisation

The total objective function to be minimised is a weighted sum of the different components, as described in eq. 2.18. The estimation could be difficult due to groups of correlated parameters, multiple local optima or flat surfaces of the objective function in the search neighbourhood. Therefore the optimisation procedure often involves a combination of the more robust simulated annealing, to make the results less sensitive to the initial (starting) values, and to the local search algorithms (Hooke and Jeeves and BFGS) in the neighborhood of the global optima.

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

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

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

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

The total objective function to be minimised is a weighted sum of the different components. The estimation can be difficult because of some or groups of parameters are correlated and therefore the possibility of multiple optima cannot be excluded. The optimisation was started with simulated annealing to make the results less sensitive to the initial (starting) values and then the optimisation was changed to Hooke and Jeeves when the 'optimum' was approached and then finally the BFGS was run in the end. The settings for the miniizers are listed in annex 3.2.8.2.

3.2.1.7 Bootstrap

To estimate the uncertainty in the model parameters and derived quantities a specialised boostrap for disparate datasets is used. The approach is based on spatial subdivisions that can be considered to be i.i.d. Refer to Elvarsson et al. (2014) and Lentin (2017) for further implementation details. The bootstrapping approach consists of the following:

- The base data are stored in a standardized data base:
  - Time aggregation: 3 months
  - Spatial aggregation: subdivision
  - Further dis-aggregation is based on a range of categories including fishing gear, fishing vessel class, sampling type (e.g. harbour, sea and survey). A full listing of data types used in the case study can be found in table 2.1, these data are stored subdivision dis-aggregated to allow for use in a bootstrap.

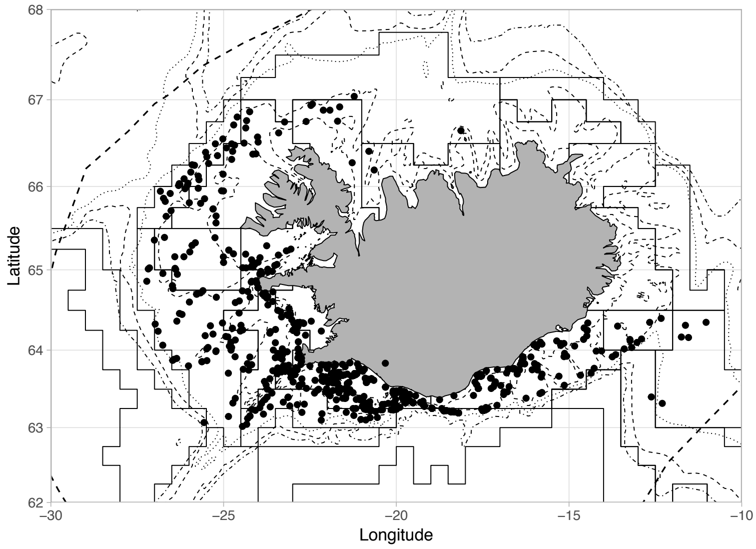

Figure 2.3: Ling in 5a. Locations of Ling catches in 5a by commercial and survey fleets in 2015 relative to the spatial subdivision on the Icelandic continental shelf area.

- To bootstrap the data, the list of subdivisions, depicted in fig. 2.3, required for the model is sampled (with replacement) and stored. For a multi–area model one would conduct the re-sampling of subdivisions within each area of the model.

- The list of re-sampled subdivisions is then used to extract data (with replacement so the same data set may be repeated several times in a given bootstrap sample).

- For a single bootstrap Gadget model, the same list of re-sampled subdivisions is used to extract each likelihood data set i.e. length distributions, survey indices and age–length frequencies are extracted from the same spatial definition.

- A Gadget model is fitted to the extracted bootstrap data set using the estimation procedure described above.

- The re-sampling process is repeated until the desired number of bootstrap samples are extracted, which in this case the total sample size is 100.

When re-sampling, data are forced to remain in the correct year and time–step so re-sampling is based on sampling spatially the elementary data units within a given modeled unit of time and space. Thus, within a modeled spatial unit the bootstrap is a re-sampling of subdivisions. This implicitly assumes data contained within each area of the model to be independent and identically distributed. Independence is justified by the definition of subdivisions. Furthermore treating them as they were from the same distribution, i.e. bootstrap replicates, appears to have little negative effect when compared to more traditional methods (Taylor 2002).

The entire estimation procedure is repeated for each bootstrap sample. In particular, since the estimation procedure includes an iterative re-weighting scheme, this re-weighting is repeated for every bootstrap sample. The point of this is that the bootstrap procedure is no longer conditional on the weights. The procedure as a whole is quite computationally intensive but can easily be run in parallel, e.g. on a computer cluster.

3.2.2 Model settings

Ling in 5a is assumed to be fairly long lived and the maximum age is set at 15 with 15 acting also as a plus group and simulation goes back to 1982, maturing at age 10 the latest. Recruitment to the immature stock component occurs at age 3, in the 1^{st} quarter. The length range in the model was between 20 and 160, in 4 cm length intervals. Recruitment is set to occur at the end of the first time-step. An overview of the data-sets and model parameters used in the model study is shown in Tables 2.1 and 2.2 respectively.

Table 2.1: Ling in 5a. Overview of the likelihood data used in the model. Survey indices are calculated from the length distributions and are dis-aggregated ("sliced") into seven groups (Table 2.6). Number of data-points refer to aggregated data used as inputs in the Gadget model and represent the original data-set. All data can obtained from the Marine and Freshwater Research Institute, Iceland.

Origin	Time-span	Length group size	Num. data-points	Likelihood function	Weight group
	Age–length distributions:				
Commercial catches	All quarters, 2001–2016	4 cm	946	See eq. 2.16	comm
Commercial catches	All quarters, 2001–2016	4 cm	449	See eq. 2.16	comm
March Survey	2^{nd}, 2001–2016	4 cm	935	See eq. 2.16	aldist.igfs
Commercial catches	All quarters, 2001–2016	4 cm	1291	See eq. 2.16	aldist.lln
	Length distributions:				
Commercial catches	All quarters, 1982–2016	4 cm	1440	See eq. 2.15	comm
Commercial catches	All quarters, 1982–2016	4 cm	693	See eq. 2.15	comm
March Survey	2^{nd}, 1985–2016	4 cm	928	See eq. 2.15	ldist.igfs
Commercial catches	All quarters, 1994–2016	4 cm	2129	See eq. 2.15	ldist.lln
	Ratio of immature:mature by length group:				
March Survey	2^{nd}, 1990–2016	8 cm	680	See eq. 2.17	matp.igfs
	Survey indices:				
March Survey	1^{st}, 1985–2016	20 – 52 cm	32	See eq. 2.14	sind1
March Survey	1^{st}, 1985–2016	52 – 60 cm	32	See eq. 2.14	sind1
March Survey	1^{st}, 1985–2016	60 – 72 cm	32	See eq. 2.14	sind1
March Survey	1^{st}, 1985–2016	72 – 80 cm	32	See eq. 2.14	sind2
March Survey	1^{st}, 1985–2016	80 – 92 cm	32	See eq. 2.14	sind2
March Survey	1^{st}, 1985–2016	92 – 100 cm	32	See eq. 2.14	sind2
March Survey	1^{st}, 1985–2016	100 – 160 cm	32	See eq. 2.14	sind2

3.2.2.1 Natural mortality

Choice of natural mortality (M) is problematic as is normally the case in stock assessments. Here M is assumed to be constant with age at 0.15.

3.2.2.2 Weight length relationship

The parameters of the weight–length relationship used in eq. 2.5 were estimated through the means of log-linear regression. Fig. 2.4 shows the observed length-weight relation compared with the fitted values.

3.2.2.3 Fleets and selection

In the model there are four commercial fleets and one survey fleet. The commercial fleets are the Icelandic longline and foreign–fleets, trawl and gillnet fleets. The selection

Table 2.2: Ling in 5a. An overview of the estimated parameters in the model.

Description	Notation	Comments	Formula
Natural mortality	M_a	Fixed at 0.15 for ages 3 to 15	See eq. 2.1
Growth function	k, L_∞	Estimated from age–length frequencies	See eq. 2.2
Growth implementation	β	n is fixed at 15 length-groups	See eq. 2.3
Fleet selection	b_f, $l_{50,f}$	One set for each of the fleets (Survey, Trawl, Longline, Gill-net and Foreign). The long-line and foreign fleets have the same selection	See eq. 2.11
Maturity ogive	λ, l_{50}		See eq. 2.8
Length at recruitment	l_0, σ_3	Mean length (at age 1) and std. deviation in recruitment length.	See eq. 2.6
Number of recruits by year	R_y	$y \in [1982, 2016]$. σ_0, i.e. std. deviation in recruitment length, based on length distributions obtained in the autumn survey.	See eq. 2.6
Initial abundance at ages 3 – 15 in 1982 by	η_{sa}	$a \in [3, 15^+]$. σ_a^2, i.e. variance in initial length at age a, based on length distributions obtained in the spring survey.	See eq. 2.7 and table 2.3
Survey catch-ability	q_f	Intercept term in a log–linear relationship with abundance. The slope term, b_g, is estimated for groups si.20-50 and si.50-60. Fixed to 1 for all other indices.	See eq. 2.14
Length–weight relationship	μ_s, ω_s	Estimated outside of the model	See eq. 2.5
Scalars	R_c, $I_{c,s}$, F_0	Recruiment, initial numbers at age and initial fishing mortality (applied to all age groups)	

Table 2.3: Ling in 5a. Initial standard deviation in length by age, see eq. 2.7 for further details

Age	σ_a	Age	σ_a	Age	σ_a
3	8.05	8	11.68	13	18.08
4	10.78	9	12.25	14	18.71
5	12.81	10	14.37	15	15.88
6	11.88	11	15.60		
7	11.41	12	16.63		

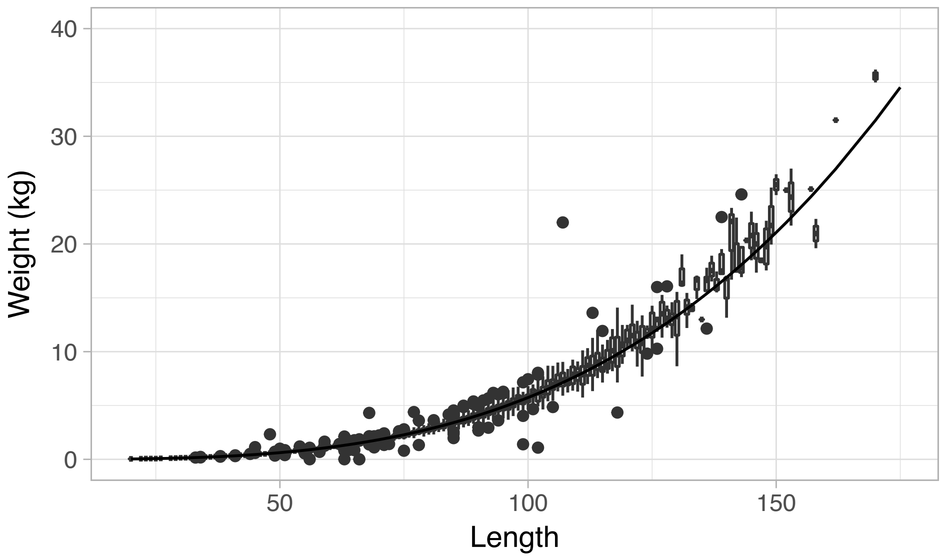

Figure 2.4: Ling in 5a. Observed length-weight relationship from the Icelandic Groundfish Survey. Estimated length weight relationship shown as a solid line.

is described by a logistic function and total catch in tonnes is specified for each time-step.

3.2.2.4 Iterative re-weighting, initial parameter- and optimisation settings

In order to assign weights to the individual likelihood components the iterative re-weighting process described in 3.2.1.5 on page 10 was used. The data-sets were grouped when over-weighting them, the rationale was that similar data-sets should contain similar information. The grouping the likelihood components, which is shown in table 2.1, was applied all survey indices together to prevent issues related to overfitting.

All runs (base and bootstrap) were started from the same initial values. The values and the boundaries are in Annex 3.2.8.1 on page 76. Settings for the optimising algorithms are shown in Annex 3.2.8.2 on page 77. All runs, both individual weighting and final runs converged.

Three types of scaling parameters were applied to the model parameters during the optimisation. First the recruitment level was scaled according to a common parameter, R_c, to allow the model to find the correct placement of the recruitment parameters. Similarly the intitial number at age for each stock component was scaled with common parameters, first a plain scalar $I_{c,s}$ and secondly by a common fishing mortality, F_0. These parameters were estimated.

3.2.3 Input data

3.2.3.1 Commercial catches

Landings

In the model there are three commercial fleets, namely commercial longlines, gillnets, trawl and foreign vessels, and a survey fleet. The longline and the foreign fleets have the same selection curve as the foreign catches, mostly from the Faroe Islands and Norway, are assumed to be caught with longlines (Table 2.4). The sources of landings of ling in 5a are four. For the period between 1993 to the present all landings of Icelandic vessels were recorded by the Directorate of Fisheries, and all landings in 5a after 2013. Prior to 1993 landings data from Icelandic vessel were recorded by Fiskifélagið, and foreign vessel prior to 2014 were obtained from Statlant and distributed to quarters in equal proportions.

Table 2.4: Ling in 5a. Commercial catches in tonnes by fleets, steps (3 month) and years.

Year	Bottom trawl				Gilnets				Longline				Foreign				Total
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	
1982	654.5	780.4	773	546	106.5	416	17	50.3	78.5	18.7	102.7	194.5	313	313	313	313	4990.1
1983	772.3	1037	938.5	398.7	117.7	302.1	21.1	7.7	297.8	39	115.2	188.8	221.8	221.8	221.8	221.8	5123.1
1984	524.4	809.2	510.7	285.2	178.7	516.1	6.5	18.9	98.6	38.2	47.7	271.4	143.6	143.6	143.6	143.6	3880
1985	220.2	674.3	631.8	440.3	112.2	481.7	3.1	15.8	135.5	22.8	59.6	192	115	115	115	115	3449.3
1986	284.4	728.8	576.5	274.9	158.1	611	14.4	21.1	104	18.8	33.4	123.1	162	162	162	162	3596.5
1987	309	961.1	831.3	533.9	205.4	684.7	51.1	95.7	88.2	14.6	41.2	337.4	205	205	205	205	4973.6
1988	465.7	1062.2	1016.4	465.2	404.7	879.7	70.5	57.1	211	12.9	84.1	353.5	190.7	190.7	190.7	190.7	5845.8
1989	305.6	837.7	767.7	442.7	289.8	1226.7	39.8	82.4	147	102.1	97.8	493.4	178.5	178.5	178.5	178.5	5546.7
1990	566.2	1012.9	607.6	430.3	351.7	601.8	60	72.5	337.8	82.7	176.6	820.9	110.2	110.2	110.2	110.2	5561.8
1991	643.6	876.7	706.6	385.3	240.5	593.6	45.9	57.4	418.8	143.1	324.1	751.2	149.8	149.8	149.8	149.8	5786
1992	308.7	590.8	523.7	286.4	262	713.3	50.8	123.3	464.9	267.5	398.1	539.3	140	140	140	140	5088.8
1993	342.1	726.8	516.6	223.8	306.4	829.6	201	124.5	267.2	248.2	229.9	306.1	130.2	130.2	130.2	130.2	4843
1994	183.1	613.6	499.6	166.6	273.8	829.3	235.5	123.9	264	72	262.6	530.1	137.8	137.8	137.8	137.8	4605.3
1995	215.9	580.6	451.4	206	202.8	342.1	184.9	146.7	373.3	168.5	204.6	655.9	115.8	115.8	115.8	115.8	4195.9
1996	268.2	649.3	384	187.2	169.7	343.6	104.2	131.6	515.5	293.2	304.5	320	94.5	94.5	94.5	94.5	4049
1997	232.6	621.4	250.9	206.3	116.4	261.1	121.1	126.1	373.6	388	349.1	588.3	74.8	74.8	74.8	74.8	3934.1
1998	149.9	649.7	260.8	136	125.9	407.5	112	62.5	413.4	650.2	294.6	341	174.8	174.8	174.8	174.8	4302.7
1999	265.8	454.3	256.7	155.2	177.5	364.2	69.8	65.5	865	464.2	400.6	434.7	155	155	155	155	4593.5
2000	258.1	399.3	148.6	152	128.2	443.6	57.9	77.2	581	422.6	288.8	263.6	16.8	16.8	16.8	16.8	3288.1
2001	211.5	243.1	150.7	105.2	230	653.5	115.4	60	431.4	159.3	340.3	166.3	121	121	121	121	3350.7
2002	220.4	369.6	214.8	106.3	159.5	413.1	23.8	48.5	263.5	294.3	325.6	400.5	418.5	418.5	418.5	418.5	4513.9
2003	176.5	359.9	285.9	106.5	129.6	250.9	19.2	54.9	521.7	442.3	501.3	751.6	169.8	169.8	169.8	169.8	4279.5
2004	185.9	509.9	332.4	139.7	140.1	320.1	30.8	55.4	830.2	287.9	232.1	675.8	220.2	220.2	220.2	220.2	4621.1
2005	267.3	801	482.7	217.6	151.3	266.9	34.1	49.1	828.5	714.3	169.7	347.8	216.2	216.2	216.2	216.2	5195.1
2006	345.2	854.2	483.6	253.8	177.1	264.7	116.2	71.8	1305.9	1232.9	537.7	668.5	280.2	280.2	280.2	280.2	7432.4
2007	290.6	779.9	571.1	267.3	180.2	288.2	82.8	81.8	1444.7	1276.8	913.7	450.2	248	248	248	248	7619.3
2008	417.3	947.1	533.4	318.6	130	212	54.8	80.5	1453.8	1311.1	1152	1127.3	385.5	385.5	385.5	385.5	9279.9
2009	485.2	1059.2	709	372.9	225.7	327.5	80	90	2195.8	1637.5	1428.1	1008.4	332.3	332.3	332.3	332.3	10948.5
2010	458.3	1104.5	930.3	456.4	154.1	54.9	88.8	67	2242	1355.8	1544	1431.4	315.8	315.8	315.8	315.8	11150.7
2011	588.7	1077.6	757.1	531.3	98.2	48.6	17.4	61.1	2090.8	1263.8	1123.2	1155.6	209.2	209.2	209.2	209.2	9650.2
2012	448.6	1194.3	842.7	454.8	55.4	117.8	29.8	41.8	2565.2	2186.5	1055.4	1713.4	280.8	280.8	280.8	280.8	11828.9
2013	486.3	1423	689.6	455.6	75.6	143.6	24.6	101.6	2900.2	2432.6	627.7	851.1	331	331	331	331	11535.5
2014	657.7	1253.9	626.9	380.4	65.6	482	44.7	81.1	3452.1	3006.9	725	1573.5	182.9	794.3	540.3	379.1	14246.4
2015	540.9	1520.5	662.6	388.8	85.4	427.6	68.4	68.8	3074.8	2475	754.4	1485.9	162.8	881.9	289.9	148.6	13036.3
2016	605.6	1096.7	568.8	367.2	60.1	548.2	48.2	24.3	1947.4	2240.3	623.3	452.2	242.1	821.9	182.7	54.6	9883.6

Length distributions

The data available for ling in 5a can be seen in table 2.5 which lists the number of available length measurements from the Icelandic fleets by years and time steps. Also length distributions from the spring survey are included in the model. Length distributions for all fleets are on four cm basis. Entries were removed from the length distribution prior to model fitting as it was deemed likely that they would have undesirable effect on the fitting process. These entries were the samples from trawls in 1982 (q4), 1984 (q1), 1989 (q3), 1992 (q4) and 1998 (q3) as these had few than 20 fish sampled that year. From longlines all samples from 1993 (q3) were removed, as the data from that quarter originates from a single fishing trip and most likely the species was incorrectly assigned to the samples. From gillnets 1 sample from 2005 (q2) was remove as it only contained a single fish.

3.2.3.2 Tuning data

The tuning data used comes from the Icelandic spring survey. The spring survey abundance indices are aggregated into seven length intervals (Table 2.6, figures 2.5 and 2.6). The survey indices are defined as the total number of fish caught in a survey within a certain length interval. 8 to 12 cm intervals are used for the indices, except the smallest and the largest length intervals where larger intervals are used. The reason for these larger length intevals is to avoid getting a zero value for these length groups in the bootstrap replicates.

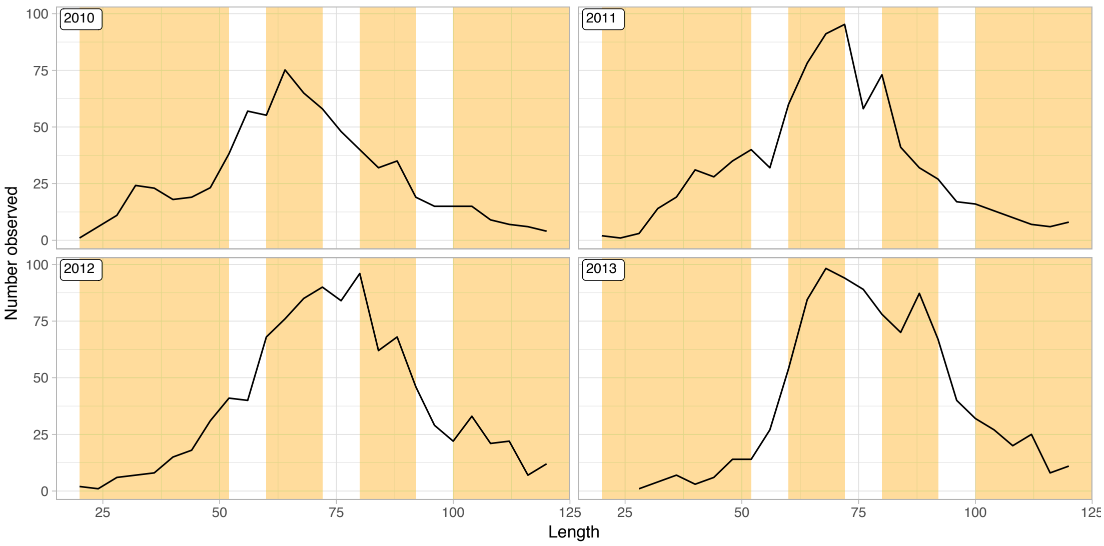

Figure 2.5: Ling in 5a. Length distributions from the Icelandic Groundfish Survey and the yellow and white polygon represent the division into length aggregated abundance indices.

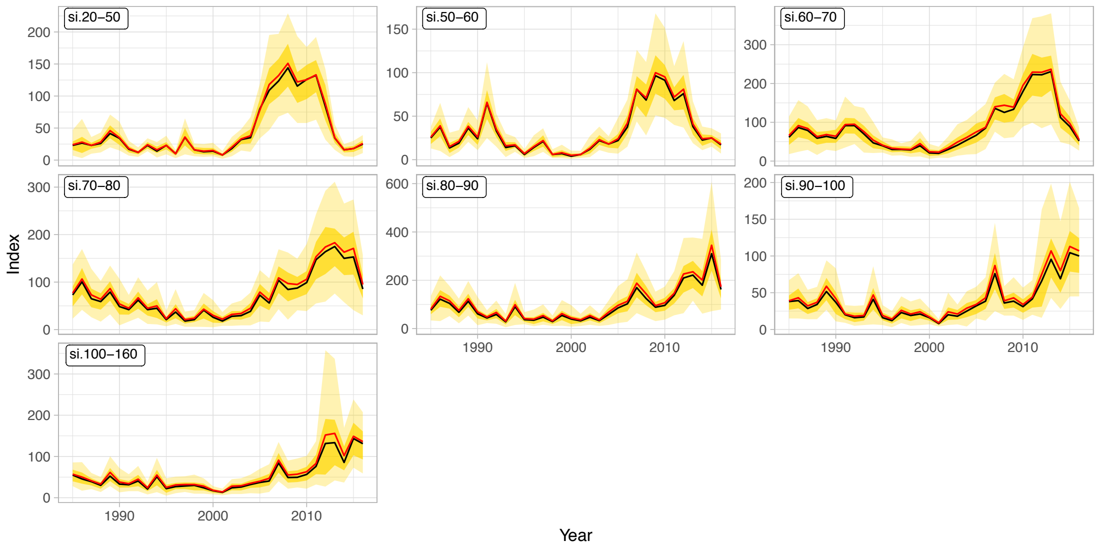

Figure 2.6: Ling in 5a. Time series of length aggregated indices used for tuning (red line), black lines and shaded regions represents bootstrap median and 90% intervals, respectively, of the indices by year.

Table 2.5: Ling in 5a:. Number of available length measurements from from the three commercial fleets used as input data into the Gadget model by years and steps (3 month). Numbers in brackets indicate the number of port- or towsamples.

Year	Bottom trawl				Gilnets				Longlines				Survey
	1	2	3	4	1	2	3	4	1	2	3	4	2
1982	0 (0)	21 (1)	0 (0)	18 (1)	0 (0)	256 (2)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
1983	59 (1)	0 (0)	0 (0)	0 (0)	62 (1)	64 (1)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
1984	20 (1)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
1985	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	370 (126)
1986	0 (0)	0 (0)	98 (2)	88 (1)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	492 (121)
1987	220 (3)	40 (1)	0 (0)	32 (1)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	383 (117)
1988	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	321 (113)
1989	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	483 (138)
1990	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	328 (121)
1991	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	326 (131)
1992	0 (0)	0 (0)	0 (0)	3 (1)	0 (0)	291 (2)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	339 (126)
1993	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	356 (1)	235 (94)
1994	13 (2)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	422 (3)	338 (96)
1995	288 (1)	0 (0)	0 (0)	0 (0)	200 (1)	262 (1)	0 (0)	0 (0)	300 (1)	0 (0)	257 (1)	591 (2)	179 (84)
1996	0 (0)	218 (2)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	853 (3)	0 (0)	400 (2)	867 (3)	186 (85)
1997	0 (0)	0 (0)	0 (0)	300 (1)	0 (0)	0 (0)	0 (0)	0 (0)	900 (3)	300 (1)	564 (2)	467 (2)	222 (86)
1998	0 (0)	381 (2)	4 (1)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	599 (2)	744 (3)	300 (1)	1009 (4)	161 (82)
1999	0 (0)	86 (1)	1 (1)	133 (1)	0 (0)	204 (2)	0 (0)	0 (0)	900 (5)	417 (3)	300 (2)	315 (3)	224 (68)
2000	150 (1)	88 (1)	139 (2)	0 (0)	0 (0)	451 (3)	0 (0)	115 (1)	163 (2)	797 (9)	379 (3)	285 (2)	153 (59)
2001	0 (0)	0 (0)	0 (0)	37 (1)	0 (0)	302 (2)	150 (1)	41 (1)	481 (3)	0 (0)	896 (7)	284 (2)	118 (56)
2002	70 (1)	94 (1)	0 (0)	57 (1)	66 (2)	300 (2)	0 (0)	0 (0)	228 (2)	159 (2)	643 (7)	474 (4)	205 (76)
2003	0 (0)	86 (1)	194 (2)	0 (0)	0 (0)	150 (1)	0 (0)	150 (1)	634 (5)	336 (3)	390 (3)	1044 (8)	225 (86)
2004	91 (1)	0 (0)	46 (1)	50 (1)	0 (0)	348 (3)	0 (0)	0 (0)	1059 (8)	356 (3)	130 (1)	1095 (8)	294 (100)
2005	43 (1)	418 (3)	0 (0)	139 (2)	0 (0)	1 (1)	0 (0)	30 (3)	892 (6)	807 (6)	236 (2)	388 (3)	426 (117)
2006	383 (3)	881 (7)	294 (2)	0 (0)	38 (1)	150 (1)	314 (3)	143 (2)	961 (8)	1367 (11)	431 (5)	595 (5)	512 (135)
2007	251 (2)	225 (2)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	1521 (11)	1061 (9)	531 (6)	548 (4)	828 (170)
2008	0 (0)	290 (3)	529 (4)	165 (2)	142 (1)	147 (1)	0 (0)	68 (1)	1396 (10)	2171 (16)	401 (3)	1879 (13)	701 (175)
2009	96 (1)	324 (3)	300 (2)	246 (2)	0 (0)	280 (2)	0 (0)	130 (2)	2783 (20)	2797 (19)	1912 (14)	1522 (10)	651 (202)
2010	150 (1)	951 (7)	984 (9)	260 (2)	0 (0)	1 (1)	56 (1)	0 (0)	2519 (17)	2154 (15)	1610 (12)	1039 (10)	726 (203)
2011	150 (1)	736 (5)	693 (5)	566 (4)	0 (0)	0 (0)	0 (0)	0 (0)	2664 (20)	1735 (12)	1337 (10)	1512 (12)	861 (234)
2012	341 (3)	1262 (9)	895 (6)	400 (3)	0 (0)	0 (0)	0 (0)	85 (1)	3802 (27)	3321 (23)	1416 (12)	2817 (19)	1025 (205)
2013	24 (1)	1364 (10)	894 (6)	177 (2)	0 (0)	150 (1)	0 (0)	117 (1)	3329 (22)	4549 (29)	663 (5)	864 (7)	994 (232)
2014	489 (4)	2402 (19)	1974 (18)	308 (3)	0 (0)	964 (8)	0 (0)	322 (3)	3496 (20)	2133 (15)	470 (4)	349 (4)	708 (191)
2015	360 (3)	2748 (24)	1878 (16)	681 (7)	31 (1)	720 (6)	580 (5)	232 (3)	1061 (9)	1541 (13)	240 (2)	473 (5)	918 (191)
2016	720 (6)	1461 (13)	843 (8)	280 (3)	0 (0)	1595 (14)	240 (2)	204 (2)	543 (5)	1419 (12)	240 (2)	161 (2)	610 (166)

Table 2.6: Ling in 5a: Length aggregation of survey indices used for tuning the model.

Name	min	max
si.20-50	20	52
si.50-60	52	60
si.60-70	60	72
si.70-80	72	80
si.80-90	80	92
si.90-100	92	100
si.100-160	100	160

3.2.3.3 Age data

In table 2.7 the available age data is listed by fleet, year and time-step (quarter). Due to observed in length at age for ling above the age of 10, individuals that have been observed to be older than 11 are classified as 11 years and older. All available age data prior to 2001 was considered to be unreliable as the method of age determination changed. Age samples from longlines in quarter 2 of years 2002 and 2003 were omitted as there were only 20 otoliths aged from a single sample.

Table 2.7: Ling in 5a. Number of available aged otoliths from the three commercial fleets and the spring survey used as input data into the Gadget model by years and steps (3 month).

Year	Bottom trawl				Gilnets				Longlines				Survey
	1	2	3	4	1	2	3	4	1	2	3	4	2
2001	0 (0)	0 (0)	0 (0)	20 (1)	0 (0)	40 (2)	19 (1)	20 (1)	60 (3)	0 (0)	119 (6)	40 (2)	54 (52)
2002	20 (1)	20 (1)	0 (0)	20 (1)	37 (2)	40 (2)	0 (0)	0 (0)	40 (2)	20 (1)	60 (3)	80 (4)	0 (0)
2003	0 (0)	20 (1)	40 (2)	0 (0)	0 (0)	19 (1)	0 (0)	0 (0)	0 (0)	20 (1)	60 (3)	158 (8)	98 (84)
2004	0 (0)	0 (0)	20 (1)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	121 (95)
2005	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	122 (84)
2006	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	183 (131)
2007	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	228 (150)
2010	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	46 (1)	0 (0)	0 (0)	242 (189)
2011	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	543 (229)
2012	70 (2)	99 (2)	20 (1)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	429 (11)	50 (1)	100 (2)	0 (0)	549 (200)
2013	0 (0)	199 (10)	120 (6)	20 (1)	0 (0)	20 (1)	0 (0)	20 (1)	319 (16)	500 (25)	100 (5)	140 (7)	633 (229)
2014	88 (4)	407 (18)	374 (18)	60 (3)	0 (0)	165 (8)	0 (0)	59 (3)	214 (9)	284 (13)	80 (4)	85 (4)	466 (187)
2015	60 (3)	476 (24)	318 (16)	120 (6)	20 (1)	117 (6)	98 (5)	59 (3)	184 (9)	265 (13)	40 (2)	105 (5)	533 (191)
2016	120 (6)	260 (13)	160 (8)	60 (3)	0 (0)	260 (13)	40 (2)	45 (2)	100 (5)	240 (12)	40 (2)	40 (2)	412 (163)

3.2.4 Results

3.2.4.1 Iterative re-weighting

Gadget allows for an extensive comparison to the fitted data-set. An overall picture of the model fit is provided in table 2.8. Overall the model is seen to fit the data relatively well, compared to the best possible fit. In the final run the squared residuals are seldomly larger than an order of 3 larger than the optimal fit. In no case is the final run the worst fit to individual likelihood component. There are some indications of conflicts between the individual datasets, as can be read from the ratio between the best score and score when other components were upweighted. This is particularly notable between the survey indices and the compositional data and between index groups `sind1` and `sind2`. This is however more likely to be related to the fact that the model is able to fit the survey indices freely when the survey indices are upweigthed as illustrated by the final score ratios.

Fig. 2.7 shows the bootstrap distribution of contribution of individual datasets by time to the overall score, calculated using eq. 2.18. Overall few outliers can be observed from the likelihood, the fit on age length distributions in the survey appears to be gradually improving from the first year of available age data (from 2001), which may be attributed to fewer samples in those years relative to the more recent years. The survey indices representing the smallest and third smallest length groups appear to have worse fit relative to their optimal fits that other indices, which is also apparent from table 2.8.

Five bootstrap replicates exhibited a negliable amount of overcomsumption (between 4 to 9 grams) in 1993, a period of high fishing mortality, the effect of which is considered minimal.

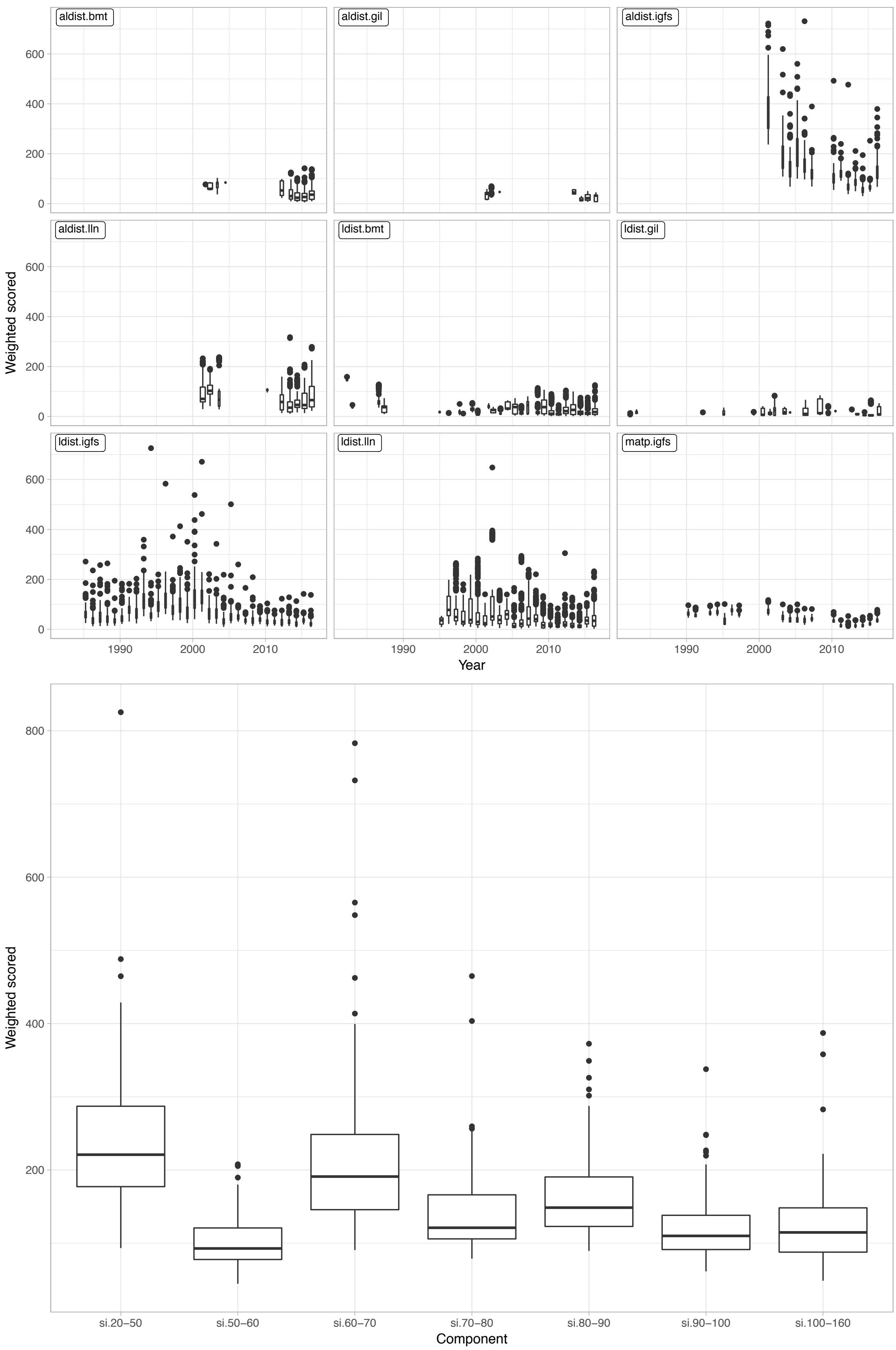

Figure 2.7: Ling in 5a. Boxplot of the bootstrap distribution of the weigthed likelihood component scores by time and component from the final model fits.

Table 2.8: Ling in 5a. Diagnostic from the iterative reweighing procedure. The lines denotes the likelihood component that was heavily weighted. Upper part is the value for each likelihood component, but the lower part denote the ratio of that component score to the score when it was upweighted.

Component	matp.-igfs	aldist.-bmt	aldist.-gil	aldist.-igfs	aldist.-lln	ldist.-bmt	ldist.-gil	ldist.-igfs	ldist.-lln	si.-100-160	si.-20-50	si.-50-60	si.-60-70	si.-70-80	si.-80-90	si.-90-100
aldist.igfs	75.72	1.698	1.332	0.1	1.866	9.955	5.492	0.525	13.06	65.28	11.67	13.27	6.454	7.06	15.98	29.44
aldist.lln	75.03	0.918	1.205	0.159	0.49	3.666	5.45	0.31	1.609	15.55	13.71	15.44	7.054	6.102	7.048	8.283
comm	75.12	0.694	0.657	0.149	1.256	1.182	0.994	0.228	8.125	33.76	13.49	16.34	64.87	66.74	66.56	65.76
ldist.igfs	75.78	1.153	1.131	0.232	0.983	3.465	4.665	0.14	2.686	26.04	13.08	13.84	23.1	23.01	23.24	25.76
ldist.lln	77.75	1.508	1.351	0.467	1.424	1.442	1.421	0.186	0.615	13.28	17.47	13.93	8.741	10.73	12.08	12.23
matp.igfs	45.86	1.345	1.181	0.699	1.256	2.106	4.52	3.618	1.215	87.63	21.07	21.79	17.81	23.73	31.68	56.36
sind1	78.33	0.992	1.057	0.219	1.011	3.93	4.776	0.261	5.297	21.74	1.004	3.538	0.693	3.662	8.987	12.81
sind2	138.2	2.272	1.875	0.95	2.398	14.66	8.73	5.742	18.08	2.447	15.72	14.06	8.334	1.319	1.37	2.285
final	74.92	0.684	0.67	0.109	0.51	1.339	0.971	0.165	0.69	7.434	4.96	8.012	2.978	3.956	4.742	6.058
aldist.igfs	1.651	2.445	2.028	1	3.808	8.422	5.527	3.741	21.246	26.678	11.624	3.751	9.31	5.353	11.664	12.884
aldist.lln	1.636	1.321	1.834	1.592	1	3.102	5.485	2.208	2.618	6.355	13.655	4.364	10.176	4.626	5.145	3.625
comm	1.638	1	1	1.49	2.563	1	1	1.623	13.218	13.796	13.436	4.618	93.58	50.599	48.584	28.779
ldist.igfs	1.652	1.66	1.722	2.321	2.007	2.931	4.695	1	4.37	10.642	13.028	3.912	33.324	17.445	16.964	11.274
ldist.lln	1.695	2.172	2.057	4.685	2.906	1.22	1.43	1.322	1	5.427	17.4	3.937	12.61	8.135	8.818	5.352
matp.igfs	1	1.937	1.798	7.007	2.563	1.782	4.549	25.769	1.977	35.811	20.986	6.159	25.692	17.991	23.124	24.665
sind1	1.708	1.429	1.609	2.2	2.063	3.325	4.806	1.859	8.617	8.884	1	1	1	2.776	6.56	5.606
sind2	3.014	3.272	2.854	9.522	4.894	12.403	8.785	40.897	29.413	1	15.657	3.974	12.023	1	1	1
final	1.634	0.985	1.021	1.097	1.042	1.133	0.977	1.173	1.122	3.038	4.94	2.265	4.296	2.999	3.461	2.651

3.2.4.2 Parameter estimates

In the base and bootstrap runs the estimates rarely hit the boundaries. In figure 2.8 the distributions of the bootstrap estimates for the growth, maturity and selection parameters is shown. For most of them the histogram indicates a nice spread of the estimates. Two parameters, $_0$ and σ_0 which are related to the estimated growth, were estimated at the boundary in a substantial portion of the bootstrap trials, suggesting that these are illdetermined. The effect of this can be considered minimal as these have little effect on the estimated biomass and fishing mortality and are effectively fixed. L_∞ was in the bulk of the bootstrap replicates estimated at the largest fish observed (or close). L_∞ and k are, as illustrated in fig. 2.9, fairly negatively correlated.

