# STOCK ASSESSMENT OF LEMON SOLE (MICROSTOMUS KITT) IN ICELANDIC WATERS USING A GADGET MODEL

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## ABSTRACT

The Gadget modelling framework was used to build a stock assessment model to analyze lemon sole population dynamics in Icelandic waters and establish its trends in recruitment and fishing mortality. Both age and length estimation by the model fit well with the observed data. Most fish caught were between age 5 to 10, and of length between 25 cm to 40 cm. The highest proportion of the catch was between age 6 and 7. The estimation of the length-age growth curve fit well with the observed commercial data for most of the years. However, the fit was not as good for the survey data, especially for the older fish. The simulated abundance trends showed that the amount of smaller fish has been stable recent years, while the amount of bigger fish (35 cm and larger) has increased in last five years. The simulated trends of the abundance of younger fish did not fit well at the highest abundance values while the fit is better for older fish. The abundances indices of fish between 10-35 cm length were relatively stable, while larger fish (between 35-60 cm) increased noticeably between 2010 to 2018. Estimated fishing mortality had fluctuated between 1990 to 2005 while it has been relatively stable for the last five years around 0.25-0.3. The biomass of mature lemon sole increased from 2,500 tonnes in 1990 to 11,000 tonnes in 2018. Since 1997, recruitment has been variable between 10 to 17 million fish per year.

This paper should be cited as:

Chen, H. 2020. *Stock assessment of Lemon sole (Microstomus kitt) in Icelandic waters using a gadget model.* UNESCO GRÓ Fisheries Training Programme, Iceland. Final project.
http://www.grocentre.is/ftp/static/fellows/document/Huixia19prf.pdf

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# 1 INTRODUCTION

## 1.1 Icelandic fisheries

Iceland is one of the world's leading countries in fisheries management, with high production and advanced marine technology. In the last decade, catch was relatively stable. 1996 to 2003 have shown the highest capture production period, about 1.80 million tonnes per year. Since 2006, the capture production has been around 1.10-1.30 million tonnes, and relatively stable (MFRI, Fisheries overview, 2019). The Icelandic fishing industry total catches amounted to more than 1.2 million tonnes in 2018. Total catches were around 75 thousand tonnes more than in 2017. Catches of pelagic species amounted to 738 thousand tonnes, with an increase of 20 thousand tonnes compared to 2017. Total demersal fish catch was 56 thousand tonnes more in 2018 compared to 2017.

There has been a call for sustainable management of fisheries in recent years. Especially, the European Union has stated that all fish stock should be managed according to maximum sustainable yield principle (Anon, 2002). Many other countries agree with this principle too. To obtain the objectives, management plans were proposed and implemented to restrict fishing effort. For example, harvest control rule (HCR) based on the available data were applied in Australasia (Butterworth & Punt, 1999).

In Iceland, fisheries management is based on scientific advice, fishing regulations, and law enforcement to sustain fish stocks and a healthy marine ecosystem (MFRI, Fisheries overview, 2019). The successful experience and advanced technology has attracted people to come to Iceland to learn about fisheries and fisheries management through various international education programs, such as GRO-FTP.

## 1.2 Lemon sole (*Microstomus kitt*) fishery in Iceland

Lemon sole is an important commercially valuable species in Iceland. It is found all around Iceland while it is mainly distributed in the west and southwest coast of Iceland, where the highest catch has also been observed. Very little is caught in the cooler waters off the northeast coasts. It is a demersal and shallow water species, mainly found on a sandy or gravel substrate, occurring at 20-200 m depths (MFRI, Lemon sole, MFRI Assessment Reports , 2019).

Lemon sole is mainly caught by demersal seine and bottom trawl. Landings in these two gears have been relatively stable over the last 15 years and account for more than 95% of the total catch (Figure 1) with demersal seine taking more than half of the total catch annually. Since 2000, around 45-85 trawlers (demersal and Nephrops trawlers) and 28-50 seiners have reported catch of 1,000 tonnes or more of lemon sole (MFRI, Lemon sole, MFRI Assessment Reports , 2019). Since 2007, the number of both bottom trawlers and seiners has decreased. However, the number of trawlers decreased sharply until 2012, reflecting general changes in the Icelandic fishing fleet toward long-lining instead of trawling. In addition, the vessel number of demersal seine and bottom trawls for catching lemon sole changed from about 160 in 1996 to about 50 in 2017.

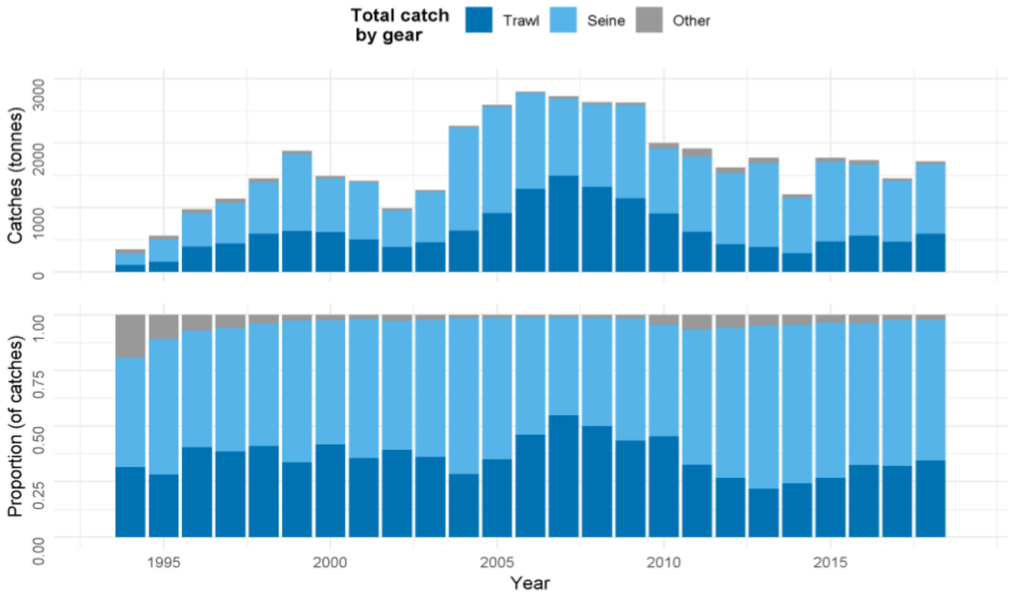

Figure 1. Total catch (landings) of lemon sole by fishing gear since 1994 in Icelandic waters (MFRI, 2019).

According to the data (Figure 2), the lemon sole advice given by the MFRI and the lemon sole TAC (total allowable catch) issued by the Minister of Fisheries and Agriculture were both exceeded by a greater amount in comparison to other commercially important flatfish species, European plaice (*Pleuronectes platessa*) and witch flounder (*Glyptocephalus cynoglossus*). In the last 3 years, catch exceeded TAC by 30% or more due to ITQ (Individual Transferable Quota) transformations into lemon sole from other species.

At present, the assessment of lemon sole stock in Icelandic waters relies on stock biomass indices and catch trends. Spring ground fish survey biomass index of lemon sole 30 cm and larger in catch is used to calculate $F_{proxy}$ (catch/survey biomass) (Veidiradgjof, 2019). The target $F_{proxy}$ was defined as 80% of the mean Fproxy during the period 2010–2015. The advice was mainly based on multiplying the most recent index value with target $F_{proxy}$ value (Veidiradgjof, 2019). Due to the high value and importance, both industry members and management in Iceland are interested in learning more about lemon sole population dynamics. The development of an analytical modelling assessment may help predict lemon sole population dynamics more broadly and accurately.

## 1.3 Objective

Analytical stock assessment models like Gadget consider various data sources, e.g., lengths, ages, maturity stages, weights etc., to reflect the outcome of biological processes of the entire fish population, such as growth and maturation. These data, along with survey indices that are assumed to reflect relative changes in population abundance over time, are placed in a statistical framework to fit the stock assessment model to all data sources at the same time. The fitted model then provides estimated abundances over time and parameters that reflect the most prudent solution of population dynamics that can be found across all data sources. The model fitting is done by assuming a kind of error that occur in the data, comparing with the actual data to predictions from the model (determined by alternative parameter values), and minimizing the distance between the predictions and observations (observation error) in order to optimize the model fit (Nyamweya, 2012). Optimization occurs by minimizing the negative log likelihood scores, which reflects minimization of the error. Since no analytical model has been developed for lemon sole stock assessment in Icelandic waters, this project aims to use the Gadget model analytical framework to further the knowledge of the population dynamics of this species around the country. The objective of this study is to conduct an analytical age- and length- structured assessment of the Icelandic lemon sole stock to improve the scientific base of the advice for this species.

### *1.3.1 Specific objectives*

1. Analyse lemon sole population dynamics in Icelandic waters and establish its trends.
2. Investigate whether the Gadget model is effective in assessing Icelandic lemon sole stock, concerning recruitment, growth and stock trends.
3. Attempt to establish recruitment and fishing mortality trends.
4. Master the Gadget modelling method, which will be helpful to do further assessment work in China.

# 2 LITERATURE REVIEW

## 2.1 Fisheries management

Fisheries management is a broad term which describes process of administering control of fishing (Dankel, Skagen, & Ulltang, 2008). The main purpose of fisheries management is to protect fishery resources from overfishing and promote sustainable exploitation while producing maximum sustainable yield for fisheries production. Fishery management strategies include the assessment methods, management tools and harvest control rules, to achieve sustainable utilisation (Punt, Butterworth, & Moor, 2016). Assessment methods are mainly determined by the data available and species life history. Advances in stock assessment techniques have led to a better scientific foundation and give more reliable advice for fisheries management (Dankel, Skagen,

& Ulltang, 2008). Management tools mainly concern regulating how much fish are taken from the ocean, such as gear modification and restriction, minimum size limit, seasonal closure, and marine protected areas. These need to be based on various kinds of data, such as species composition, catch-per-unit-effort of fishing, spatial patterns of harvesting, single or multiple species populations, fishing mortality, etc. Harvest control rules mainly concern when and how much to adjust management. These are informed by data indicating how fishing is affecting stocks.

In addition, among the management methods, the ecosystem approach in marine fisheries has received increasing attention in recent years. The ecosystem approach considers environmental forcing on fish stocks and for all impacts of fishing activities, which involves the biological and technical interactions between the stocks (Rice, 2011). Even the effects of other stocks such as prey or predator species are considered in assessment and management. These methods may give the management more scientific and reasonable advice. However, the data these methods need are supplied by stock assessment models, and therefore a reasonable starting point is to begin with a reliable stock assessment that can later be fit into a more complex ecosystem scenario, as is the goal of this study.

## 2.2 Stock assessment methods

The purpose of stock assessment is mainly to develop the methods with fishery data to guide management practices and develop marine exploitation sustainably. The models used in fisheries assessment provide a mathematical-statistical base for interpreting information and predicting trends, provide reference points such as Maximum Sustainable Yield (MSY), harvest rates etc., to guide management measure and keep fishing within sustainable limits (Lorenzen, Cowx, Entsua-Mensah, & et.al, 2016). Quantitative stock assessment methods have been used in marine fisheries for a long time (Saila, 1993) and rely on extensive and long-term data collection, as well as complex analytical procedures. Common models such as logistic growth and the Schaefer model, catch models, biomass dynamics models, surplus production models, age structured models, integrated models (length- and age-based), etc. have been used for stock assessment and management for a long time. Especially, the integrated models have received more attention in recent years. However, in China, because of limited and poor data, the stock assessment methods mainly include catch-MSY model, GLM (generalized linear model), GAM (generalized additive models), Fox model and Bayesian model.

## 2.3 Gadget model

Gadget (Globally applicable Area Disaggregated General Ecosystem Toolbox) model is a multispecies and ecosystem model with a powerful and flexible framework (Begley & Howell, 2004). Gadget models take many features of the ecosystem into account:

One or more species, multiple areas, maturation, reproduction and recruitment, multiple commercial and survey fleets (Stefansson G. , 2003). An appropriate integration of different components of a model (e.g. catches, gears), can be done by using likelihood components. It also can integrate species interaction and the impact of fisheries exploiting on that species (Taylor, Begley, Kupca, & et.al, 2007). In addition, the Gadget modelling framework is flexible, freely available and has low data demands. It is possible to integrate sets of data into the same model with incomplete time series data at different aggregation levels and scales (Bartolino, Colloca, Taylor, & et.al, 2011). An age-length structured Gadget model has been built for hake in the central Mediterranean Sea (Bartolino, Colloca, Taylor, & et.al, 2011). A size- and age-structured assessment of ling (*Molva molva*) and tusk (*Brosme brosme*) in Icelandic waters has been developed in Gadget as well (Elvarsson B. , Woods, Björnsson, & et.al, 2018). Gadget has been widely applied in stock assessment because of its flexibility, low data demands, and the ability to integrate many features.

## 2.4 Lemon sole (*Microstomus kitt*) biology

Lemon sole is benthic fish and belongs to the *Pleuronectidae* family. It is common in the eastern Atlantic, from the White Sea and Iceland to the Bay of Biscay (Kélig, Romain, Cécile, & et.al, 2010). Its distribution is mainly on sand and gravel seabed from 20 to 200m. It was concluded that species may spawn wherever it is found from the conclusion of the Scottish research vessels. However, it is also supported that most of the spawning takes place in certain favoured places where the fish are normally found in dense concentrations (Rae, 1965). Lemon sole has a long spawning period and extend over from February to August (Mcintosh, 1897) (Bowman & Rae, 1935). It produces a large number of eggs. It was reported that the number of ova is over 150,000 of a 12.5 inches fish and 670,000 of a 15 inches fish (Fulton, 1890). And the lemon soles seems begin their demersal or bottom-living life when they are about an inch long (Rae, 1965). The lemon sole two years age or less are regarded as immature and from two years onwards mature. Male lemon sole mature earlier than females. More than half fish begin to spawn in their third year for males and in their fourth year for females (Rae, 1965). At the five years age, most female are fully mature. The growth rates for the both sexes of Icelandic lemon sole are the same during the first few years of life. After maturity, the female fish appear to grow more quickly than the male (Rae, Lemon soles at Iceland, 1924-1939, with special reference to Faxa Bay., 1948). Only a small proportion of males become larger than 35 cm, whereas about the same proportion of females grows larger than 40 cm (MFRI, 2019). In Iceland, spawning takes place from April to September. In Iceland, sexual maturity in males is 3–4 years, and in females is 4–6 years. About half of the males reached maturity at the length of 13 cm and females reached the level at 24 cm length in Iceland (MFRI, 2019). Lemon sole are bottom feeders ( Davenport, Kjørsvik, & Haug, 1990). It has been suggested that lemon sole less than 15 cm total length inhabit rocky areas from 50–100 m, because they were rarely caught by contemporary sampling methods (Jennings, Hewlett, & Flatman, 1993). The annual species-specific fishing mortality of lemon sole (Rae, The lemon sole, 1965) was modelled of 14% by Beam trawl and 14% by Otter trawl in North sea (Piet, Hal, & Greenstreet, 2009).

# 3 METHODOLOGY

## 3.1 Study area

The Icelandic waters ecoregion includes the shelf and surrounding waters inside the Icelandic EEZ (Figure 2). The region is located at the south of the Arctic Circle, inside the junction of the Mid-Atlantic Ridge and the Greenland–Scotland Ridge (MFRI, 2017). During recent years, lemon sole is mainly distributed on the west and south coasts. There was just a little catch on the north and east of Iceland (MFRI, 2019).

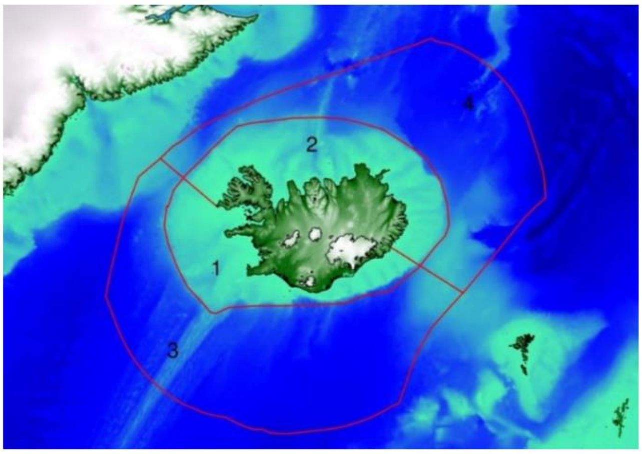

Figure 2. The Icelandic ecoregion and subareas (MFRI, ICES Ecosystem Overviews Icelandic Waters Ecoregion, 2017).

## 3.2 Data collection

The Icelandic spring groundfish survey began in 1985 and covers the most important distribution area of the lemon sole. The Icelandic autumn groundfish survey began in 1996 (MFRI, 2019). During the surveys, bottom trawl is used to catch lemon sole and other fish. However, the main nursery areas of lemon sole are thought to be in shallow water habitats, which is unsuitable for demersal trawling. Although both autumn survey and the spring survey have the similar signals for lemon sole, the number of specimens caught in the autumn survey is low, ranging between 20 and 260, therefore the autumn survey data is not used in this assessment model. A designated flatfish survey with beam trawl was started in 2016 to cover most of the recruitment grounds of lemon sole and other flatfish species, but as it was only started 3 years ago, the series is not long enough to include in this assessment model (MFRI, 2019).

Otoliths of lemon sole have been collected since 1999. Annually 11-38 samples (50 fish in each sample) have been collected from demersal seine and 3-21 samples from demersal trawl (MFRI, 2019). The catches of each vessel were recorded. Biological data from the commercial catches of bottom trawls and demersal seine fleet were collected from landings by scientists and technicians of the Marine and Freshwater Research Institute (MFRI) in Iceland. The biological data collected are mainly length (to the nearest cm), weight, otoliths for age determination, sex and maturity stage. During catch and surveys, catch tonnes, age, length, weight, recruitment index, maturation, biomass indices, juvenile index, Fproxy (catch/survey biomass), fishing effort data is available. In this project, length aggregation of survey indices was used for fitting the model.

### 3.3 Setup of a Gadget run

A schematic description of the Gadget model for lemon sole is shown in Figure 4. The components of the model are illustrated there, which is a single species and one research area model. This model mainly includes three parts, the main components, likelihood and the observation. The main component encompasses the basic data on lemon sole fishing, such as commercial catch data by two kinds of fleets and survey data, the proportion of mature data, etc. The data sources mainly include age-length distribution, length distribution, maturity proportion and the indices. The relationship from one component to another is shown in this diagram.

The overall likelihood is calculated by comparing the simulated output with the available real data (red lines in Figure 3), to make the model statistically usable (Nyamweya, 2012). These data are named as “likelihood data” and each dataset used is called a “likelihood component”. Then the statistical relationship needs to be specified or the purpose of comparing simulation results with the observed data (Taylor, Begley, Kupca, & et.al, 2007). The data used as likelihood components depend on data availability and the aim of the model. In this project, length distributions, age–length keys, and survey abundance indices will be used in the model. The model will combine a wide selection of the available data to find the best fit by using a maximum likelihood approach.

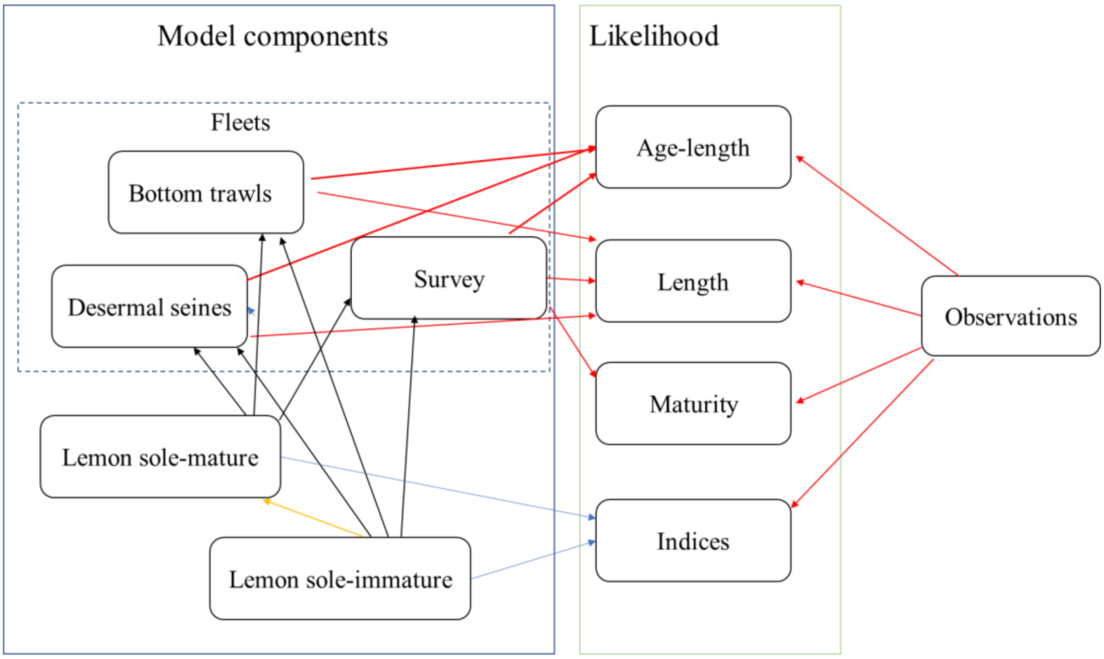

Figure 3. Schematic description of the Gadget model for lemon sole. Lines represent flow from one model component to the other. Red lines represent the flow of model predictions and observations which are utilized in the likelihood. Black lines indicate the consumption of the mature and immature stock components by fleets. Orange line represents the growth from immature to mature stock components. Grey lines indicate the predictions from survey indices to likelihood.

All the data used in the Gadget model are summarized in Table 1, including the time range, fleet type, weight group type and the data source for different distribution analyses. Both Age-length distributions and Length distributions were calculated from commercial and survey data; Survey indices were calculated from the length distributions and are disaggregated into seven groups (Table 1). In addition, catches were directly removed from the population. Gear-specific time series of catch can be obtained from official statistics.

Table 1. Overview of data used in the Gadget model. Num. data-points represent the original data set. Weight groups represent groupings used in the iterative re-weighting algorithm, common weight groups receive the same weights when individual likelihood scores are summed to form the total likelihood.

| Origin | Time-span | length group size | Num. data-points | Weight group |
|---|---|---|---|---|
| Age-length distributions: | | | | |
| Demersal seine | All quarters,1996-2018 | 4 | 100 | comm |
| Bottom trawls | All quarters,1995-2018 | 4 | 112 | comm |
| March survey | 2nd, 2001-2014 | 4 | 1009 | aldist.igfs |
| Length distributions: | | | | |

| | | | | |
|---|---|---|---|---|
| Demersal seine | All quarters,1991-2018 | 4 | 12 | comm |
| Bottom trawls | All quarters,1995-2018 | 4 | 117 | comm |
| March survey | 2nd,1990-2018 | 4 | 2635 | ldist.igfs |
| | | | | |
| Ratio of immature/mature by length groups | | | | |
| March survey | 2nd,1990-2018 | | | |
| | | | | |
| Survey indices: | | | | |
| March survey | 2nd,1990-2018 | si.10–20 | 225 | si.ind |
| March survey | 2nd,1990-2018 | si. 20–25 | 353 | si.ind |
| March survey | 2nd,1990-2018 | si. 25–30 | 446 | si.ind |
| March survey | 2nd,1990-2018 | si. 30–35 | 778 | si.ind |
| March survey | 2nd,1990-2018 | si. 35–40 | 598 | si.ind |
| March survey | 2nd,1990-2018 | si. 40–45 | 203 | si.ind |
| March survey | 2nd,1990-2018 | si. 45–60 | 38 | si.ind |

## 3.4 Operating model

Gadget and various potential sub-models and options were operated according to the Gadget User Guide (Begley J. , 2017) and a course on Gadget (Elversson & Woods, n.d.). In this work a specialized database system, MFDB (Lentin, 2014), is used to extract data for the model set up. The database of MFDB is mainly built for the needs of stock assessment and ecosystem studies (Kupca, 2006). This database procedure is used in conjunction with a specialized R package, Rgadget (Elvarsson & Lentin, 2016). This R package allow rapid and reproducible model building and analysis within the Gadget framework (Elvarsson B. , Woods, Björnsson, & et.al, 2018).