Estimates of recruitment parameters are shown in figure 2.11. In no case did they hit the boundaries and the estimates show a fairly symmetric spread. The spread in after 2013 large uncertainty, as is to be expected given the data available than can inform on recruitment. The base run follows the median of the bootstrap estimates closely. The estimated initial population is illustrated in fig. 2.12. As in the case of the estimated recruitment little concernable bias was observed in the based compared with the bootstrap medians.

The bootstrap distribution of the catchability estimates, described in eq. 2.14, is illustrated in fig. 2.13. The figure illustrates that the mode of the catchability is on centered around the 60 to 70 cm length group and starts to taper off for larger fish.

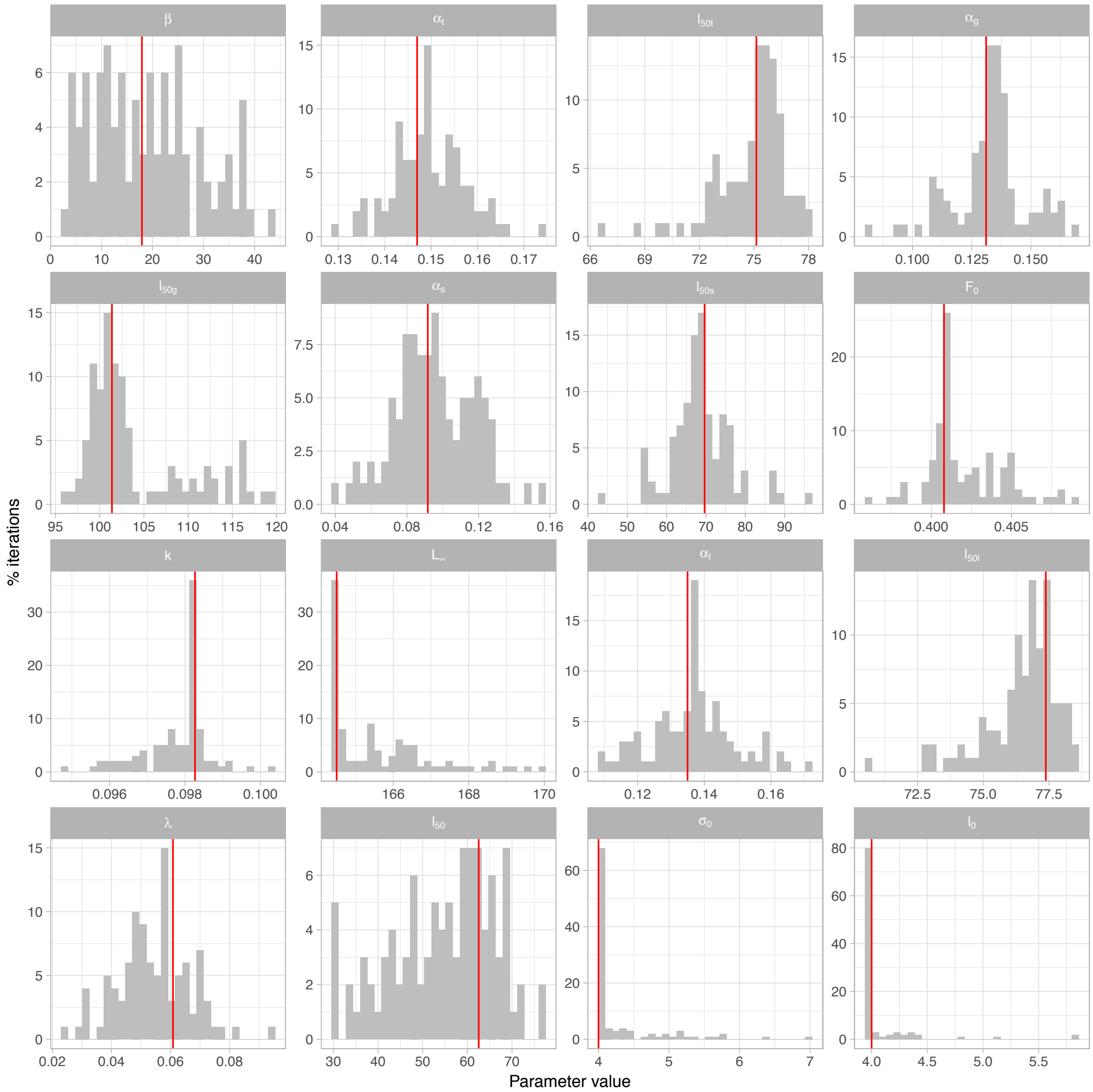

Figure 2.8: Ling in 5a. Histogram of parameter estimates from 100 bootstrap samples, the red line indicates the estimate from the base run

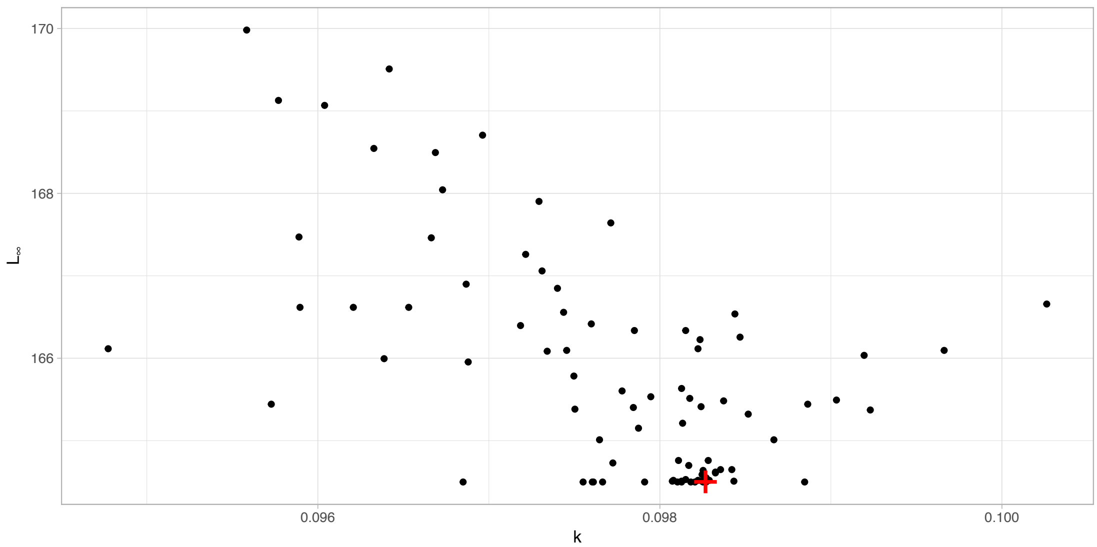

Figure 2.9: Ling in 5a. X-Y scatterplot of the bootstrap estimates of L_∞ and k. The red cross indicates the base run estimate.

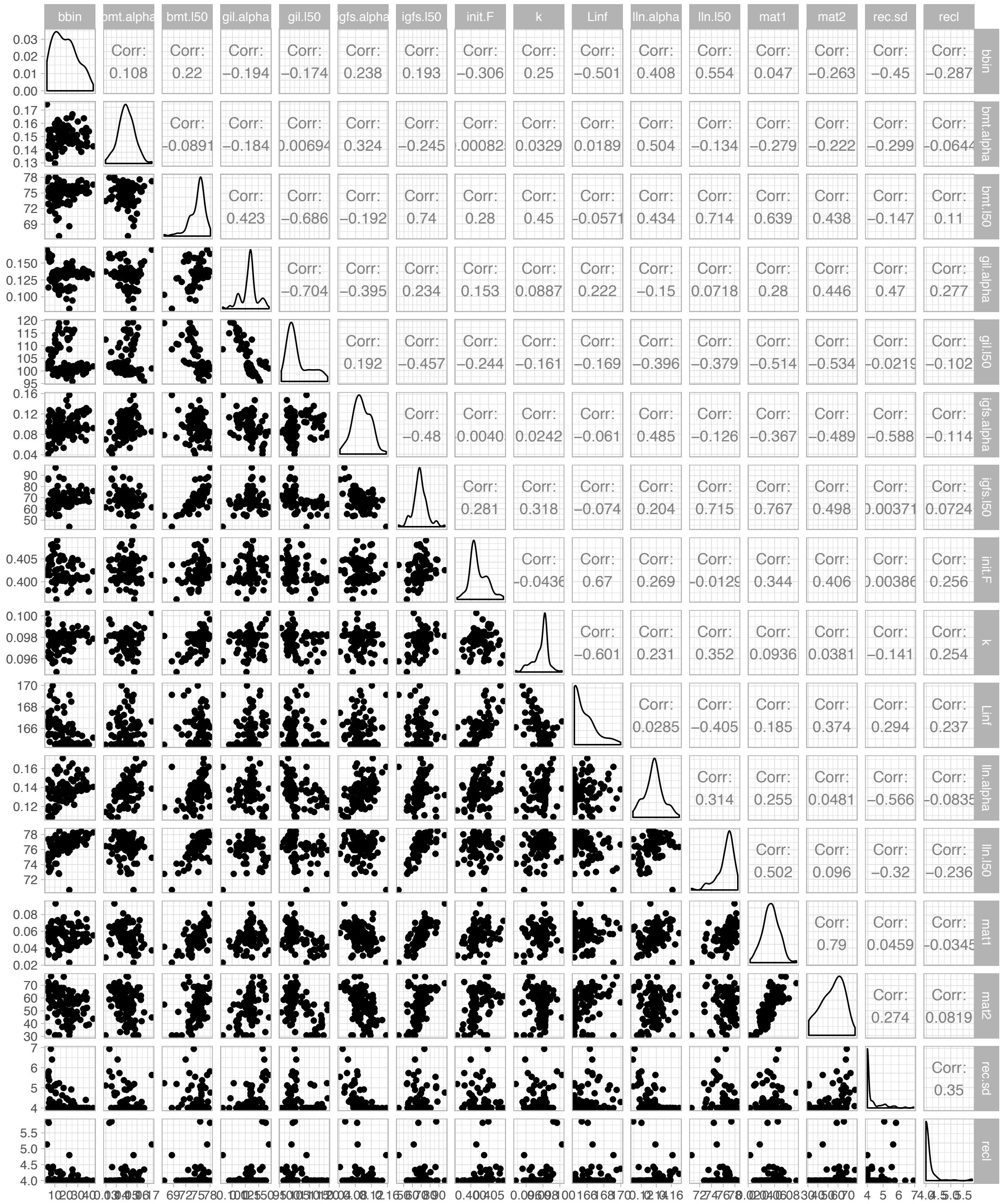

Figure 2.10: Ling in 5a. Pairs-plot of all parameters except those related to the number of recruits and initial number at age.

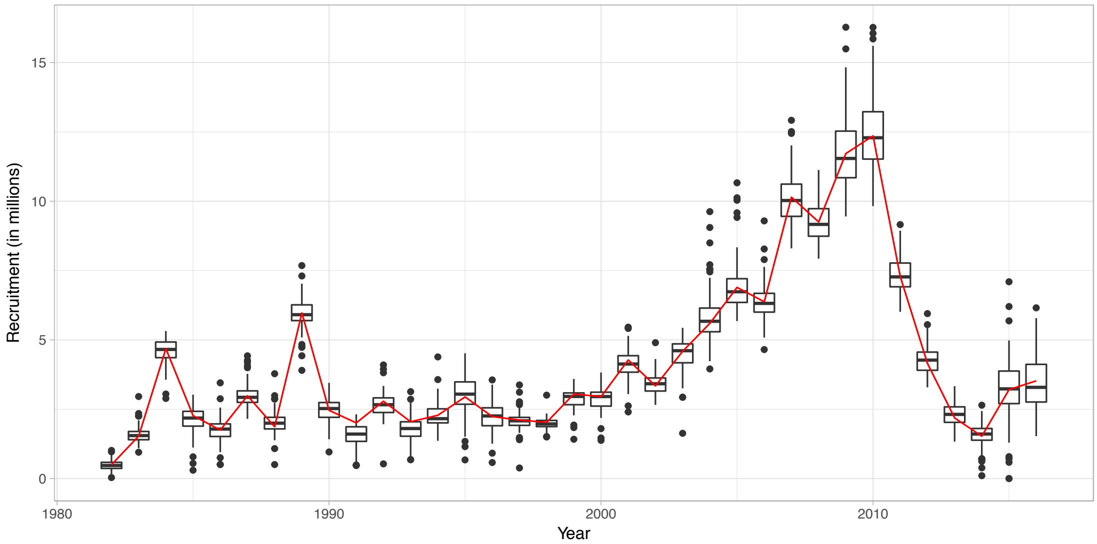

Figure 2.11: Ling in 5a. Boxplots of annual recruitment (age 3) bootstrap estimates, the red line indicates the estimate from the base run.

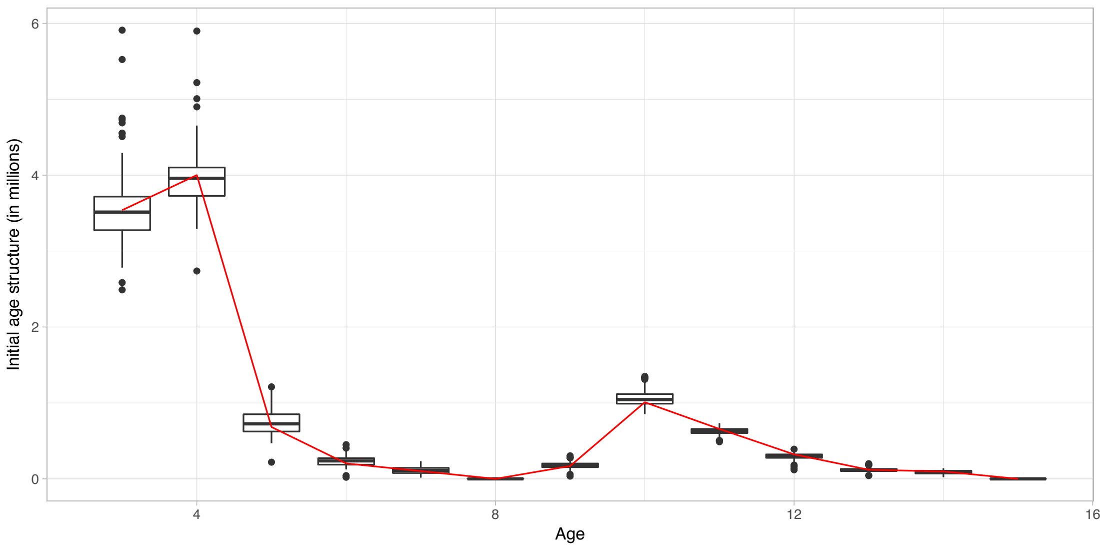

Figure 2.12: Ling in 5a. Boxplots of initial age structure bootstrap estimates, the red line indicates the estimate from the base run.

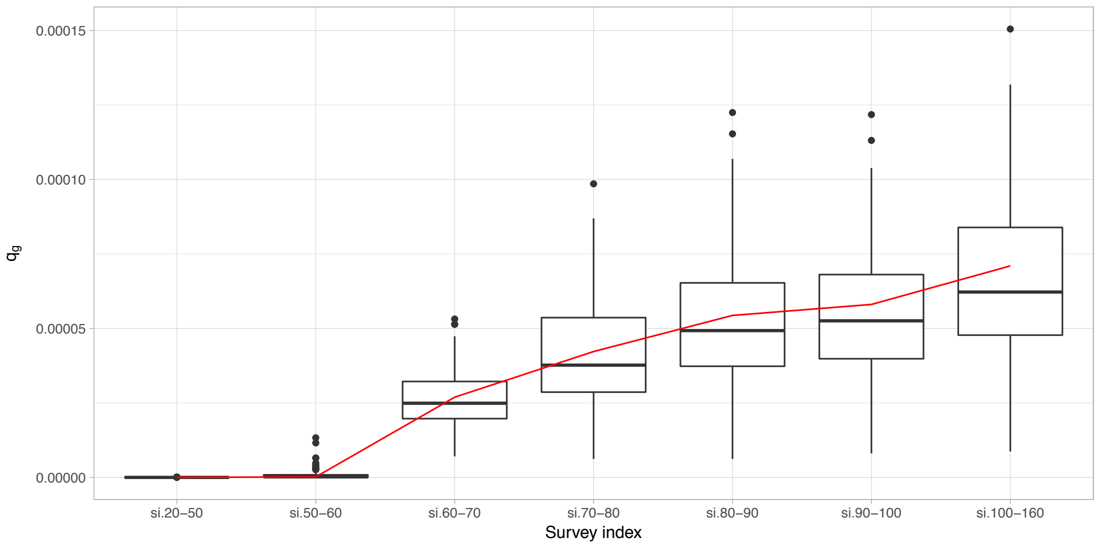

Figure 2.13: Ling in 5a. Boxplot of estimated catchability parameters, q_g, as a function of the survey index length group.

3.2.4.3 Fit to individual data sets

Abundance indices

The fit to the abundance indices is shown in fig. 2.14 and as X-Y scatter plot on a log-scale in fig. 2.15. For all length-group the fit is fairly good, as the model appears to follow the trends of the survey indices. For the larger length groups the model appears to be a tendency to predict a larger biomass than that was observed. When looking at the X-Y scatter plot the assumption of a slope of 1 (i.e. a linear relationship between index and abundance) appears to be fair for the larger length groups, combined with estimating the slope for the smallest two groups.

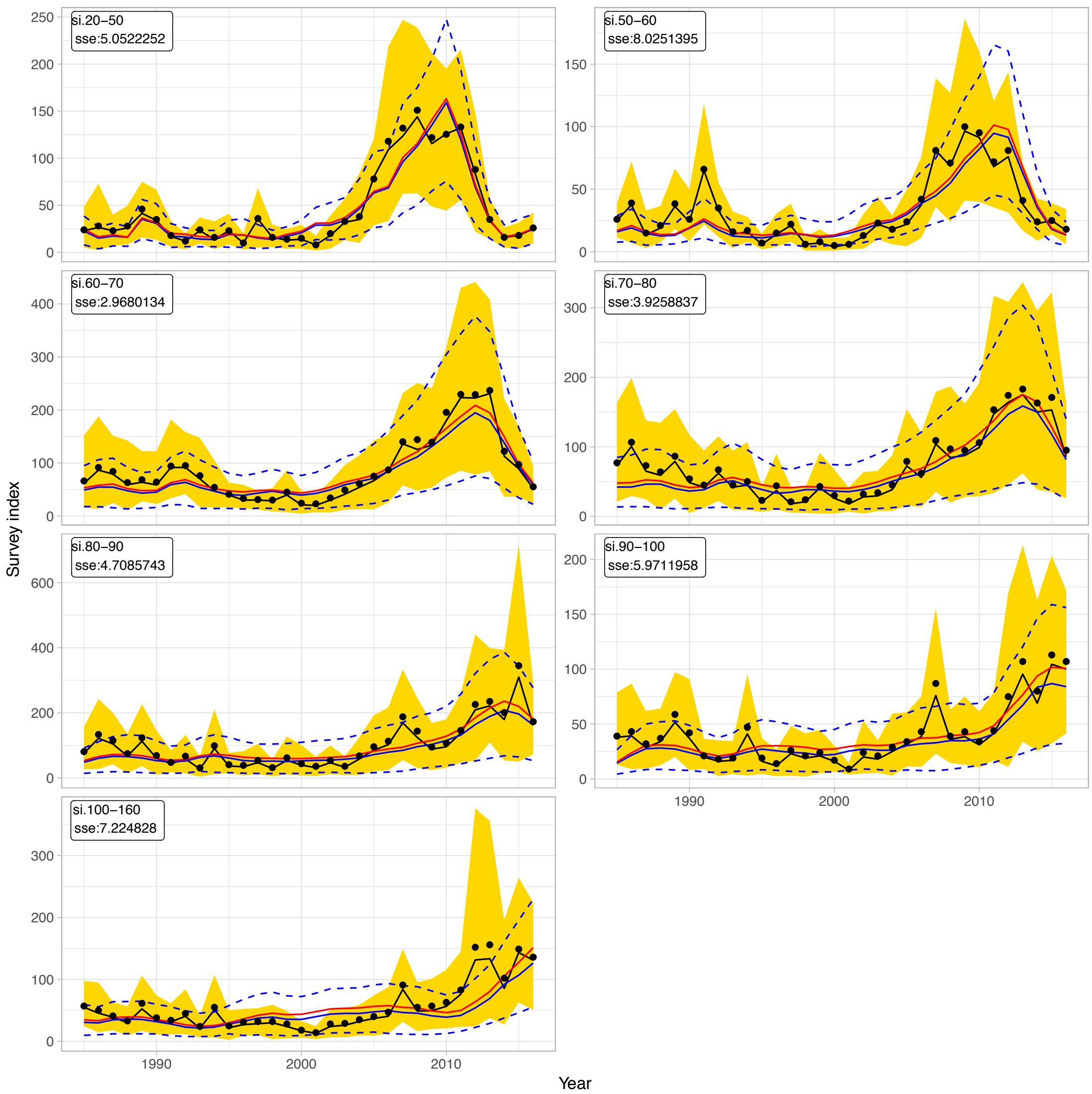

Figure 2.14: Ling in 5a. Bootstrap distribution of the length aggregated abundance indices from the spring survey compared with the predicted survey indices. The black line is the bootstrap median and the yellow area is the 5 and 95% percentiles of the bootstrapped indices, while the black points indicate the survey index. The blue solid line is the median of the predicted indices from the bootstrap runs and the blue dotted line the 5 and 95% percentile. The red line is the predicted indices from the base model.

Length distributions

In figure 2.16 examples of the bootstrapped data and their data from the spring survey and commercial samples in the second quarter of 1996 and 2015 is shown. In general it is observed that the fit to the length distributions is fairly good. Notably the examples from 2015 contain cells that have a lot of samples/measurements (with the exception of the gillnet samples) which is apparent from the smoother empirical length distributions. In contrast fewer samples were taken in 1996, where only 218 measurements (2 samples) from the trawl fishery are available, and the survey samples are considerably fewer.

Length distributions from the spring survey and commercial catches and their respec-

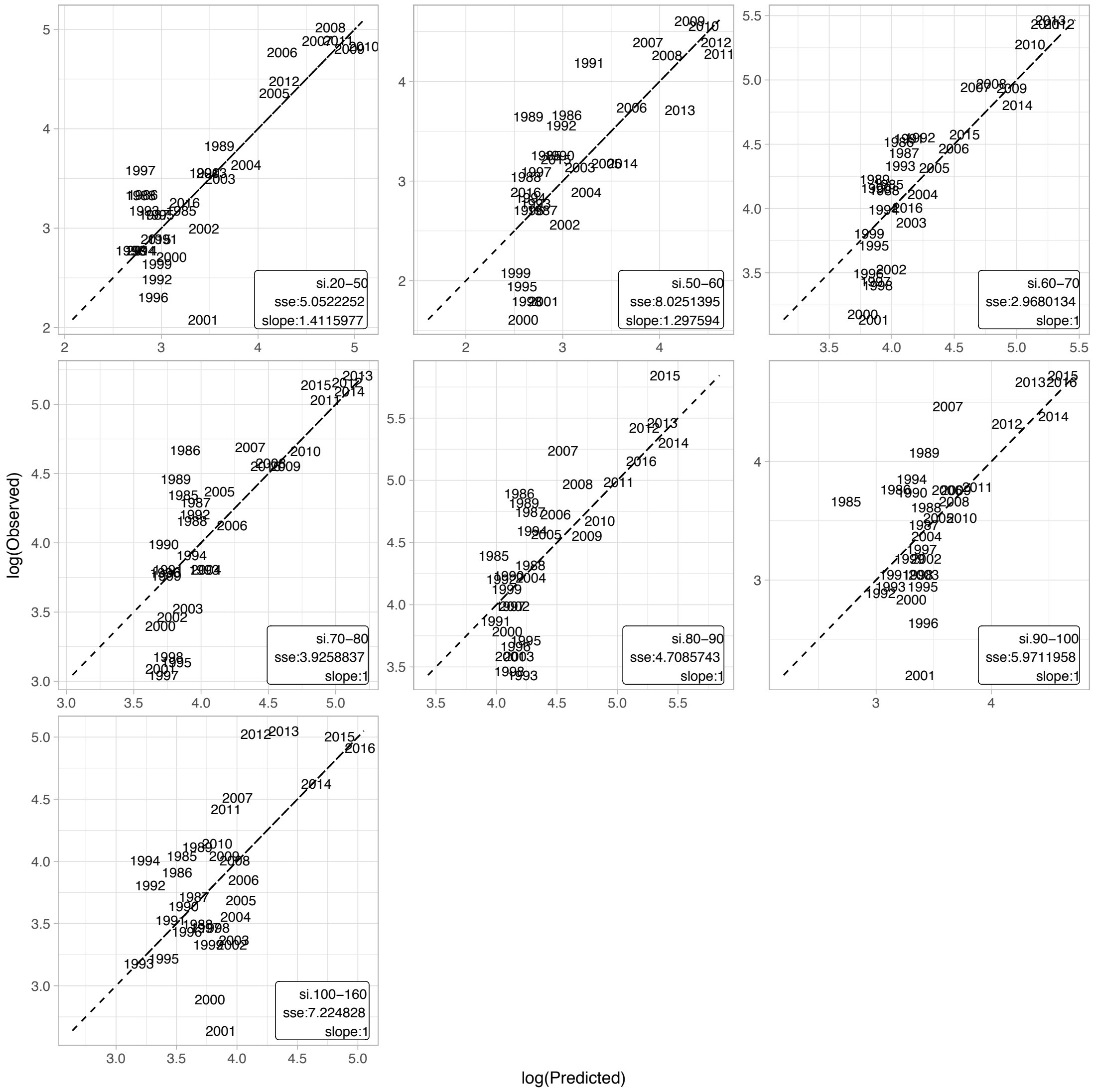

Figure 2.15: Ling 5a. Predicted survey index as a function of the observed values on the log-scale. The panels indicate the index length group, the dashed line denotes a line with slope 1 and the labels denote the year.

tive fits are illustrated in figures 2.17 to 2.21, from the base model and all data. The fit to samples from the trawl and longline fishery is seen to improve in the terminal years, as data becomes more readily available, while the fit to gillnet samples is acceptable given the amount of available data. In comparison the fit to the survey length distributions is good.

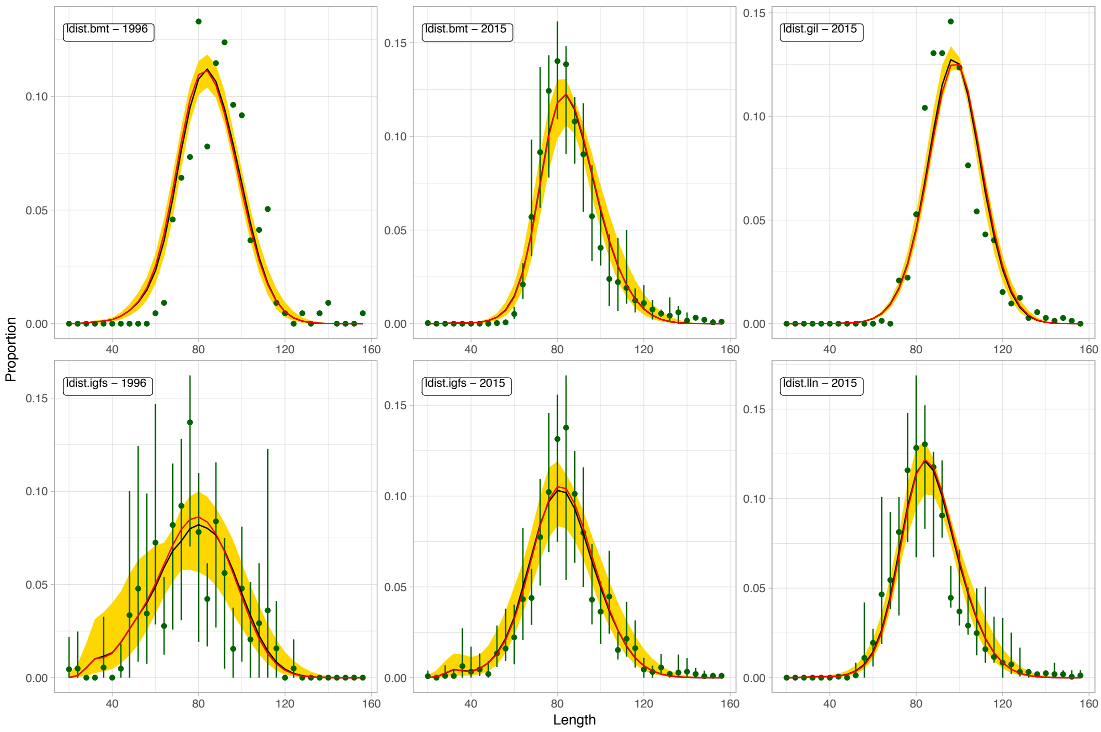

Figure 2.16: Bootstrap length distribution from both survey and commercial samples compared with model estimates. Green points and vertical bars denote the median and 90% interval of the bootsrap distribution of observed values, while the solid lines and golden ribbon the median and 90% intevals of the bootstrapped estimates by the model. The solid red line indicates the fit from the baseline model.

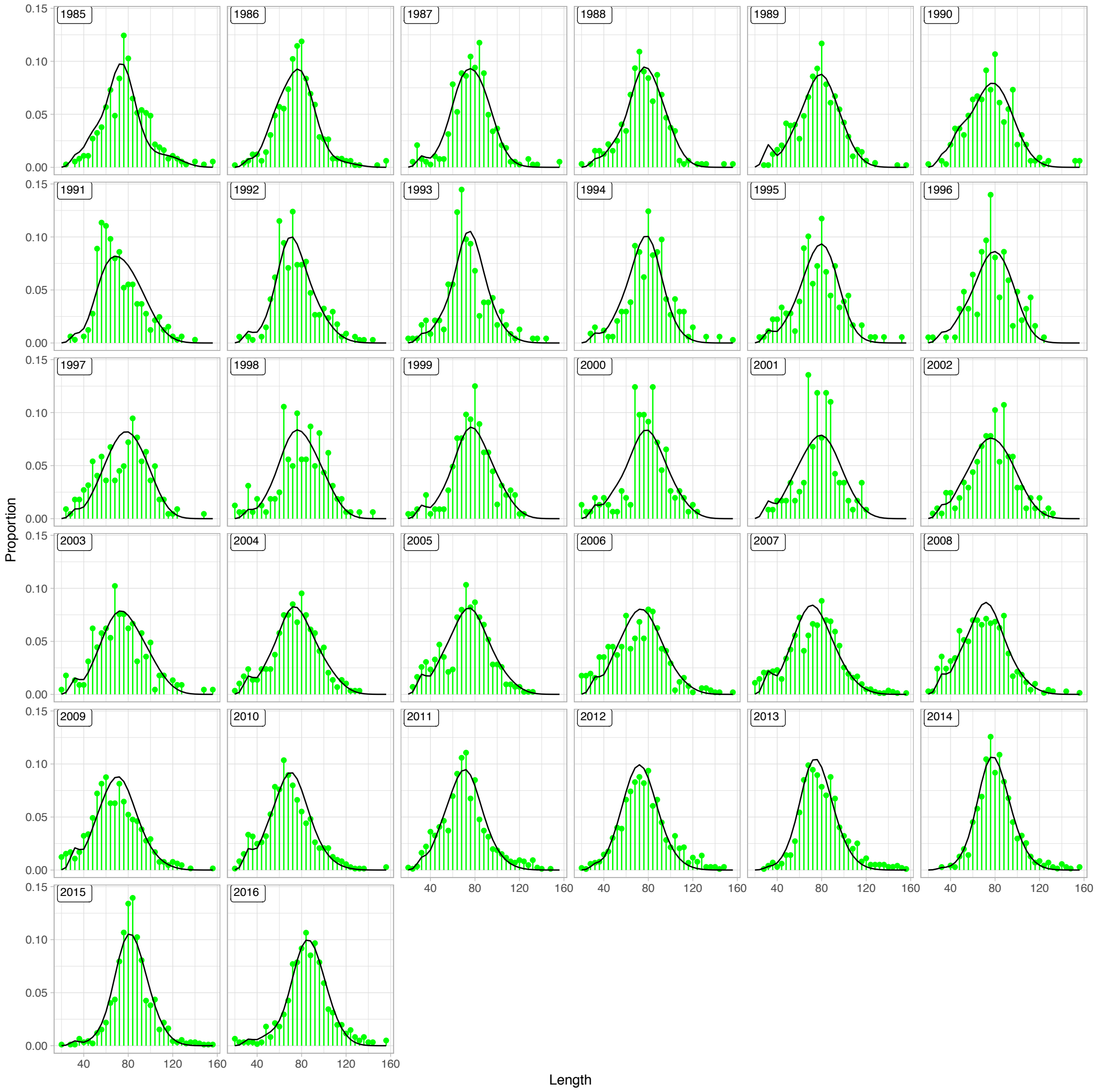

Figure 2.17: Length distribution from survey. Points denote the observed values, solid lines the predictions by the base model.

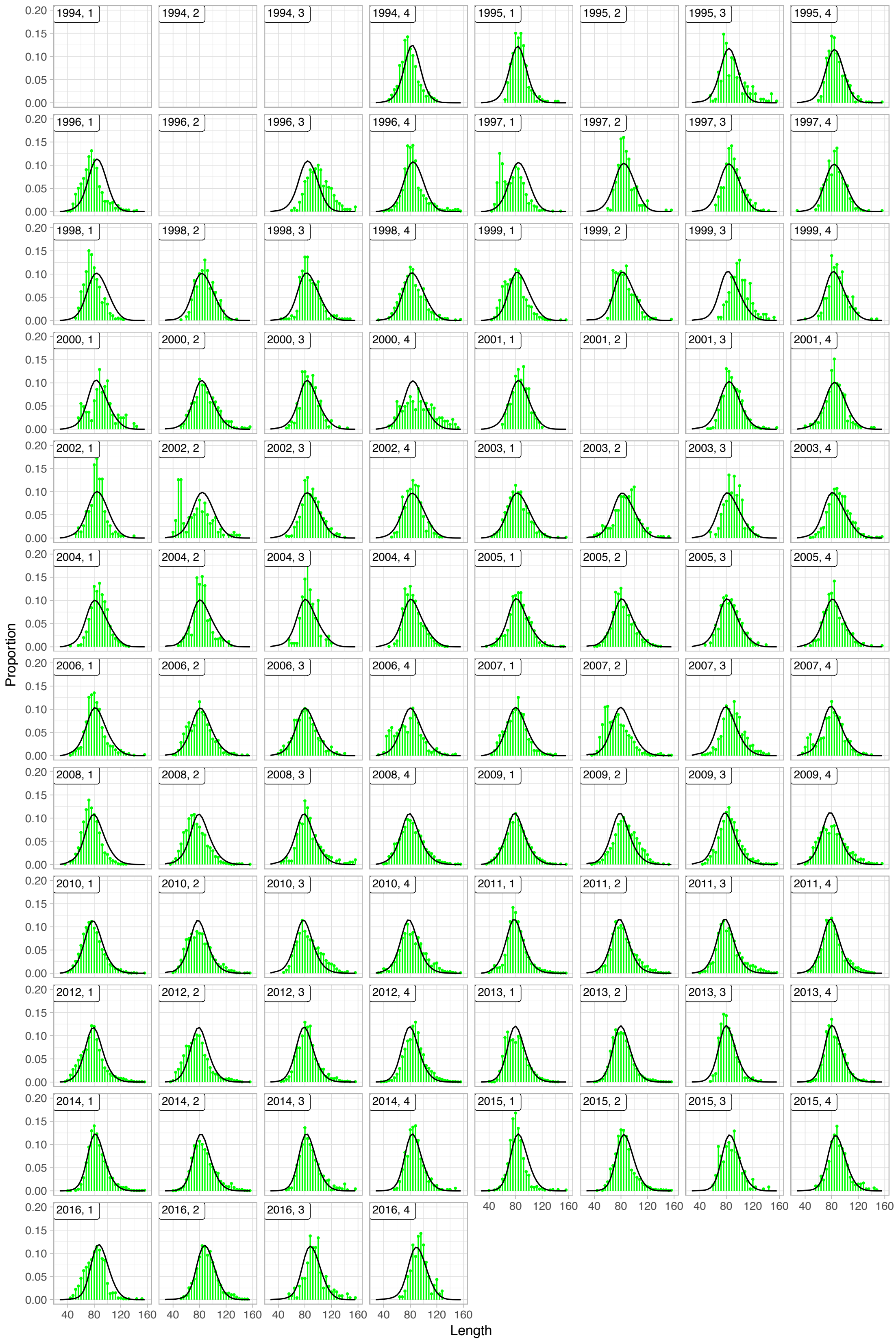

Figure 2.18: Length distribution from the longline fleet. Points denote the observed values, solid lines the predictions by the base model.

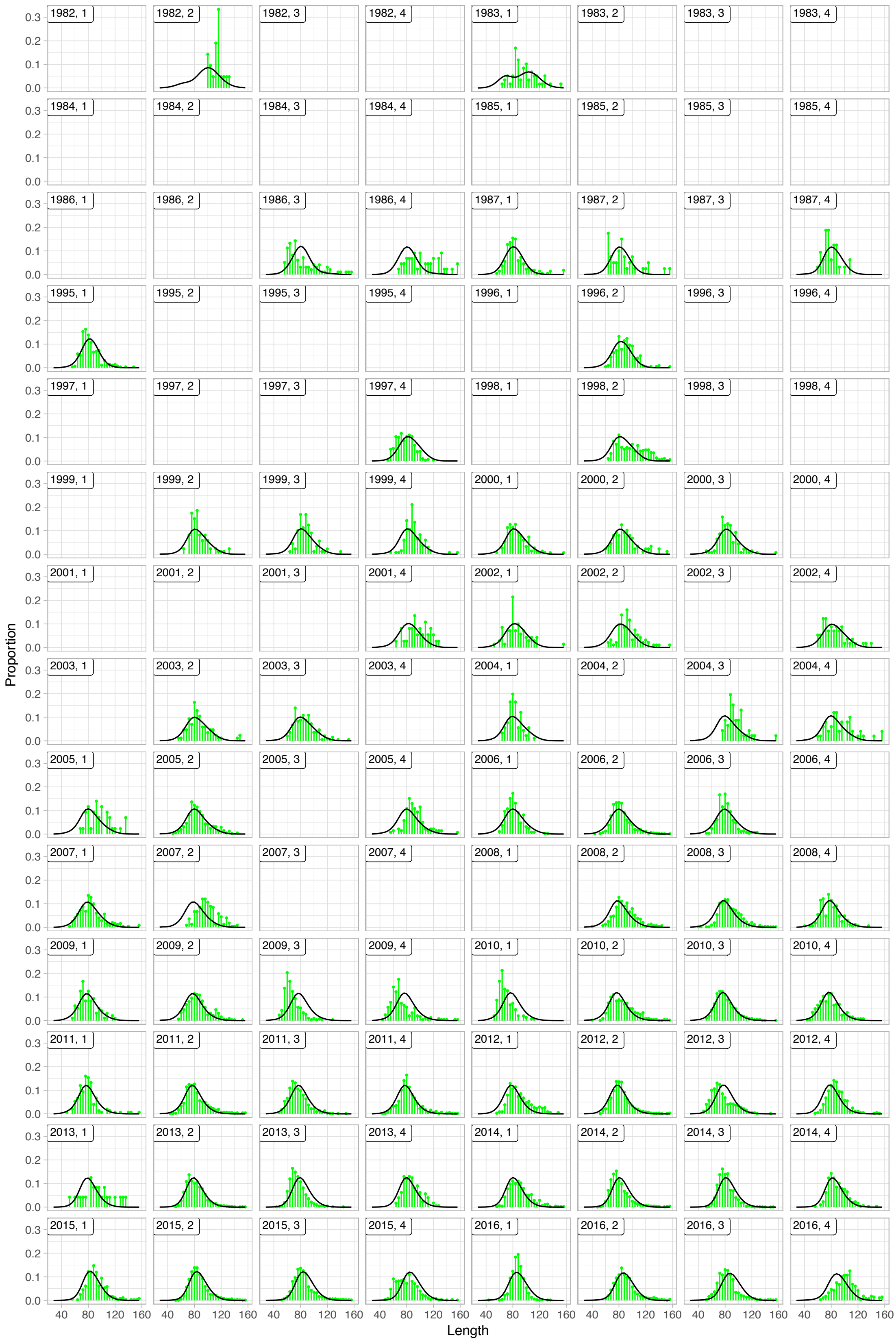

Figure 2.19: Length distribution from the bottom trawl fleet. Points denote the observed values, solid lines the predictions by the base model.