### *3.4.1 General gadget model framework*

Gadget models contain a series of equations including several unknown parameters. An age-length based model will be used in this project. Inputs to the program that defines its structure include: number of years (in this case 1990-2018 was studied), number of time steps within a year (in this case 1 year was divided into 4 steps), number of areas (in this case area was set to 1), how many fleets are included (in this case two commercial fleets, bottom trawls and demersal seine, and survey fleet), and how many stock subcomponents are included (in this case 1 immature and 1 mature stock component), the range of age (1-15 year) and length bins (3-70 cm and 15-70 were set to immature and mature respectively). Therefore, the numbers of fish predicted ($N_{y,t,r,a,l}$) at the most disaggregated level are numbers at year $y$, time step $t$, area $r$, age $a$, and length $l$. Population dynamics are described by a series of processes, including body growth, maturation, and recruitment. These processes are described by a series of parameters. Fixed processes include: natural mortality (M = 0.15), l50 of maturity fish (mat2=20) and Length-weight relationship based on lengths and weights obtained in the survey. Estimated processes include: growth according to a von Bertalanffy growth equation, growth dispersion, recruitment length, fishing selectivity, maturity ogive, initial abundances and survey catchability. A fishing process on both the mature and immature fish is described by a selectivity curve (logistic and estimated by fleet) and the resulting catches. The resulting catches are direct removals from the populations according to the catch data (no observation error), so the predicted length-, age-, and maturity compositions are back-calculated according to the estimated selectivity curve and population composition predicted by the model at the time of the fishing event. Because the Gadget model acts as a simulator, output of the model is in its rawest form $N_{y,t,r,a,l}$ described above. However, these numbers can be summed/aggregated at different levels to form predictions for comparing with data (e.g., length group distribution, age-length distribution, maturity proportions, population indices in length intervals), or other derived quantities used to describe population dynamics and the effects of fishing (e.g., total biomass levels, fishing mortalities, recruitment). $N_{y,t,r,a,l}$ can be multiplied by expected weights at age and length ($W_{a,l}$) before summing to create biomass quantities. Output also includes derived quantities or relationships that are estimated in the model-fitting process include maturity ogives, and initial population sizes age, and fleet selection.

During the estimation procedure, predictions from the outputs are compared to the observed real data to get likelihood scores, to make the model statistically usable. To get a goodness of fit of each model component, then an overall likelihood component is calculated that sums the likelihood from each data source. Summing without weights implies that each data source is trusted equally, and that each data point contributes equally to the final overall likelihood. However, because some data sources may be more uncertain or contain many more data points (with little added information), weights are commonly used to combine individual likelihoods to form a final overall score. The Rgadget package in R was used to run an iterative re-weighting algorithm to calculate the best weight for each component separately, or according to groupings if these are chosen. The last step is that the individual likelihood components are combined into a single objective function (weighted likelihood function) to do the final optimization, in which parameters are adjusted until convergence on a minimum overall likelihood score is reached.

### *3.4.2 Specifications of the lemon sole model*

The lemon sole model runs from 1990 to 2018 in quarterly time-steps and covers only a single area (Icelandic water). The lemon sole population was simulated in this model. The immature fish was simulated from age 1 to age 4. The length range considered is 3–70 cm, aggregated in 2 cm intervals. The mature fish was simulated from age 3 to age 15. The length range considered is 15–70 cm, aggregated in 2 cm intervals. Two fishing fleets were simulated in the model, along with one survey fleet. The bottom trawlers and other gears were regarded as one and the demersal seine fisheries were regarded as other one. Several parameters will be calculated according to the equations shown below.

### 3.4.3 Growth

The growth process (G) including length and weight will be modeled, based on a simplified version of the von Bertalanffy growth equation as follows (Bartolino, Colloca, Taylor, & et.al, 2011) (Bertalanffy, 1938):

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

Where $L\infty$ is the upper boundary length, and $t$ is time and $k$ is the annual growth rate.

In addition, dispersion of the growth increment ($G_{l'}^{l}$) was modelled based on beta-binomial density (Stefánsson, 2005), all of which are estimated (Table 2).

$G_{l'}^{l} = B(\alpha, \beta, n)$

With a mean $\alpha\beta = \Delta l$

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

Among them, n was fixed as the maximum length group steps, β was estimated.

### 3.4.4 Natural mortality

Most often, in stock assessment natural mortality is assumed to be constant. The same assumption might be used here, and a reasonable value for natural mortality was investigated through a literature search and preliminary investigation of length distributions. In this modelling it was set to M = 0.15 (Table 2).

### 3.4.5 Fishing Selectivity

Trawlers and demersal seines display different selectivity. To target different portions of the stock, length-based selectivity will be approximated through an exponential $l_{50}$ suitability function, and will be modelled as:

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

where $S_f(l)$ is the selectivity of fishing fleet $f$ on length $l$, and $b_f$ and $l_{50,f}$ are fleet-specific parameters describing the logistic selectivity curve (Table 2).

### 3.4.6 Maturation

Maturation is modelled as unidirectional movement from the immature (s=0) to the mature (s=1) stock component, was shown as below (Elvarsson, Woods, & Höskuldur , 2018):

$$A_{a,l',l,s,y,t} = \begin{cases} N_{a,l',s'=0,y,t} \times m_{l}^{l'} & if\ s = 1\ and\ t > 1 \\ -N_{a,l',s'=0,y,t} \times m_{l}^{l'} & if\ s = 0\ and\ t > 1 \end{cases}$$

Where $m_l^{l'}$ is the proportion of immatures being mature after growing from length $l'$ to l, which is defined as below:

$$m_l^{l'} = \begin{cases} \frac{\lambda(l-l\prime)}{1+e^{-\lambda(l-\ l_{50})}} & if\ \ a < a_{maxmat} \\ m_l^{l\prime} = 1 & if\ a\ = a_{maxmat} \end{cases}$$

where $l_{50}$ is the length at 50% maturity and is fixed as 20, after which all fish are mature.

### 3.4.7 Recruitment

The number of recruits each year (Ry) is estimated within the model based on the equation as below:

$$N_{a_{min},l,s=0,y,t\prime} = R_y p_l$$

Where *N* denotes the recruitment numbers enters in population, *t'* denotes the time-step of recruitment, *s* = 0 represent the immature, *l* denotes the length group, and $p_l$ denotes the recruited proportion in length-group *l*. $p_l$ is calculated by a normal density, in which mean length was set to the initial length ($l_0$). The initial length was calculated through the growth formulation (showed above) with the recruitment age was set to 1 and variance of the recruitment age *a'* ($\sigma_{0,a}^2$) (as shown in table 2).

Table 2. Overview of parameters used in the operating model. Estim. means if the parameters were estimated. The comments state the meaning of each parameter and fixed values.

| Parameters | Notation | Estim. | Comments |
|---|---|---|---|
| Natural mortality | Ma | No | 0.15 for all ages |
| Growth function | k, $L\infty$, $l_0$ | Yes | Maximal growth rate, asymptotic length, and initial length (at age 1). |
| Growth dispersion | $\beta$, n | Yes,<br>No | n=4 max length group increase in a time step |
|  | $b_f$, $l_{50f}$ | Yes | Fleet-specific |
| Maturity ogive | $\lambda$, $l_{50}$ | Yes |  |
| Variance in length at recruitment | $\sigma_{0,a}^2$ | Yes | For a=1, $y \in [1990, 2018]$ |
| Variance around initial mean lengths | $\sigma_a^2$ | No |  |
| Number of recruits | $R_y$ | Yes |  |
| Initial abundances | $v_{s,a}$ | Yes | For $a \neq 1$, y=1990 |

| | | | |
|---|---|---|---|
| Survey catchability | $q_g$, $b_g$ | Yes | Intercepts and slopes term in a log–linear relationships of indices with abundances. The slope $b_g$ is fixed to 1 for all indices |
| Length-weight relationship | $\mu_s$, $\omega_s$ | No | Based on lengths and weights obtained in the survey |
| Scalars | $R_c$, $I_{c,s}$, $F_0$ | Yes | Scaling coefficients for recruitment, initial numbers at age, and initial fishing mortality (applied to all age groups) |

### *3.4.8 Likelihood*

Length distributions and length- and age- distributions modelled for both surveys and commercial fishery components will be compared to the data as proportions respectively through the sum of squares function as follows.

$$l_f = \sum_y \sum_t \sum_l (\pi_{f,l,y,t} - \pi'_{f,l,y,t})^2$$

Where $l_f$ denotes the fish number at a particular length or age. *f* denotes the fleet, *y* denotes the year, *t* denotes the time-step, *l* denotes the length. The proportions were calculated as below:

$$\pi_{f,l,y,t} = \frac{\sum_{a'} \sum_{s'} O_{f,a',l,s',y,t}}{\sum_l{}' \sum_{a'} \sum_{s'} O_{f,a',l',s',y,t}}$$

and

$$\pi'_{f,l,y,t} = \frac{\sum_{a'} \sum_{s'} C_{f,a',l,s',y,t}}{\sum_l{}' \sum_{a'} \sum_{s'} C_{f,a',l',s',y,t}}$$

Where $\pi_{f,l,y,t}$ is the proportion of the total fish observed to belong to a certain time-step/fleet/length/year combination (*t*, *f*, *l*, *y*), and $\pi'_{f,l,y,t}$ is the corresponding proportion in the modelled population. Predicted maturity proportions are likewise compared to data proportions using a sum of squares. The negative sum of squares is used as a proxy for negative log-likelihood to be minimized as an objective function.

For the survey index likelihood calculation, a sum of squares of a log linear regression will be used to test the fitness between the modelled data ($N'_{g,y,t}$) and the observed index ($I_{g,y}$) in the likelihood components, as shown in the following equation (Bartolino, Colloca, Taylor, & et.al, 2011) (Elvarsson, Woods, & Höskuldur , 2018)：

$$l_g^{SI} = \sum_y \sum_t \left(logI_{g,y} - \left(logq_g + b_g logN'_{g,y,t}\right)\right)^2$$

Where

$$N'_{g,y,t} = \sum_{l\epsilon g}\sum_{a}\sum_{s} N_{a,l,s,y,t}$$

Where $I_{g,y}$ denotes the summed survey index within indicated length range, $N'_{g,y,t}$ denotes the modelled index within the length range (as shown in table 1, length was divided in seven groups ), $q_g$ denotes the catchability, $b_g$ control the shape of the power function which relates the abundance index, here $b_g$ is set to be 1.

### *3.4.9 Optimization*

The last step in the Gadget approach is to estimate the parameters using one or more algorithms to optimize parameter values iteratively. Survey index, length distribution, age-length, and maturity are considered as components separately. In this procedure, the individual likelihood components are combined into a single objective function (Weighted likelihood function) (Stefansson G. , 2003) (Taylor, Begley, Kupca, & et.al, 2007). Simulated annealing and Hooke and Jeeves algorithms were used to minimize the likelihood function with weights set using the iterative reweighting algorithm. The scores that give the lowest negative log-likelihood score gives a measure of how well the simulated model fits the data. The number of simulated annealing iterations was set to 2,000,000, number of Hooke & Jeeves iterations was set to 150,000 and number of bfgs iterations was set to 10,000 (Elvarsson, Woods, & Höskuldur , 2018).

# 4 RESULTS

The optimization results are shown here, such as length distribution, age-length distribution, and the weighted-likelihood score. Model results after optimization, including several parameters estimates and fishing mortality, biomass, and recruitment and the lemon sole population dynamics estimates are shown as well.

## 4.1 Population indices

The fish abundance trends of different length bins are shown in the Figure 4. The simulated fish abundance in different length bins does not fit well with the observed data at highest abundances, especially for younger fish. The simulated trends for older fish fit better most likely due to low catches of the smaller fish. The fish abundance indices of length bins 10-20 cm was about 200-400/year since 2000 to 2018. The highest values appeared in 2000. The fish abundance of the length bins 20-25 cm began to increase since 2000 and arrived the peak in 2002. The abundance was kept between 400-600/year after 2003. The fish abundance of length bins 25-30 cm was stable 700-100/year from 2003 to 2018. The highest abundance was in 2003. The fish of length bins 30-35 cm are the most abundant. The abundance was kept about

2000/year relatively stable from 2004 to 2018 and the peak value showed in 2005. As analyzed, the abundance peaks are moving as the fish grows.

For the larger fish (length bins 35-40 cm, 40-45 cm and 45-60 cm), abundance increased during 2010-2018. For the fish whose length is between 35-40 cm, the abundance increased from 1000 to 1500/year in these 8 years, or a 50% increase. The abundance of the fish in the 40-45 cm and 45-60 cm length bins, the abundance was relatively low but nonetheless had an obvious increase in the last eight years as their index increased from 160 to 650 (400% increase) and 20 to 180 kilograms/30mins (900% increase) respectively.

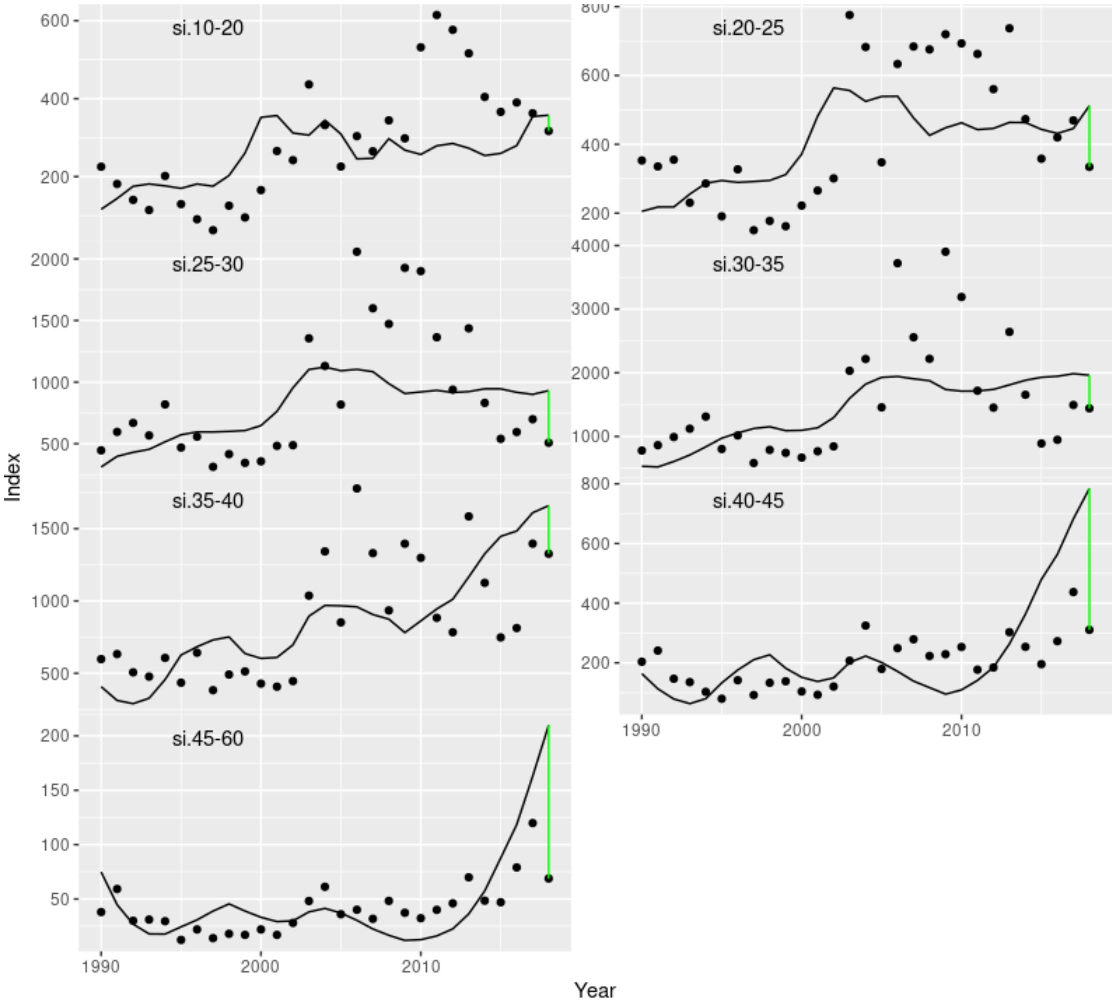

Figure 4. Estimates of the abundance trends of different length bins fish. The dot points are the observed data and the black line is the simulated value.

## 4.2 Likelihood score

The likelihood score for the age-length and length distribution of bottom trawls and demersal seines are relative concentrated. The likelihood score of length distributions are lower (Figure 5). However, the likelihood score of age-length and length distribution for survey data are dispersed. The mature proportion of survey data is relative concentrated but high.

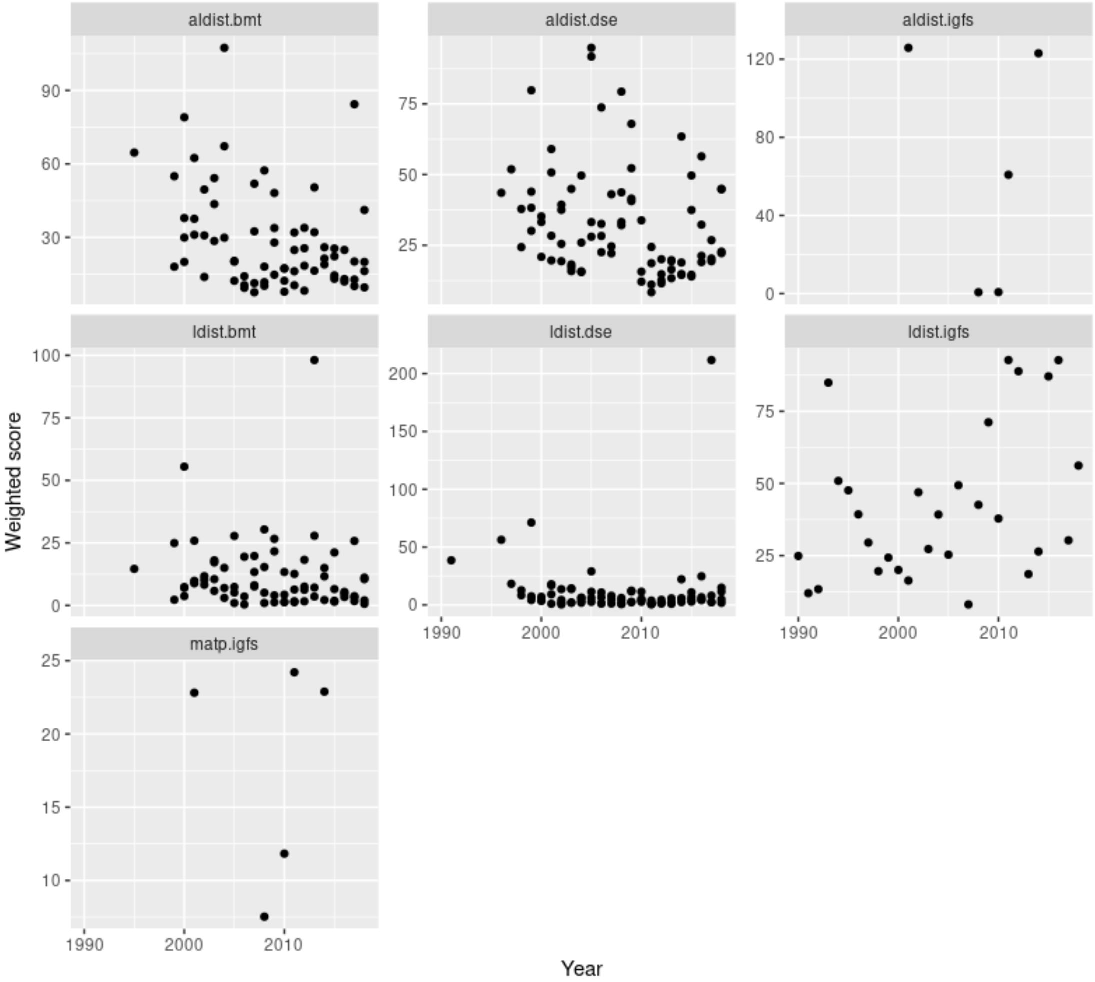

Figure 5. Weighted likelihood score of age-length distribution and length distribution of bottom trawls, demersal seines and survey respectively, and the likelihood of mature proportion of survey.

### 4.3 Age distribution

The proportion of different age fish caught by bottom trawls was estimated by the gadget modelling and fits the observed data relatively well. The estimated proportion peak overlaps with the observed data peak in most of the years, with few exceptions (1996 step 2, 1999 step 3, 2000 step 1, 2000 step 3, 2000 step 4 and 2001 step 3). During these periods, the estimated age was lower than the observed data. However, the estimated age was older than the observed data in 2007 step 4 for bottom trawls catch (Figure 6).

The age distribution from demersal seine was also estimated by the gadget modelling. The estimated age peak overlaps with the peak in the observed data in most of the years, with few exceptions (1997 step 2, 1999 step 2, 1999 step 4 and 2002 step 4), were the estimated age was lower than the observed data. However, the estimated age was higher than the observed data in 2005 step 4, 2007 step 1, 2007 step 2, 2007 step 3 and 2009 step 4 for demersal seine catch (Figure 7). Compared to the result of the bottom trawls, there is no same estimation error (at the same time point) which suggests reliability of the estimates. In addition, the fish caught by bottom trawls and demersal seines are mainly distributed from the age between 5 to 10, the highest selectivity is of fish age 6 to 7.

Few samples from the survey have been age read, and the model therefore struggles fitting the age distribution to the observed data, especially in 2001 step 2 and 2014 step 2 (Figure 8). The selectivity fit the reality.

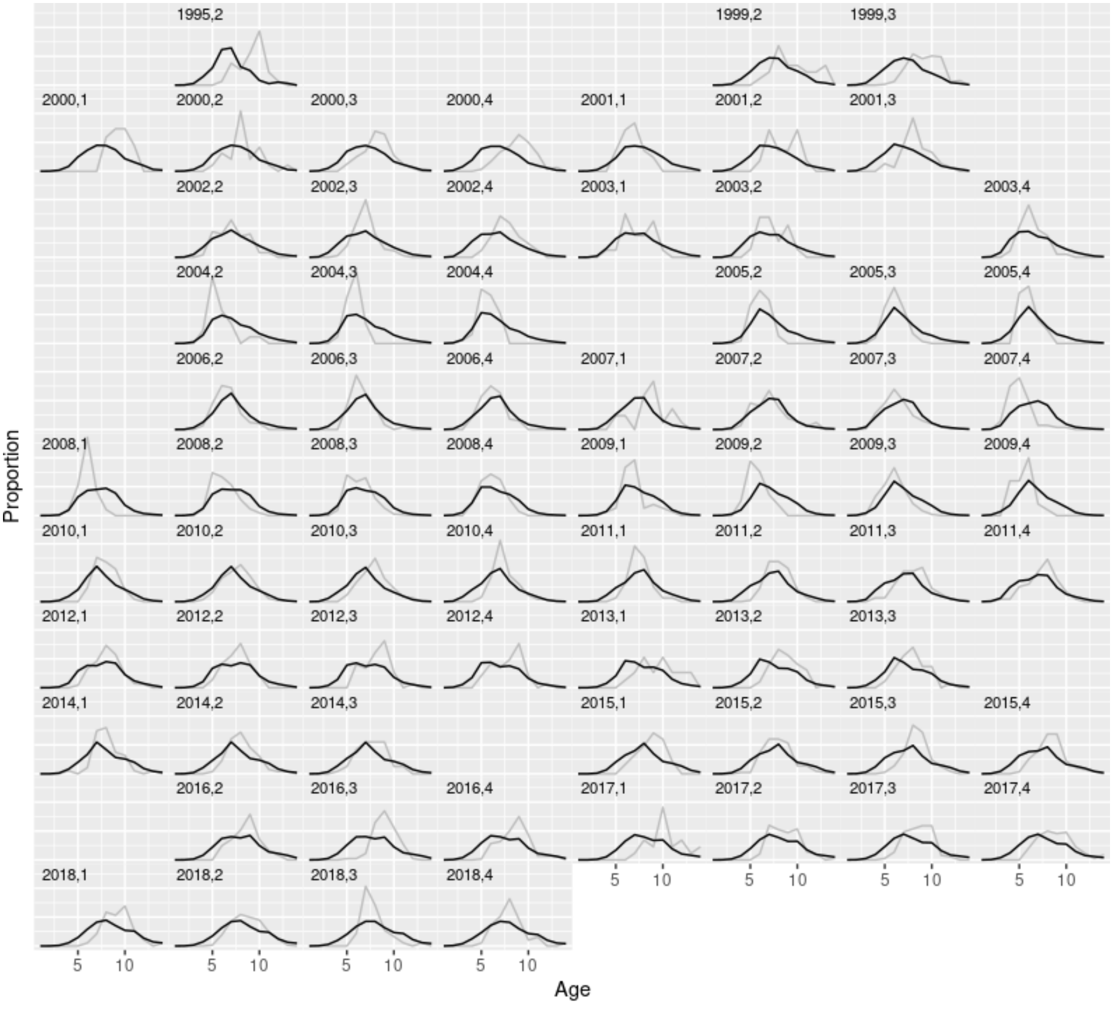

Figure 6. Age composition from bottom trawl. The grey lines are the observed data and the simulated age structures are the black lines.