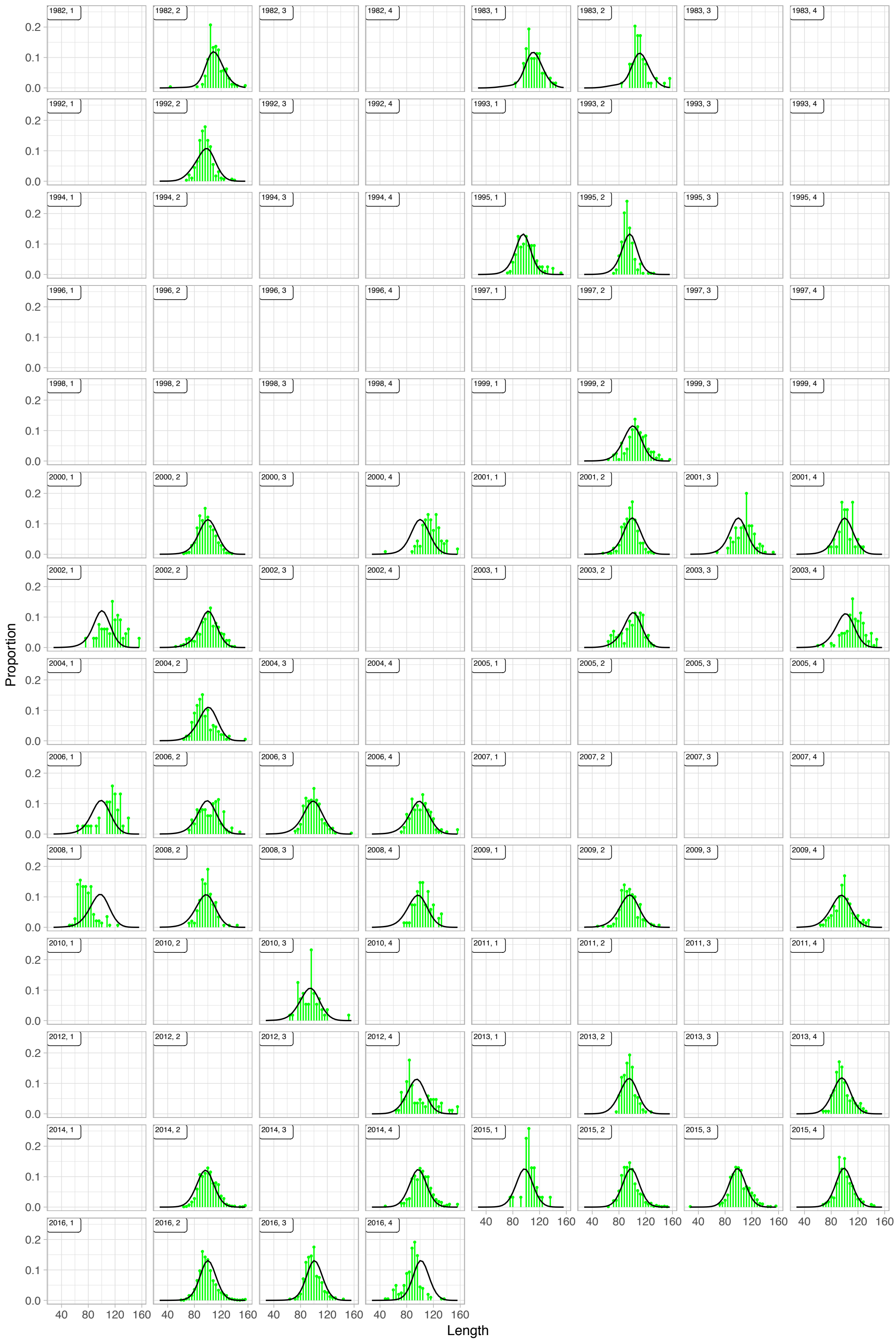

Figure 2.20: Length distribution from the gillnet fleet. Points denote the observed values, solid lines the predictions by the base model.

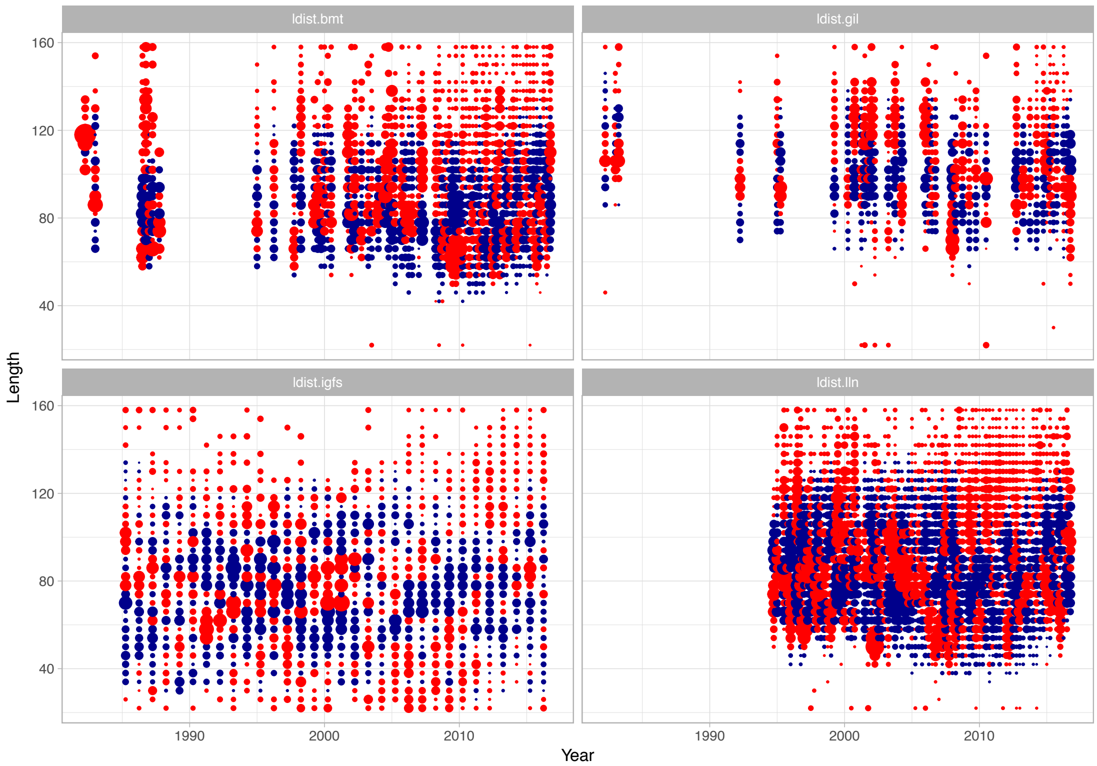

Figure 2.21: Ling in 5.a. Standardised residual plots for the fitted length distribution from the commercial and survey fleets. Red points denot a model underestimate and blue points an overestimated. The size of the points denote the scale of the standardised residual.

3.2.4.4 Age–length distributions

In fig. 2.22 examples of the bootstraped proportions at age compared with model estimates from commercial and survey age samples. In general the model appears to capture the proportions at in the commercial catches (fig. 2.24 to 2.26), while some discrepancy is observed within quarters of the same year. Fig. 2.22 illustrates this where samples within the same quarters exhibit different proportion at age, but overall the central tendency within year and/or gear is captured.

Growth in the model estimated based on the age-length distribution. The model fit to the available information on growth can be observed from figures 2.27 to 2.30 from survey to gillnet samples respectively. In general the model appears to fit the observed growth quite well until the age of 11 where the average length of the samples 11 years and older appears to be higher than the model predicts.

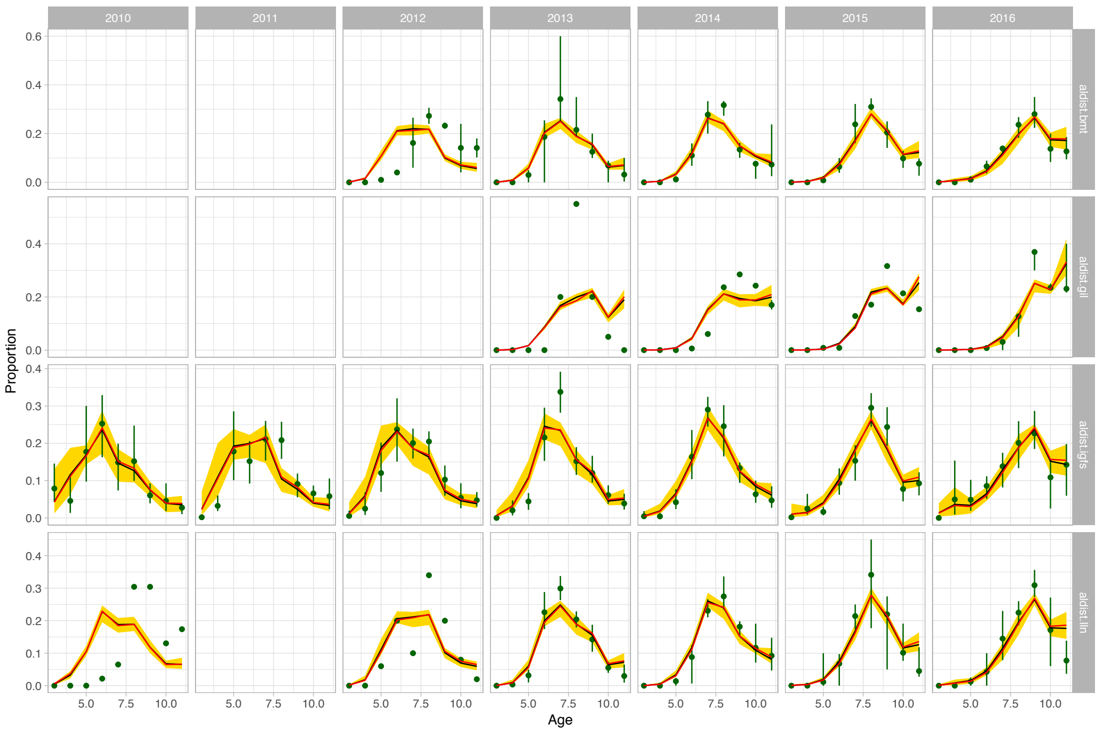

Figure 2.22: Bootstrap age distribution from both survey and commercial samples compared with model estimates from 2008 onwards in quarter 2. Green points and vertical bars denote the median and 5 and 95% percentiles of the bootsrap distribution of observed values, while the solid lines and golden ribbon the median and 5 and 95% percentiles of the bootstrapped estimates by the model. The solid red line indicates the fit from the baseline model. Note that age 11 is a plus group.

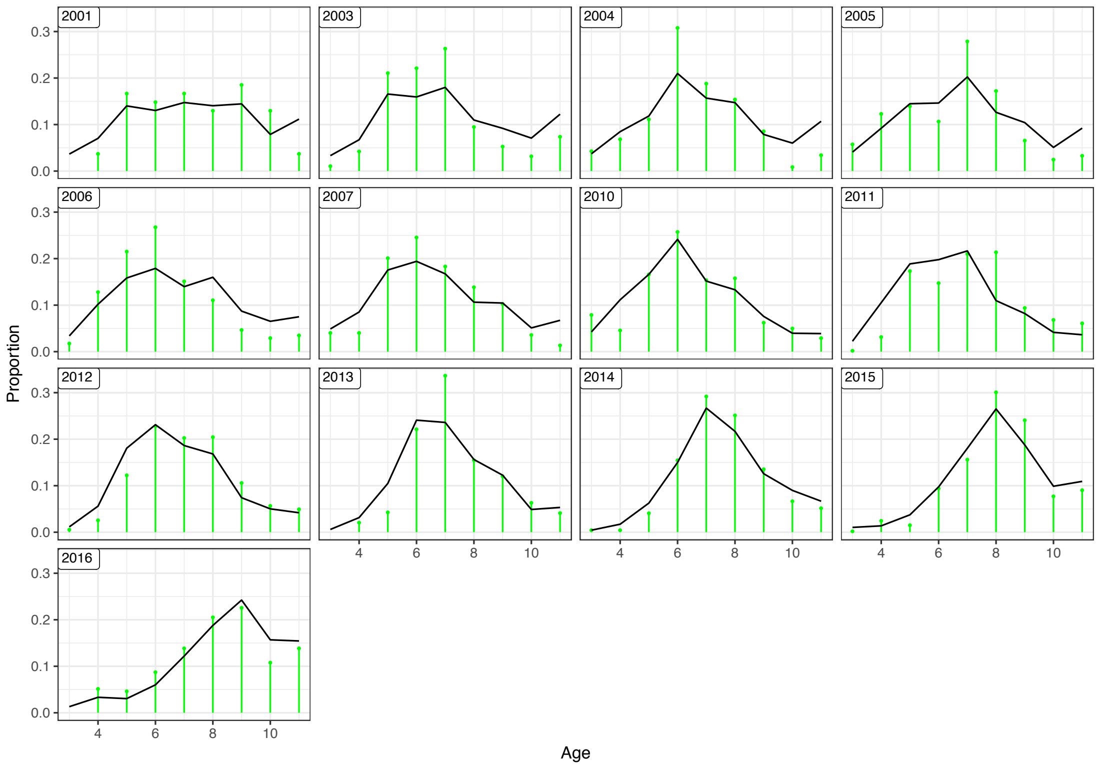

Figure 2.23: Age distribution from the March survey. Points denote the observed values, solid lines the predictions by the base model.

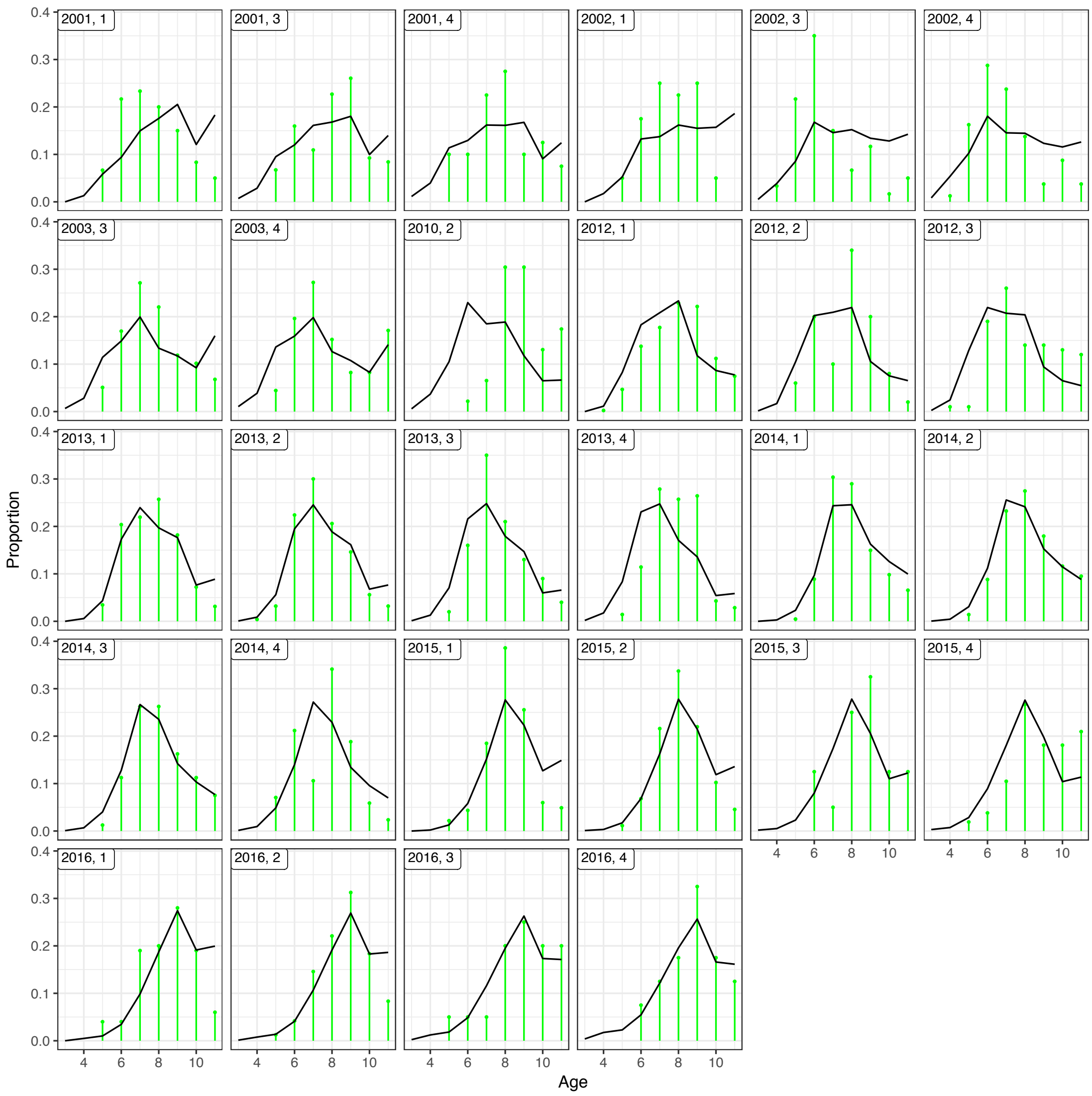

Figure 2.24: Age distribution from the longline fleet. Points denote the observed values, solid lines the predictions by the base model. Note that age 11 is a plus group.

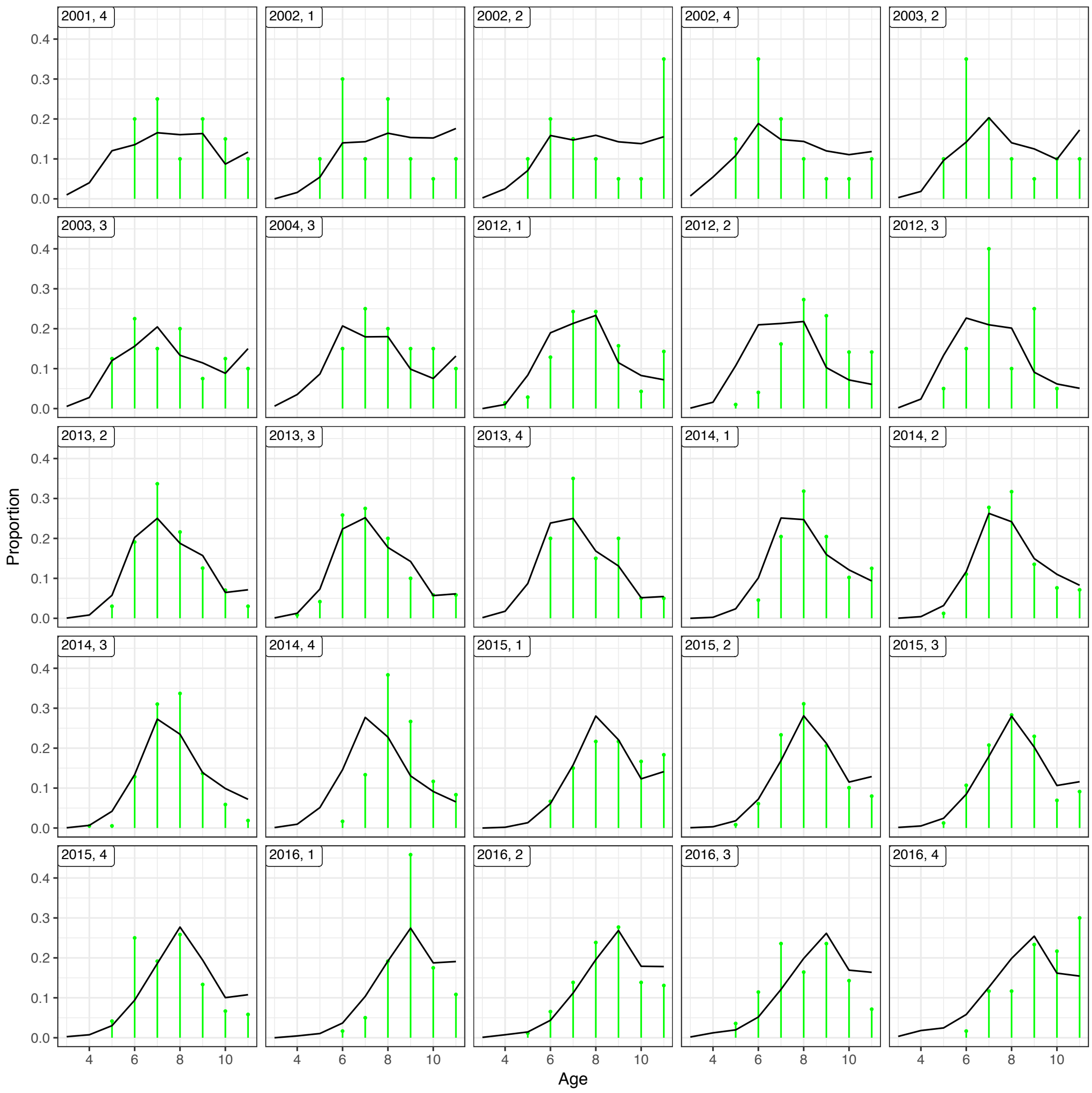

Figure 2.25: Age distribution from the bottom trawl fleet. Points denote the observed values, solid lines the predictions by the base model. Note that age 11 is a plus group.

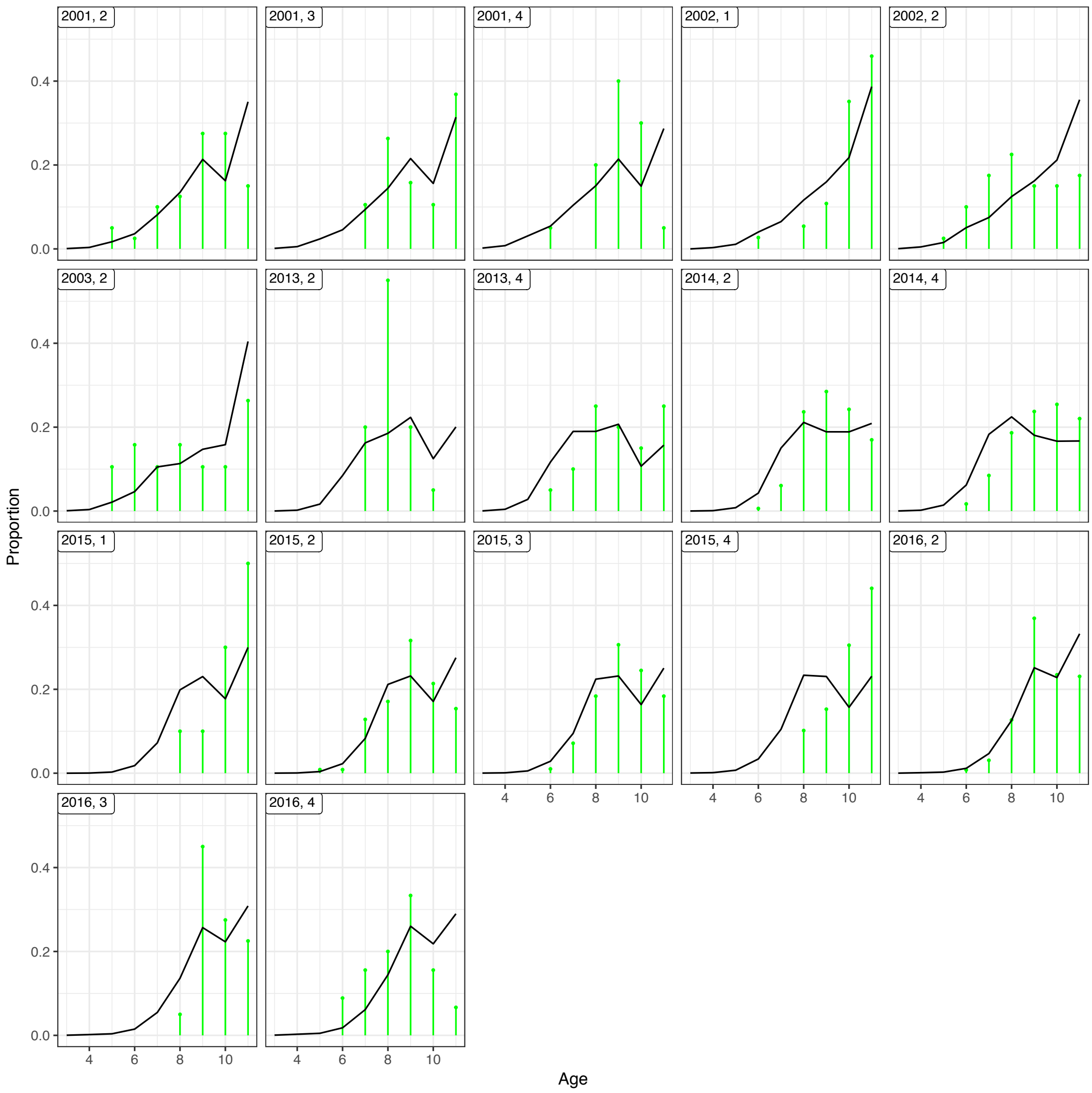

Figure 2.26: Age distribution from the gillnet fleet. Points denote the observed values, solid lines the predictions by the base model. Note that age 11 is a plus group.

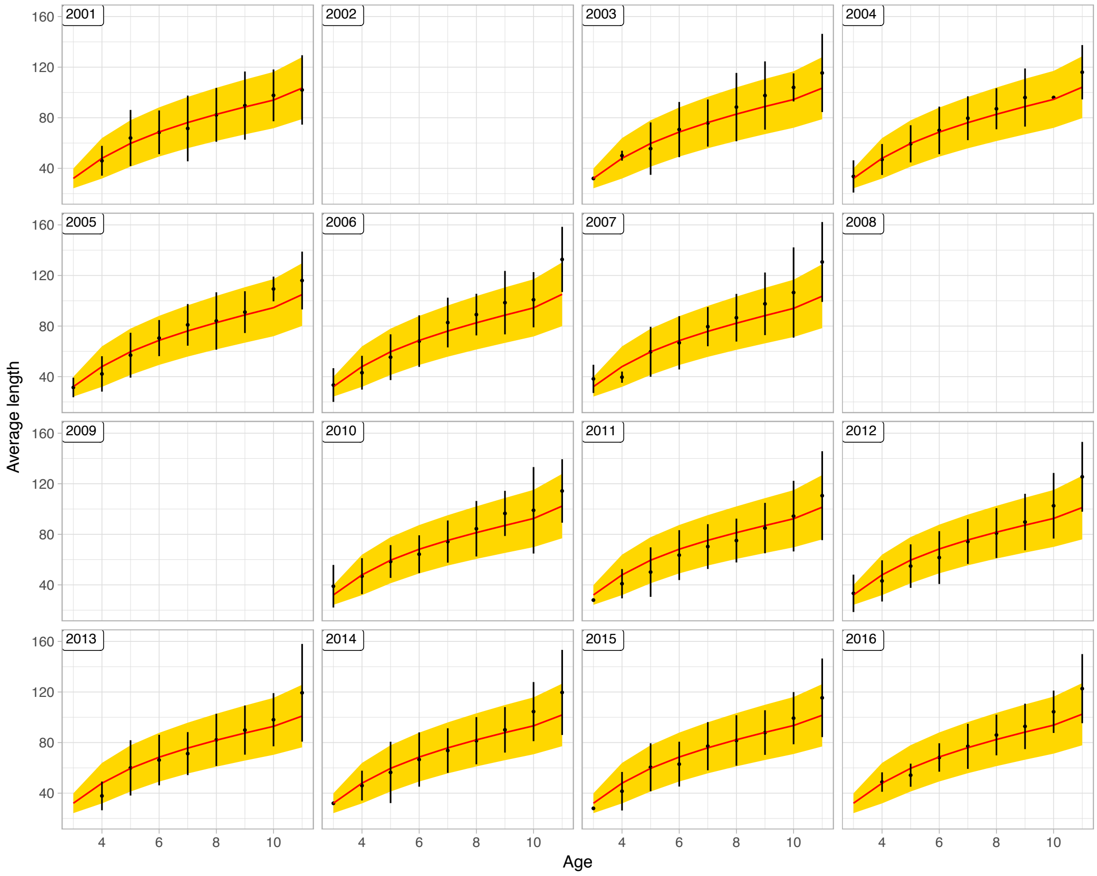

Figure 2.27: Ling in 5a. Fitted length at age by year compared to observed values from the Icelandic spring survey. The black point and vertical bar denotes the observed mean and 95% confidence intervals of length at age, while the golden ribbon and red line indicates the model estimates. Note that age 11 is a plus group and empty panels indicates lack of measurements.

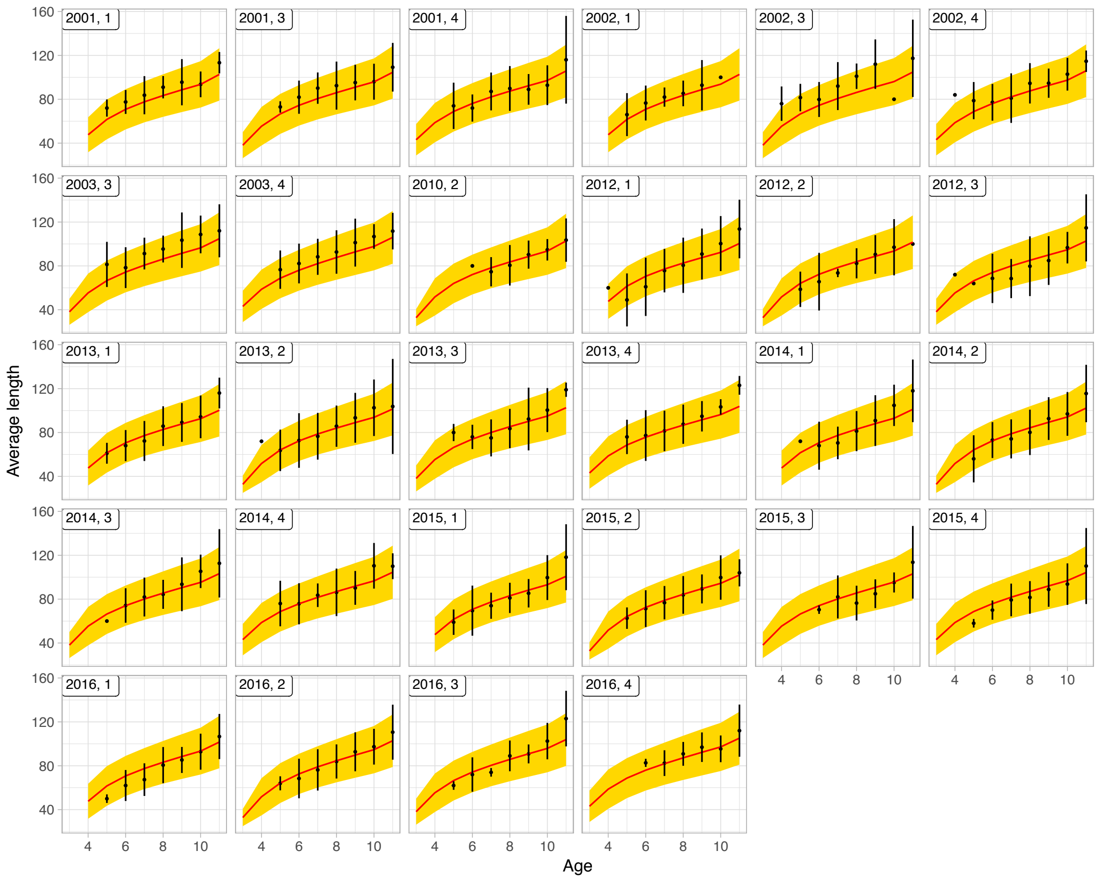

Figure 2.28: Ling in 5a. Fitted length at age by year compared to observed values from the longline samples. The black point and vertical bar denotes the observed mean and 95% confidence intervals of length at age, while the golden ribbon and red line indicates the model estimates.

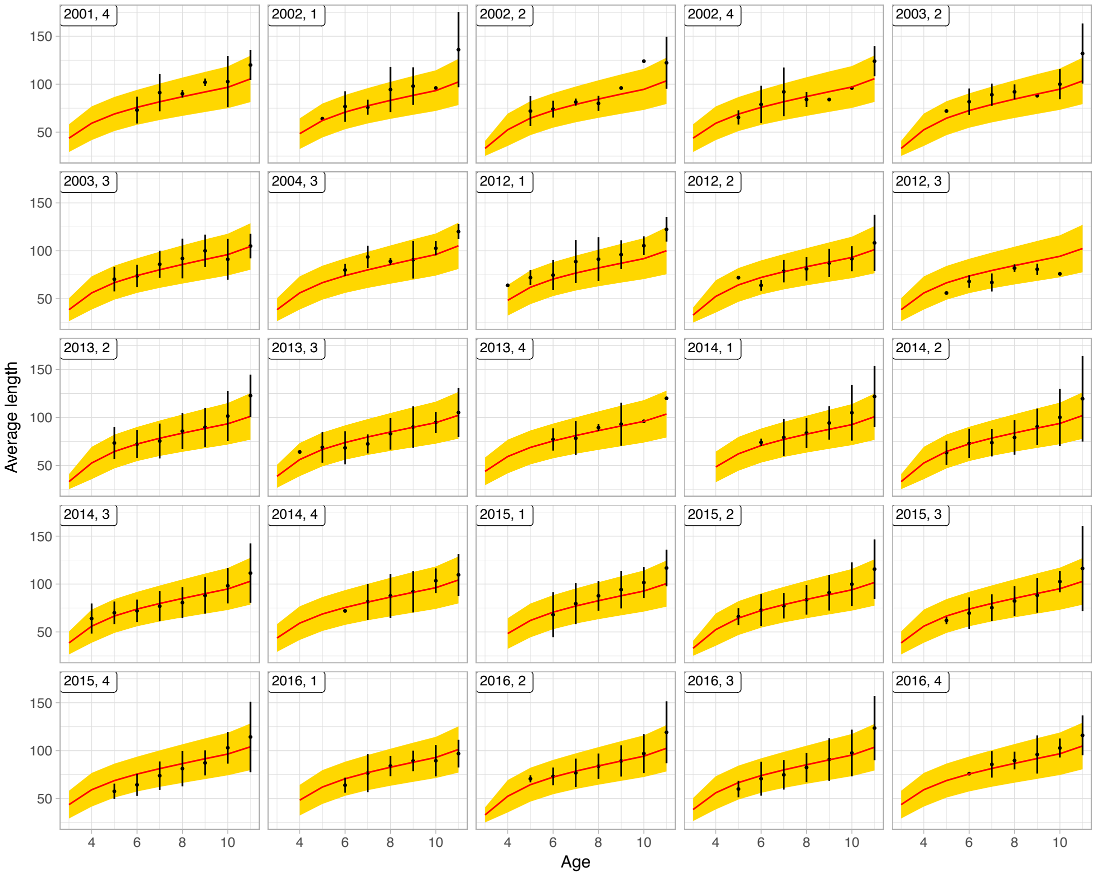

Figure 2.29: Ling in 5a. Fitted length at age by year compared to observed values from the bottom trawl samples. The black point and vertical bar denotes the observed mean and 95% confidence intervals of length at age, while the golden ribbon and red line indicates the model estimates. Note that age 11 is a plus group.

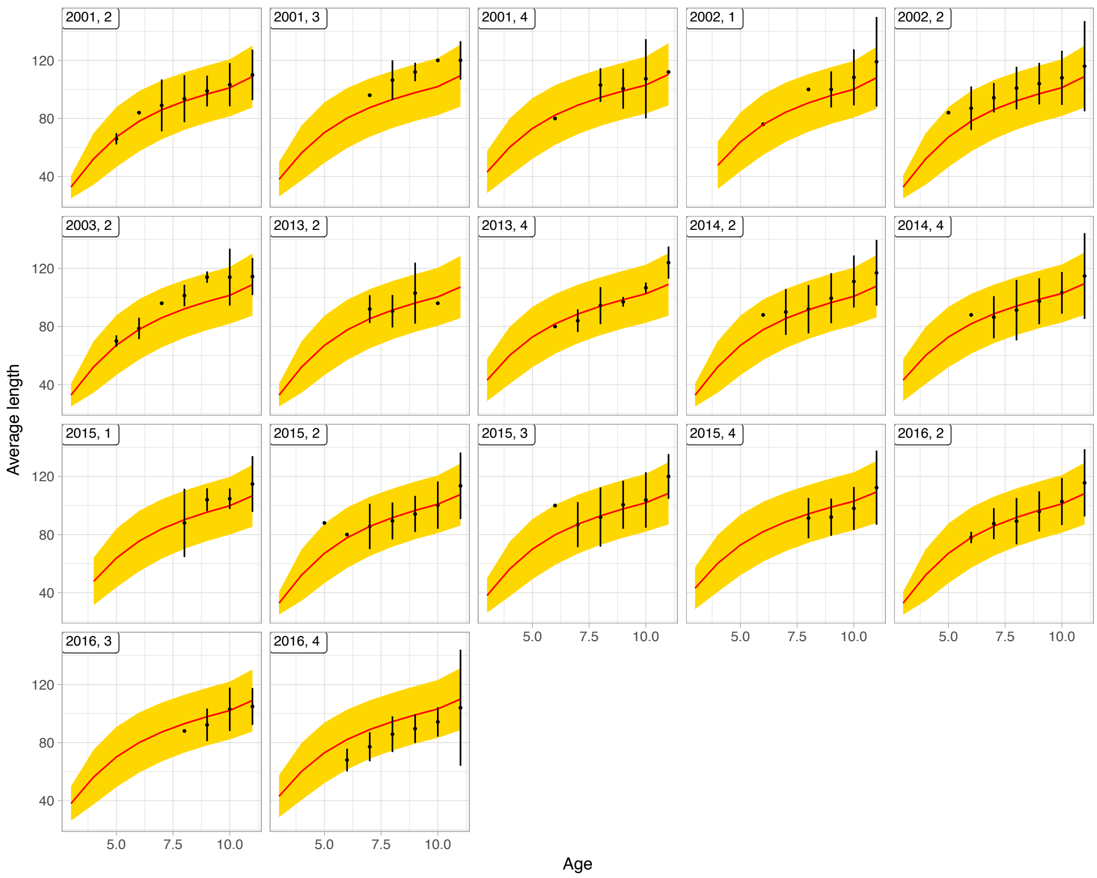

Figure 2.30: Ling in 5a. Fitted length at age by year compared to observed values from the gillent samples. The black point and vertical bar denotes the observed mean and 95% confidence intervals of length at age, while the golden ribbon and red line indicates the model estimates. Note that age 11 is a plus group.

Figure 2.31: Ling in 5.a. Standardised residual plots for the fitted age distribution from the commercial and survey fleets. Red points denot a model underestimate and blue points an overestimated. The size of the points denote the scale of the standardised residual.

3.2.4.5 Maturity

The estimated maturity at length and the observed values from the spring survey are contrasted in fig. 2.32. Some discrepancy can be observed from from the figure, notably in 1991 and 2001 where model predicts a lower and higher maturity proportion, respectively, than observed. Overall the model appears to capture the general structure of the data.

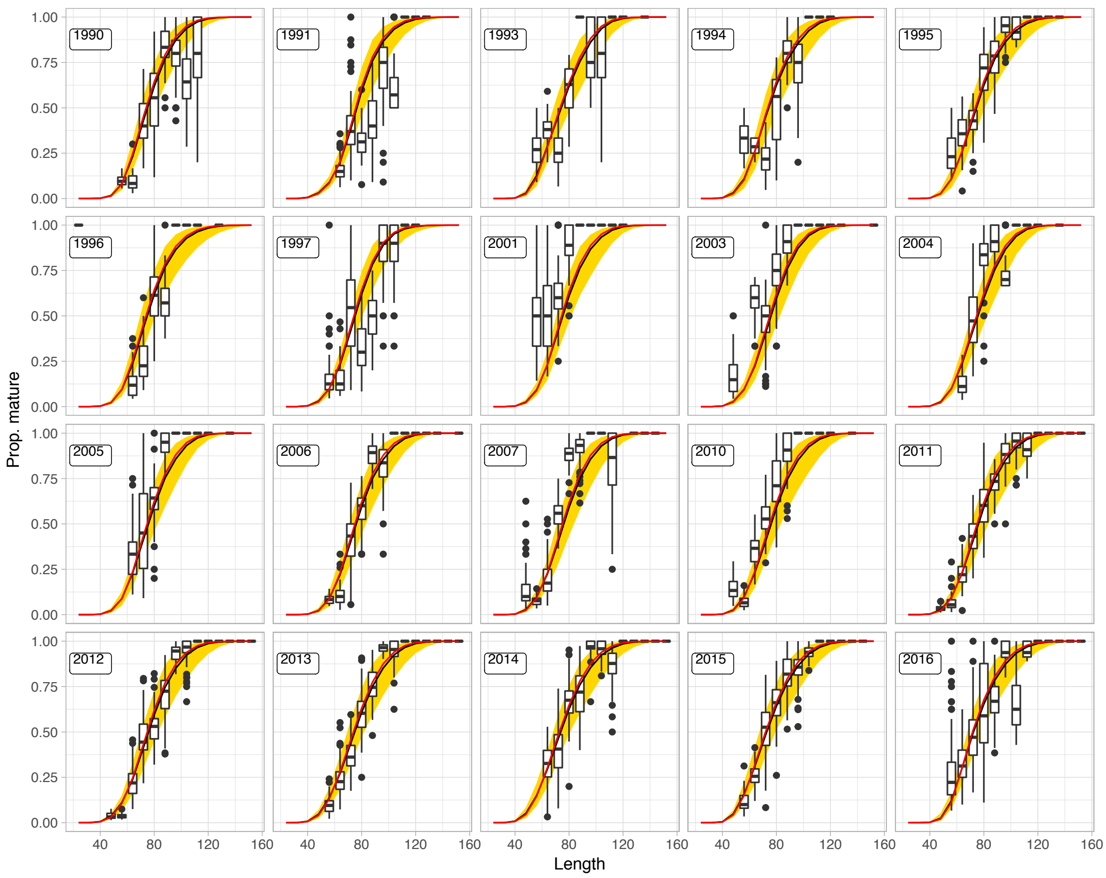

Figure 2.32: Ling in 5a. A boxplot of the bootstrap distribution of the maturity at length from the Icelandic spring survey compared to the bootstrap confidence and median of model estimates, indicated by a gold ribbon and a solid black line. Base model estimates are shown as a red line.