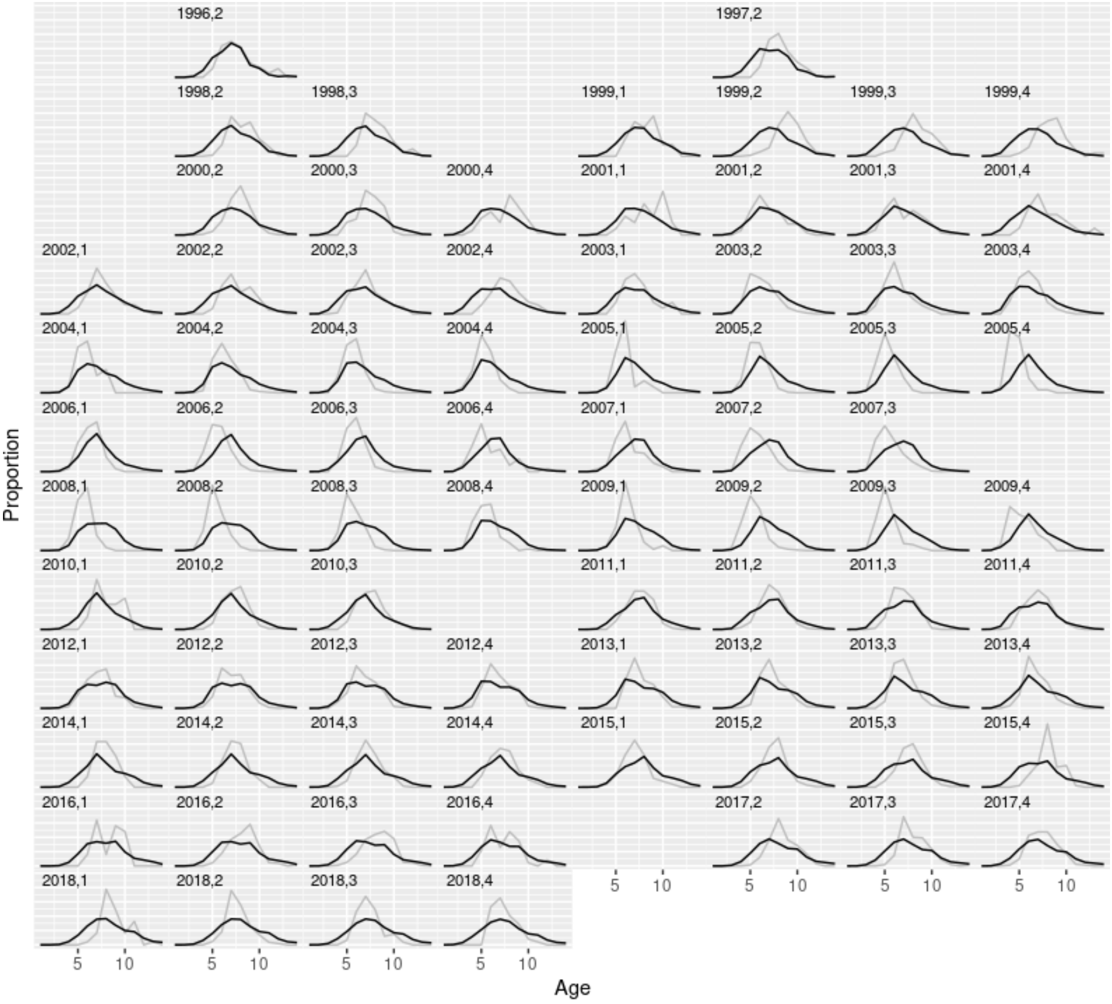

Figure 7. Age composition from the demersal seines. The grey lines are the observed data and the simulated age structure are the black lines.

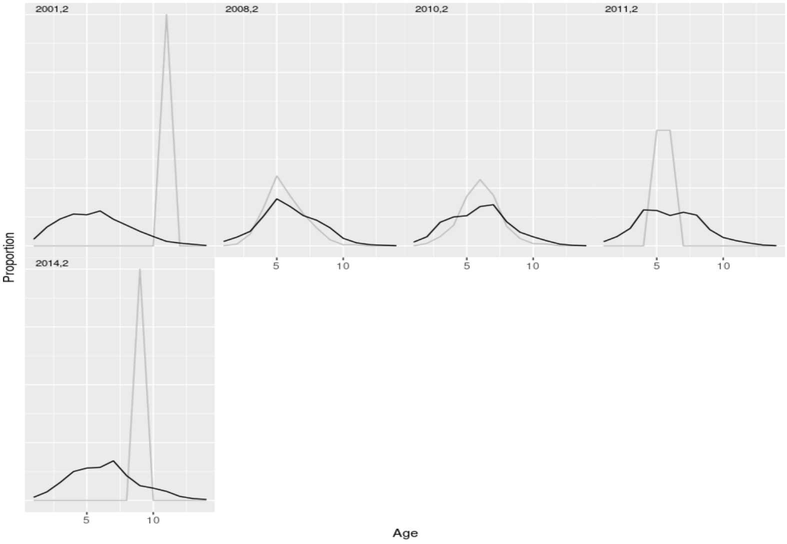

Figure 8. Age composition from the survey. The grey lines are the observed data and the simulated age structure are the black lines.

As shown in the residual bubble plots for prediction of age distribution (Figure 9), The prediction is good for commercial catch in general. There are positive and negative estimation for different age fish every year. In general, the positive and negative estimation appeared alternately for different age fish in commercial data, except that for the small age fish (below age 6), there were always positive estimation before 2010 and negative estimation after 2010 to present. That might because of the otoliths of small aged fish are hard to read.

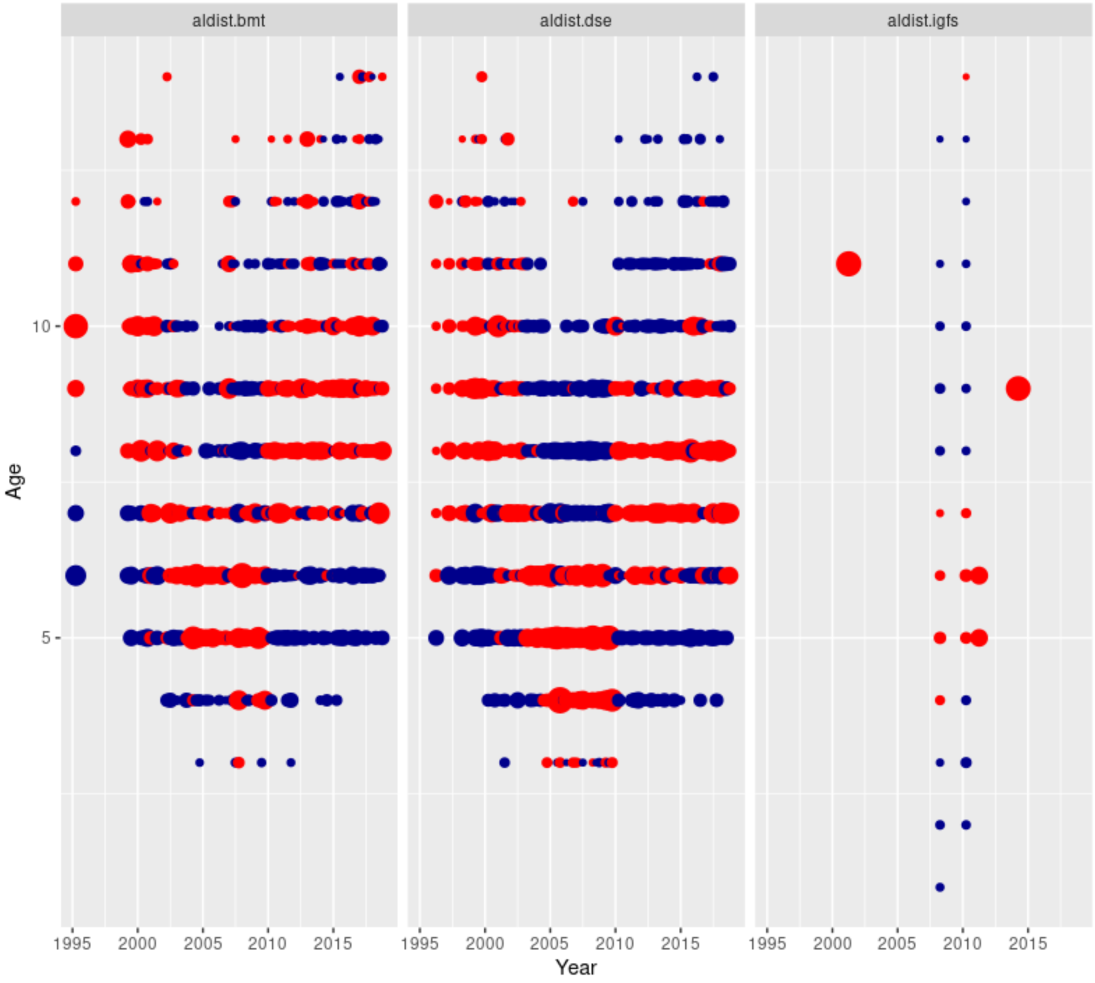

Figure 9. Residual bubble plots for predication of age distributions by bottom trawls (the left one), demersal seines (the middle one) and survey fleets (the right one). The red bubble means the positive prediction, the blue bubbles means the negative prediction.

## 4.4 Length distribution

In general, the estimated length distribution from bottom trawls fit well with the observed data in most years. However, the estimated length is smaller than the observed data in 2000 step 1, 2007 step 4 and 2018 step 1 while the estimated length is larger than the observed data in 2001 step 1 (Figure 10).

For the demersal seine catch, the estimated length proportion of lemon sole fit well with the observed data (Figure 11). However, the estimated length is smaller than the observed data in 2016 step 1 and 2018 step 1 while the estimated length is larger than the observed data in 1996 step 2 and 1999 step 1. Compared with the simulation results of bottom trawls, there is no similar simulation error happened in the same year by the two different methods. That means the error observed is not because of the modeling calculation, but rather bias in the sampling procedure.

According to the length composition graph of the survey data (Figure 12), all the estimation curves fit well with the observed data about the length distribution. With the exception that the distribution of small fish does not fit well in 2012 step 2 and 2016 step 2. This might be because of few samples of smaller fish. The fish caught by different fleets length are mainly distributed between 25 cm to 40 cm.

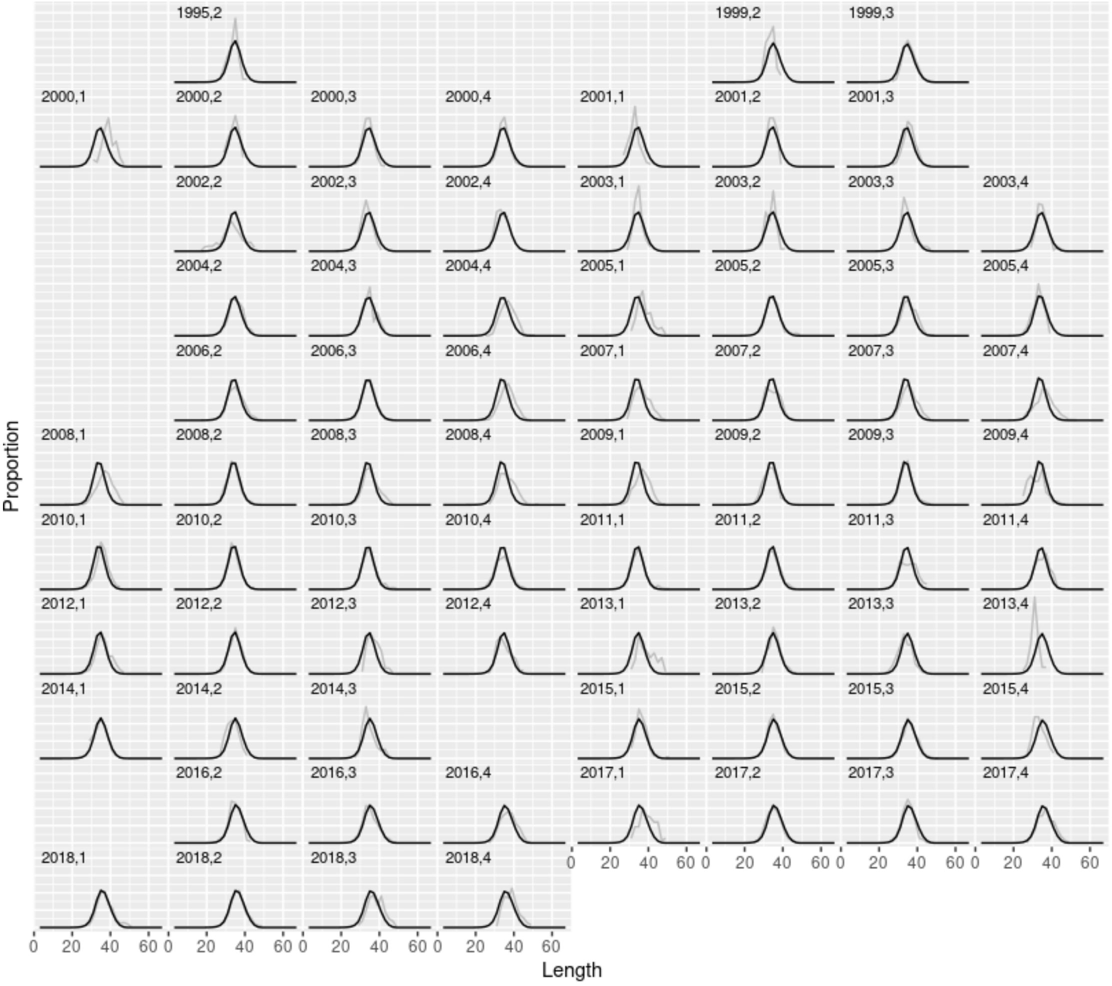

Figure 10. Length composition from the catch of bottom trawls. The grey lines are the observed data and the simulated length structure are the black lines.

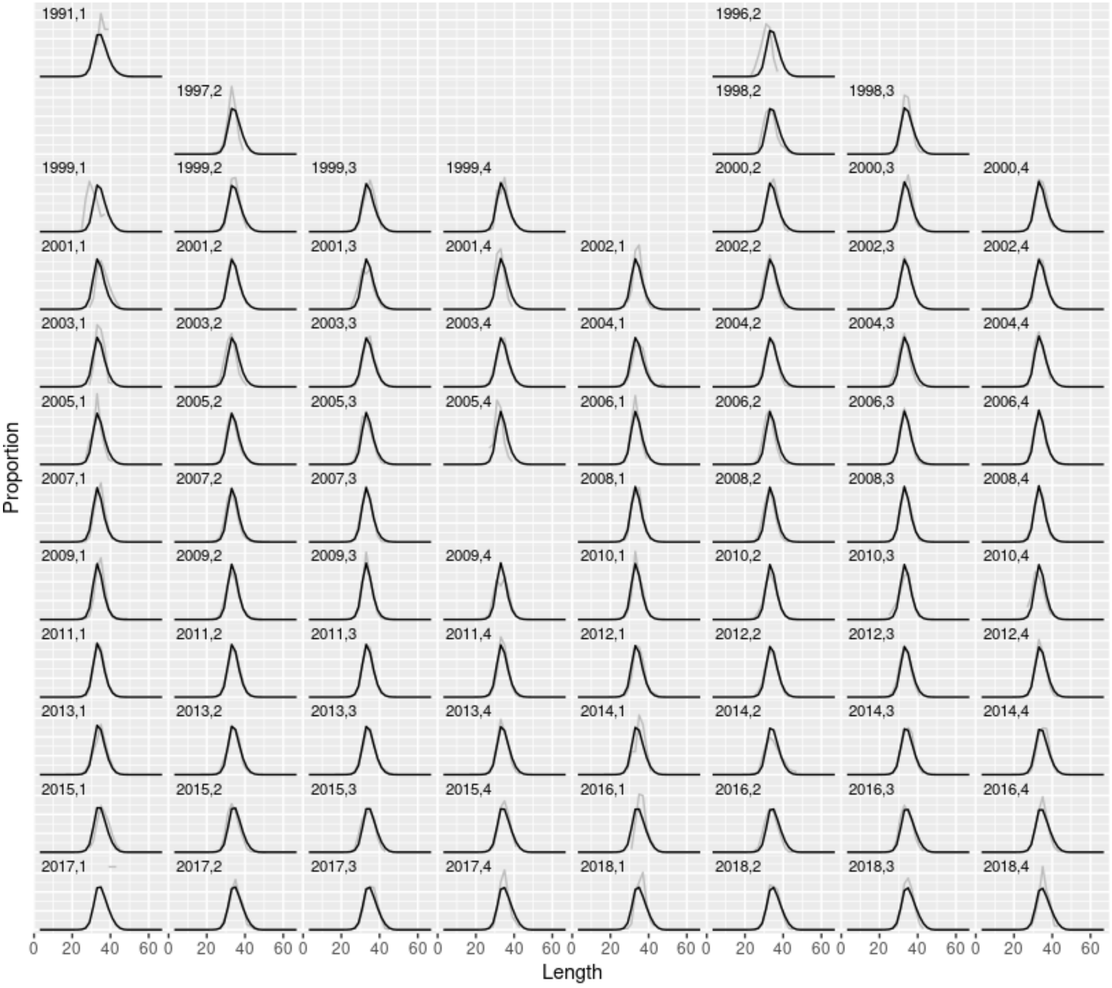

Figure 11. Length composition from the catch of demersal seines. The grey lines are the observed data and the simulated length structure are the black lines.

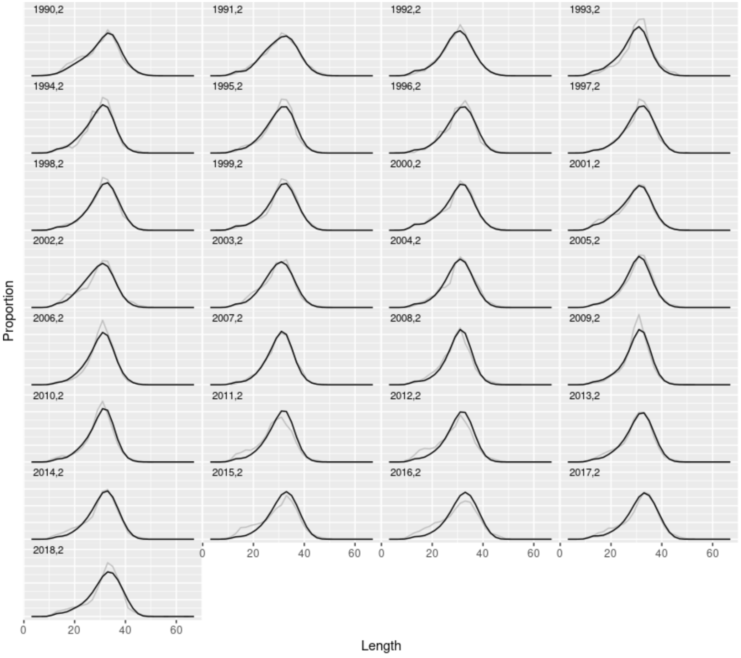

Figure 12. Length composition from the survey data. The grey lines are the observed data and the simulated length structure are the black lines.

The residual bubble plots for prediction of length distribution was shown in Figure 13. Just a few big bubbles appear in these three graphs. The prediction is good overall. There are positive and negative estimation for different length fish every year. In general, the positive and negative estimation appeared alternately for commercial data. But for survey data, there are obvious positive estimation for small fish (10-20 cm), and negative estimation for middle length fish (24-42 cm) in recent years.

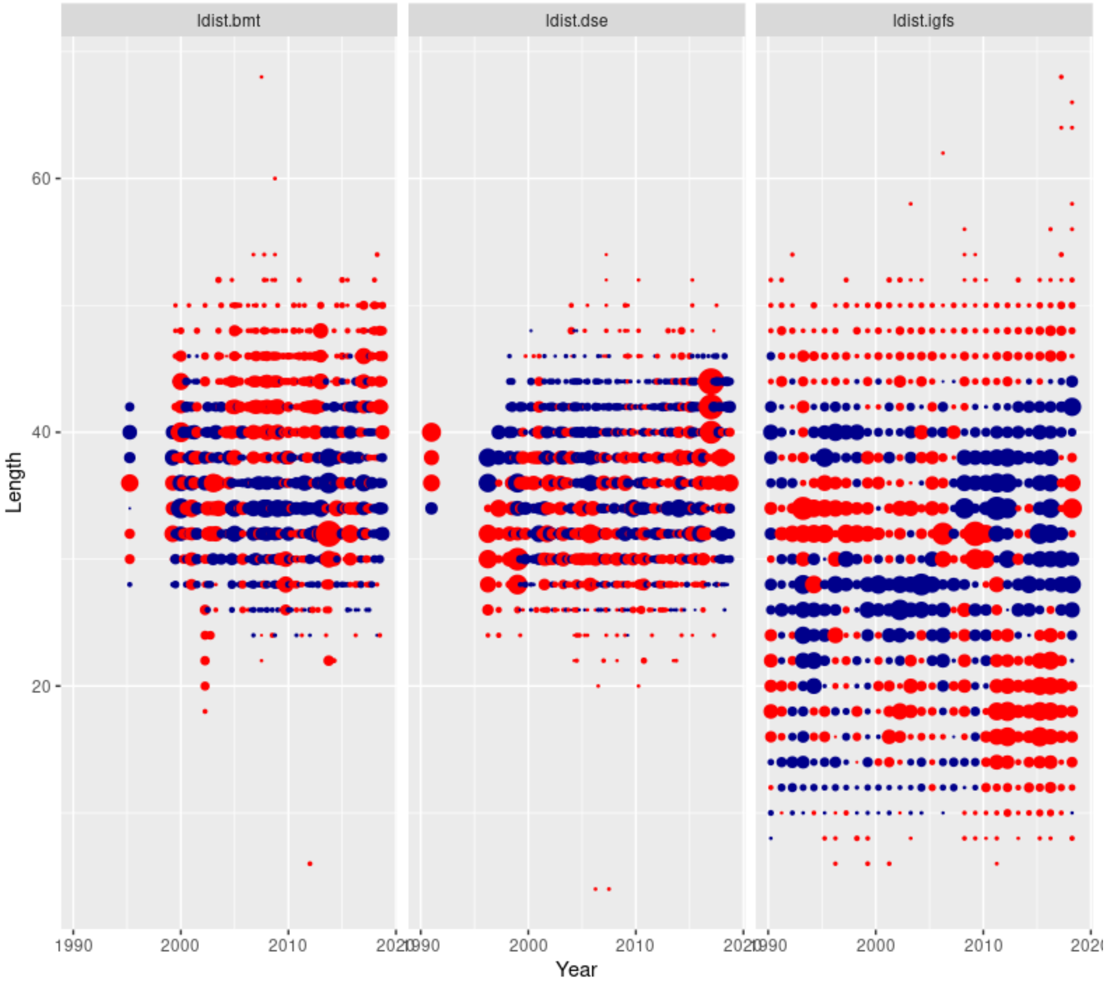

Figure 13. Residual bubble plots for predication of length distribution by bottom trawls (the left one), demersal seines (the middle one) and survey fleets (the right one). The red bubble means the positive prediction, the blue bubbles means the negative prediction.