3.2.5 Estimates

3.2.5.1 Growth

In the model, information on growth of ling is obtained from the aged otoliths (see subsection 3.2.3.3). In figure 2.33 examples of the growth estimates are presented. In the model L_∞ and k are estimated. In figure 2.33a predictions of the growth curve using the bootstrap estimates of of the growth process pre-exploitation, i.e before any mortality occurs in the model, are plotted (black solid line and blue area). On top of that the bootstrap estimates of mean length at age in 2016 are plotted (black dashed line and yellow area). There is some difference between these two growth curves which can be attributed to fishing mortality (size selective). The growth curves in figure 2.33a look plausible. In figure 2.33b the bootstrap estimates of the standard deviation (s) of mean length at age in the population in 2016 are presented. The estimates of s increase rapidly from the age of 3 to age 5, after that the increase is slower. For the oldest age groups the estimates of s decrease again slightly, due to the size selectivity in the model, with a slight increase in the last age group due to the continued growth in the plus group.

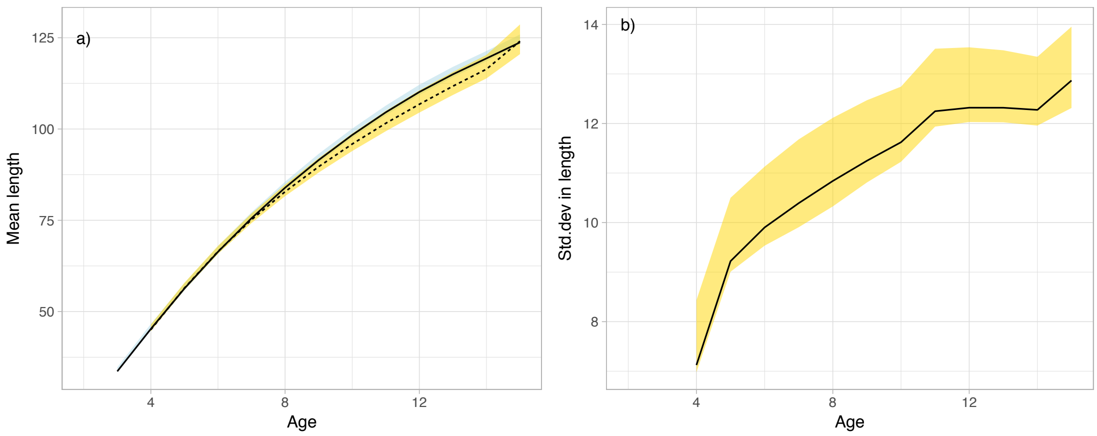

Figure 2.33: Ling in 5a: Estimates of growth from the gadget model. a) Predicted growth from bootstrap estimates of initial population mean length at age (median: black solid line) and 5-95% inter quantile range (blue area) and predicted mean length in stock in 2016 from the bootstrap estimates (median: black dashed line) and 5-95% inter quantile range (yellow area). b) Bootstrap estimates of standard deviation of length at age in 2016 (black line: median, yellow area 5-95% quantiles).

3.2.5.2 Predicted age-structure

Having a large plus group in the model can indicate either to low natural mortality or to slow growth rate, or a combination of both. The predicted catch in numbers (Figure 2.34) shows that the main age groups in the catches according to the model are ages 5 to 12 and hardly any ling older than age 13 is caught. Similarly, stock abundance declines rapidly after the age of 9 and the plus group (15) is very close to zero in most cases (Figure 2.35). Uncertainty in rectruitment in the terminal years of the model appears to have an effect on the abundance estimates in the final years.

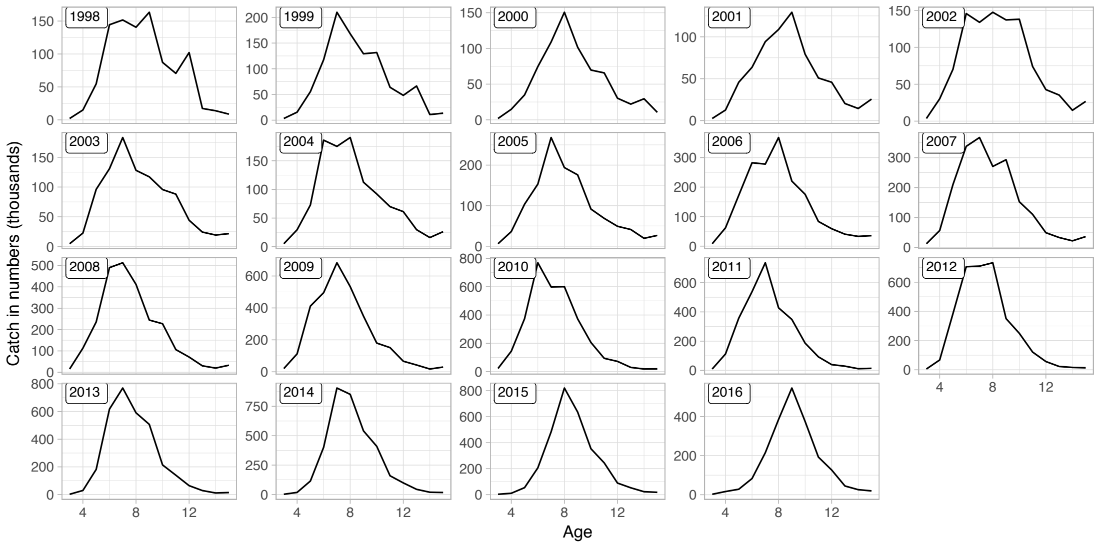

Figure 2.34: Ling in 5a. Estimates of catch in numbers from the base-run.

Figure 2.35: Ling in 5a. Estimates of abundance by age and year, log transformed. Black solid line and golden ribbon indicate the bootstrap median and 95% inter-quantile range.

3.2.5.3 Selectivity

The estimated selection curves for model fleets are shown in fig. 2.36 along with the respective bootstrap 95% interquantile range. The longline and trawl fleets selectivity were not substantially different, with median values of $l_5 0$ of 76.91 cm (72.93 – 78.28) and 75.37 cm (69.96–77.55) respectively. The l_{50} in the survey was estimated to be slightly lower, or 68.28 cm, but higher uncertainty ranging between 54.18 cm to 86.92 cm. The l_{50} of the gillnet fleet was considerably higher or 101.62 cm (97.97 – 101.62).

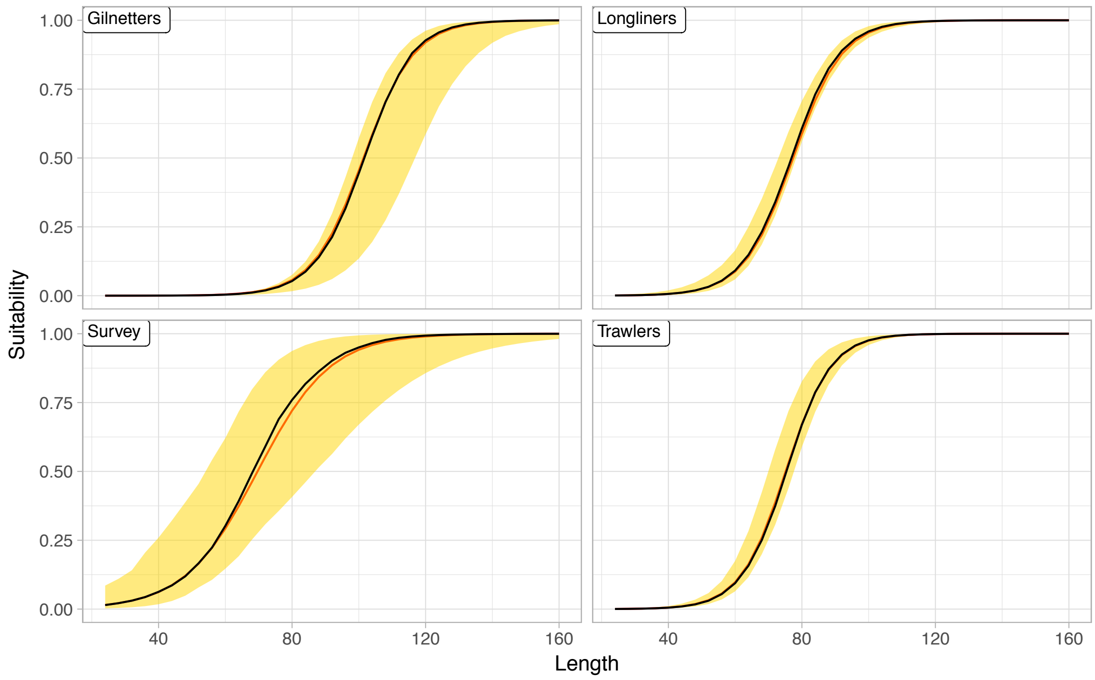

Figure 2.36: Ling in 5a. Bootstrap estimates of selection curves from the fleets in the model. Black lines is the median and shaded area the 5-95% interquantile range. Red lines indicates estimate from the base model.

3.2.5.4 Population estimates

The model predicts that total biomass is currently starting to decline from its peak level in 2014. Simlarly reference biomass and the spawning stock biomass SSB are starting to decline but still at a level considerably higher that ever observed (Figure2.37). The SSB reached its lowest point at 9.93 kt in 1991. The bootstrap runs indicate that uncertainty about population estimates has been increasing in recent years, in accordance with the increase in the variance of the survey indices and fewer datapoints behind those estimates.

The coefficient of variation (CV) of the population estimates from the bootstrap runs is on average around 0.15 for the SSB, 0.15 for the reference biomass (>75 cm), and 0.16 for recruitment. However in the assessment year the CV of SSB and reference biomass is around 0.25 and 0.28 respectively, the range for these two metrics is between 0.1 to 0.26 and 0.09 to 0.28. For recruitment the range is 0.08 to 0.4.

Catches of immature fish, in terms of total biomass caught, is estimated to have varied between 12.4 % in 1982 to 26.5% in 2011 and in 2016 the estimated proportion is 12.6%.

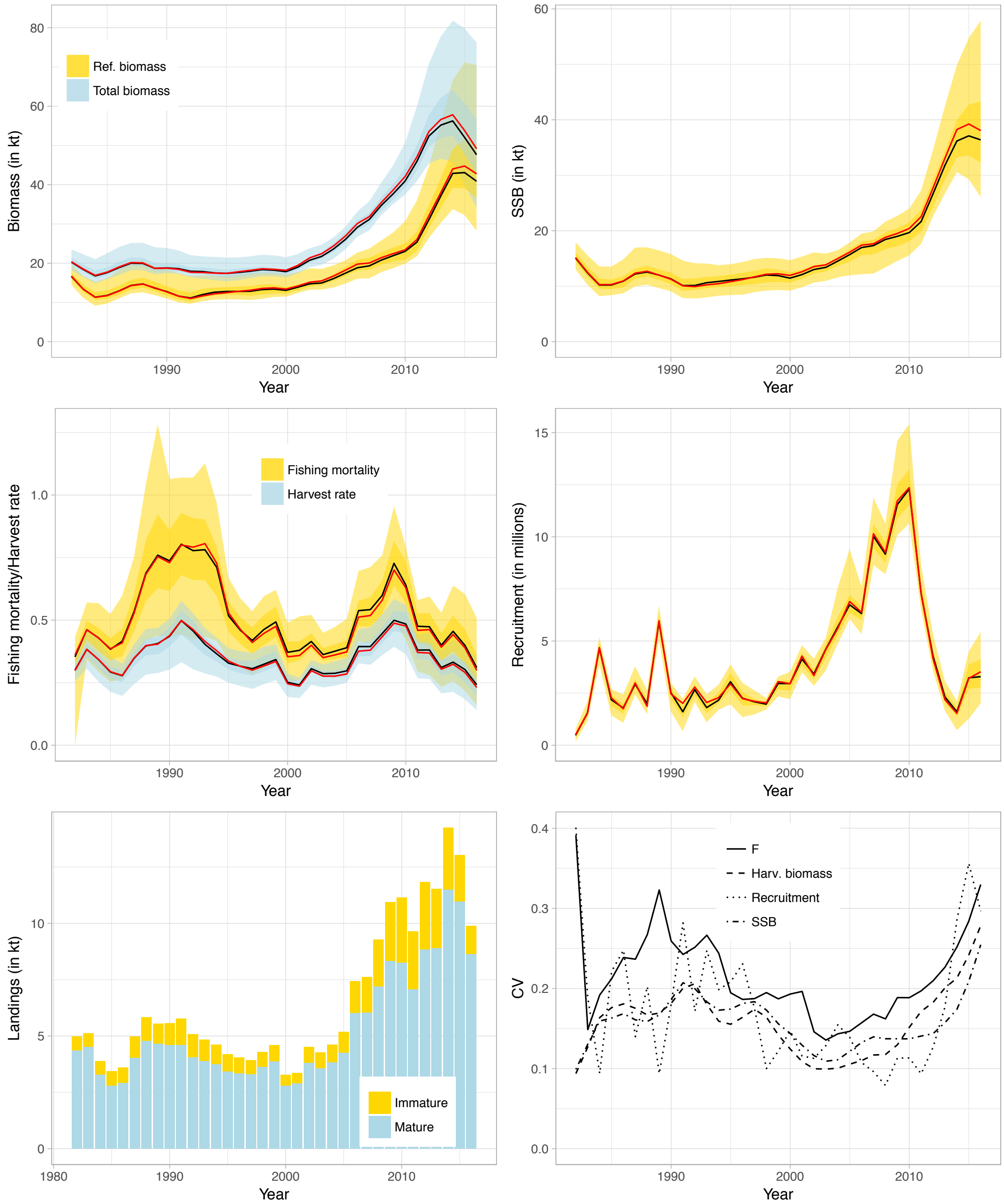

Figure 2.37: Ling in 5a. Estimates of biomass, reference biomass (ling larger than 75 cm, knife-edge) and spawning stock biomass. Estimates of recruitment in millions and fishing mortality (age 15^{+}). Black line is the median of bootstrap estimates, yellow area is the range between the 5-95% quantiles of the bootstrap estimates and the red line is the results of the base-run. Estimates of coefficient of variation (CV) for reference biomass, fishing mortality, recruitment and SSB.

3.2.5.5 Analytic retrospective analysis

In figure 2.38 the results of an analytical retrospective analysis are presented. The analysis indicates that there is a downward revision of biomass (SSB and reference) in 2012 to 2014 and subsequently an upward revision of F. Estimates of recruitment in the years between 2007 to 2010 fluctuate wildly.

Two things have to be considered when looking at figure 2.38. First is that these fluctuations are roughly within the 95% bootstrap interquantile range, although there appears to be a one way correction each consecutive year while 2015 and 2016 models appear roughly inline with one another. This is appears to be related to the discounting of peak values of the survey indices in the latter half of the first decade of this century (See figure 2.39) when more data on the subsequent decrease emerged. Therefore as the increase in the indices is discounted each year, as the signal (increase) does not transfer to the larger length groups, the biomass estimates are reduced.

The second thing is that the tuning indices until very recently exhibited a "one-way" trend in addition of being fairly noisy. So under these circumstances, while the historical assessment is fairly stable, the uncertainty in the current (or contemporary) estimate of the stock status is likely exhibit a strong correlation with previous years assessment.

It is also worth noting that the bulk of the age structured data is in the last 15 years, and the bulk after 2010, and therefore a very informative data is being omitted, this specially affects the recruitment estimates. Also the lack of age data back in time, in contrast with traditional age based assessments appears to result in greater variation in historical estimates.

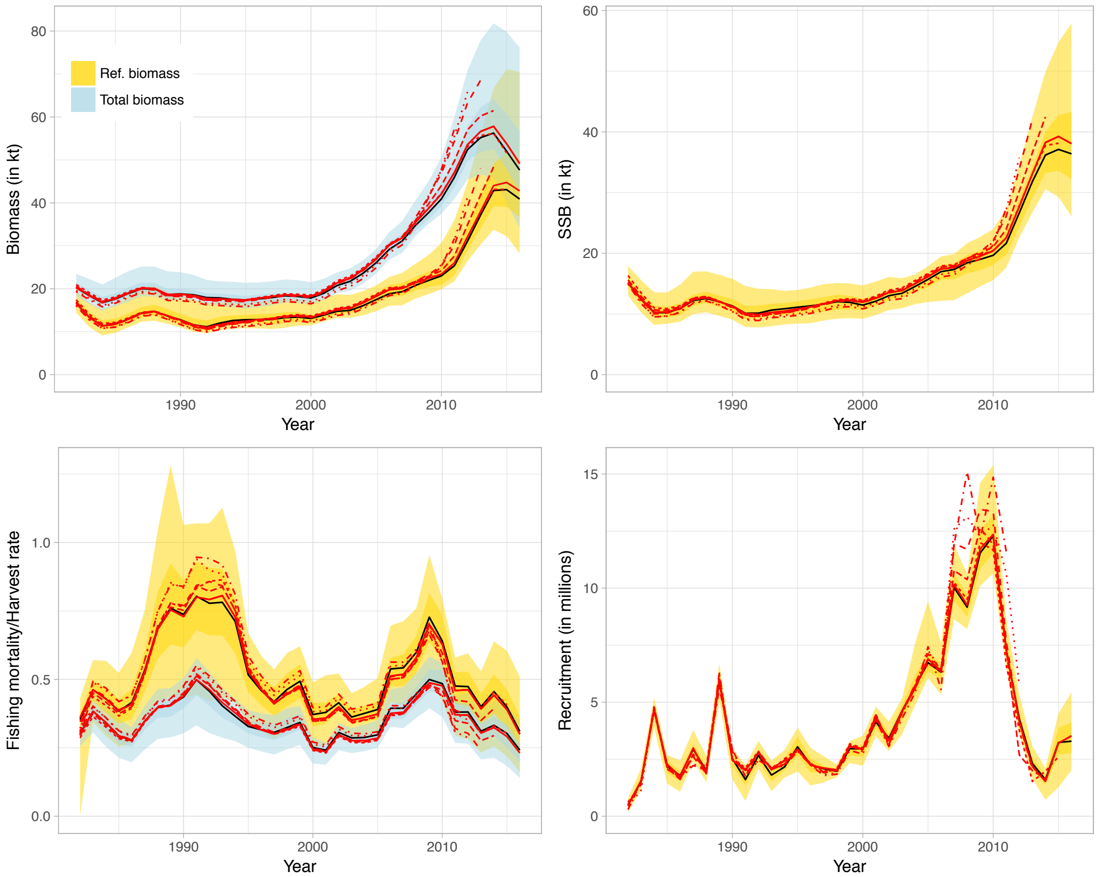

Figure 2.38: Ling in 5a. Analytical retrospective analysis from the Gadget model. Estimates of biomass, reference biomass (ling larger than 75 cm, knife-edge) and spawning stock biomass. Estimates of recruitment in millions and fishing mortality (age 15^{+}). Black line is the median of bootstrap estimates, yellow area is the range between the 5-95% quantiles of the bootstrap estimates and the red line is the results of the base-run. The various dotted lines indicate the retrospective model estimates.

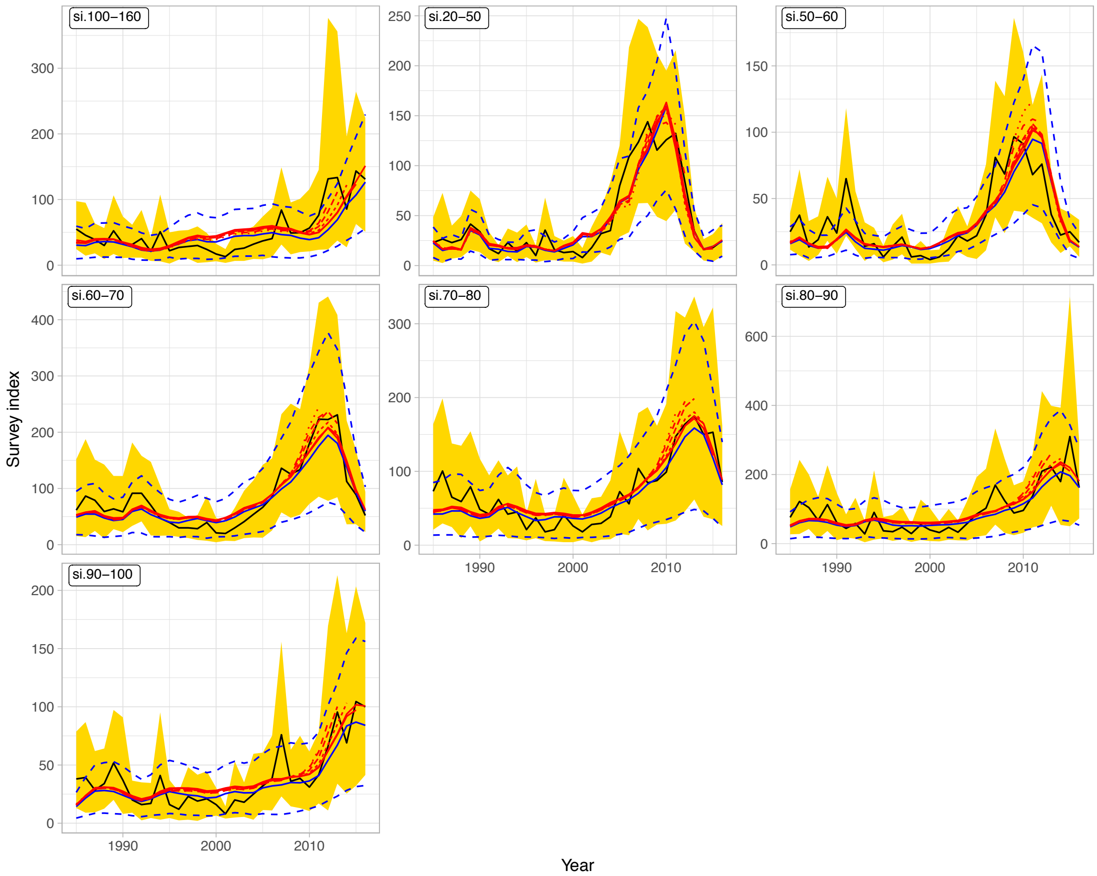

Figure 2.39: Ling in 5a. Analytical retrospective analysis of the fit to the survey indices.

3.2.5.6 Changes since last benchmark

For the 2017 benchmark the main changes to the assessment model are:

- The model building process is built up from scratch such that it would allow for it to be reproducible. The scripts that generate the assessment are currently available from github.com/fishvice/mfdb-hafro-etl and github.com/fishvice/gadget-models
- The model now estimates explitly the maturity process by setting up two sub-stocks, immmature and mature, allowing for the direct estimate of the spawning stock biomass. In comparison, in previous iterations of the assessment model, the spawning stock biomass was estimated based on the combination of a maturity at length ogive and the model estimates of number at length.
- Age readings where fish have been assigned an age of 11 or older are now grouped together before comparing with the model output. This is done as age of ling is harder to determine after the age of 11 and number samples of old fish are fairly low.
- Age readings prior to 2001 have been omitted from the input data as these ototliths were read using a different (older) method that is perceved to be incorrect.
- The q for the two survey indices representing the smallest length groups is now estimated, which appears to stabilise the retro, as suggested in fig. 2.38.
- The lengthgroup size was increased from 1 cm to 4 cm while at the same time the maximum size was decreased to 160 cm (from 180 cm previously). This resulted in a 50% reduction in computing time.

Comparison between the contemporary assessment model and the updated assessment model is shown in fig. 2.40. Current assessment of the stock is more or less in-line with previous assessment, while historical biomass estimates are substantially lower from the contemporary assessment model when compared with the updated asseesment model. It is also worth noting that the historical retrospective, using this previous model, revealed a substantial revision between years.

These differences between the two models is considered to be related to changes done during the revision. For example the addition of the maturity at length data, can additionally inform on the level between the two stock components. The differences in the recruitment estimates can be attributed to the omission of age data prior to 2001.

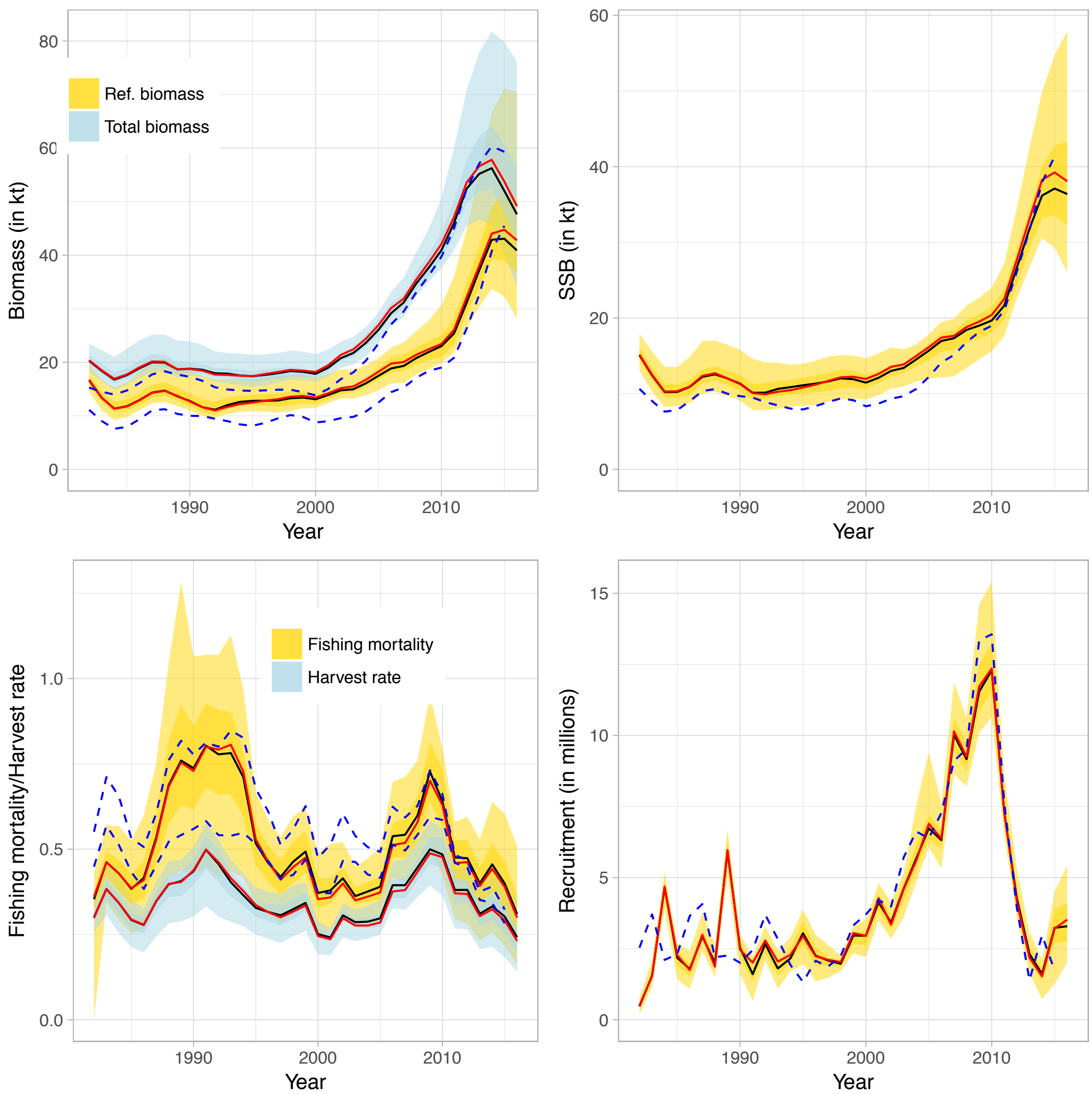

Figure 2.40: Ling in 5a. Comparison with last year assement results. Estimates of biomass, reference biomass (ling larger than 75 cm, knife-edge) and spawning stock biomass. Estimates of recruitment in millions and fishing mortality (age 15^+). Black line is the median of bootstrap estimates, yellow area is the range between the 5-95% quantiles of the bootstrap estimates and the red line is the results of the base-run. The blue dashed lines denote last years assessment.

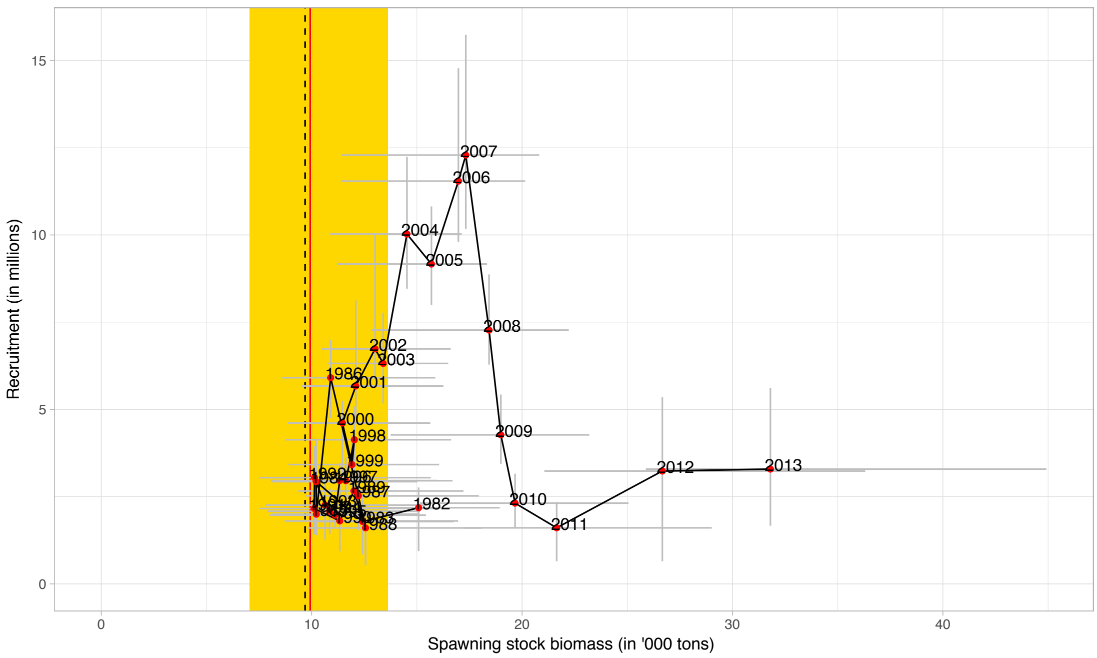

Figure 2.41: Spawing stock biomass recruitment relationship for ling in 5a. Uncertainty in recruitment and SSB is indicated with 95% quantile intervals. The yellow vertical bar represents the distribution of B_{loss}.

3.2.6 Reference points

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 fishing mortality, but for some stocks the reference points are determine in terms of harvest rate, i.e. the amount of catches relative to a reference biomass (s.a. spawning stock biomass, or biomass of fish larger than a minimum size or older than a minimum age). For ling in 5a the suggested management plan will be determined in terms of the harvest rate of the total biomass above 75 cm.

The following sections describe the derivation of the management reference points both in terms of harvest rate (H) and fishing mortality (F). The model for the stock recruitment and assessment error which in combination with the bootstrap results is used to project the stock status stochastically in order to derive the PA and MSY reference points.

3.2.6.1 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. 2.41. The figure shows a relatively narrow dynamic range of SSB and no evidence of impaired recruitment. Further discussion on the recruitment spike can be found in section 3.2.9. In this situation, according to the ICES technical guidelines, B_{lim} can not be estimated

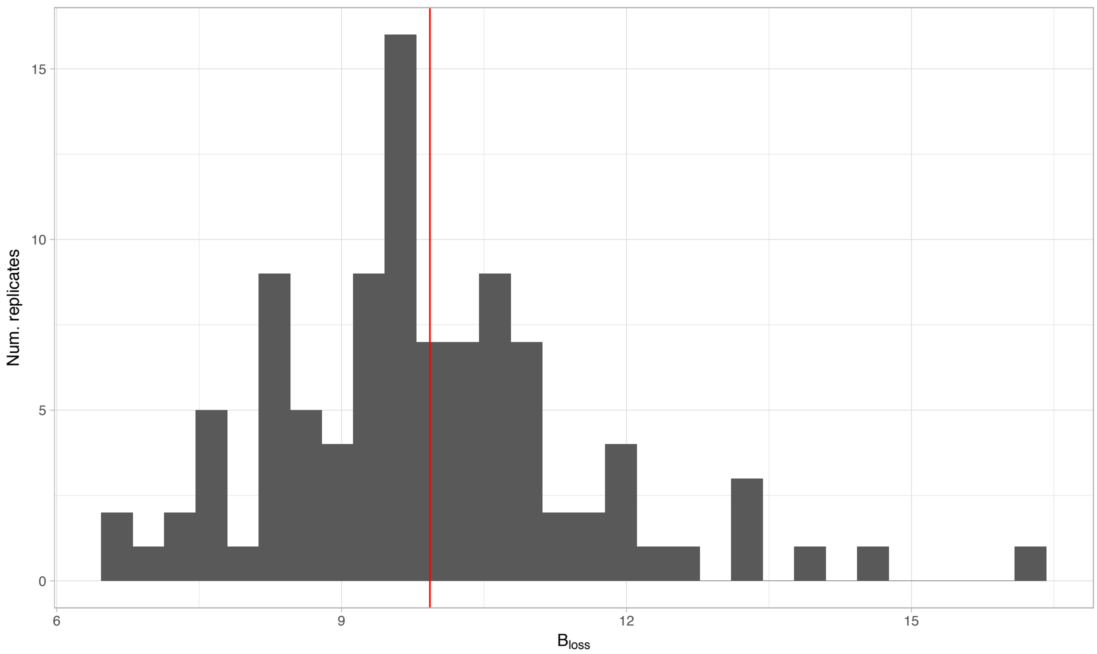

Figure 2.42: Histogram of the bootstrap distribution of B_{loss} where the red line indicates the base model estimate.

from these data and that the lowest observed SSB during that period (i.e. B_{loss} = SSB(1992) = 9.93 kt), which is the lowest observed biomass from the base–line model, is an appropriate value at which to set either as B_{pa} or B_{lim}, depending on the the perception of the historical fishing mortality. As the fishing mortality is perceived to have since mid 1990s varied between 0.3 and 0.5 on fully recruited, equivalent F_{5-10} of 0.15 to 0.3 it is suggested that $B_{pa} = B_{loss}$.

In line with ICES technical guidelines, since B_{pa} but not B_{lim} can be estimated, a proxy for B_{lim} can be calculated based on the inverse of the standard factor, $e^{\sigma * 1.645}$ where σ is 0.2, used for calculating B_{pa} from B_{lim}. Therefore, a proxy for B_{lim} could be set at $B_{pa}/e^{1.645*0.2} = 9.93/1.4 = 7.09kt$.

3.2.6.2 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. 2.41), the ICES guidelines suggest that the “hockey-stick” recruitment function is used, i.e.

$$R_y = \bar{R}_y \min(1, S_y/B_{loss}) \tag{2.19}$$

where R_y is annual recruitment, S_y the spawning stock biomass, B_{loss} 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 the historical distribution using a block-bootstrap, randomly drawn block starting years and including 6 consecutive years in the blocks. This is done to account for intra-correlation in the recruitment time–series, as illustrated in fig. 2.43. The timing of the recruitment in the model occurs at the end of the 1^{st} time-step, using the projected spawning stock biomass at the same time.

3.2.6.3 Management procedure in forward projections

Observation error and to some degree model error are addressed by the bootstrap approach employed in here. Issues related to the stock structure have been discussed in WGDEEP-2007, which suggested that ling 5a should be assessed as single stock unit. Analytical retrospetive analysis indicates a degree of autocorrelation in observation error, while this is a concern it assumed that this is caused by inconsistencies in the survey indices.

Illegal landings and discards by Icelandic fishing vessels are considered to be negligible and it is assumed that foreign vessel catches will be part of the management plan when implemented. It is assumed therefore implementation error would be virtually none. The largest source of error outstanding is the extent of process error, in particular variation in the stock recruitment relationship, and the assessment error.

The descision rule evaluated follows the methodology set out in AGICOD2009. The rule evaluation framework can be classified as simulation without an assessment feedback (ICES 2006), i.e. it is thus assumed that the simulation within the operating model represents the true stock dynamics. Errors in the assessment procedure that relate to harvest advice model are emulated as:

$$\hat{B}_y^{ref} = e^{E_y} B_y^{ref} \tag{2.20}$$

where B_y^{ref} is the reference biomass, $E_y = \sigma(\rho\epsilon_{y-1} + \sqrt{1-\rho^2}\epsilon_y)$ is the assessment error and σ is CV of the reference biomass, ρ the autocorrelation between assement years and $\epsilon_y \sim N(0,1)$. Then the decision which allocates catches to the fleets is simply a scalar applied to the estimate of the reference biomasss:

$$TAC_{y+1} = H\hat{B}_y^{ref} \tag{2.21}$$

where the evaluation assumes that 2 quarters elapse between the time at which the reference biomass is estimated and the beginning of the fishing year to which the TAC applies. This is to approximate the situation that will normally be encountered when providing advice in practice, where the stock assessment will cover until the end of quarter 1 and the fishing year goes from September 1 to August 31[6].

For ling in 5a B_y^{ref} is the biomass of fish larger than 75 cm at the assessment step, the corresponding CV set at 0.28 i.e the CV of the reference biomass. The autocorrelation in assessment error ρ is set to 0.8 which is perceived as the upper limit to potential correlation. Figure 2.44 illustrates the deviation of the reference biomass as estimated in the last year of the analytical retrospective compared with the most recent assement.

[6]In real applications the harvest rate will be scaled when SSB is below $B_{trigger}$ according to the ratio between SSB and $B_{trigger}$

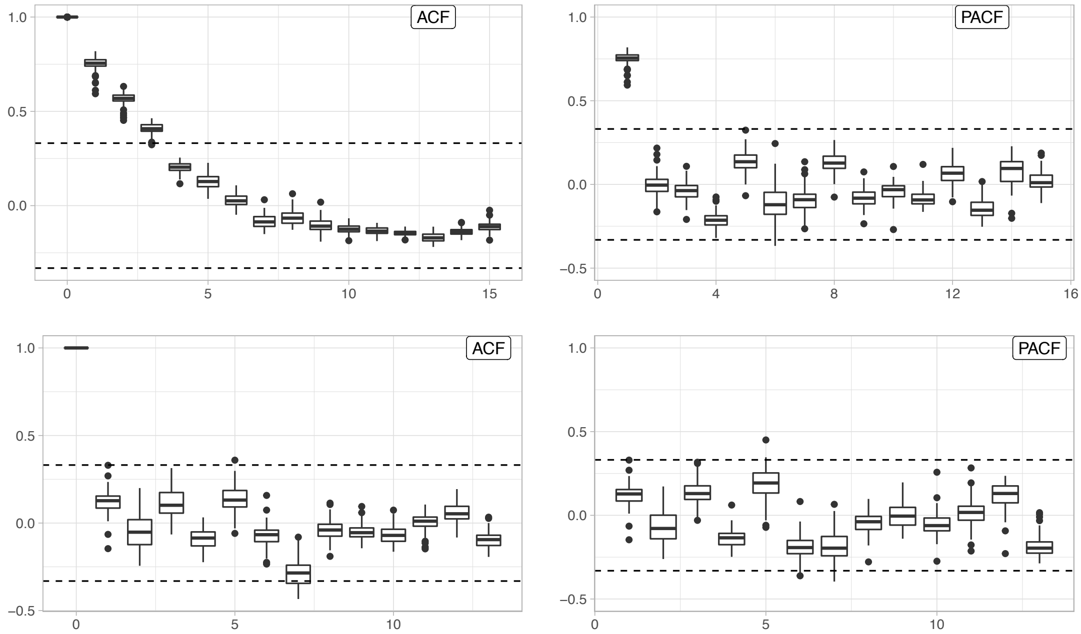

Figure 2.43: Estimated autocorrelation (left panels) and partial autocorrelation (right panels) in recruitment. Top panels indicate the correlation including all estimates of recrutitment while the bottom panels recruitment exluding estimates after 2005. The dashed lines illustrate the standard 95% uncertainty region.

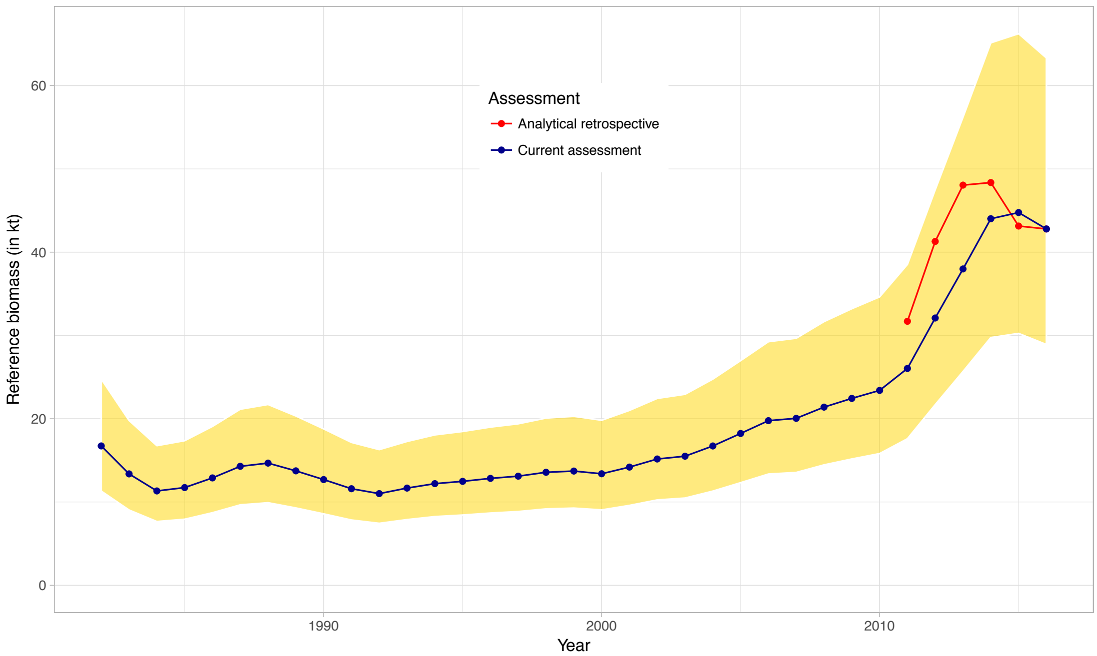

Figure 2.44: ling in 5a. Current assement of the reference biomass of ling (> 75 cm) compared with assessment from the analytical retrospective estimate of the terminal biomass. The shaded yellow ribbon represents the uncertainty (CV = 0.28) at the terminal year.

3.2.6.4 Setting H_{lim} and H_{pa}

According to the ICES guidelines, the precautionary reference points are set by simulating the stock using the stock-recruitment relationship described in section 3.2.6.2, based on a wide range of harvest rates, (see eq. 2.21), ranging from 0 to 1 and setting H_{lim} as the H that, in equilibrium, gives a 50% probability of SSB $> B_{lim}$ without assessment error, described in eq. 2.20. From this F_{lim} is set as the equilibrium fishing mortality when H_{lim} is applied. H_{pa} is then set as the harvest rate that would lead to the equilibrium fishing mortality of F_{pa}. F_{pa} is defined as the $F_{lim}/e^{1.645\sigma}$ where σ is the CV of the estimated fishing mortality in the assessment year.

The simulation predicted the stock status was projected forward 300 years. For each bootstrap model estimate the stock status was projected 10 times, resulting in a total of 1000 samples. The spawning stock biomass was calculated based on model output after 2060. This is done to ensure that the stock had reached an equilibrium under the new fishing mortality regime.

The results from the long term simulations are shown in the top panels of fig. 2.45; the value of H, H_{lim}, resulting in 50% long–term probability of SSB $> B_{lim}$ was estimated at 0.56 (an equivalent F of 0.70). As the CV of F in 2016 is 0.33, F_{pa} is estimated as $0.71/1.72 = 0.41$. The equivalent harvest rate is then $H_{pa} = 0.35$.

3.2.6.5 Maximum sustainable yield

An additional simulation experiment where, in addition to recruitment and bootstrap variations, assessment error was added the harvest rate that would lead to the maximum sustainable yield, H_{msy}, was estimated. From the simulation annual total landings c_y were calculated after 2060. Average annual landings and 90% quantiles were used to determine the yield by H. Figure 2.46 shows the evolution of catches, SSB and fishing mortality for select values of H are shown. The equilibrium yield curve is shown in figure 2.45, where the maximum average yield, under the recruitment assumptions, is 7.85 thousand tons with a 95% interval of for the yield 3.64 and 15.00 thousand tons. Table 2.9 shows the equilibrium results by harvest rate for select statistics.

H_{msy} is estimated to be 0.24. The evolution of the spawning stock biomass is shown in figure 2.46. Equilibrium spawning stock biomass is shown in figure 2.45. The spawning stock biomass obtained at H_{msy} is estimated at 31.20 thousand tons at $H = 0.24$ with an upper quantile of 58.16 thousand tons and lower quantile of 14.32 thousand tons.

In-line with ICES technical guidelines the MSY $B_{trigger}$ is set as B_{pa}, as the stock has not been managed according to F_{msy}, or equivalents thereof, for more than 5 years.

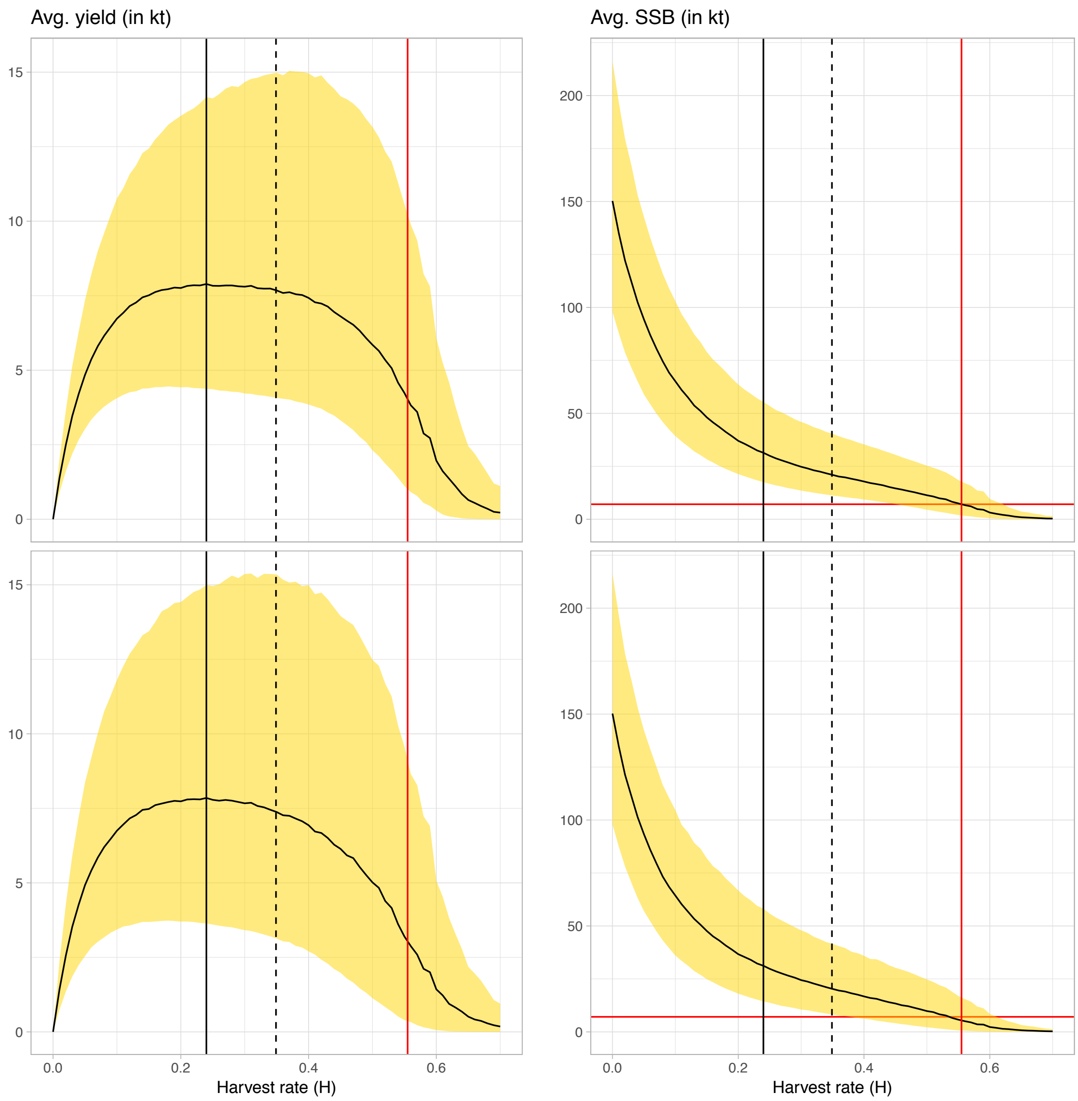

Figure 2.45: Ling in 5a. Equilibrium catch (left) and SSB (right) curves as a function of H. Top panels show the results with process error while the bottom panels have furter added assessment uncertainty. The black solid curves indicate the median projected catch and SSB and the shaded yellow region the 5% – 95% percentiles. Vertical lines indicate H_{lim} (red), H_{pa} (dashed) and H_{msy}. The horizontal red line indicates B_{lim}.

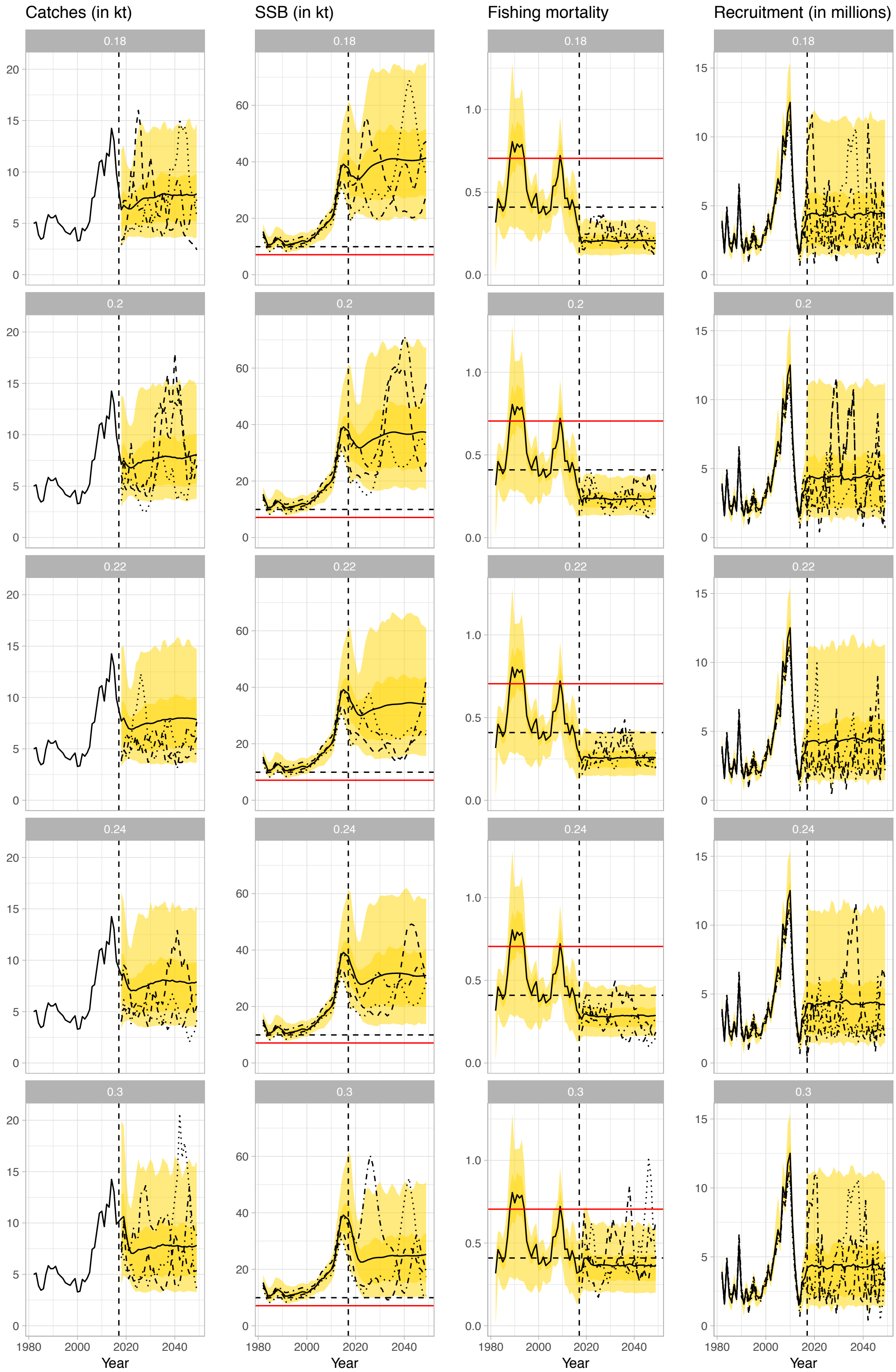

Figure 2.46: Ling in 5a. Projected catches, spawning stock biomass and fishing mortality for select target harvest rates. Red and black dashed horizontal lines represent the limit and pa reference points respectively for SSB and F.

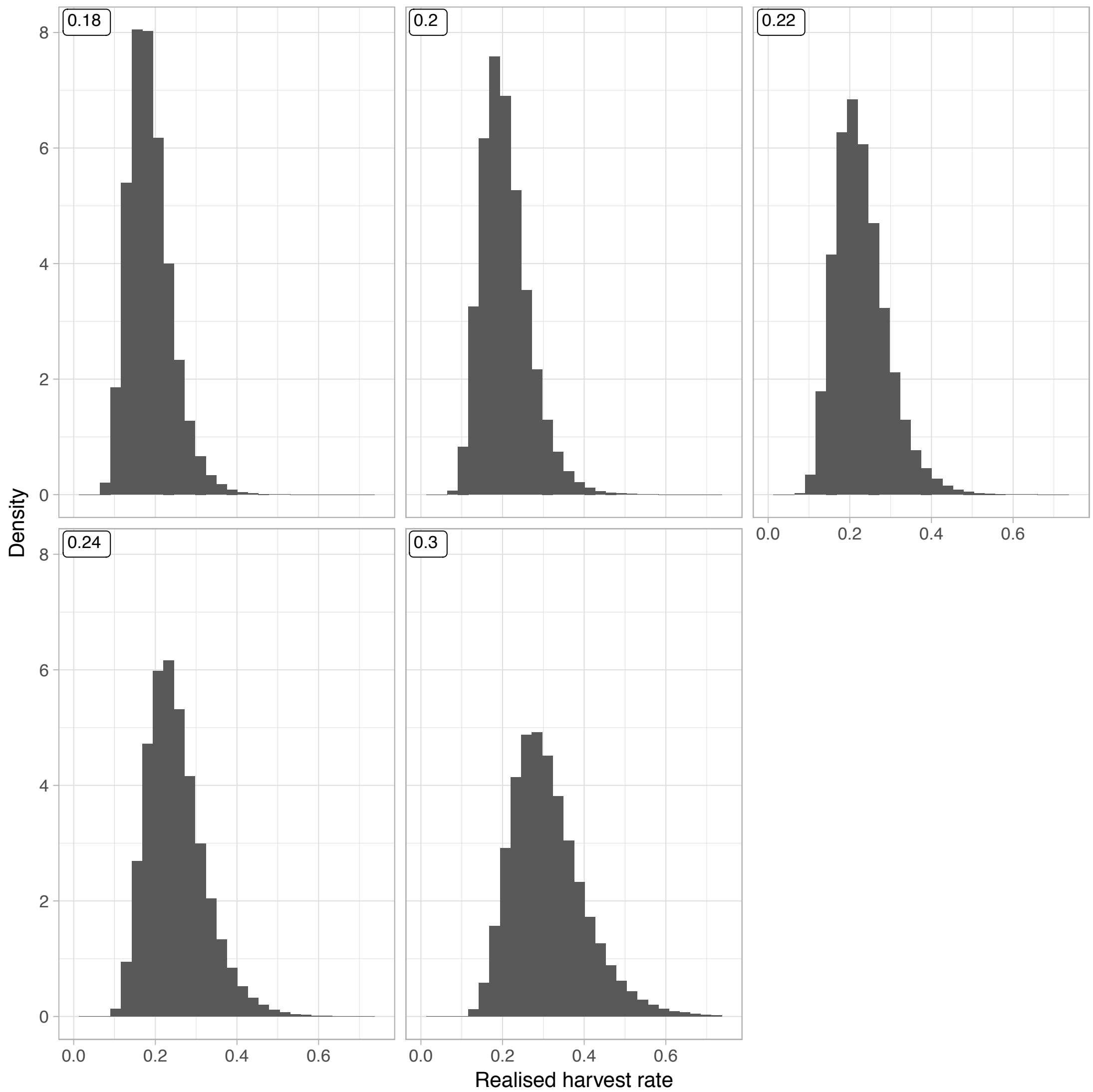

Figure 2.47: Ling in 5a. Distribution realised harvest rates as a function target harvest rates

Table 2.9: Ling in 5a. Equilibrium averages of yield, fishing mortality (F at age 15^+) spawning stock biomass (SSB), recruitment and probility that SSB falls below either B_{pa} or B_{pa} at any point in time from forward projections of the stock status of ling.

Harvest rate	Eq. yield	F	SSB	Recruitment	$P(\exists y \vert SSB_y < B_{pa})$	$P(\exists y \vert SSB_y < B_{lim})$
0.06	5.42 (2.84,9.21)	0.065 (0.040,0.099)	86.00 (52.21,133.53)	4.35 (1.42,11.21)	0.00	0.00
0.07	5.85 (3.02,10.02)	0.076 (0.047,0.116)	79.48 (47.43,125.08)	4.33 (1.42,11.16)	0.00	0.00
0.08	6.20 (3.17,10.75)	0.088 (0.054,0.134)	73.25 (43.15,116.52)	4.30 (1.42,11.17)	0.00	0.00
0.09	6.47 (3.33,11.27)	0.099 (0.060,0.152)	68.42 (39.55,110.44)	4.32 (1.41,11.14)	0.00	0.00
0.1	6.75 (3.43,11.81)	0.111 (0.067,0.170)	64.33 (36.04,104.72)	4.33 (1.42,11.17)	0.00	0.00
0.11	6.96 (3.54,12.27)	0.122 (0.074,0.189)	60.22 (33.51,97.69)	4.34 (1.42,11.17)	0.00	0.00
0.12	7.16 (3.57,12.69)	0.133 (0.081,0.207)	56.76 (31.26,94.19)	4.34 (1.42,11.19)	0.00	0.00
0.13	7.28 (3.63,12.99)	0.146 (0.087,0.227)	53.30 (28.68,89.19)	4.33 (1.41,11.16)	0.00	0.00
0.14	7.45 (3.69,13.31)	0.158 (0.094,0.247)	50.57 (26.90,86.51)	4.36 (1.42,11.19)	0.00	0.00
0.15	7.48 (3.69,13.44)	0.170 (0.101,0.266)	47.63 (24.86,81.93)	4.32 (1.41,11.19)	0.00	0.00
0.16	7.61 (3.70,13.75)	0.182 (0.107,0.287)	45.06 (23.39,78.20)	4.33 (1.42,11.20)	0.00	0.00
0.17	7.66 (3.72,14.11)	0.195 (0.114,0.308)	43.09 (21.85,75.90)	4.34 (1.41,11.22)	0.01	0.00
0.18	7.71 (3.73,14.22)	0.207 (0.121,0.329)	40.78 (20.42,72.48)	4.34 (1.42,11.18)	0.02	0.00
0.19	7.75 (3.72,14.39)	0.218 (0.127,0.348)	38.81 (19.26,69.69)	4.33 (1.42,11.21)	0.04	0.00
0.2	7.73 (3.70,14.42)	0.232 (0.135,0.373)	36.68 (18.02,66.76)	4.32 (1.42,11.15)	0.09	0.01
0.21	7.80 (3.70,14.59)	0.245 (0.142,0.394)	35.33 (17.07,64.09)	4.32 (1.42,11.19)	0.14	0.01
0.22	7.81 (3.69,14.76)	0.257 (0.148,0.416)	33.98 (16.08,62.06)	4.33 (1.42,11.17)	0.18	0.03
0.23	7.80 (3.65,14.84)	0.270 (0.155,0.441)	32.27 (15.23,59.51)	4.31 (1.41,11.16)	0.30	0.05
0.24	7.85 (3.64,15.00)	0.284 (0.163,0.463)	31.20 (14.33,58.17)	4.33 (1.41,11.19)	0.40	0.07
0.25	7.78 (3.60,14.96)	0.297 (0.169,0.486)	29.76 (13.75,55.83)	4.31 (1.42,11.14)	0.50	0.10
0.26	7.76 (3.56,15.02)	0.311 (0.176,0.510)	28.56 (12.97,53.92)	4.29 (1.41,11.11)	0.61	0.17
0.27	7.78 (3.53,15.17)	0.324 (0.183,0.537)	27.49 (12.20,52.45)	4.30 (1.40,11.18)	0.70	0.23
0.28	7.76 (3.51,15.31)	0.339 (0.190,0.564)	26.48 (11.74,50.90)	4.30 (1.40,11.13)	0.82	0.29
0.29	7.71 (3.46,15.22)	0.351 (0.195,0.585)	25.58 (11.19,49.41)	4.28 (1.40,11.10)	0.85	0.37
0.3	7.67 (3.41,15.36)	0.367 (0.203,0.614)	24.43 (10.51,47.95)	4.26 (1.37,11.10)	0.93	0.48
0.31	7.69 (3.39,15.38)	0.379 (0.210,0.639)	23.74 (10.21,46.74)	4.29 (1.36,11.07)	0.96	0.56
0.32	7.58 (3.33,15.23)	0.394 (0.217,0.667)	22.80 (9.65,44.93)	4.23 (1.34,11.03)	0.98	0.64
0.33	7.53 (3.27,15.37)	0.411 (0.224,0.700)	21.95 (9.13,43.72)	4.22 (1.31,11.04)	0.99	0.74
0.34	7.45 (3.20,15.36)	0.426 (0.231,0.729)	21.08 (8.65,42.37)	4.19 (1.28,10.98)	0.99	0.81
0.35	7.38 (3.13,15.35)	0.438 (0.237,0.753)	20.27 (8.15,41.56)	4.15 (1.24,10.90)	1.00	0.86
0.36	7.27 (3.04,15.17)	0.454 (0.243,0.785)	19.51 (7.70,40.49)	4.10 (1.19,10.81)	1.00	0.91
0.37	7.25 (3.01,15.08)	0.468 (0.251,0.810)	19.04 (7.45,39.57)	4.12 (1.15,10.81)	1.00	0.92
0.38	7.15 (2.88,15.10)	0.484 (0.257,0.841)	18.20 (7.02,37.84)	4.06 (1.07,10.73)	1.00	0.96
0.39	7.07 (2.83,14.96)	0.499 (0.263,0.872)	17.55 (6.59,37.13)	4.03 (1.04,10.66)	1.00	0.98
0.4	6.93 (2.70,14.99)	0.514 (0.269,0.904)	16.74 (6.21,35.94)	3.96 (0.96,10.53)	1.00	0.98
0.41	6.72 (2.59,14.69)	0.531 (0.276,0.940)	16.00 (5.83,34.39)	3.86 (0.88,10.39)	1.00	0.99
0.42	6.67 (2.42,14.74)	0.546 (0.282,0.973)	15.59 (5.29,34.26)	3.82 (0.76,10.32)	1.00	0.99
0.43	6.51 (2.29,14.51)	0.565 (0.288,1.012)	14.73 (4.90,32.99)	3.76 (0.72,10.20)	1.00	1.00
0.44	6.28 (2.11,14.23)	0.580 (0.294,1.048)	13.98 (4.47,31.39)	3.63 (0.61,9.96)	1.00	1.00
0.45	6.14 (1.99,13.95)	0.594 (0.299,1.085)	13.39 (4.09,30.27)	3.55 (0.48,9.83)	1.00	1.00
0.46	5.92 (1.79,13.80)	0.614 (0.304,1.125)	12.57 (3.64,29.34)	3.46 (0.44,9.67)	1.00	1.00
0.47	5.83 (1.65,13.65)	0.632 (0.309,1.159)	12.13 (3.33,28.38)	3.38 (0.36,9.50)	1.00	1.00
0.48	5.53 (1.46,13.28)	0.647 (0.313,1.202)	11.37 (2.86,27.21)	3.22 (0.26,9.28)	1.00	1.00
0.49	5.27 (1.31,12.88)	0.667 (0.319,1.245)	10.62 (2.54,25.93)	3.11 (0.22,9.06)	1.00	1.00
0.5	5.02 (1.13,12.48)	0.686 (0.323,1.297)	9.82 (2.15,24.75)	2.95 (0.12,8.71)	1.00	1.00
0.51	4.83 (0.99,12.28)	0.704 (0.326,1.339)	9.34 (1.86,23.57)	2.83 (0.11,8.43)	1.00	1.00
0.52	4.39 (0.83,11.68)	0.723 (0.329,1.392)	8.29 (1.55,22.04)	2.62 (0.09,7.99)	1.00	1.00
0.53	4.16 (0.69,11.26)	0.742 (0.331,1.442)	7.75 (1.26,20.98)	2.47 (0.06,7.78)	1.00	1.00
0.54	3.62 (0.52,10.28)	0.765 (0.334,1.497)	6.59 (0.95,18.94)	2.15 (0.05,7.09)	1.00	1.00
0.55	3.20 (0.40,9.58)	0.784 (0.333,1.567)	5.76 (0.67,16.94)	1.92 (0.03,6.66)	1.00	1.00
0.56	2.88 (0.33,8.66)	0.811 (0.331,1.641)	5.07 (0.57,15.55)	1.71 (0.02,6.39)	1.00	1.00
0.57	2.59 (0.23,8.28)	0.832 (0.330,1.718)	4.48 (0.40,14.25)	1.52 (0.02,6.05)	1.00	1.00
0.58	2.12 (0.15,7.24)	0.858 (0.328,1.785)	3.55 (0.27,11.98)	1.25 (0.01,5.60)	1.00	1.00
0.59	2.00 (0.11,6.91)	0.880 (0.321,1.887)	3.44 (0.19,11.15)	1.20 (0.01,5.41)	1.00	1.00

3.2.6.6 Proposed target harvest rate

When considering the candidate harvest rate for ling in 5a on may want to investigate the marginal gain of increasing the harvest rate in terms of equilibrium yields. Even with catch rates as low as 0.13 the equilibrium yields are roughly comparable with that of the H_{msy}. In addition short term forward projections illustrated in fig. 2.46 indicate that for harvest rates will have adapted (on average) to their equilibrium catch levels within a decade from now.

The proposed target havest rate, of 0.18 illustrated in fig. 2.48, is considered safe and precautionary as it is lower than any precautionary reference points listed in the sections above. Furthermore it can be considered consistent with the ICES MSY approach, while lower than the estimated H_{msy} of 0.24, the expected long term yield is less that 2% lower. The expected 5% and 95% percentiles of true harvest rates, when setting catches according 0.18, are 0.12 and 0.28 respectively, as illustrated by figure 2.47.

Table 2.10: Ling in 5a. Summary of reference point proposed for ling in 5a. The fishing mortality is relative to ages 15^+ and harvest rates correspond to the reference biomass of B_{75cm^+}.

Framework	Reference point	Value	Technical basis
MSY approach	MSY $B_{trigger}$	9.93 kt	B_{pa}
	H_{msy}	0.24	The harvest rate that maximises the median long-term catch in stochastic simulations with recruitment drawn from a block bootstrap of historical recruitment, with block size 6, scaled according to a hockey stick recruitment function with B_{lim} as defined below.
	F_{msy}	0.284	The median fishing mortality when an harvest rate of H_{msy} is applied.
Precautionary approach	B_{lim}	7.09 kt	$B_{pa}/e^{1.645\sigma}$ where $\sigma = 0.2$
	B_{pa}	9.93 kt	SSB(1992), corresponding to B_{loss}
	H_{lim}	0.56	H corresponding to 50% long-term probability of SSB $> B_{lim}$
	F_{lim}	0.70	F corresponding to H_{lim}
	F_{pa}	0.41	$F_{lim}/e^{1.645\sigma}$ where $\sigma = 0.33$
	H_{pa}	0.35	H corresponding to F_{pa}
Management plan	H_{mp}	0.18	H such that $F \leq F_{msy}$, long-term yield is consistent with MSY while leading to high stock biomass
	$B_{trigger}$	9.93 kt	Set as B_{pa} as the stock has not been harvested at F_{msy}, or equivalents thereof

3.2.7 Conclusions

Overall the gadget model presented here captures the overall trends in the data, and in spite of minor mis-fits the model is usable for assessing the stock and to base advice to managers.

In a complicated such as the gadget model that has many parameters and many data-sets of varying quality it is to be expected that there may be problems with some parameters and fit to some data-sets.

The main problem the model has, as would any other models, is the rapid increase in the survey indices in recent years and the large CV of these indices in that period. This is more a data problem than a model problem and given the decrease in the last 5

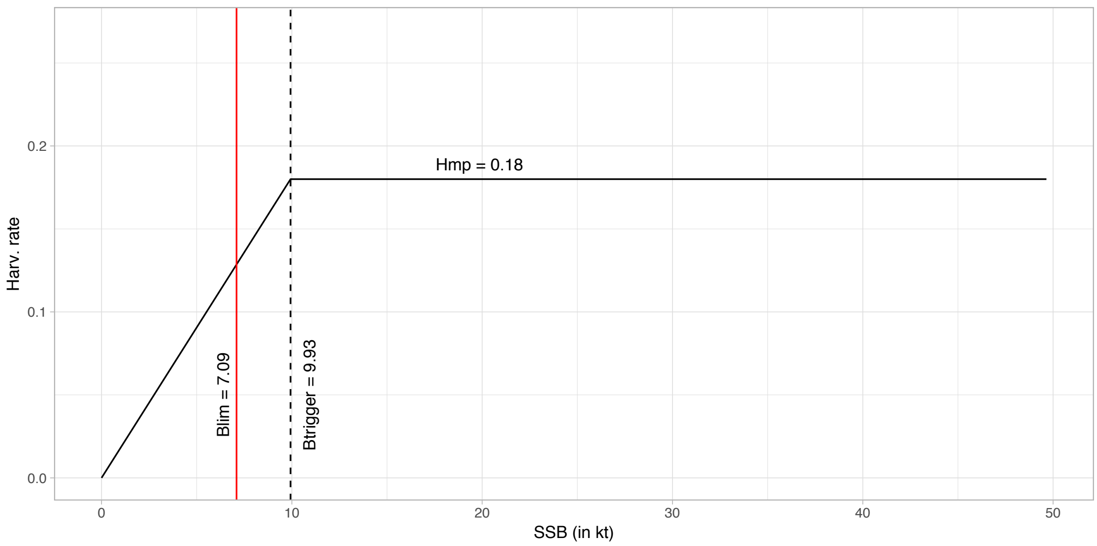

Figure 2.48: Ling in 5a. Graphical presention of the proposed managment rule. The black solid line indicates the harvest rate relative to the >75cm biomass as a function of the SSB

years in the smaller length groups in the tuning series this may resolve it self in coming years.

Most parameters are well defined except for the ones relating to gillnets, the reason being the limited data for this fleet. Catches from gillnets have been decreasing in recent years. For example catches in gillnets were around one third to half of ling catches in 2000 to 2001 but have now decreased to around 7% of Icelandic commercial catches in 2016. This is the result of changes in fleet dynamics and regulations. It may even be justifiable to omit the gillnet fleet in the future from the model. Anyway the problems with the gillnet fleet in the model are of minor importance in the current fishery.

Another parameter that is poorly defined is the σ_0 that is the standard deviation of recruitment length. This is also of minor importance as ling does not enter the fishery until the age 5 and 6, but by then the β-parameter has created a standard deviation in the length at age.

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3.2.8 Annex

3.2.8.1 Initial parameter values and boundaries

```
; input file for the gadget model
; created automatically from Rgadget
; 06-ling/08-back2150/params.in - Sat Feb 25 20:21:44 2017
switch value lower upper optimise
ling.Linf 160 100 200 1
ling.k 90 40 100 1
lingimm.walpha 2.21156217031841e-06 1e-10 1 0
lingimm.wbeta 3.20649742614076 2 4 0
ling.bbin 6 1e-08 100 1
lingimm.M 0.15 0.001 1 0
lingimm.init.scalar 200 1 300 1
ling.init.F 0.4 0.1 1 1
lingimm.init.3 1 0.001 1000 1
lingimm.init.4 1 0.001 1000 1
lingimm.init.5 1 0.001 1000 1
lingimm.init.6 1 0.001 1000 1
lingimm.init.7 1 0.001 1000 1
lingimm.init.8 1 0.001 1000 1
lingimm.init.9 1 0.001 1000 1
lingimm.init.10 1 0.001 1000 1
ling.recl 12 4 20 1
ling.mat1 70 10 200 1
ling.mat2 73 54.75 91.25 1
ling.rec.scalar 400 1 500 1
ling.rec.1982 1 0.001 1000 1
ling.rec.sd 5 4 20 1
ling.rec.1983 1 0.001 1000 1
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ling.rec.2016 1 0.001 1000 1
lingmat.M 0.15 0.001 1 0
lingmat.init.scalar 200 1 300 1
lingmat.init.5 1 0.001 1000 1
lingmat.init.6 1 0.001 1000 1
lingmat.init.7 1 0.001 1000 1
lingmat.init.8 1 0.001 1000 1
lingmat.init.9 1 0.001 1000 1
lingmat.init.10 1 0.001 1000 1
lingmat.init.11 1 0.001 1000 1
lingmat.init.12 1 0.001 1000 1
lingmat.init.13 1 0.001 1000 1
lingmat.init.14 1 0.001 1000 1
lingmat.init.15 1 0.001 1000 1
lingmat.walpha 2.21156217031841e-06 1e-10 1 0
lingmat.wbeta 3.20649742614076 2 4 0
ling.igfs.alpha 0.5 0.01 3 1
ling.igfs.l50 50 10 100 1
ling.lln.alpha 0.5 0.01 3 1
ling.lln.l50 50 10 100 1
ling.bmt.alpha 0.5 0.01 3 1
ling.bmt.l50 50 10 100 1
ling.gil.alpha 0.5 0.01 3 1
ling.gil.l50 50 10 100 1
```

3.2.8.2 Settings of optimisation routines

```
[simann]
simanniter 100000 ; number of simulated annealing iterations
simanneps 1e-03 ; minimum epsilon, simann halt criteria
t         30000000   ; simulated annealing initial temperature
rt        0.85  ; temperature reduction factor
nt        2     ; number of loops before temperature adjusted
ns        5     ; number of loops before step length adjusted
vm        1     ; initial value for the maximum step length
cstep     2     ; step length adjustment factor
lratio    0.3   ; lower limit for ratio when adjusting step length
uratio    0.7   ; upper limit for ratio when adjusting step length
check     4     ; number of temperature loops to check
[hooke]
hookeiter 40000  ; number of hooke & jeeves iterations
hookeeps  1e-04 ; minimum epsilon, hooke & jeeves halt criteria
rho       0.5   ; value for the resizing multiplier
lambda    0     ; initial value for the step length
[bfgs]
bfgsiter  10000 ; number of bfgs iterations
bfgseps   0.01  ; minimum epsilon, bfgs halt criteria
sigma     0.01  ; armijo convergence criteria
beta      0.3   ; armijo adjustment factor
```

3.2.9 Explaining changes in recruitment

3.2.9.1 Temporal changes in recruitment

The relationship between the estimated spawning stock and recruitment is shown in figure 2.41. In the Gadget model for Ling in 5a the annual recruitment, during the observation period, is estimated as a fixed effect without any consideration of the size of the spawning stock biomass. This means that no formal stock recruit relationship is defined. This is allowed by information on past recruitment such as age and length distributions and survey indices. It can be observed that for time periods where less data is available on recruitment, such as recruitment in the most recent years, have higher levels of uncertainty.

Ling in 5a has experienced an unusual spike in recruitment, when compared to years prior to 2003. There could be two different reasons for this observation, impaired recruitment due to over exploitation or environmental changes. In the following sub-subsections these theories will be explored.

3.2.9.2 Impaired recruitment

Catches in 1950 to the mid seventies were around 10 thous. tonnes annually but in the eighties and nineties fell to 3 to 4 thous tonnes. After 2005 catches increased again to similar levels as before (10 thous tonnes). So the decrease in recruitment would be the result of over-exploitation. This may certainly be the case when considering historical fishing mortality (Figure 2.49). However there is no information available on fishing mortality or harvest rates for ling in 5a before 1982, when catch levels were high for over 25 years.

3.2.9.3 Environmental factors

Since 2000 bottom temperature has been increasing on the western and north-western part of the shelf (Figure 2.50). This increase in temperature has opened up areas for species that are on the northern fringe of their distributional range as can be seen from changes in indices of several of such species such as ling, tusk, anglerfish and lemon sole (Figure 2.51).

There does seem to be a strong correlation between the increase in the southern species in figure 2.51 and the increase in temperature in figure 2.50.1, 2.50.2 and 2.50.3. However in 2.50.4 wich is the longest time series going back to 1945 and comes from the northern part of the shelf there is no increase in temperature around 2000. However it can be seen that there was a significant drop in temperature on the northern part of the shelf in the early seventies. This strongly suggests that the waters around Iceland in the fifties and sixties ware considerably warmer than in the seventies to nineties. It is therefore not unlikely that the changes in catches observed in figure 2.49 are to a large extend driven by changes in the environment.

The increase in the biomass shown in figure 2.51 coinsided with a rapid increase in recruitment indices of these species as can be seen in figure 2.52. The striking thing from figure 2.52 is that for three of the four species the juvenile indices have decreased rapidly from a recod high in 2005-2009 to very low levels. This may indicate that the increase in temperature may not on its own be sufficient to ensure continued high recruitment. There could be other envirionmental factors at play, such as species interactions, predation

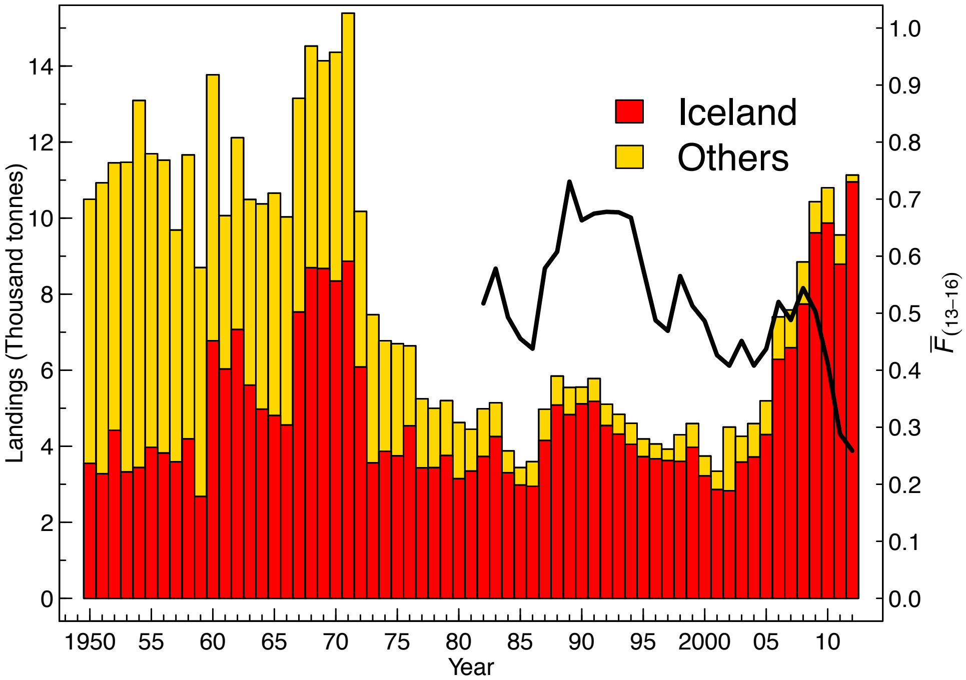

Figure 2.49: Ling in Va: Catches in 1950 to 2012 and estimates of fishing mortality from the Gadget model from 1982 to 2012.

on juveniles or even density dependent factors. However there is no guarantee for a continued good recruitment in coming years.

3.2.9.4 Conclusions

Given the data presented above it seems plausible that the sudden increase in ling and other southern species on the Icelandic shelf is driven mainly by changes in the environment and anecdotal evidence indicates that the decline in catches in the seventies may be similarly driven by decrease in temperature on the Icelandic shelf.