## 4.5 Growth

The prediction of the age-length curve fit well with the observed length-age data in bottom trawling and demersal seines for most of the years (Figure 14 and Figure 15). The age data in the survey was limited. Just five years sampling of age were collected in the survey. Among the five times, age data was limited in three years and we only have enough age data in 2008 step 2 and 2010 step 2. However, the estimation of the age-length does not fit well in these two years based on survey data, especially for the older fish (above age 8). The observed fish are longer than the estimation for the fish above age 8 (Figure 16). Compared to the same time of the commercial catch, the estimation of commercial age-length fit relatively well with the observed data in these two years. Even in 2010 step 2, the observed length of fish age 10 is lower than estimation both for bottom trawls and demersal seines.

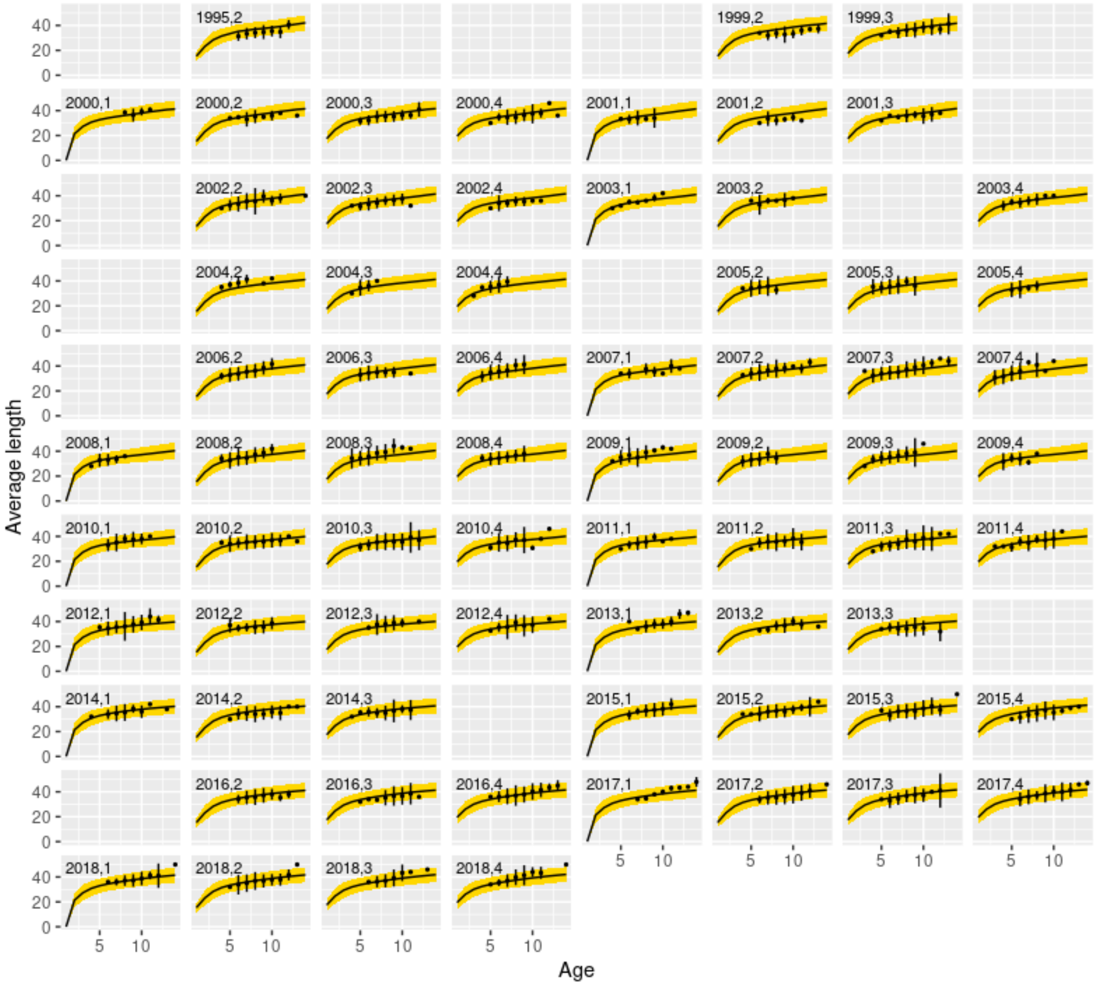

Figure 14. Estimated growth curve based on the catch of bottom trawls. The black spots are the observed data. The black lines and yellow shaded areas represent the median and 5–95% interquartile range of the predicted age, respectively.

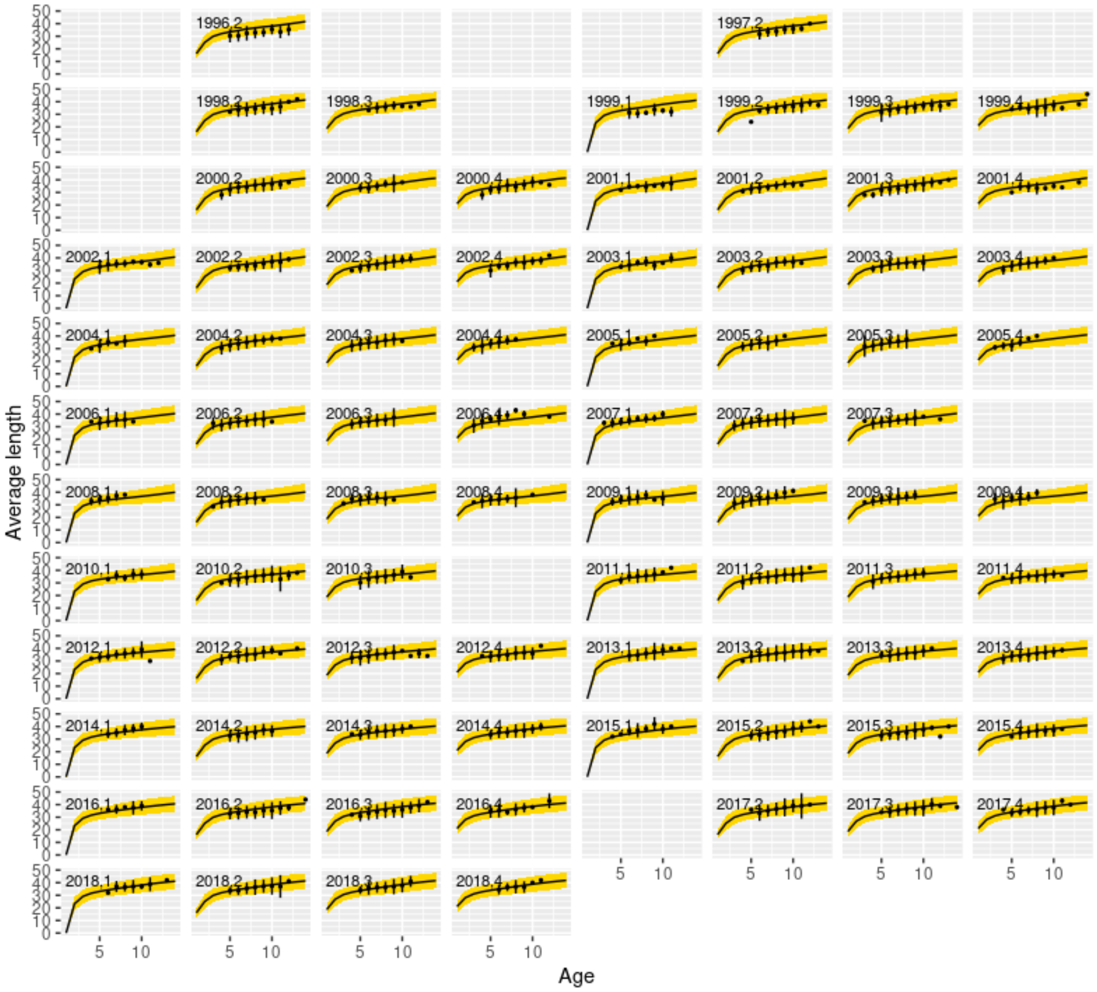

Figure 15. Estimated growth curve based on the catch of demersal seines. The black spots are the observed data and the black lines and yellow shaded areas represent the median and 5–95% interquartile range of the predicted age, respectively.

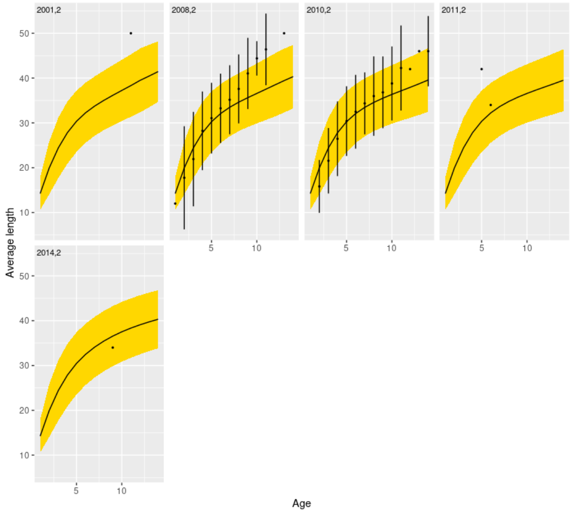

Figure 16. Estimated growth curve based on the survey data. The black spots are the observed data and the black lines and yellow shaded areas represent the median and 5–95% interquartile range of the predicted age, respectively.

## 4.6 Stock proportion

The relationship between the length and the proportion of the fish that was mature is shown in Figure 17. When the length is about 27 cm, almost half the fish are mature. When the length is above 27 centimetres, the proportion of mature grows rapidly, until around 40 cm length when the proportion of mature lemon sole is close to 100%.