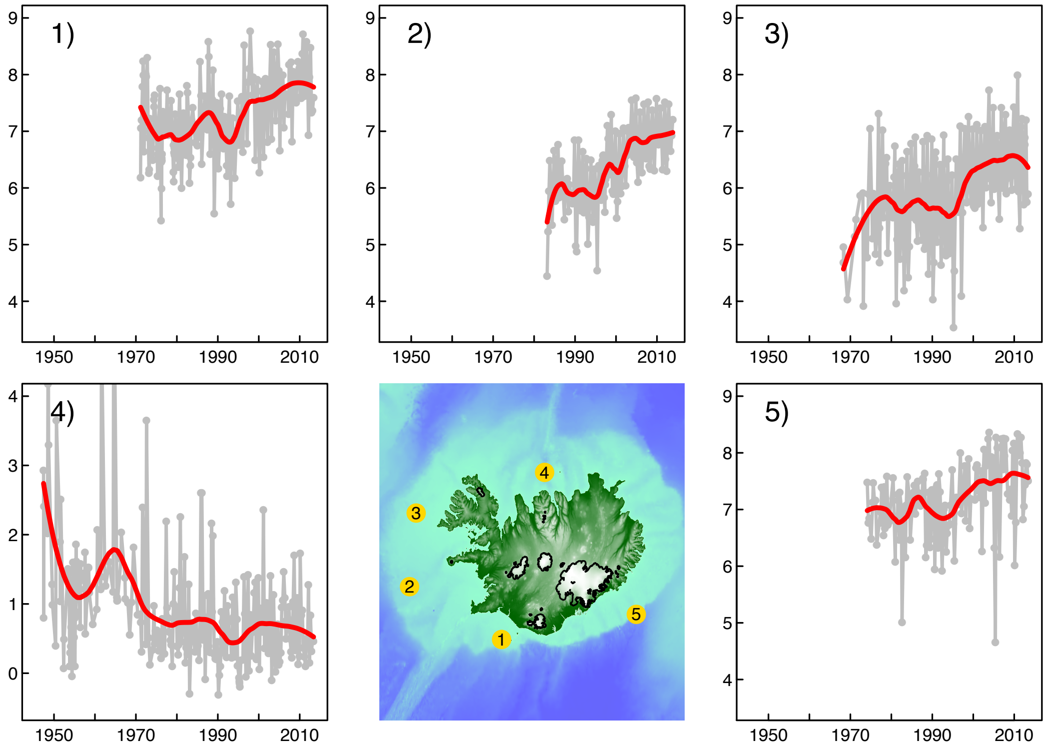

Figure 2.50: Changes in bottom temperature in selected areas around Iceland by year.

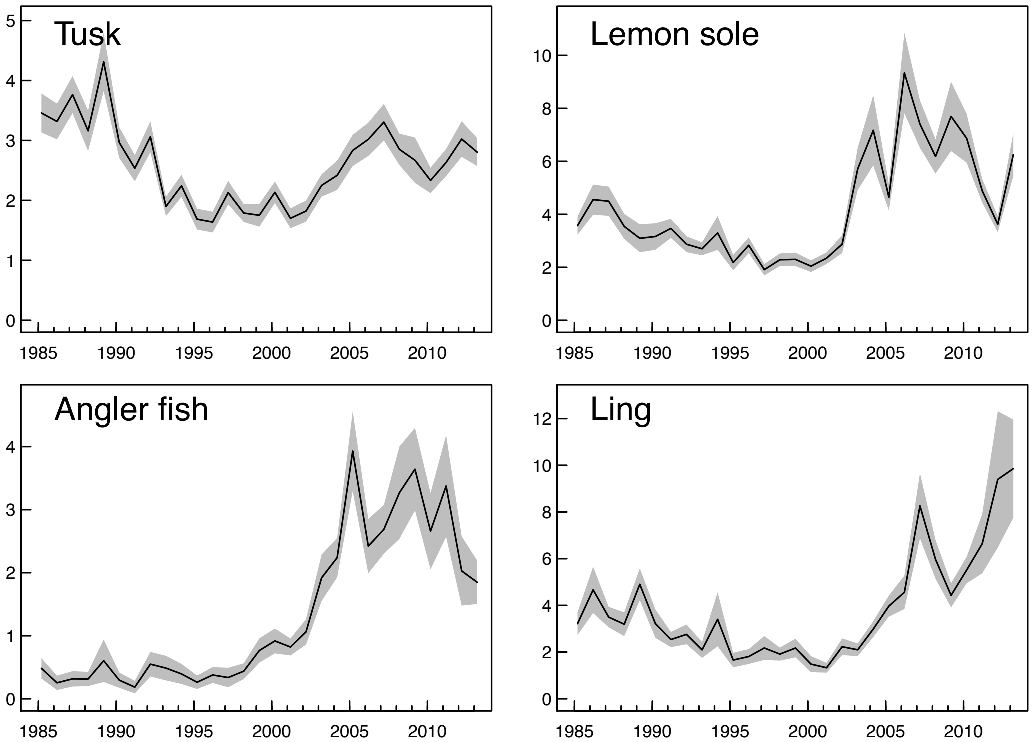

Figure 2.51: Changes in biomass indices for several southern species in 5a from the Icelandic spring survey.

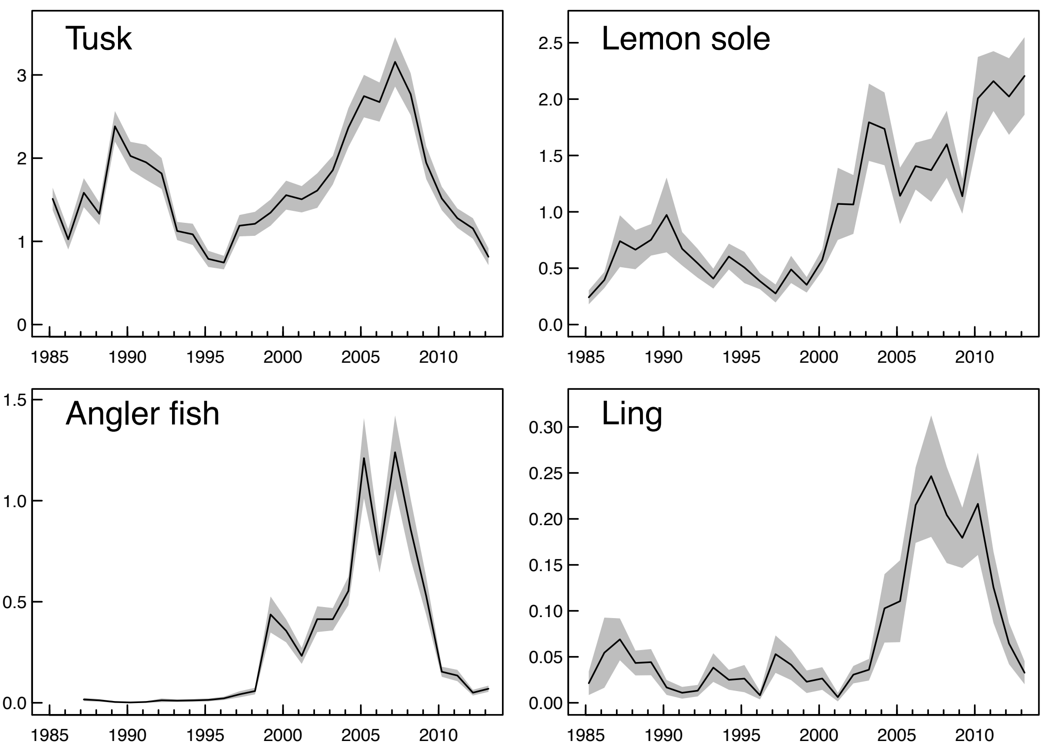

Figure 2.52: Changes in juvenile abundance indices for several southern species in 5a from the Icelandic spring survey.

3.3 Reviewers' report

Carmen Fernández (Spain) and Alfonso Pérez (the Netherlands)

The reviewers examined the stock assessment and Management Strategy Evaluation (MSE) document submitted by Icelandic scientists in advance of the WKICEMSE workshop and provided comments by correspondence. Some of the aspects raised by the reviewers were addressed by correspondence and an updated document was prepared by Icelandic scientists. The workshop then provided a further opportunity to discuss the work in detail. This led to some additional updates of the scientific document. The final version appears in Section 3.2 of the WKICEMSE report. Most of the reviewers' comments were clarifications or referred to aspects that could be explored in future work rather than being urgent matters that needed to be resolved or changed immediately. Many of the reviewers' comments are common to ling and tusk (see Section 2.3 of the WKICEMSE report for the comments on tusk).

3.3.1 Overall conclusion

All the work done in advance by correspondence as well as the presentations and clarifications during the workshop allow concluding that the settings of the stock assessment model, the data used and the model fit are adequate, and that results generated by the assessment model can be used for providing fisheries advice as an ICES Category 1 stock (stocks with quantitative assessments). Aspects identified for additional future consideration are noted below, under "Comments on stock assessment".

The estimation of the precautionary and MSY reference points has been conducted in accordance with the ICES guidelines.

The MSE work that has been developed is of high quality, and pays appropriate attention to uncertainty. The work conducted provides an appropriate technical basis to respond to the harvest control rule evaluation ICES has been requested to undertake. The harvest control rule assessed in this workshop has an HR_{MGT}=0.18 on B(75+ cm) and a trigger point for SSB at MGT $B_{trigger}$= B_{pa} = 9.93 kt, with the harvest rate reduced proportionally when SSB is estimated to be below the trigger. This rule is precautionary (it leads to less than 5% probability of SSB < B_{lim} in all years) and, while based on a harvest rate which is below HR_{MSY}=0.24, the simulations indicate a similar level of long-term catch as HR_{MSY}; this is because the resulting curve of average catch in equilibrium versus harvest rate is flat-topped, with the average long-term catch at HR_{MGT}=0.18 being only 2% below that corresponding to HR_{MSY}=0.24. Therefore, the proposed harvest control rule can be considered to be in conformity with the MSY approach.

3.3.2 Comments on stock assessment

Overall the performance of the stock assessment model developed with Gadget was good. The diagnostics did not show any major issues in the model's ability to follow the average patterns of the main processes determining the productivity of the stock. Unlike in the tusk assessment, the maturity process and the survey selectivity submodels for ling did not show special possibilities for improvement. However a few points were still suggested by the reviewers for future exploration:

- It was suggested that the assumed constant natural mortality-at-age (M=0.15 for all ages) could be contributing to the retrospective pattern observed in the estimated recruitment. For this reason a further exploration of variable natural mortality values at-age was suggested. Different alternatives to estimate values and patterns of change in M as a function of fish age have been proposed (e.g. Gislason *et al.*, 2010). Despite the fact that these methods are based on the evaluation of life-history traits which have been optimized evolutionarily in an environment without fishing, it is expected that the usual negative exponential patterns of decrease of natural mortality with age in the younger ages and/or increase in M due to senescence likely occur. This is especially valid given that fishing mortality in Icelandic waters has not been considered extreme in the past and has showed declining patterns in the last decade. This recommendation is specially made for ling, although it would also be recommended for tusk as an exploratory analysis.

- The stock assessment which forms the basis of all work presented to WKICEMSE, including the retrospective plots in Figure 38 of Section 3.2, used data until the end of 2016. In similar future work, it will be better if the stock assessment replicates as closely as possible the data situation most likely encountered when annual assessments are conducted for the stock, i.e. the data included in the stock assessment go to the end of quarter 1 rather than to the end of the year.

3.3.3 Comments on reference points

The biomass reference points (B_{lim}, B_{pa} and MSY $B_{trigger}$) were calculated in line with ICES guidelines. The stock assessment results show a relatively narrow dynamic range of SSB and an absence of any reduced recruitment signals at the low SSB end of historical values, as estimated by the stock assessment (Figure 41 of Section 3.2). Based on this, in combination with historical harvest rates which are not considered to have been overly high, B_{pa} was set at B_{loss}. This was discussed during the workshop, and accepted by both workshop participants and reviewers.

As discussed in the reviewers' report for tusk, there seems to be a preference in Iceland to express fishing pressure using harvest rates (HR) instead of fishing mortality F. The HRs presented for this stock refer to biomass of fish above the 75 cm of length. Historically this length value has been reported as the limit that defines the harvestable biomass (estimated from the commercial selectivity). Therefore, the fishing pressure reference points were expressed both in terms of harvest rates (HR_{lim}, HR_{pa}, HR_{MSY}) and F (F_{lim}, F_{pa}, F_{MSY}). The reviewers consider that both ways of characterising fishing pressure reference points are valid.

3.3.4 Comments on harvest control rule evaluation

The technical work supporting this evaluation was very similar to the work done for tusk, on which the reviewers commented in Section 2.3. After interaction by correspondence between the reviewers and the scientists doing this work, the original assumptions for simulating future recruitment (which excluded the high 2005–2010 recruitments and assumed independent recruitment across years) were changed to randomly drawing from six-year blocks of historical recruitment without excluding any of the historical recruitment estimates. This change led to higher values of future simulated recruitment and SSB, but did not change the main conclusions from the evaluation. The approximately six-month delay that occurs between the assessment and the start of the fishing year was accounted for in the MSE work.

The range of MSE simulation outputs that has been provided to examine the performance of fishing at different harvest rates (graphs showing the development of the stock, fishing pressure and catch over the next 30 years, as well as in long-term equilibrium) is appropriate. As noted above, the proposed harvest control rule that ICES has been requested to evaluate is based on a harvest rate HR_{MGT}=0.18 and a trigger point at MGT $B_{trigger}$ = 9.93 kt = B_{pa} (with the harvest rate being reduced proportionally when SSB is estimated to be below the trigger). This proposed harvest rule is precautionary (it leads to less than 5% probability of SSB < B_{lim} in all years) and the simulations indicate a flat-topped equilibrium catch curve for reference biomass above 75 cm (B75+). According to this curve, although HR_{MGT} is below HR_{MSY}=0.24, the resulting average long-term catch at HR_{MGT}=0.18 is only 2% below that corresponding to HR_{MSY}=0.24.

As with all work where simulations into the future are conducted, it must be kept in mind that there is uncertainty associated with results. The workshop suggested that the performance of the harvest control rule should be reviewed after some years, e.g. after about five years, and this is considered appropriate by the reviewers.

3.3.5 References

Gislason, H., N. Daan, J. C. Rice and J. G. Pope. 2010. Size, growth, temperature and the natural mortality of marine fish. Fish and Fisheries, 11: 149–158. doi:10.1111/j.1467-2979.2009.00350.

4 Herring

4.1 Summary of work during the WKICEMSE workshop

The scientific work prepared by Icelandic scientists on Management Strategy Evaluation (MSE) of harvest control rules for herring, for which the reviewers had already provided comments by correspondence, was presented and discussed in detail during the WKICEMSE. Several aspects were explored and clarified during the workshop discussions, and a change to the way recruitment is simulated was implemented (with the aim of increasing the realism of the simulated recruitment in the Management Strategy Evaluation). All technical details and workshop conclusions are included in Sections 4.2–4.5, with main points of discussion also covered in the reviewers' report (Section 4.6).

It is noted that the possibility of *Ichthyophonus* epidemic adds considerable uncertainty to the evaluation.

The workshop spent considerable time discussing the properties of the harvest control rule presented to ICES for evaluation. The evaluation is obviously based on the best information and knowledge available at this time. As is always the case, there is uncertainty associated with simulations into future years, with the possibility that non-anticipated changes occur. The workshop considers that it would be appropriate to review the performance of the rule after some years, e.g. after approximately five years.

4.2 Introduction

This report is a response to a request made by the Icelandic Ministry of Industries and Innovation to the Marine and Freshwater Research Institute on forming a harvest control rule (HCR) for Icelandic summer-spawning herring as a basis for a management plan to be adopted. Furthermore, the Ministry requested ICES in a letter dated 22 December 2016 (Reference: ANR16120290/20.8.0) to evaluate if this HCR is consistent with the precautionary approach and in accordance with the ICES MSY approach.

4.2.1 Stock development

Historically, there were two local herring stocks around Iceland, Icelandic summer-spawners and Icelandic spring-spawners. Both of them collapsed in the early 1970s, but before that their stock size was estimated to have been at similar level (Jakobsson, 1980). While the stock of spring-spawners has not recovered so far, the stock of summer-spawners recovered relatively quickly and reached pre-collapse level in the late 1980s (Figure 4.4.1.1). Following appearance of strong year classes in the early 1990s, the spawning–stock biomass (SSB) reached a historical high level around 2008 but has since then been decreasing, despite low fishing mortality (0.09–0.3), because of poor recruitment and mortality caused by *Ichthyophonus*. The 2016 assessment indicates that SSB in 2017 is 303 thousand tonnes, or just above B_{pa} (=MSY $B_{trigger}$=273 thousand t).

4.2.2 Advice and management

The practice has been to manage fisheries on this stock at $F = F_{0.1}$ (= 0.22 = F_{pa}) for more than 20 years, where F is weighted average F by number-at-age 5–10 in the stock. However, no formal management strategy has been developed or proposed until now. The annual total allowable catch (TAC) is decided by the Ministry of Fisheries. Since 1985, the final TAC has more or less followed the recommended TAC given by the MRI with very small discrepancy (ICES, 2016). The ICES assessment working group (NWWG) has pointed out that this management has been successful in the past, despite biased assessments for years where the stock size in the assessment year tended to be overestimated (Figure 4.4.1.3. below). A biased assessment resulted, for example, in fishing mortality during 1987 to 2008 of 0.31 on average (weighed $F_{5\text{-}10}$), or approximately 40% higher than the intended target of $F_{0.1}$=0.22, although below the current F_{pa}. This high F occurred despite the fact that the managers followed the scientific advice and restricted quotas with the aim of fishing at the intended target. Nevertheless, during this period, SSB remained above B_{lim} and reached a record high level around 2008.

As an aside, but in response to a request for clarification by workshop participants, Figure 4.2.2.1 shows the timeframe within the annual assessment process in relation to the most recent data coming into the assessments. The stock assessment model works internally with a year that goes from January 1 to December 31.

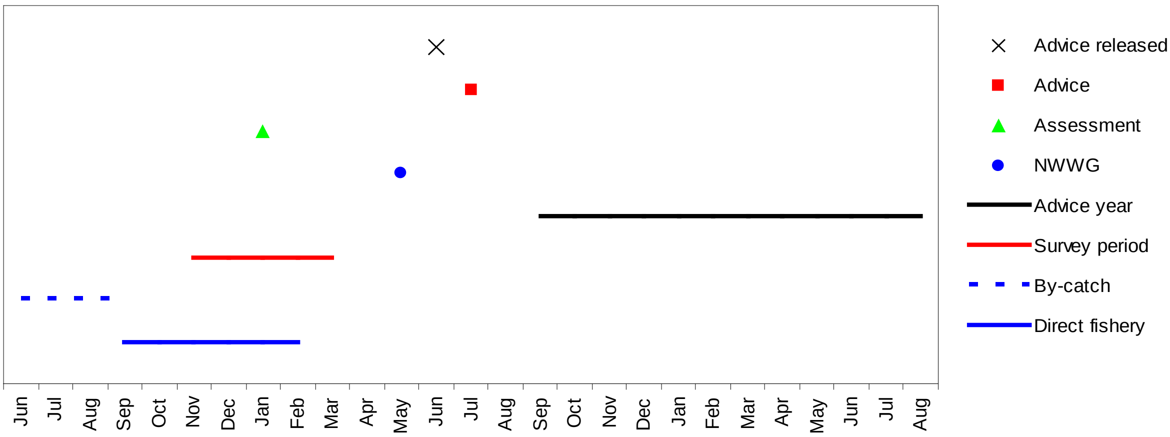

Figure 4.2.2.1. Diagram of the time frame and workflow of most recent data going into the annual assessment of Icelandic summer-spawning herring, which shows the period of the direct fishery, the period of bycatch in the mackerel fishery (no fishery in March–May) and the period of the acoustic surveys. More than 80% of the catches have been taken in October–December. The survey timing has been somewhat variable or from October–February. In stock assessment models done in the calendar year Y the catches in July Y-1 to February Y are allocated to the calendar year Y-1. The survey is at the end of the catch period in the end of calendar year Y-1 or start of calendar year Y (the assessment year).

The catches are modelled by the Baranov's equation assuming catches evenly distributed throughout the year. The assessment is done in May and the calculated stock numbers apply to January 1st of that year. Stock weights are weights from the catches that are taken late in the year, so the timing of stock numbers and stock weights does not match. Spawning stock is calculated for spawning time (July 1st); as the January–February catches are moved to the year before, the stock numbers from January–July are only reduced by half the annual natural mortality.

4.2.3 Feasible harvest control rules for the stock

With respect to selection of harvest control rules (HCR) for the stock, there are several things that need to be considered. The stock can be characterized as long-lived, consisting of many year classes, it has highly variable recruitment, a huge range in historical stock size, and (therefore) statistically significant stock–recruitment relationship. Rapid decrease in the stock size has also been observed, and might happen in the future, because of lethal infection caused by *Ichthtophonus* sp (see below). This all means that catch stabilisers are probably not desirable for the stock, with the cost of more variable catches.

Other things to consider are that the first information on size of recruiting year classes to the fishery (start to appear at age 3) becomes available from juvenile survey at age 1, while age-at-maturity is poorly determined and treated as fixed for the purpose of stock assessment and providing catch advice. Moreover, recruiting year classes to the fishable stock at age 3 are sometimes found schooling separated from the adult stock during the main autumn/winter fishing season and have occasionally been targeted by the fleet. However, in-season area closures are enforced to protect them based on a regulation of the herring fishery set by the Icelandic Ministry of Fisheries in October 1992 (no. 376); i.e. areas are closed if more than 20% of the catches consist of herring ≤27 cm. All above features favour biomass HCRs, based on proportion of biomass above certain age or proportion of SSB, or alternatively HCRs that refer to a specific fishing mortality in the fishing year (e.g. F_{MSY} as is currently applied).

The current advice rule for the stock uses $F_{w5\text{-}10}$=0.22 and $B_{trigger}$ = B_{pa} = 273 kt (Figure 4.2.3.1). Consequently, the resulting catches from the rule depend on SSB if the SSB is below B_{pa}. An alternative rule could be to use proportion of some biomass (B4+, B5+, or SSB) and set $B_{trigger}$ to B_{lim} (Figure 4.2.3.1). Lower $B_{trigger}$ should be accompanied by lower harvest ratio/fishing mortality to make the rule equally precautionary.

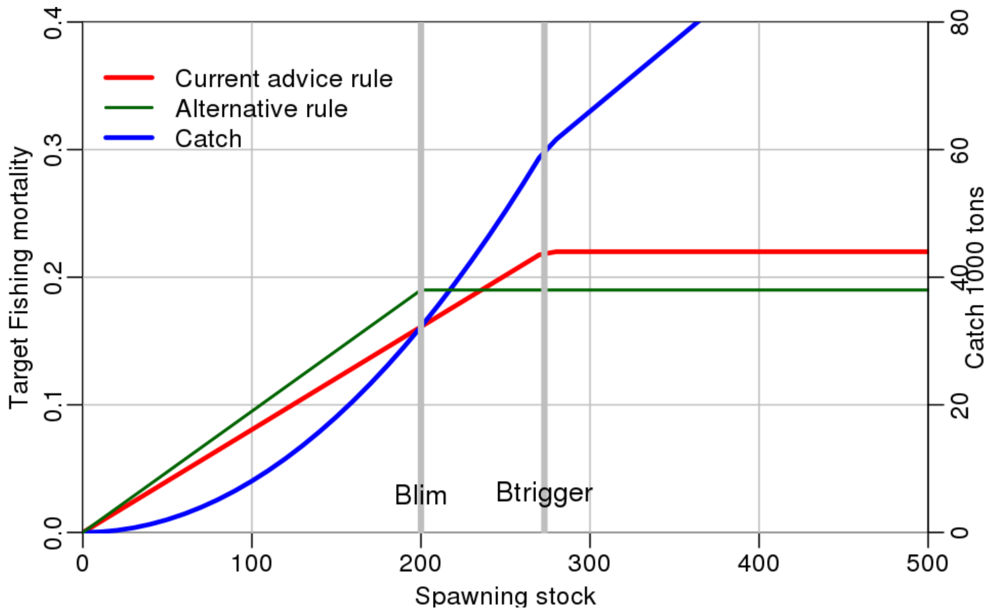

Figure 4.2.3.1. Description of the current HCR (and resulting catches from it) and possible alternative HCR.

4.2.4 Reference points

The PA reference points were verified and revised during the stock assessment meeting in 2016 (ICES, 2016). On the basis of the stock–recruitment relationship derived from a time-series covering 1947–2015, keeping B_{lim}=200 kt was considered reasonable, as the Study Group on Precautionary Reference Points for Advice on Fishery Management also concluded in February 2003. Other PA reference points were derived (in 2016) from B_{lim} in accordance with the ICES Technical Guidelines resulting in: B_{pa}= 273 kt ($B_{pa} = B_{lim} \times e^{1.645\sigma}$, where $\sigma = 0.19$); $F_{lim} = 0.61$ (F that leads to SSB = B_{lim}, given mean recruitment); F_{pa}= 0.43 ($F_{pa} = F_{lim} \times \exp(-1.645 \times \sigma)$, where $\sigma = 0.18$).

The MSY based reference points for the stock are based on an exploratory work presented at the NWWG meeting in 2011 in a form as requested by ICES (ICES, 2011b). The HCS program Version 10.3 (Skagen, 2012) was used to evaluate possible points based on the MSY framework that could be a basis for a management plan and Harvest Control Rule later. A number of different runs was made with varying settings. The results implied that $F_{0.1}$=0.22 could be a valid candidate for F_{MSY}. The reference points are examined in relation to the evaluation below.

4.2.5 The objectives

The main objective here is to test via data simulations if several Harvest Control Rules for fishery management of Icelandic summer-spawning herring are in conformity with the ICES MSY approach. To be so, the harvest rate must result in maximum (or close to maximum) average long-term yield and fulfil the precautionary criterion of no more than 5% probability of the stock being below B_{lim} in all years in the short term and the long term.

The Icelandic Ministry of Fisheries sent a request to ICES (Annex 1) to evaluate four different harvest control rules:

(HCR-1) Current advice rule of $F_{5\text{-}10}$=0.22[1], where the F is weighted by stock numbers, with SSB $B_{trigger}$=273 kt.

(HCR-2) Biomass rule of 19% harvest rate on B4+ with SSB $B_{trigger}$=273 kt (equivalent to current advice rule).

(HCR-3) Biomass rule of 17% harvest rate on B4+ with SSB $B_{trigger}$=B_{lim}=200 kt.

(HCR-4) Biomass rule of 15% harvest rate on B4+ with SSB $B_{trigger}$=B_{lim}=150 kt.

Additionally, the workshop examined the following rule:

(HCR-5) Biomass rule of 15% harvest rate on B4+ with SSB $B_{trigger}$=B_{lim}=200 kt

Rule 5 was not part of the request but leads to similar results as Rule 4.

In the biomass HCRs (HCRs 2–5), the age 4+ biomass refers to numbers at the beginning of the year.

[1] In the request from the Icelandic ministry of fisheries, the age range for F was 5–14. It is considered an error as the current harvest rule on basis of MSY approach refers to age groups 5–10. Consequently, all the evaluations below and reportings are based on age 5–10.

The SSB refers to numbers at July 1st. In all rules, SSB is calculated from the SSB estimated by the stock assessment on January 1, and assuming half year of natural mortality (M).

The rules include provisions for the following action when *Ichthyophonus* is detected:

In HCR-1, the M used is higher in years with *Ichthyophonus*. SSB in the assessment year is calculated based on half the estimated M for that year. The catch forecast is calculated with additional M in the Baranov's catch equation ($C_y = \sum C_{way} N_{ay} \frac{F_{ay}}{Z_{ay}} (1 - e^{-Z_{ay}})$) that assumes F and M are occurring continuously through the year. Therefore, approximately half of the additional M in the assessment is included when calculating C_y compared to the other rules that calculate C_y based on biomass in the beginning of the year.

In HCRs 2–5, SSB in the assessment year is calculated based on half the fixed M (0.1), independently of *Ichthyophonus* epidemic or not. If *Ichtyophonus* mortality is suspected in the year before the assessment year, then the assessment takes that into account. In that case the survey at the end of the *Ichtyophonus* year is available for estimation of extra M.

In HCR-2 and HCR-3 the target harvest rate is reduced by 1/3 when *Ichthyophonus* is detected. In HCR-1, HCR-4 and HCR-5 the target F or harvest rate is not changed in relation to *Ichthyophonus* epidemics.

To meet the objectives, an analytical assessment of the stock is done with a model (ADGISAHA) and this model is then used for a forward simulation (i.e. as an "Operating Model" or, in other words, to represent the "true" population and fishery dynamics in the simulation) to evaluate different harvest control rules by accounting for relevant errors, bias and biological variability (i.e. "Management Strategy Evaluation", MSE).

4.3 Materials and methods

4.3.1 Technical description of the ADGISAHA model

The ADGISAHA assessment used in this work is based on a statistical catch-at-age model that assumes a constant selection pattern-at-age for the fishery (allowing for changes in selection at pre-determined years). Correlation of residuals of different age groups in the survey used for tuning the assessment is estimated as part of the stock assessment. A detailed description of the model can be found in Björnsson (2016; WD13).

The simulation analyses to evaluate the HCRs (MSE), which uses the fitted ADGISAHA assessment model as the Operating Model, were based on 1000 iterations for each harvest rate or HCR. The rules were tested in a scenario assuming no further *Ichthyophonus* epidemic and in a scenario assuming an epidemic starting every 10th year on average (and lasting for three consecutive years). In addition, the HCRs were tested including *Ichthyophonus* mortality in the first three years (2017–2019) because of observations of new infection occurring in the winter 2016/2017, presumably causing additional mortality in the spring 2017 and during 2018–2019 if the epidemic resembles the 2009–2011 epidemic.

4.3.2 Input data

4.3.2.1 Catch-at-age and acoustic survey indices

The catch-at-age data used in the assessment go back to 1947 and represent catches of the summer-spawning herring stock alone. The survey data used for tuning in the analytical assessment derive from acoustic surveys conducted on the overwintering grounds of the adult population during the autumn/winter and exists for 1974 to present, but only the data from 1987 to 2015 are applied in the modelling work below. It provides age disaggregated indices. Details on the catch and survey data are provided in the Stock Annex (PDF) and annual assessment reports of the ICES expert group NWWG. Note that mass mortalities of herring of 55 kt that took place in the winter 2012/2013 in Kolgrafarfjörður (Óskarsson *et al.*, 2013) are added to the catches in the analytical assessment of the stock, instead of having it as additional M (Stock Annex; see further below).

4.3.2.2 Weight-at-age

The weight-at-age in the stock is estimated from the commercial catch samples combined over the whole fishing area (ICES, 2011a). Since the fishery takes place in the autumn and the winter (around September through January), the weight-at-age represents that period.

For the simulations in ADGISAHA model a different approach was used. In the Operating Model the "true" weight-at-age was found by multiplying the average values from 1996-2015 by an autocorrelated lognormal year factor: $W_{ya} = \overline{W_a} e^{\delta_y}$ where $\delta_y = \rho \times \delta_{y-1} + \varepsilon_y$ with $\varepsilon_y = N(0, \sigma^2(1-\rho^2))$. Here σ and ϱ were estimated from the data resulting in σ=0.1 and ϱ =0.7. $\overline{W_a}$ is the average of 1996–2015. Year factor is not a perfect description of the variability in mean weight-at-age, where the observed correlation between adjacent age groups is ~0.85, so the variability in stock size caused by the mean weight-at-age is on the higher side compared to what has been observed. Density-dependence is not noticed in the data (Figure 4.3.2.1) and, therefore, not implemented in the simulations. The resulting mean weight-at-age for ages 5 and 8 are shown in Figure 4.3.2.2.

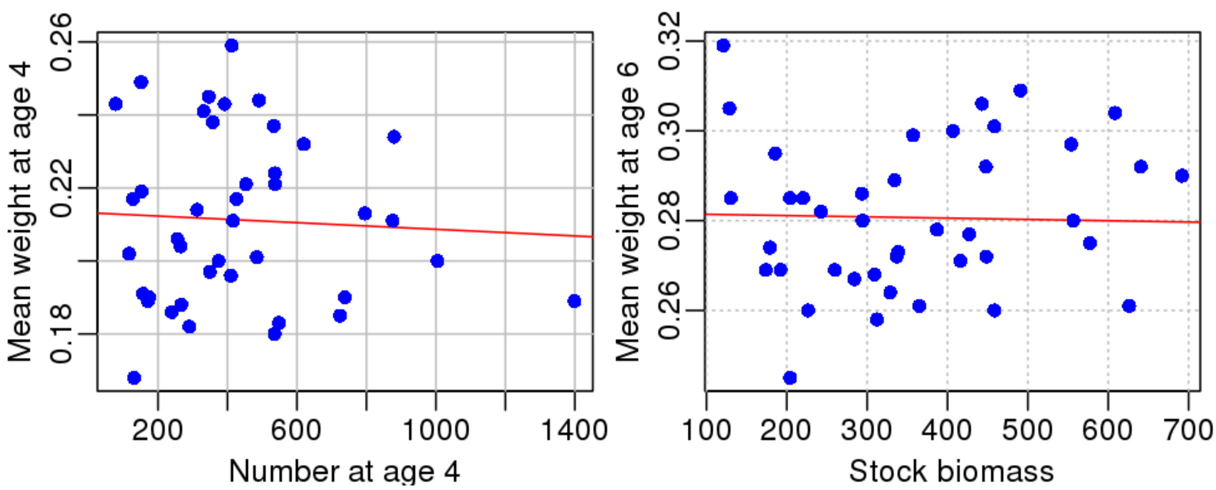

Figure 4.3.2.1. The relation between mean weight-at-age 4 against number-at-age 4 (left) and mean weight-at-age 6 against SSB.

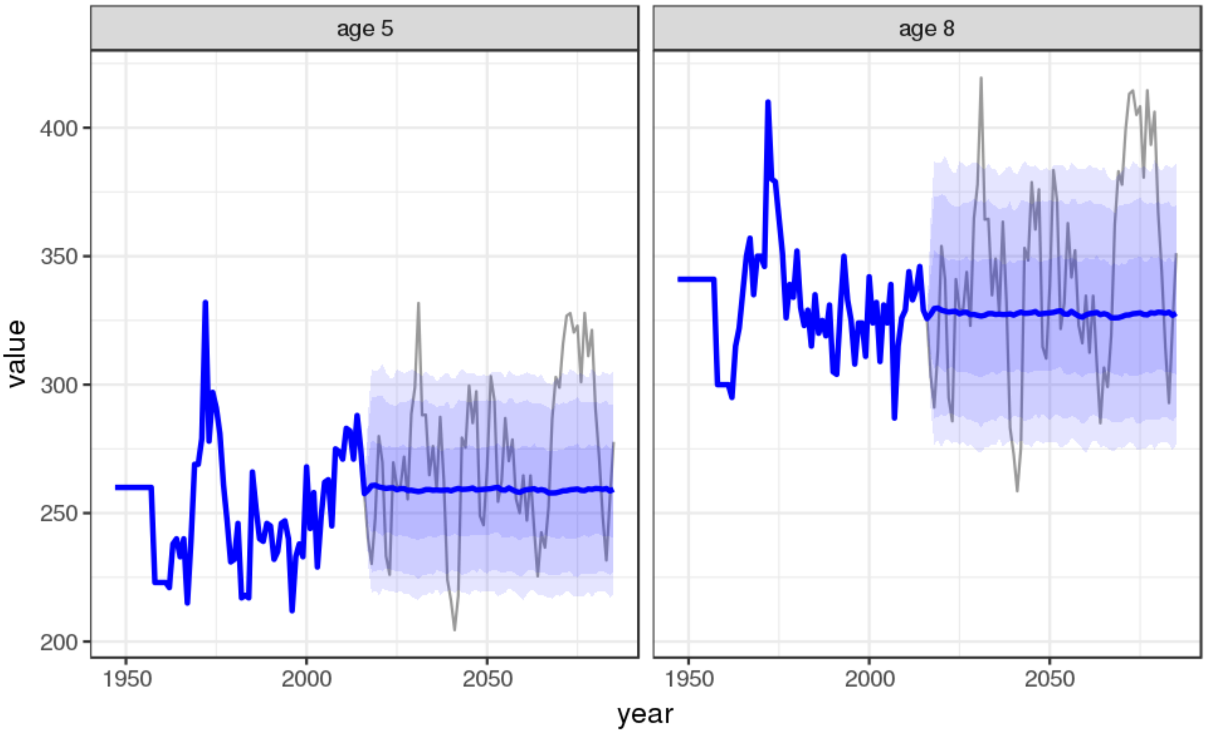

Figure 4.3.2.2. Mean weight-at-age of ages 5 and 8. The shaded areas show 5, 10, 25, 75, 90 and 95th quantiles. The blue line shows the average. The grey line shows iteration # 1000.

4.3.2.3 Maturity-at-age

The maturity-at-age of the Icelandic summer-spawning stock was until 2006 estimated annually from the commercial catches alone. Such estimates are subject to various sources of error including that the year classes that are becoming mature might have spatial distribution that is linked to whether they are mature or not. For example, mature individuals of a given year class would be more likely to join the older fully mature age groups than the immature individuals. The estimate of maturity-at-age from the catch samples can be incorrect because the most important age groups are poorly represented in the commercial catches. That was the main reason for the decision taken in the 2006 assessment that the maturity-at-age from then onwards was fixed, based on analyses of catch and survey data, and is as follows:

Age	<3	3	4	5+
Proportion mature	0.00	0.20	0.85	1.00

These values were evaluated in the benchmark assessment in 2011 and considered appropriate (ICES, 2011a). They are used throughout this work.

4.3.2.4 Natural mortality

Natural mortality for this stock has been assumed to be constant, M=0.1, for the whole range of ages and years (ICES, 2011a; Stock Annex, PDF). However, because of the *Ichthyophonus* infection in the stock, a higher M has been set for the years 2009–2010 (see Table 4.3.2.1; ICES, 2016). These values of $M_{infection}$ have been added to the fixed natural mortality of the stock, M=0.1, for these two years. The mortality imposed by the *Ichthyophonus* outbreak was revised in 2013 on the basis of research results, and was then assumed to have occurred only in the first two winters. High prevalence of infection has though been observed in the stock until present, and indication for new infection in 2015 and 2016. Recent results on the outbreak suggest revision on additional M because of the infection once again (Óskarsson *et al*., 2017). These results indicate that infection mortality took place over the first three winters instead of two, and that only 30% (i.e. multiplier on $M_{infected}$=0.3; 95% CI=0-0.65) of the infected fish died, instead of 100%, during these years. This will result in less total infection mortality and will be recommended to be used in the future assessment of the stock from 2017 onwards.

Table 4.3.2.1. The estimated natural mortality caused by *Ichthyophonus* infection ($M_{infected}$) in Icelandic summer-spawning herring in the winter 2008/2009 to 2010/11 (years referring to the autumns) for age groups 3 to 13+; M=0.1 + $M_{infected}$ × 0.3.

Age (years)	$M_{infected}$ 2009	$M_{infected}$ 2010	$M_{infected}$ 2011
3	0.39	0.64	0.10
4	0.39	0.64	0.53
5	0.39	0.59	0.52
6	0.39	0.53	0.50
7	0.39	0.50	0.44
8	0.39	0.48	0.46
9	0.39	0.47	0.49
10	0.39	0.46	0.46
11	0.39	0.44	0.34
12	0.39	0.43	0.35
13+	0.39	0.44	0.35

In the ADGISAHA assessment presented below, the multiplier used for these three years was estimated in a similar way, or as a single factor for all ages and years. The estimated value of log of the factor is -1.00, and the multiplier is, therefore, $e^{-1.00}$=0.36.

In addition to the added mortality because of *Ichthyophonus* infection, additional natural mortality is also added because of two incidents of mass mortality in the winter 2012/2013 in a fjord called Kolgrafafjörður (Óskarsson *et al*., 2013). Total 55 kt was estimated to have died there and the cause was oxygen depletion in a semi-closed fjord. Because of the nature of the mortality estimate, it is incorporated in the ADGISAHA stock assessment as an addition to the catches of that winter and not as M. This is the same approach as in the analytical assessment of the stock (ICES, 2016). The mortality ("catch") estimated for the Kolgrafafjordur incident is confounded with the estimated M in 2009–2011, so that higher mass mortality there would reduce the value estimated for M.

4.3.2.5 Stock–recruitment function

A stock–recruitment relationship for this herring stock is relatively well defined (Figure 4.3.2.3), as the stock was heavily depleted in the late sixties (Figure 4.4.1.1). Future recruitment in the MSE is simulated by a hockey-stick stock–recruitment function with random annual deviations. It was noted at the meeting that the standard deviations of the recruitment residuals in the fit to the historical data increased with reduced spawning stock (Figure 4.3.2.3). If this feature is not taken into account by the model, it could result in an estimated CV for recruitment deviations which is too large for the range of future higher SSB values generated by the MSE under the harvest rates in the proposed HCRs. Therefore, the stock-recruitment model setup was changed to allow it to estimate how the CV of the residuals changes with stock size. The scaled residuals resulting from this setup do not depend on the size of the spawning stock (Figure 4.3.2.4) and their autocorrelation is lower (0.3 with the new setup versus 0.4 with the previous one, for first order lag). The implications of this change in setup for future simulations are that future recruitment is based on a CV of approximately 0.5, instead of 0.75, leading to reduced variability in recruitment. The breakpoint in the stock-recruitment relationship changes from 219 to 250 kt, but R_{max} is very similar. Average recruitment does, therefore, change, as the lognormal bias correction factor ($e^{0.5\times\sigma^2}$) changes from 1.32 to 1.13. The *Ichthyophonus* multiplier decreased from 0.41 to 0.36, so the effect of *Ichthyophonus* is relatively smaller.

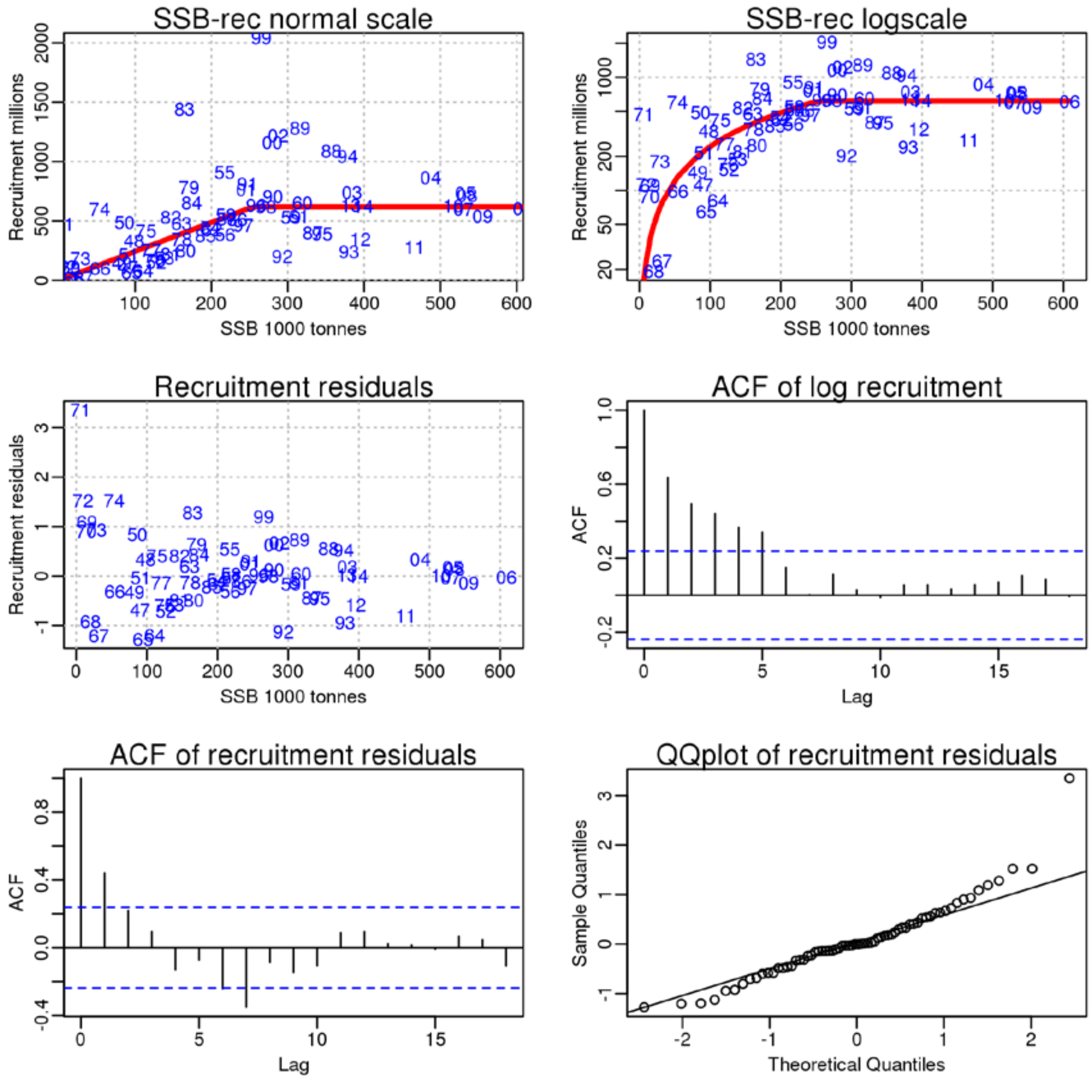

Figure 4.3.2.3. SSB–recruitment relationship and autocorrelation of recruitment and residuals, where σ is a function of SSB.

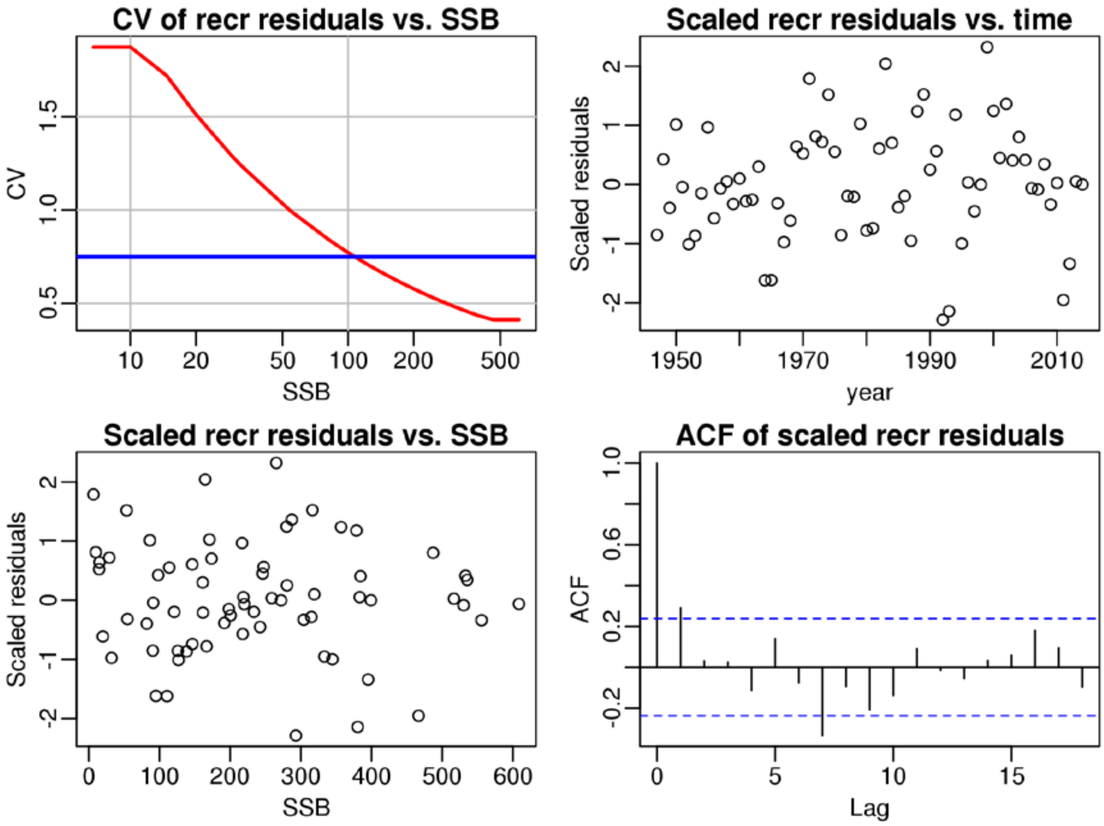

Figure 4.3.2.4. Summary of investigations of the SSB–R relationship. The horizontal line in the first figure shows the estimate obtained using constant CV (0.75).

4.3.2.6 Selection pattern

The selection for the different age groups used in the short term prognosis for the stock conducted annually by ICES has varied since 1989 (Figure 4.3.2.5). Since the benchmark assessment in 2011, the selection has been set equal to average of the three last years for ages 3 and 4, but fixed at 1.0 for ages 5+ (ICES, 2011a), where: $\text{Selection}_{\text{age x}}=F_{\text{age x}}/F_{5\text{–}10,\ \text{weighed}}$.

The selection pattern used in the prediction affects the value of $F_{5\text{–}10}$ that is considered “in conformity with the MSY approach”. Six different selection patterns are shown in Figure 4.3.2.6. The harvest ratio is highest and biomass lowest when young fish is included in the selection pattern (Table 4.3.2.2). Average selection from the ADGISAHA model (“Ave sel” pattern in Figure 4.3.2.6) leads to similar results as the selection that has been used in prognosis (“Used in prognosis” pattern in Figure 4.3.2.6), the harvest rate is 0.158 for the selection that has been used for prognosis and 0.165 for the estimated average selection from the ADGISAHA model. The harvest rate in these analyses is based on B3+ to get an indication of proportion removed from the total stock, not to suggest that proportion of B3+ is a good harvest control rule. The conclusion here is that the selection pattern used to calculate the catch with the HCR should be a part of the HCR specification. All simulations of HCR-1 calculate the catch based on the selection pattern called “Used in prognosis” in Figure 4.3.2.6. The catch in HCRs 2–5 is calculated from a harvest rate on B(4+), so no selection pattern needs to be specified for these HCRs (but using B4+ is, of course, specifying some kind of selection pattern to generate advice; B5+ would be a different one).

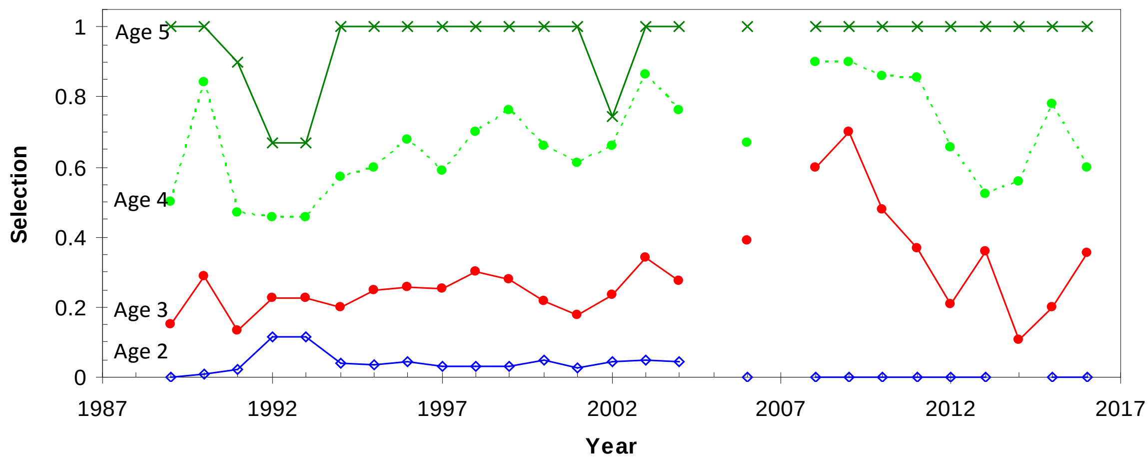

Figure 4.3.2.5. The selection for age groups 2–5 used historically in the short term projection conducted annually by ICES for Icelandic summer-spawning herring.

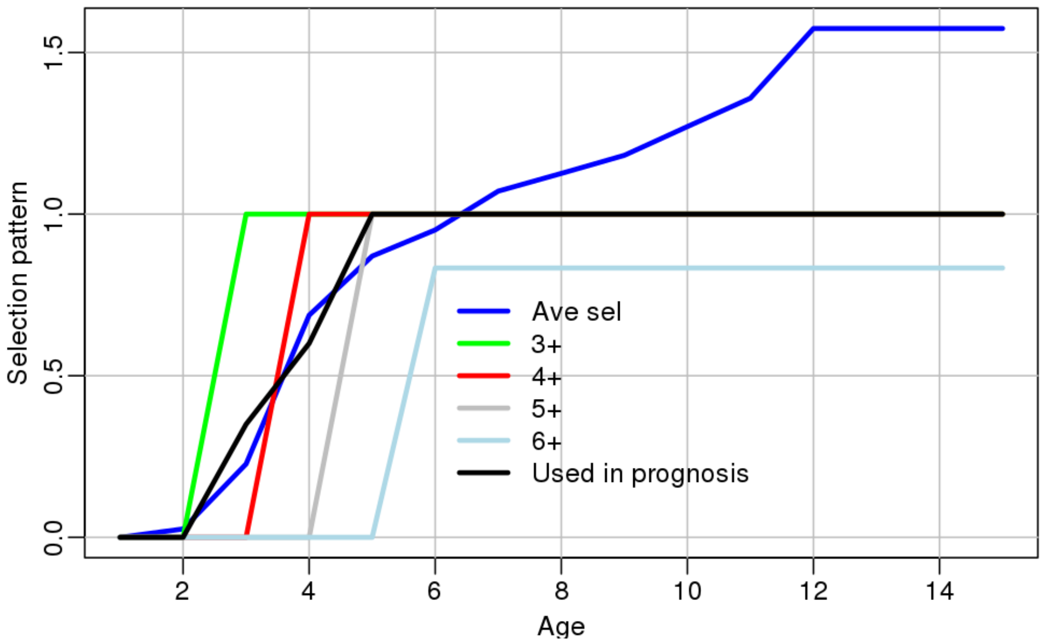

Figure 4.3.2.6. Selection patterns investigated.

Table 4.3.2.2. Average long-term harvest ratio C/B3+, biomass 3+ and SSB for the six different selection patterns shown in the figure above, all values are based on fishing mortality of 0.22 of ages 5–10.

	Hrate	B3+	SSB
Average selection	0.17	546.95	417.28
3+	0.19	468.91	347.82
4+	0.16	563.25	431.42
5+	0.14	655.83	523.34
6+	0.14	647.56	512.49
Used in prognosis	0.16	559.89	431.99

4.3.2.7 Assessment error

HCR evaluations require assessment error to be included in the simulations. The assessment error is assumed to be lognormal, applied as a year factor to all age groups in the beginning of the assessment year. $\hat{N_{ya}} = N_{ya} \times e_y^{\delta} \times e^{\beta}$ where $\delta_y = \rho \times \delta_{y-1} + \epsilon_y$ with $\varepsilon_y = N(0, \sigma^2(1-\rho^2))$. β is the bias in the assessment or really the additional bias as the lognormal distribution has a bias of $e^{0.5\sigma^2}$.

Bias in the assessment has been a problem for this stock. In the period 1994–2008 fishing mortality exceeded 0.22 (F_{target}) in 13 of the 15 years, and average F was 0.32 (the exact number could depend on the assessment model used). Most of this bias in F is caused by overestimation of the stock (see "Assessment error" in Section 4.3.2) and seen as retrospective pattern in the assessment (Figure 4.4.1.3). The ADGISAHA model used for the HCR simulations was used to investigate the bias in assessment (Björnsson, 2017a; see WD 1). The result was that the bias in F was between 30–40% with traditional retrospective runs, but closer to 10–15% if the catchability of the survey was fixed at the 2016 estimate. Traditional retros indicate that it took more than 15 years for the estimate of the survey's to stabilize. The long period required is caused by large variability in q from period to period, and relatively low F that makes the assessment converge slowly. Therefore, using the bias value of 0.15 on log scale was thought to be more representative of the current situation and was taken forward in the evaluations. In addition to the bias, a stochastic lognormal error with rho=0.7 and σ=0.25 was used. The lognormal error is unbiased on log scale but has a bias of $e^{0.5\times0.25(\hat{}2)}$ =1.03 on ordinary scale. The total bias is 0.15 on log scale but 18% on ordinary scale.

4.4 Results

4.4.1 Assessment with the ADGISAHA model

The assessment is based on a separable model based on catch data from 1946–2015, ages 2–15, tuned with survey data from 1988–2015. Correlation of residuals of different age groups in the survey is estimated. As indicated earlier, a more detailed description of the model can be found in Björnsson (2017a; WD13).

Using the estimated infection mortality (the multiplier =1; Table 4.3.2.1) in addition to the fixed M (0.1) in the assessment leads to a much larger spawning stock in the beginning of 2009 than in any other year in the time-series, and recruitment values for the year classes 2003–2007 that have no support in acoustic measurements (Figure 4.4.1.1). Therefore, the assessment presented here is based on a model where the M in excess of 0.1 during 2009–2011 is multiplied by an estimated factor and the uncertainty of that factor is included in the stochastic simulations. The estimated value of the multiplier is confounded with the amount assumed to have been killed in Kolgrafafjordur in 2012. Including the Kolgrafarfjordur mortality the estimated value of log of the factor is -1.00 and, consequently, $e^{-1.00}$=0.36, meaning that the additional M is reduced by 64%. Excluding the Kolgrafafjordur mortality leads to a higher value of the factor, i.e. higher estimated M to fit mortality in 2009–2012 to survey indices.

The estimated biomass of age 4+ from the ADGISAHA model over the years 1987–2016 was very similar to the results of NFT-Adapt model used in the analytical assessment of the stock annually conducted by NWWG, when the same multiplier on the infection M was used (Figure 4.4.1.2). Moreover, the retrospective pattern was more or less the same (Figure. 4.4.1.3), which gives support to using the assessment bias obtained from the ADGISAHA model in the MSE (Section 4.3.2).

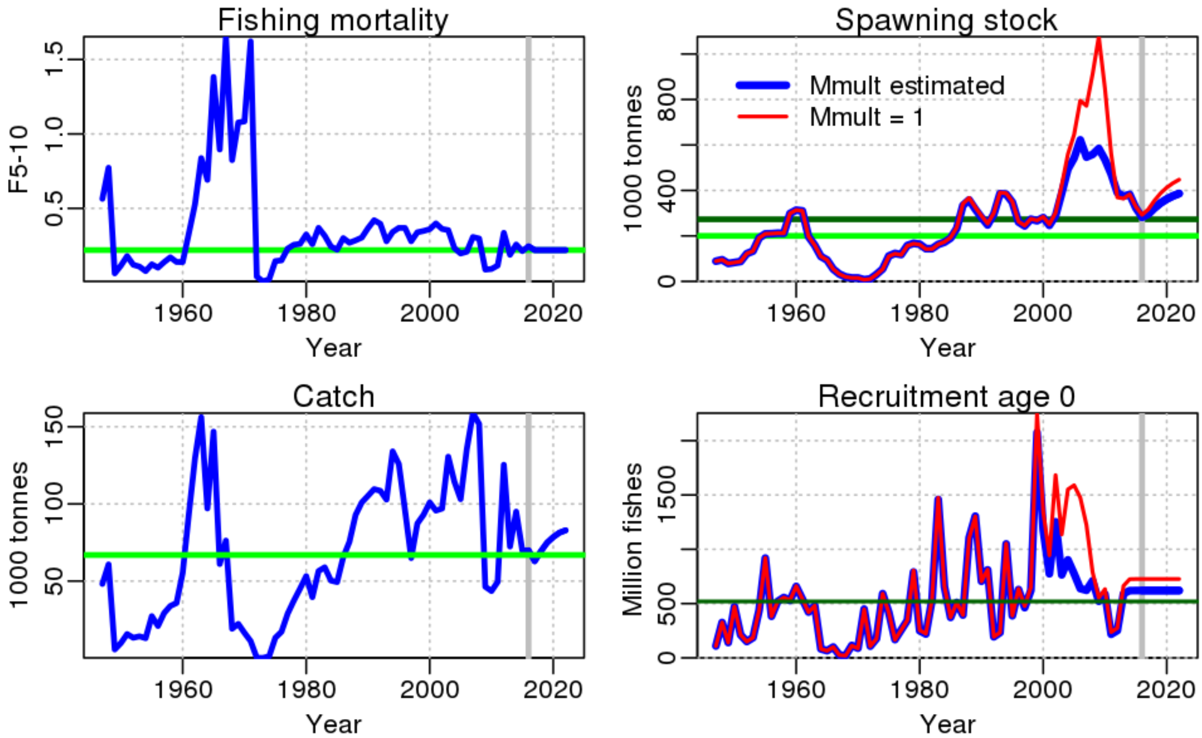

Figure. 4.4.1.1. Summary of assessment results. Results not estimating a multiplier on M (i.e. assuming a multiplier equal to 1) in 2009–2011 compared to the assessment estimating a multiplier on M in 2009–2011. The catch includes the Kolgrafafjordur mass mortality in 2012.

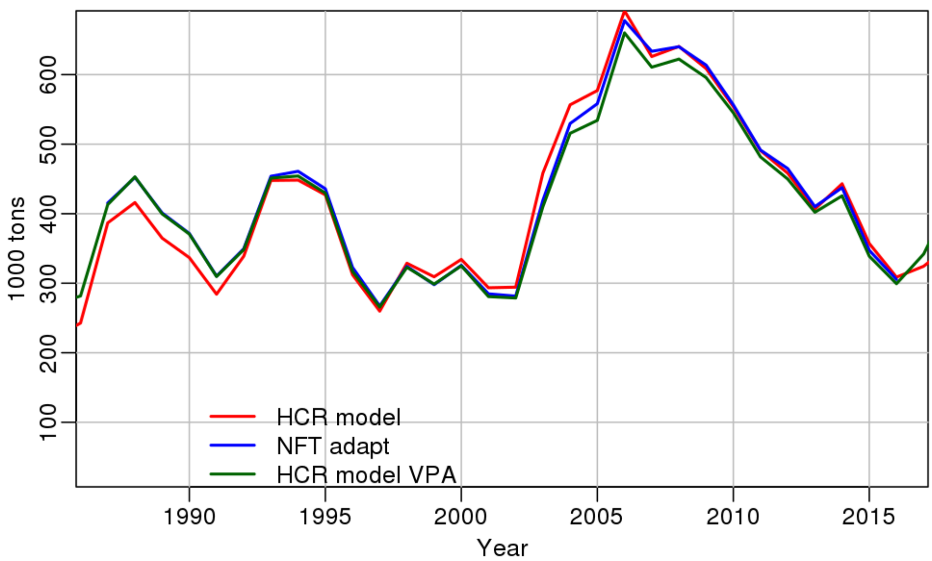

Figure 4.4.1.2. Comparison of biomass 4+ as estimated from NFT adapt model (used annually for the stock assessment) and the separable model used for the HCR evaluation (labelled "HCR model"), where the same multiplier on the extra M in 2009–2011 (0.418) was used.

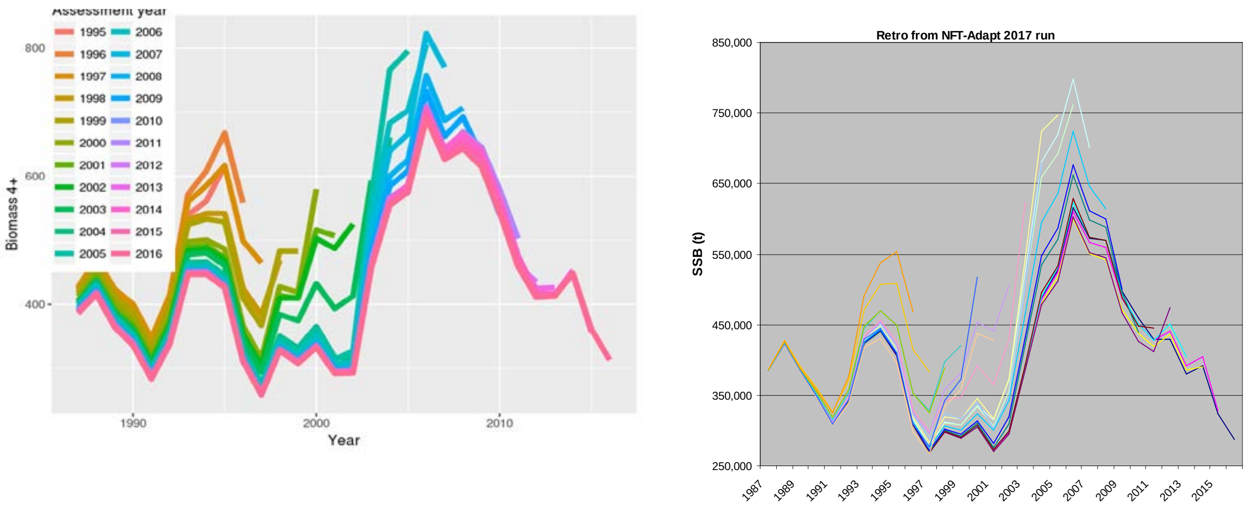

Figure. 4.4.1.3. Comparison of retrospective pattern of biomass 4+ in the assessment years 1995–2016 from the ADGISAHA model used for the HCR evaluation (left panel) and of SSB from a NFT-Adapt (usual model for annual stock assessment) assessment run in 2017 (right panel).

The scatter of SSB–recruitment pairs shows the typical positive correlation between R_{max} (represents approximately the productivity of the stock) and SSB_{break} (Figure 4.4.1.4). For this stock, the SSB–recruitment relationship is relatively well defined as the range of SSB observed is large.

Correlation between the multiplier on "extra infection M" during 2009–2011 and R_{max} is positive (Figure 4.4.1.5). The relationship is weak but multiplier = 0 leads to average R_{max}=580 while multiplier = 1 leads to R_{max}=705 or 30% higher productivity in the stock. The 90% range of the multiplier is between 0.08 and 0.5, a range leading to ≈15% difference in average productivity.

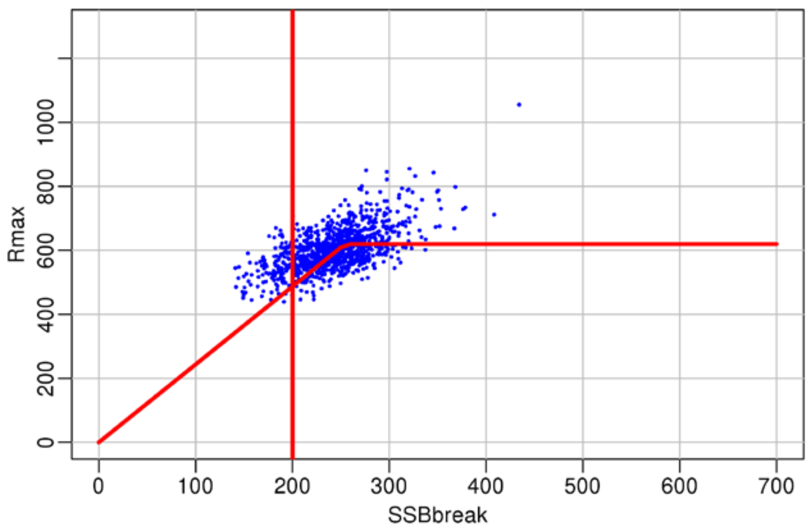

Figure 4.4.1.4. Scatter of SSB_{break} and R_{max}.

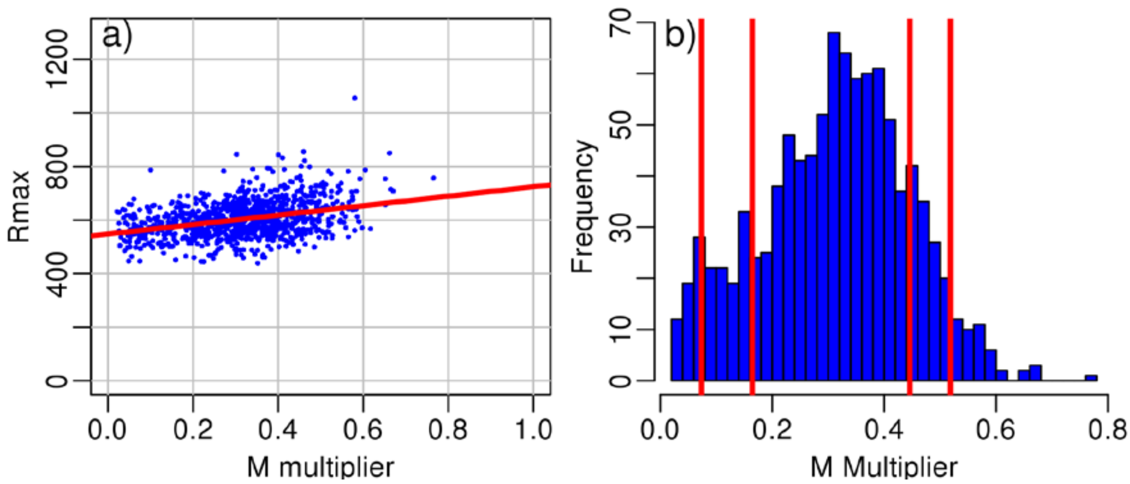

Figure 4.4.1.5. a) Scatterplot of M multiplier and Rmax. b) Histogram of estimated M multiplier. The vertical lines are 5th, 16th, 84th and 95th percentiles. The average value is 0.36.

4.4.2 HCR evaluation with the ADGISAHA model

More detailed description of the results presented below can be found in Björnsson (2017b; WD02).

The long-term simulation results (assuming M=0.1, i.e. no *Ichthyophonus*) show that, when basing TAC on proportion of B4+, median catch is maximized around the harvest rate (HR) = 0.19 when assuming an assessment bias of 0.15 and at around HR = 0.22 if no assessment bias is assumed (Figure 4.4.2.1). The HR resulting in 5% probability of SSB being below B_{lim} in the long-term is 0.20 with assessment bias and 0.23 without assessment bias. The results are based on $B_{trigger}$=0, so no trigger is required to make the HCRs fulfil P(SSB < B_{lim}) ≤ 0.05 in the long term. One important result is that the gain in yield going from 0.15 to 0.19 is only 2-4% and the variability in catches decreases with reduced HR (Tables 4.4.2.2 and 4.4.3.1).

Figure 4.4.2.2 is the counterpart of Figure 4.4.2.1 for a strategy based on fishing at a constant $F_{5\text{-}10}$ (weighted by fish number) instead of a constant harvest rate. Figure 4.4.2.2 shows that the top of the equilibrium yield curve is quite flat, with a range of values of F corresponding very similar yield values. The target fishing mortality in HCR-1 (0.22, which corresponds to the current F_{MSY} value ICES uses for this stock) is within the range of F values that maximize median long-term catch when the assessment bias is assumed to be 0.15 and is below the F leading to 5% probability of SSB < B_{lim}. If no assessment bias is assumed, then F_{MSY} is 0.24 and the F leading to 5% probability of SSB < B_{lim} = 0.27. The current reference point of F_{MSY} = 0.22 is, on basis of these simulations, still considered appropriate and it is suggested that it should be left unchanged.

The results of the different HCRs, as probabilities of the stock going below B_{lim} in each of the years 2018–2026 under different scenarios of future epidemic outbreaks and assessment bias, are summarized in Table 4.4.2.1. The resulting percentiles of the catches, SSB, F, harvest rate and biomass of age 4+ under the different scenarios in the long term are summarized in Table 4.4.2.2.

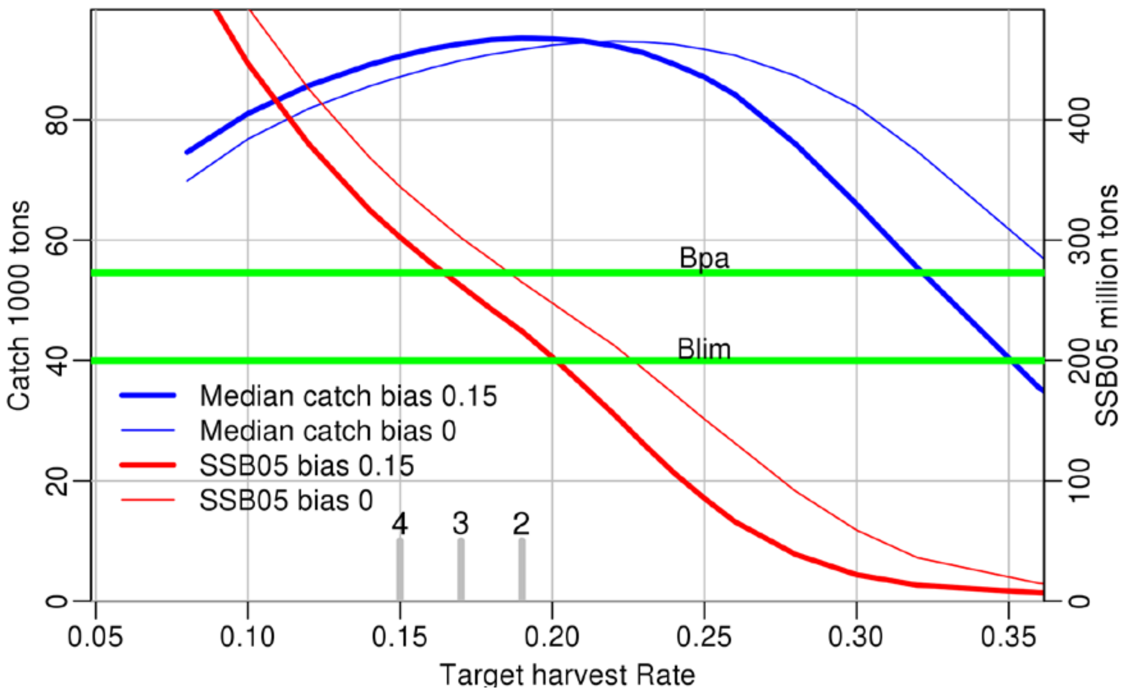

Figure 4.4.2.1. Median catch and fifth percentile of SSB at "equlibrium" (long-term). The harvest rate of HCRs 2–4 (0.19, 0.17, 0.15, respectively) are shown. No $B_{trigger}$. Assessment bias is 0.15 or none, as indicated in the figure.

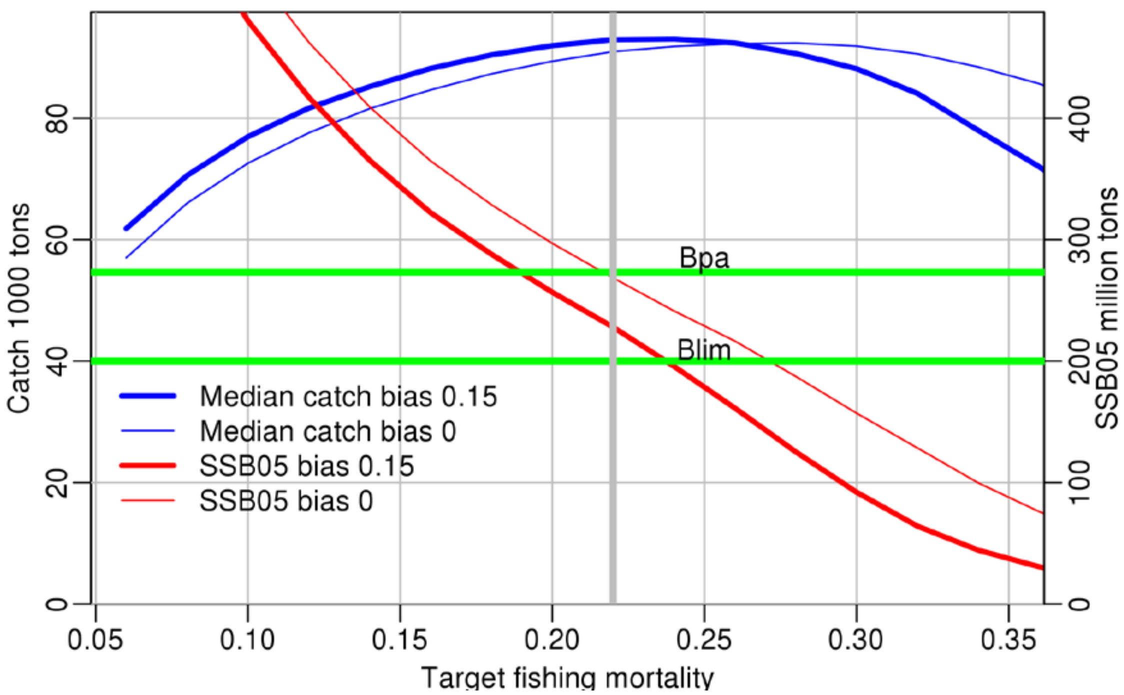

Figure 4.4.2.2. Median catch and fifth percentile of SSB at "equlibrium" (long-term). The fishing mortality of HCR 1 (0.22) is shown. No $B_{trigger}$. Assessment bias is 0.15 or none, as indicated in the figure.

Table 4.4.2.1. Results of simulation of the five Harvest Control Rules tested for the years 2018–2026 showing the probabilities of SSB going below B_{lim}=200 kt with and without 15% assessment bias under the assumption of (a) no *Ichthyophonus* epidemic in the coming years, (b) 10% annual probability of an *Ichthyophonus* 3-year epidemic starting, and (c) *Ichthyophonus* epidemic will take place in 2017–2019 and, thereafter, there is a 10% annual probability of a 3-year epidemic starting again. Values above 0.05 are bold.

(a) No Ichthyophonus epidemic									
Bias = 0									
Rule\Year	2018	2019	2020	2021	2022	2023	2024	2025	2026
Rule-1	0.009	0.004	0.007	0.005	0.002	0.003	0.004	0.006	0.005
Rule-2	0.009	0.005	0.008	0.005	0.003	0.003	0.004	0.005	0.005
Rule-3	0.008	0.004	0.005	0.004	0.002	0.002	0.001	0.000	0.004
Rule-4	0.005	0.003	0.004	0.002	0.000	0.000	0.000	0.000	0.000
Rule-5	0.005	0.003	0.004	0.002	0.000	0.000	0.000	0.000	0.000
Bias = 0.15									
Rule\Year	2018	2019	2020	2021	2022	2023	2024	2025	2026
Rule-1	0.019	0.010	0.013	0.013	0.018	0.025	0.017	0.019	0.023
Rule-2	0.021	0.012	0.013	0.016	0.020	0.025	0.018	0.019	0.024
Rule-3	0.012	0.007	0.009	0.006	0.011	0.007	0.006	0.011	0.010
Rule-4	0.008	0.004	0.004	0.005	0.003	0.002	0.000	0.000	0.003
Rule-5	0.008	0.004	0.004	0.005	0.003	0.002	0.000	0.000	0.003
(b) 10% probability of Icht. all years									
Bias = 0									
Rule\Year	2018	2019	2020	2021	2022	2023	2024	2025	2026
Rule-1	0.023	0.026	0.024	0.024	0.02	0.018	0.019	0.021	0.029
Rule-2	0.015	0.011	0.011	0.014	0.008	0.011	0.008	0.009	0.017
Rule-3	0.014	0.010	0.006	0.009	0.007	0.006	0.004	0.006	0.012
Rule-4	0.019	0.020	0.018	0.017	0.014	0.012	0.006	0.012	0.017
Rule-5	0.019	0.019	0.016	0.016	0.013	0.010	0.005	0.011	0.016
Bias = 0.15									
Rule\Year	2018	2019	2020	2021	2022	2023	2024	2025	2026
Rule-1	0.032	0.041	0.038	0.037	0.050	**0.057**	**0.052**	**0.055**	**0.06**
Rule-2	0.022	0.025	0.025	0.027	0.027	0.031	0.025	0.03	0.033
Rule-3	0.021	0.016	0.017	0.017	0.017	0.019	0.013	0.019	0.025
Rule-4	0.025	0.029	0.023	0.027	0.024	0.025	0.019	0.025	0.027
Rule-5	0.025	0.029	0.022	0.027	0.024	0.024	0.017	0.023	0.027
(c) Icht. epidemic in 2017-2019 and 10% probability of epidemic after 2019									
Bias = 0									
Rule\Year	2018	2019	2020	2021	2022	2023	2024	2025	2026
Rule-1	0.029	0.045	**0.068**	0.046	0.037	0.037	0.031	0.032	0.036
Rule-2	0.017	0.016	0.027	0.018	0.017	0.016	0.011	0.017	0.021
Rule-3	0.014	0.017	0.026	0.013	0.017	0.010	0.009	0.010	0.018
Rule-4	0.027	0.034	**0.056**	0.038	0.027	0.027	0.02	0.022	0.021
Rule-5	0.026	0.031	**0.054**	0.036	0.026	0.023	0.016	0.017	0.020
Bias = 0.15									
Rule\Year	2018	2019	2020	2021	2022	2023	2024	2025	2026
Rule-1	0.044	**0.089**	**0.126**	**0.089**	**0.081**	**0.082**	**0.078**	**0.075**	**0.078**
Rule-2	0.02	0.027	0.049	0.040	0.039	0.039	0.033	0.037	0.041
Rule-3	0.017	0.024	0.037	0.026	0.027	0.025	0.019	0.022	0.030
Rule-4	0.036	**0.060**	**0.083**	**0.058**	0.045	0.049	0.045	0.044	0.046
Rule-5	0.036	**0.059**	**0.081**	**0.056**	0.043	0.044	0.038	0.039	0.045

Table 4.4.2.2. The percentiles (as indicated) of the long-term simulations when "equilibrium" has been reached (2060+) with assessment bias of 15% (a and c), without assessment bias (b and d); with *Ichthyophonus* epidemic in 2017–2019 and, thereafter, a 10% annual probability of a 3-year epidemic starting again (c and d), and without infection (a and b).

(a) Bias = 0.15 and no Ichth. epidemic

Fishing mortality					
Rule	5%	16%	50%	84%	95%
Rule-1	0.166	0.196	0.255	0.334	0.397
Rule-2	0.159	0.189	0.248	0.329	0.394
Rule-3	0.146	0.169	0.219	0.287	0.343
Rule-4	0.126	0.146	0.188	0.246	0.293
Harvest rate					
	5%	16%	50%	84%	95%
Rule-2	0.148	0.173	0.216	0.271	0.312
Rule-3	0.138	0.158	0.195	0.243	0.28
Rule-4	0.122	0.14	0.172	0.214	0.247
SSB					
	5%	16%	50%	84%	95%
Rule-1	235	289	390	523	622
Rule-2	232	286	387	519	617
Rule-3	260	319	428	568	671
Rule-4	300	364	480	627	739
Biomass age 4+					
	5%	16%	50%	84%	95%
Rule-2	259	321	433	583	693
Rule-3	288	354	475	629	744
Rule-4	330	398	525	686	808
Catch					
	5%	16%	50%	84%	95%
Rule-1	51	68	94	128	157
Rule-2	50	68	95	131	161
Rule-3	54	67	93	127	156
Rule-4	54	66	91	123	150

(a) Bias = 0 and no Ichth. Epidemic

Fishing mortality	5%	16%	50%	84%	95%
Rule-1	0.133	0.162	0.218	0.294	0.354
Rule-2	0.125	0.154	0.21	0.286	0.348
Rule-3	0.116	0.138	0.185	0.25	0.303
Rule-4	0.1	0.119	0.159	0.214	0.259
Harvest rate	5%	16%	50%	84%	95%
Rule-2	0.12	0.145	0.188	0.243	0.284
Rule-3	0.112	0.133	0.169	0.218	0.255
Rule-4	0.099	0.117	0.149	0.192	0.225
SSB	5%	16%	50%	84%	95%
Rule-1	272	334	444	590	700
Rule-2	271	331	442	586	696
Rule-3	300	366	485	638	756
Rule-4	341	412	540	702	825
Biomass age 4+	5%	16%	50%	84%	95%
Rule-2	299	366	488	647	765
Rule-3	329	400	531	698	820
Rule-4	371	446	584	759	888
Catch	5%	16%	50%	84%	95%
Rule-1	49	66	91	125	154
Rule-2	48	66	92	128	158
Rule-3	52	64	90	124	153
Rule-4	51	63	87	120	147

(c) Bias = 0.15 and Icht. epidemic

Fishing mortality					
Rule	5%	16%	50%	84%	95%
Rule-1	0.152	0.187	0.25	0.331	0.393
Rule-2	0.124	0.159	0.224	0.309	0.376
Rule-3	0.118	0.146	0.199	0.271	0.329
Rule-4	0.129	0.15	0.194	0.254	0.304
Harvest rate					
	5%	16%	50%	84%	95%
Rule-2	0.112	0.143	0.197	0.257	0.3
Rule-3	0.107	0.131	0.178	0.231	0.27
Rule-4	0.122	0.139	0.172	0.214	0.247
SSB					
	5%	16%	50%	84%	95%
Rule-1	190	245	342	476	576
Rule-2	210	265	363	493	588
Rule-3	227	291	398	534	635
Rule-4	218	291	410	560	671
Biomass age 4+					
	5%	16%	50%	84%	95%
Rule-2	229	292	401	549	658
Rule-3	246	316	435	588	702
Rule-4	235	316	448	617	736
Catch					
	5%	16%	50%	84%	95%
Rule-1	34	53	81	115	143
Rule-2	34	50	79	117	147
Rule-3	37	50	77	113	141
Rule-4	40	53	77	109	136

(d) Bias = 0 and Icht. epidemic

Fishing mortality	5%	16%	50%	84%	95%
Rule-1	0.121	0.154	0.214	0.291	0.352
Rule-2	0.099	0.13	0.189	0.268	0.332
Rule-3	0.097	0.12	0.168	0.235	0.29
Rule-4	0.103	0.123	0.164	0.221	0.268
Harvest rate	5%	16%	50%	84%	95%
Rule-2	0.093	0.119	0.17	0.229	0.273
Rule-3	0.09	0.111	0.154	0.205	0.244
Rule-4	0.099	0.117	0.149	0.192	0.225
SSB	5%	16%	50%	84%	95%
Rule-1	222	282	390	535	644
Rule-2	243	303	410	550	655
Rule-3	259	327	444	592	704
Rule-4	248	328	458	622	744
Biomass age 4+	5%	16%	50%	84%	95%
Rule-2	260	329	448	604	719
Rule-3	278	353	480	644	765
Rule-4	267	352	494	673	804
Catch	5%	16%	50%	84%	95%
Rule-1	33	51	79	112	140
Rule-2	32	48	77	113	143
Rule-3	35	48	74	108	137
Rule-4	38	50	74	105	132

4.4.3 Effects of *Ichthyophonus* epidemics in the future

In the *Ichthyophonus* period 2009–2011 average annual M increased by 0.16 (Figure 4.4.3.1) with $\sigma_{\log(Minfection)}$=0.3 (Section 4.3.2). The total additional M over the three years was, therefore, 0.48. If this kind of incidents occurred every 20th year, the average M would increase to 0.26 in three years out of 20 on average, so the average M would be $\frac{17}{20}\times 0.1+\frac{3}{20}\times 0.26=0.124$. This increase will, on average, lead to smaller spawning stock and reduce the F leading to P(SSB<B_{lim})=0.05. The average additional M of 0.024 is 11% of the target fishing mortality 0.22 (age 5–10). The increase in M applies to more age groups (also age 3) than fishing mortality, so an increase of 0.024 corresponds to more increase in fishing mortality than 0.024. The effect of this increase in mortality is still less than the effect of the bias in 1994–2008, when average F is 30+% higher than intended F.

The average disease mortality from 2009–2011 (0.16) is 80% of target fishing mortality), so closing the fisheries would have been close to enough to compensate for the mortality.

To look at the effects of *Ichthyophonus* on future yield, the model was run with (a) 100% probability of *Ichthyophonus* epidemic in the next three years (2017–2019) and, thereafter, a certain annual probability of an epidemic starting again in that year, and (b) a certain annual probability of an epidemic starting in that year, for each year after 2017. Each epidemic is assumed to last for three consecutive years, with a distribution of "additional M" as shown in Figure 4.4.3.1.

When *Ichthyophonus* infection is detected some action can be taken but it should depend as little as possible on exact estimates of M. Setting a TAC for next fishing year does, of course, require prediction of the stock half a year ahead using the estimated M, but to let HR_{target} in addition depend on the estimated M would increase variability in advice. This problem of the HR_{target} depending on the estimated M will though pop up when B_{pa} is approached, so the possibility of reducing $B_{trigger}$ to B_{lim} or lower and decreasing the HR_{target} appears once again.

The actions considered were:

1) Reducing $B_{trigger}$ to 150 kt and HR_{target} to 0.15. Keeping the standard management plan when an epidemic is detected. Predict SSB in the assessment year using base M (0.1). (HCR-4).

2) Reducing HR_{target} by 33% or 50% when an epidemic is detected. Looking at possible values of HR_{target} satisfying precautionary criteria. Predict SSB in the assessment year using base M (0.1). (HCR-2 and HCR-3).

The starting point for the investigation is to look at the case where *Ichthyophonus* is continuously ongoing, and SSB–Rec relationship is as estimated for a healthy stock. The results (Figure 4.4.3.2) show that the maximum average catch is around 50 kt but the 5th percentile of the spawning stock is below B_{lim} to as low HR as ~0.04. Figure 4.4.3.2 corresponds to the case without any $B_{trigger}$. A common sense policy for this situation could be an HR≈0.1–0.15 and a $B_{trigger}$ =75 kt, but the main problem is to know when we have this situation. Although we do not expect to have this situation, the results here should be kept in mind in the short term (five years) as the disease seems to have started again. This scenario of continuous epidemic is not considered realistic, but if it were to happen, the reference points and HCR would have to be revised.

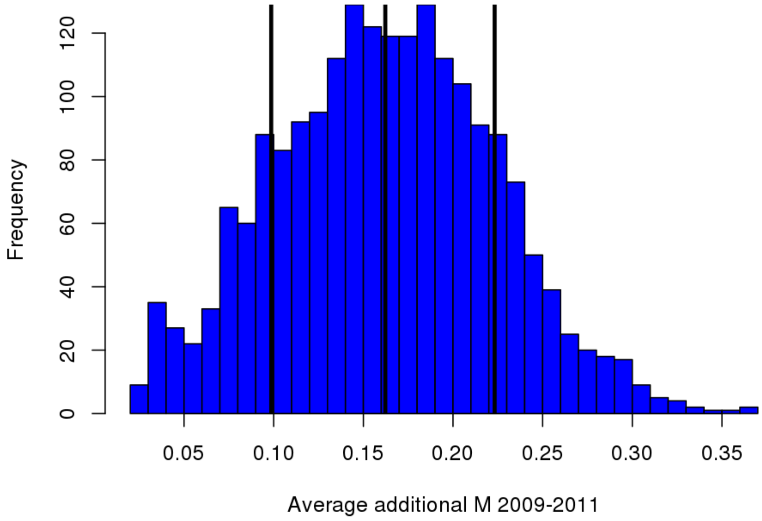

Figure 4.4.3.1. Average annual M in excess of 0.1 in the years 2009–2011. The figure corresponds to age 7 but the age groups that are most important in the fishable stock have similar M. The vertical lines show the average, 16th and 84th percentiles, approximately corresponding to ±1 standard deviations of the estimate.

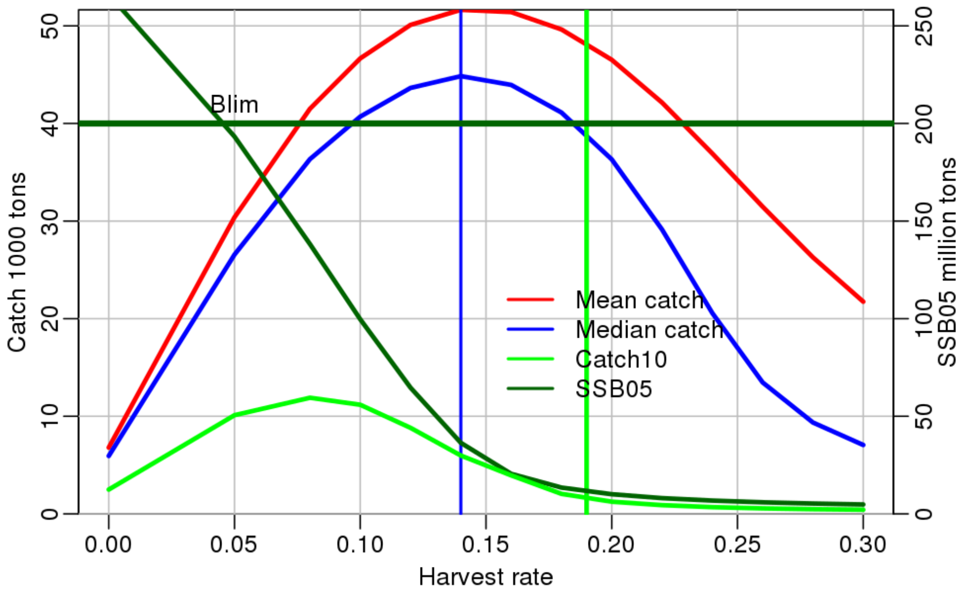

Figure 4.4.3.2. Continuous *Ichthyophonus* epidemic, $B_{trigger}$ = 0. Average, median and 10th percentile of catch at "equlibrium" (long-term). Fifth percentile of SSB is also shown. The blue vertical line is the harvest rate that maximises catch, whereas the green vertical line is the harvest rate that maximises catch under "normal circumstances". Assessment Bias 0.15.

Development of spawning–stock biomass (Figure 4.4.3.3) under the different HCRs show that stock size will continue to decrease in the first years because of poor recruitment entering the stock and the *Ichthyophonus* epidemic set for 2017–2019. The catches will show the same pattern (Figure 4.4.3.4) with the highest catches in the first years, and correspondingly lowest SSB, for HCR-1 but lowest catches for HCR-3.

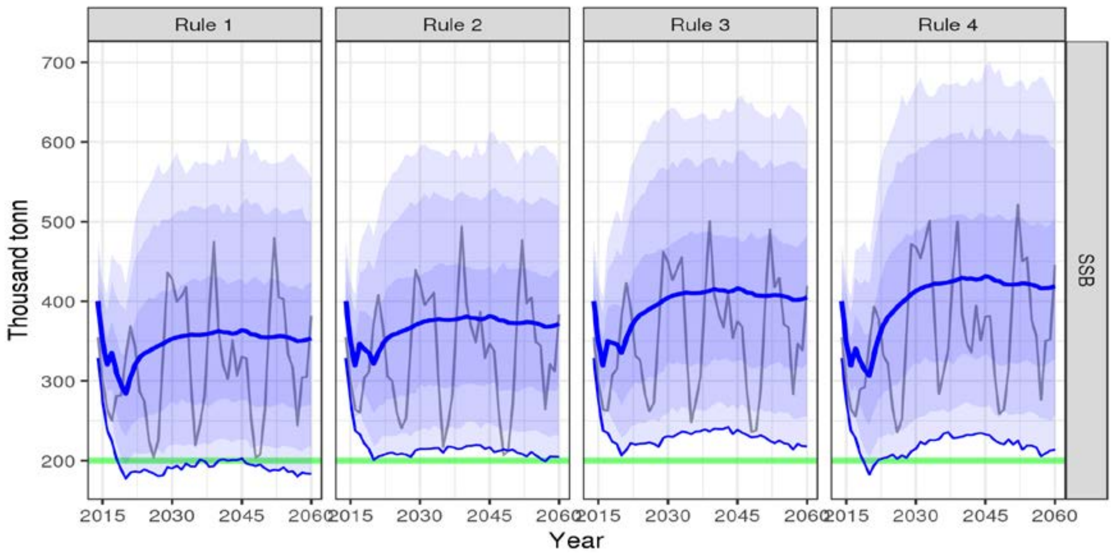

Figure 4.4.3.3. Development of SSB for the four different HCRs. The shaded areas show 5, 10, 25, 75, 90 and 95th percentiles and the blue lines the median. One individual run is shown. The horizontal lines show B_{lim}=200 kt. Assessment bias 0.15. The scenario assumes an *Ichthyophonus* epidemic during 2017–2019 and, thereafter, a 10% annual probability of a three-year epidemic starting again in that year.

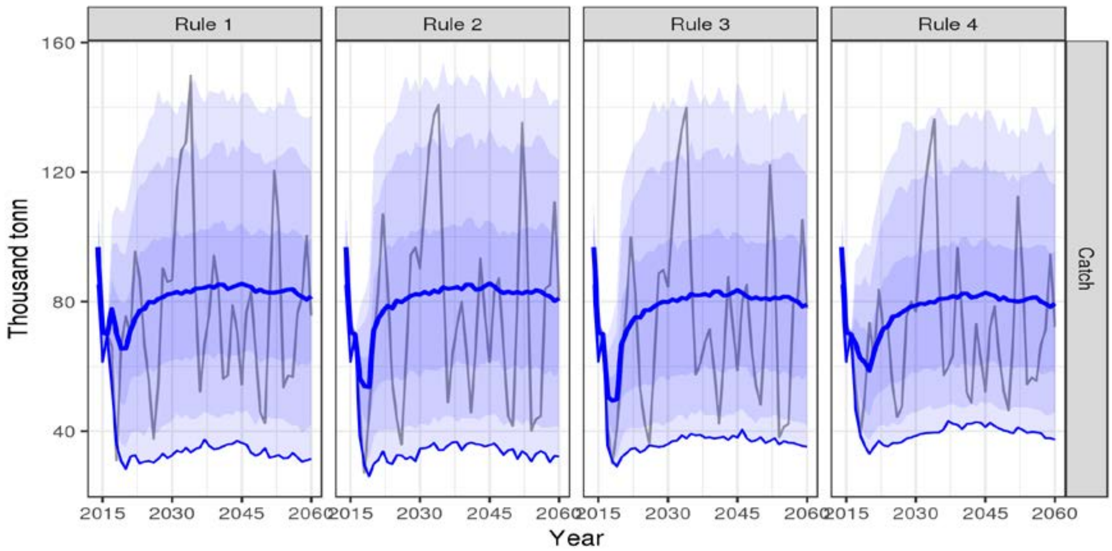

Figure 4.4.3.4. Development of catch for the four different HCRs. The shaded areas show 5, 10, 25, 75, 90 and 95th percentiles and the blue lines the median. One individual run is shown. Assessment bias 0.15. The scenario assumes an *Ichthyophonus* epidemic during 2017–2019 and, thereafter, a 10% annual probability of a three-year epidemic starting again in that year.

Table 4.4.3.1. Average, median, 10th percentile and, 5th percentile and standard deviation of the catches in the long run. 10 percent probability of *Ichtyophonus* starting each year.

Rule	Average	Median	10th percentile	5th percentile	Standard dev
Rule 1	84	80.8	43.4	33.5	33.1
Rule 2	83.6	79.5	42.4	33.6	34.9
Rule 3	81.6	77.2	43.9	36.8	32.7

Rule 4	81.3	77.5	46.9	39.9	30
Rule 5	81.3	77.5	47.2	40.2	30.1

Table 4.4.3.2. Relative interannual variability in catches in the long run, measured as percent change in catch between years, assuming 15% assessment bias and 10% probability of *Ichtyophonus* starting in each given year. The table shows fifth, 10th, 25th, 75th, 90th and 95th percenctile of the change. The bold values correspond to decreased catch. For example, using Rule 4 there is 5% probability of 32.8% or more reduction in catches.

Rule	5%	10%	25%	75%	90%	95%
Rule 1	36.2	29.1	16.2	18.5	41.6	59.7
Rule 2	40.8	32.6	18.1	21.7	48.1	69.1
Rule 3	36.9	29.8	16.6	19.4	42.2	58.9
Rule 4	32.8	26.5	14.8	17.1	35.8	49
Rule 5	33.2	26.8	15	17.3	36.3	49.8

In the long term Rules 4 and 5 give most stability of catches but lowest average catch (Tables 4.4.3.1 and 4.4.3.2). That stability is caused by the standard feature of lower fishing pressure leading to more stability in catches and no special action taken when *Icthyophonus* is detected, unlike in Rules 2 and 3 which decrease the harvest rate when the disease is detected.

4.4.4 Conclusions

In relation to the management of the stock and the work presented above, it is noted that the average annual catches over the period 1987–2016 are 97 kt, which is 0.49 times B_{lim}=200 kt and 0.35 times $B_{trigger}$ (273 kt). This implies a conservative fishery management, given that such low ratios are not found for many assessed fish stocks.

All the HCRs tested were found to be precautionary and in conformity with the MSY approach, assuming assessment bias up to 0.15, under scenarios of no further *Ichthophonus* epidemics. This can be seen from the results in the tables and figures in Section 4.4.2, which show the rules result in long-term yield consistent with MSY and have no more than 5% probability of SSB < B_{lim} in all years in the short and long term.

With an *Ichthyophonus* epidemic occurring in 2017–2019, but assuming no assessment bias, all the HCRs resulted in no more than 5% of SSB < B_{lim}, except in year 2020 for HCRs 1, 4 and 5 (Table 4.4.2.1). Assuming an assessment bias of 0.15, HCR-2 and HCR-3 remain precautionary. In this situation, HCR-4 and HCR-5 result in more than 5% probability of SSB < B_{lim} in 2019–2021, although the probability becomes less than 5% in the long run. HCR-1 cannot be considered precautionary under these conditions, as it results in more than 5% probability of SSB < B_{lim} in most years.

The difference demonstrated here is expected. HCR-2 and HCR-3 reduce the harvest rate by $^1/_3$ when *Ichthyophonus* is detected. No action is taken in HCR-4 and HCR-5, but their base harvest rate (0.15) is relatively low. The action in HCR-1 is through increased M in the catch forecast and a relatively high $B_{trigger}$ in the HCR; this action does not work well with assessment bias. HCR-1 is therefore the rule most sensitive to *Ichthyophonus* epidemics.

The HCRs above have different advantages and disadvantages and are not equally sensitive to uncertainty and different scenarios about the development and frequency of the *Ichthyophonus* epidemics and the foreseen continuation of low SSB in the next years. Selection and adoption of one of them for managing the fishery of the stock should take these aspects into consideration.

4.5 References

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4.6 Reviewers' report

Carmen Fernández (Spain) and Alfonso Pérez (the Netherlands)

The reviewers examined the Management Strategy Evaluation (MSE) documents prepared by Icelandic scientists in advance of the WKICEMSE workshop and provided comments by correspondence. The workshop then provided a further opportunity to discuss the work in detail and to make some additional checks and a modification to the simulation procedure for recruitment. The outcomes of the work appear in Sections 4.1–4.5 of the WKICEMSE report.

4.6.1 Overall conclusion

The reviewers conclude that the work is of high quality and provides an appropriate technical basis to respond to the request formulated to ICES by Icelandic authorities. The reviewers agree with the conclusions of the workshop.

A significant complication in the evaluation is that an *Icthyophonus* epidemic infection occurred in recent years, which is considered to have increased M (by some amount) during 2009–2011. A new infection outbreak seems to have started recently and there is great uncertainty about the potential frequency of future epidemic outbreaks. The harvest control rules evaluation tried to accommodate this highly uncertain situation by exploring the consequences of several scenarios of future frequency of epidemic outbreaks.

4.6.2 Comments

The technical basis for the simulations is quite intricate and a summary is presented here:

The Operating Model (OM) used in the Management Strategy Evaluation (MSE) is conditioned using a statistical catch-at-age stock assessment model, different from the VPA-type model used for the ICES "official" assessment for this stock. The statistical catch-at-age model was fitted using a much longer time-series of data than the ICES official assessment, covering the herring depletion period in the early 1970s. The statistical catch-at-age model is fitted to the stock assessment data using MCMC. Each of the 1000 kept MCMC parameter sets is then be carried forward into the simulation (MSE) part.

The OM assumes a constant selection-at-age pattern over time. Recruitment in the OM is simulated using a hockey-stick S–R relationship, incorporating annual recruitment deviations, where the latter follow a Normal AR(1) process in log-scale, with σ dependent on SSB (to account for an observed increase in σ at low SSB, according to the historical data) and autocorrelation ρ=0.3, which was estimated from the residuals of the log(recruitment) fits to the historical data.

The true weights-at-age in the OM are simulated as: log(W(y,a)) = log(average W(y,a) during years 1996–2015) + δ(y), where δ (y) has a zero-mean Normal AR(1) distribution, with σ=0.1 and ρ=0.7, which were estimated from the observed historical data. Maturity-at-age is assumed throughout to be fixed and identical to the maturity-at-age used in the stock assessment (i.e. 0% for ages < 3, 20% at age 3, 85% at age 4, and 100% for ages ≥ 5).

Two types of HCR were examined to provide catch (in tonnes) for the fishing year y/(y+1):

a) HCRs where the catch is obtained by applying a fishing mortality F_{MGT} * min{1, SSB(y)/ MGT $B_{trigger}$} to the population abundance-at-age at the start of the fishing year. The selection-at-age pattern used to calculate the catch is the same that has been used for the ICES advice in recent years (i.e. selection = 0 for ages < 3; approximately 0.35 at age 3; approximately 0.6 at age 4; 1 for ages ≥ 5).

b) HCRs where the catch is obtained by applying a harvest rate HR_{MGT} * min{1, SSB(y)/MGT $B_{trigger}$} to the age 4+ biomass in year y.

The MSE assumes that, when applying the HCR, the following assumption is made about weights-at-age in year y: W_{HCR}(y,a)=W(y-1,a); this results in W_{HCR}(y,a) values different from the true W(y,a) values in the OM. Additionally, based on a retrospective analysis, assessment error is assumed to be as follows: log($N_{estimated}$(y,a)) = log(N_{true}(y,a)) + bias + γ(y), where the bias=0.15 accounts for historically observed overestimation of population abundance, and γ(y) follows a Normal AR(1) distribution with mean=0, σ=0.25 and ρ=0.7. Once a catch (in tonnes) has been calculated from the HCR, it is converted into true catch in numbers-at-age in the OM using the true weights and fishery selection-at-age pattern in the OM.

In addition to the comments provided by the reviewers in advance of the WKICEMSE workshop, the following main issues were discussed during the workshop:

The methodology used to specify assessment error for the MSE, based on retrospective analysis, was considered appropriate. However, this retrospective analysis was conducted based on the statistical catch-at-age assessment model which, as noted above, differs from the VPA-type model used by ICES to assess this stock. The question therefore arose as to the extent to which the two assessments provide comparable results and have similar retrospective behaviour. Some exploration of this had been already been done by Icelandic scientists and retrospective patterns were examined during the workshop and were seen to be very similar.

A related issues is that a certain selection-at-age pattern, constant over the years, is used in the OM based on the results of the statistical catch-at-age model. This selection pattern is different from the annually-varying selection-at-age estimated by the ICES VPA-type assessment. The possible impact of this difference on the MSE results was discussed during the workshop. It was concluded that the selection patterns estimated by both models are reasonably similar. To gain some additional understanding of the impact of the OM selection pattern on the results, the 5th percentile of the equilibrium SSB (for an HR=0.19) was calculated based on knife-edge selection at-ages 4 and 6 and seen to result in similar values (202 and 218 kt, respectively).

The findings from the above explorations allow concluding that the properties of both assessments are sufficiently similar for the purpose of the MSE.

It was clarified during the workshop that the F used in HCRs of type a) is the weighted (by population numbers) average F of ages 5–10, not of ages 5–14. This had been wrongly reported in the documents submitted to the workshop.

The reviewers noted that the simulated recruitment values seemed (from the plots shown) to be somewhat on the optimistic side, and that the annual log(recruitment) deviations in the historical data showed some preponderance of negative values and suggested that the magnitude of the residuals might decrease with SSB. As many of the historical SSB values are low (given that the statistical catch-at-age assessment includes the herring depletion period), these resulted in a large estimate of σ, which, in combination with the bigger SSB values occurring in the MSE simulations and the log-normal recruitment assumption, resulted in some rather large simulated future recruitment in the MSE. The workshop therefore decided to investigate an alternative scenario based on a historical S–R fit incorporating an SSB-dependent σ function. This was seen to provide a better fit to the historical data and produced simulated future recruitment that, intuitively, seemed more realistic and it was, therefore, adopted as the base case for the simulations. From the checks conducted, this will likely not impact MSE results in a major way.

Perfect correlation between ages is assumed for the true weights-at-age in the OM, so the weights of all ages go up and down exactly in the same year. By contrast, the observed data correlation between adjacent age groups is 0.85. In workshop discussions it was concluded that the likely overall effect of this OM assumption is to make the MSE more precautionary but, based on previous MSE work with other stocks, it should have only a minor effect.

The workshop did not suggest any modifications of the ICES Precautionary Approach or MSY reference points for the stock. The stock–recruitment historical estimates used during the MSE work were based on the statistical catch-at-age model. The two different stock–recruitment hockey-stick fits conducted for this work had breakpoints around 220 kt (first fit done with constant σ) or around 250 kt (second fit done with σ dependent on SSB), which are above B_{lim} (200 kt). The exact location of the breakpoint is sensitive to assumptions or ways of conducting the stock–recruitment fit, and the workshop considered there was no need to change B_{lim} now. This should be re-examined in future benchmarks, when all the stock's reference points are normally reviewed. The F_{MSY} value so far used by ICES is 0.22 at ages 5–10, weighted by population numbers at those ages. The yield curves examined during the workshop indicate that this value remains appropriate; it should be noted that this is assuming 15% bias (overestimation of stock abundance) in assessment, otherwise the F_{MSY} value would be approximately 15% higher. It was observed that an F_{MSY}=0.22 corresponds to less than 5% long-term probability that SSB(y) < B_{lim}. A harvest rate on B(4+) with a similar level of risk is HR=0.19 and a yield curve indicates that this HR value corresponds to HR_{MSY}; as noted above, all this is assuming 15% assessment bias.

ICES has been asked to evaluate 1 HCR of type a), and 3 HCRs of type b). The four HCRs correspond to the following combinations: F or harvest rate (F=0.22, HR=0.19,0.17,0.15), SSB trigger value (273,273,200,150) kt, action to be taken when an epidemic is occurring (include increased M in the short-term forecast, reduce the HR by 33%, reduce the HR by 33%, keep the same HR).

To answer the request, the workshop focussed, on the one hand, on whether the HCRs result in $P(SSB(y) < B_{lim}) \leq 5\%$, on an annual basis, for all years in the short, medium and long terms. The complicated aspect of this is how to handle *Icthyophonus* epidemics, and a range of scenarios were considered when evaluating the $P(SSB(y) < B_{lim})$. The reviewers consider the choice of scenarios selected for the MSE appropriate. Interpreting results under a variety of scenarios is challenging, but it seems clear from the results that Rules 2 and 3 result in $P(SSB(y) < B_{lim}) \leq 5\%$ in all years and scenarios examined. Rule 4 occasionally resulted in more than 5% probability, although the probability was below 5% in almost all years as well as in the long term. In contrast with this, Rule 1 had a probability above 5% in most years in the scenarios that considered possible future *Icthyophonus* epidemics in combination with 15% assessment bias.

For examining conformity with the MSY approach, curves representing average catch in long-term equilibrium versus F or HR were computed and seen to be flat-topped, with the F or HR in all 4 rules corresponding to catches which are within 5% of MSY. Two of the HCRs have SSB trigger values lower than the ICES MSY $B_{trigger}$ reference point (273 kt), but the original request indicates that the SSB trigger values used in the HCR should have < 5% probability of being encountered when fishing at the HR_{MGT}; the two HCRs with lower SSB triggers also have a lower HR and lead to a very similar probability of $SSB(y) < B_{lim}$.

From the above findings, it follows that Rules 2 and 3 fulfil the combined criteria of maximizing long-term yield while resulting in $P(SSB(y) < B_{lim}) \leq 5\%$, on an annual basis, for all years (short, medium and long term). The situation is slightly less clear cut for Rule 4, but points to the same conclusion, except that $P(SSB(y) < B_{lim})$ may occasionally exceed 5%. Rule 1 does not fulfil the 5% probability criterion taking into account the current situation where the occurrence of future *Icthyophonus* epidemics (in combination with assessment bias) cannot be dismissed as an unrealistic scenario.

Annex 1: Iceland requests to ICES

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Ministry of Industries and Innovation

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Reykjavík December 22, 2016
Reference: ANR16120290/20.8.0

Subject: Adoption of management plans for Icelandic summer spawning herring, ling and tusk and evaluation of ICES of the adopted harvest control rules for these species.

The Government of Iceland is in the process of formally adopting management plans for Icelandic summer spawning herring (5a), ling (5a) and tusk (5a14.

The management strategy for Icelandic summer spawning herring, ling and tusk 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.

A part of the management plan is the adoption of harvest control rules (HCR) for the three stocks for setting annual total allowable catch (TAC). The HCR adopted should be precautionary and in accordance with the ICES MSY approach.

The generic form of the HCR is the following:
1. When the spawning stock biomass (SSB) in the assessment year is estimated to be above SSB_{MGT}, the TAC in the following fishing year will be set based on a F_{MGT}.
2. When the SSB in the assessment year is estimated to be below SSB_{MGT}, the TAC in the following fishing year will be based on F_{MGT} * ($SSBy/SSB_{MGT}$).

The value of SSB_{MGT} should be defined in such a way that the estimated SSB in the assessment year when fishing at F_{MGT} has a low probability of being below SSB_{MGT} (<5%). The HCR could also be based on proportion of reference biomass in the assessment year instead of fishing mortality in the advisory year.

The work will be carried out by national experts at the Marine and Freshwater Research Institute with input from managers and stakeholders. During this process the HCR will be formed and the stock specific values of F_{MGT} and SSB_{MGT} will be defined. The HCR, along with technical documentation will be submitted to ICES for review by 20th of March 2017.

The Government of Iceland requests ICES to evaluate whether these 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. For ling and tusk the evaluation should also include review of input data and the applied assessment methodology (Benchmark). It is expected that the ICES advice for the 2017/2018 fishing year for Icelandic summer spawning herring (5a), ling (5a) and tusk (5a14) be based on the above mentioned HCR.

On behalf of the Minister of Fisheries and Agriculture

Baldur P. Erlingsson Hinrik Greipsson

Cc: The Marine Research Institute

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ICES - International Council for
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Reykjavík April 19, 2017
Reference: ANR16120290/20.8.0

Subject: Request for evaluation of management plans for Icelandic summer-spawning herring, ling and tusk

In a letter from 22nd of December 2016 the Icelandic Ministry of Industries and Innovation requested ICES to evaluate management plans for Icelandic summer-spawning herring (5a), ling (5a) and tusk (5a14).

After consultations with scientists from the Marine and Freshwater Institute and stakeholders the Ministry of Industries and Innovation asks ICES to explore the consequences of the following candidate harvest control rules and to evaluate if they are in conformity with the ICES MSY-approach:

Ling

The spawning stock biomass trigger (MGT $B_{trigger}$) is defined as 9.93 kt, the reference biomass is defined as the biomass of ling 75+ cm and the target harvest rate (HR_{MGT}) is set to 0.18. In the assessment year (Y) the TAC for the next fishing year (September 1 of year Y to August 31 of year Y+1) is calculated as follows:

When SSB_Y is equal or above MGT $B_{trigger}$:

$$TAC_{Y/y+1} = HR_{MGT} * B_{Ref,y}$$

When SSB_Y is below MGT $B_{trigger}$:

$$TAC_{Y/y+1} = HR_{MGT} * (SSB_y / MGT\ B_{trigger}) * B_{Ref,y}$$

Tusk

The spawning stock biomass trigger (MGT $B_{trigger}$) is defined as 6.24 kt, the reference biomass is defined as the biomass of tusk 40+ cm and the target harvest rate (HR_{MGT}) is set to 0.13. In the assessment year (Y) the TAC for the next fishing year (September 1 of year Y to August 31 of year Y+1) is calculated as follows:

When SSB_Y is equal or above MGT $B_{trigger}$:

$TAC_{Y/y+1} = HR_{MGT} * B_{Ref,y}$

When SSB_Y is below MGT $B_{trigger}$:

$TAC_{Y/y+1} = HR_{MGT} * (SSB_y/MGT\ B_{trigger}) * B_{ref,y}$

Herring

Rule 1 (The current advisory rule):

The spawning stock biomass trigger (MGT $B_{trigger}$) is defined as 273 kt and the target fishing mortality F_{MGT} as 0.22. Fishing mortality is the average for agegroups 5 to 14 weighted by stock numbers. In the assessment year (Y) the TAC for the next fishing year (September 1 of year Y to August 31 of year Y+1) is calculated as follows:

When SSB_Y is equal or above MGT $B_{trigger}$:

$TAC_{Y/y+1}$ based on $F_Y = F_{MGT}$

When SSB_Y is below MGT $B_{trigger}$

$TAC_{Y/y+1}$ based on $F_Y = F_{MGT} * (SSB_y/MGT\ B_{trigger})$

Rule 2 (Biomass equivalence of the current advisory rule):

The spawning stock biomass trigger (MGT $B_{trigger}$) is defined as 273 kt, the reference biomass (B_{Ref}) is defined as the biomass of herring aged 4 and older and the harvest rate (HR_{MGT}) is set to 0.19. In the assessment year (Y) the TAC in the next fishing year (September 1 of year Y to August 31 of year Y+1) is calculated as follows:

When SSB_Y is equal or above MGT $B_{triggerT}$:

$TAC_{Y/Y+1} = HR_{MGT} * B_{Ref,y}$

When SSB_Y is below MGT $B_{trigger}$:

$TAC_{Y/Y+1} = HR_{MGT} * (SSB_y/MGT\ B_{trigger}) * B_{ref,y}$

HR_{MGT} is reduced by 33% when icthyophonus is detected.

Rule 3

The spawning stock biomass trigger (MGT $B_{trigger}$) is defined as 200 kt, the reference biomass (B_{Ref}) is defined as the biomass of herring aged 4 and older and the harvest rate (HR_{MGT}) is set to 0.17. In the assessment year (Y) the TAC in the next fishing year (September 1 of year Y to August 31 of year Y+1) is calculated as follows:

When SSB_Y is equal or above MGT $B_{trigger}$:

$TAC_{Y/y+1} = HR_{MGT} * B_{Ref,y}$

When SSB_Y is below MGT $B_{trigger}$:

$TAC_{Y/y+1} = HR_{MGT} * (SSB_y / MGT\ B_{trigger}) * B_{ref,y}$

HR_{MGT} is reduced by 33% when icthyophonus is detected.

Rule 4

The spawning stock biomass trigger (MGT $B_{trigger}$) is defined as 150 kt, the reference biomass (B_{Ref}) is defined as the biomass of herring aged 4 and older and the harvest rate (HR_{MGT}) is set to 0.15. In the assessment year (Y) the TAC in the next fishing year (September 1 of year Y to August 31 of year Y+1) is calculated as follows:

When SSB_Y is equal or above MGT $B_{trigger}$:

$TAC_{Y/y+1} = HR_{MGT} * B_{Ref,y}$

When SSB_Y is below MGT $B_{trigger}$:

$TAC_{Y/y+1} = HR_{MGT} * (SSB_y / MGT\ B_{trigger}) * B_{ref,y}$

No further action taken during icthyophonus epidemics.

Hoping that this explains the request sufficiently.

Respectfully,

On behalf of the Minister of Fisheries and Agriculture

Sigurgeir Thorgeirsson
Ph.D. Senior Adviser

Annex 2: Working documents presented to the workshop

Working Document 1: "Uncertainty in assessment of Icelandic summer spawning herring", by Höskuldur Björnsson.

The document presents the results of an investigation on the retrospective pattern of the Icelandic herring stock assessment. The stock assessment model used in the investigation is the same one used to condition the harvest control rule evaluations. The model gives very similar indications about the development of the stock to the NFT-ADAPT model that is used for the annual assessment of this stock. The results from this work are used to incorporate assessment error in the harvest control rule evaluations.

Working Document 2: "Evaluation of Harvest Control Rule for Icelandic summer spawning herring", by Höskuldur Björnsson.

The document develops a management strategy evaluation in order to test the performance of several harvest control rules for the Icelandic herring stock. An aspect that substantially complicates the evaluation is the possibility of *Ichthyophonus* disease outbreaks occurring in the future, increasing mortality in the population during the years with epidemic. The evaluation therefore considers scenarios without and with future *Ichthyophonus* disease outbreaks. Assessment bias (overestimation of stock size) is also considered, based on patterns observed in the past.

Working Document 3: "A Gadget assessment of Tusk in 5a", by Bjarki Þór Elvarsson.

The document describes a Gadget stock assessment of Tusk in 5.a and the development of precautionary reference points. The model is able to follow trends in the tuning data and the fit to other datasets is good. Bootstrap runs indicate that the CV of reference biomass estimates in the time-series is around 8% on average but around 20% in the terminal years to to high variability in survey indices in that period and little other data on the incoming year classes.

The reference points were determined following the ICES technical guidelines but instead of fishing mortality, harvest rate in terms of biomass of fish larger than 40 cm was used. The estimates were obtained based on stochastic forward projections on the stock status under wide range of harvest rates. The projections considered factors such as assessment error and recruitment variations.

Working Document 4: "A Gadget assessment of Ling in 5a", by Bjarki Þór Elvarsson.

This document describes a Gadget stock assessment of Ling in 5.a and the development of precautionary reference points. The model is able to follow trends in the tuning data and the fit to other datasets is good. Bootstrap runs indicate that the CV of reference biomass (>75 cm) estimates in the time series is around 0.15 on average but around 0.28 in the terminal years to to high variability in survey indices in that period and little other data on the incoming year classes. The reference points were determined following the ICES technical guidelines but instead of fishing mortality, harvest rate in terms of biomass of fish larger than 75 cm was used. The estimates were obtained based on stochastic forward projections on the stock status under wide range of harvest rates. The projections considered factors such as assessment error and recruitment variations.

Working Document 13: "Working document on assessment model for Norwegian Spring Spawning Herring", by Höskuldur Björnsson.

The document describes the technical details of the stock assessment model used to condition the harvest control rule evaluations for the Icelandic herring stock. The working document was written in 2016 and refers to the Norwegian Spring-Spawning herring stock; however, the basic technical aspects remain unchanged in its application to the Icelandic summer-spawning herring stock.

Annex 3: List of participants

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Annex 4: Stock annexes

The table below provides an overview of the WGDEEP Stock Annexes updated at WKICEMSE. Stock Annexes for other stocks are available on the ICES website Library under the Publication Type "Stock Annexes". Use the search facility to find a particular Stock Annex, refining your search in the left-hand column to include the *year*, *ecoregion*, *species*, and *acronym* of the relevant ICES expert group.

STOCK ID	STOCK NAME	LAST UPDATED	LINK
lin.27.5a	Ling (Molva molva) in division 5.a (Iceland Grounds)	May 2017	lin-icel
usk.27.5a14	Tusk (Brosme brosme) in subarea 14 and division 5.a (East Greenland and Iceland Grounds)	May 2017	usk-icel