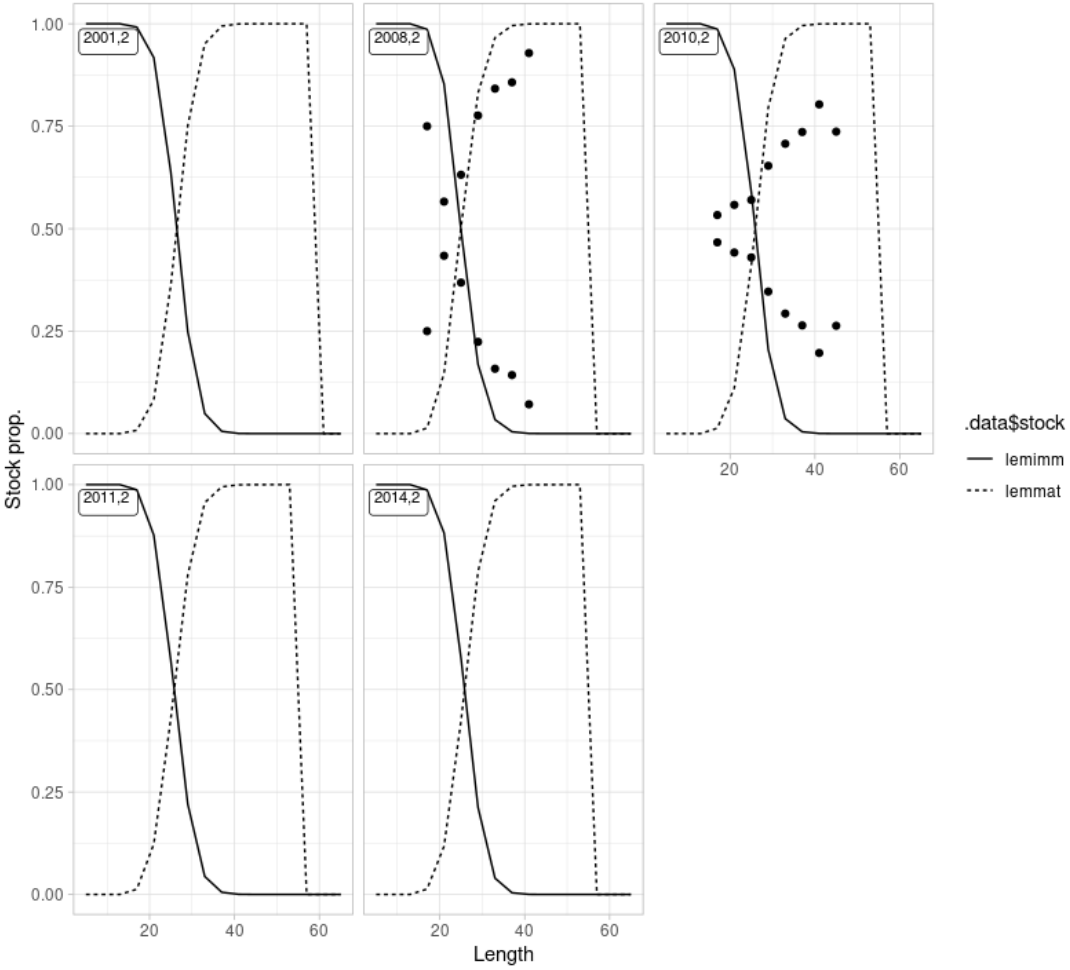

Figure 17. Estimated proportion of the lemon sole which is mature/immature. Lemimm refers to immature lemon sole, lemmat refers to mature lemon sole.

## 4.7 Age composition

The number of fish of all ages decreased between 2005 to 2011 (Figure 18). However, the number of fish of each age was relatively stable or slightly increasing between 2012 to 2018. In the year 2018, there is a higher proportion of older fish while the total biomass increased markedly. Compared to other age groups, the number of age 5 fish was relatively low. Compared to last year (2017), the fish of age 5 (age 4 in 2017) did not decrease.

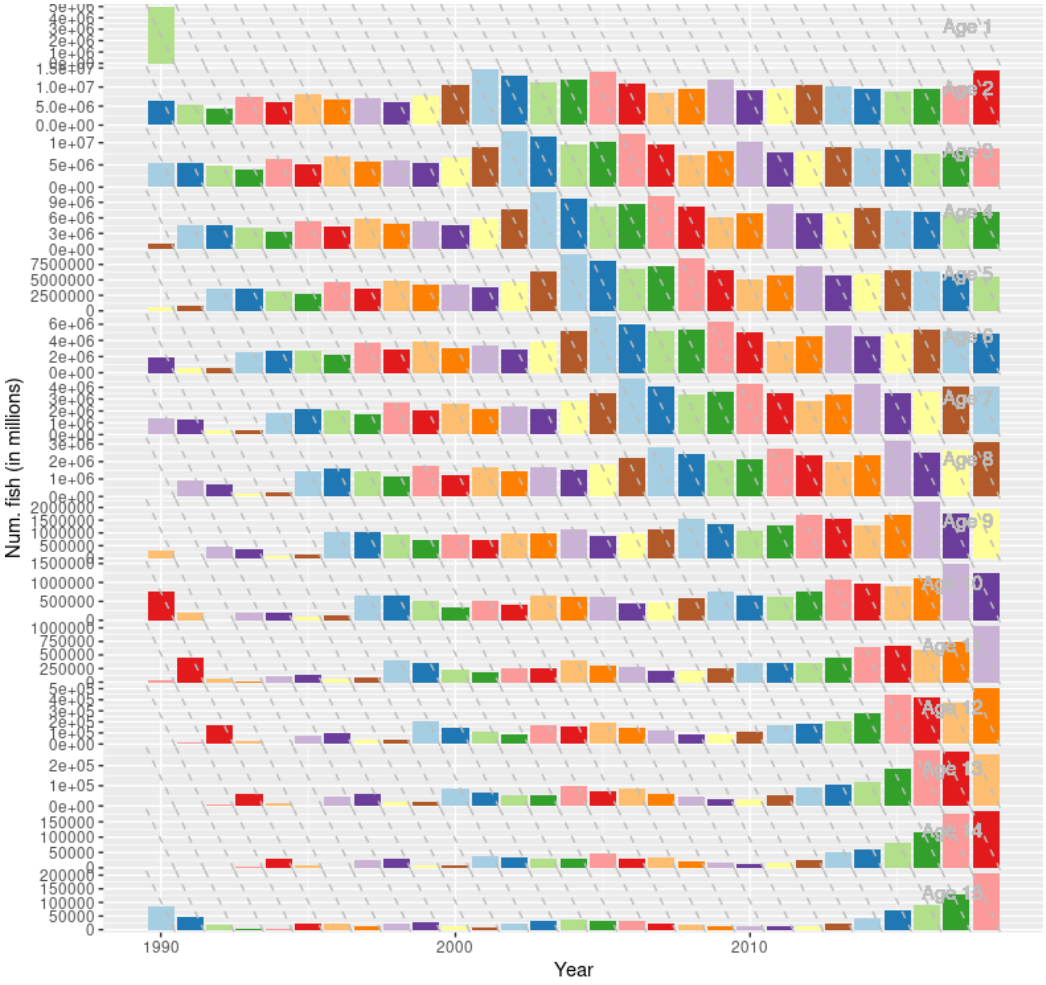

Figure 18. Age composition, each oblique line (same colour histogram) refers to one age lemon sole.

## 4.8 Fishing mortality

The estimated fishing mortality of immature and mature lemon sole showed that the fishing mortality of immature lemon sole was high between 1990 and 1993. Since 1994, the fishing mortality has been around 0.1, especially in the last eight years (Figure 19). The fishing mortality of mature lemon sole had large fluctuations between 1990 and 2005. It increased sharply from 1990 to 1991, 1994 to 1999, and 2003 to 2005. The highest fishing mortality estimated was 0.8 in 1992 and 2009. In last five years, the fishing mortality has been relative stable around 0.25-0.3.

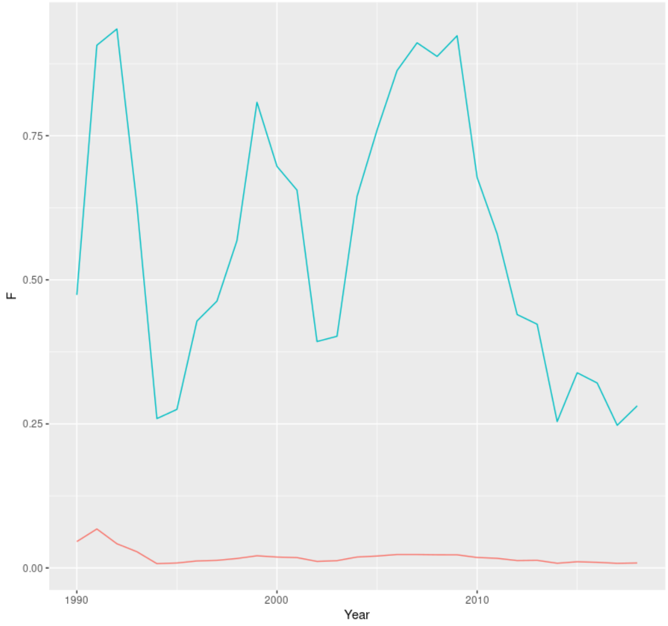

Figure 19. Fishing mortality of immature and mature lemon sole. Red line refers to immature lemon sole, blue line refers to mature lemon sole.

## 4.9 Biomass

The estimated biomass of mature lemon sole increased from 2,500 tonnes in 1990 to 11,000 tonnes in 2018. There was a slight decrease in the biomass from 1998 to 2001, and from 2005 to 2010, while an increase was observed over other periods. The biomass of immature lemon sole was about 1,000 tonnes in 1990 when it increased to 2,500 tonnes in 2003 and has been stable around 2,000 tonnes since 2004 (Figure 20).

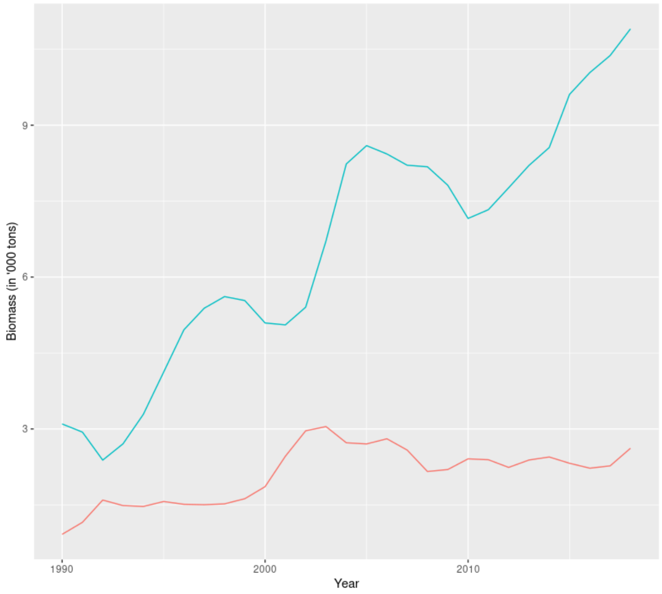

Figure 20. The biomass of immature (red line) and mature lemon sole (blue line).

## 4.10 Catch

In 1995, the catch was around 500 tonnes and it increased to 1,800 tonnes in 1999 but after that it decreased slightly. The lowest catch amount was about 950 tonnes in 2002. Then there was a sharp increase from 2002 to 2004 when the catch increased almost 2.5 times to around 2,500 tonnes and was the highest catch period from 2004 to 2009. From 2012 to now, the catch amount has been relatively stable around 1,500 tonnes. The proportion of immature lemon sole has always been very low (Figure 21).

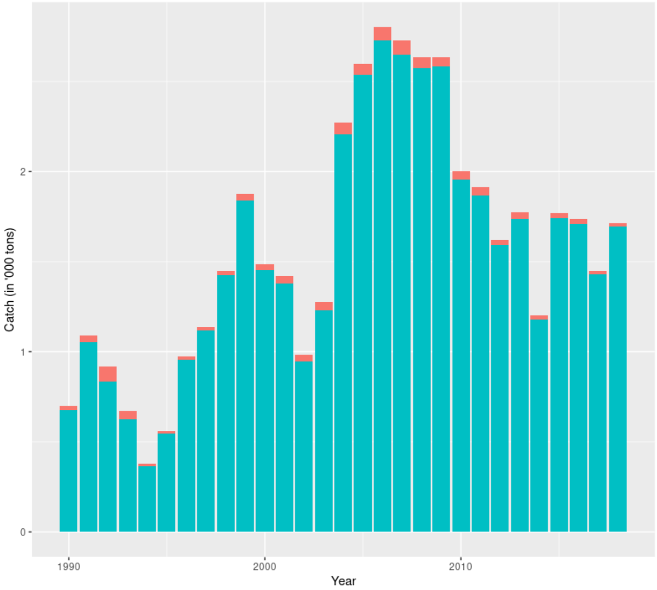

Figure 21. The estimated catch of immature and mature lemon sole. Red parts refer to immature lemon sole, blue part refers to mature lemon sole

## 4.11 Recruitment

The recruitment of immature lemon sole was around 6 million fish in 1990, but increased sharply in the years that followed up to around 17 million fish in 2000. After that, the recruitment of immature lemon sole has fluctuated between 10 to 17 million per year (Figure 22).

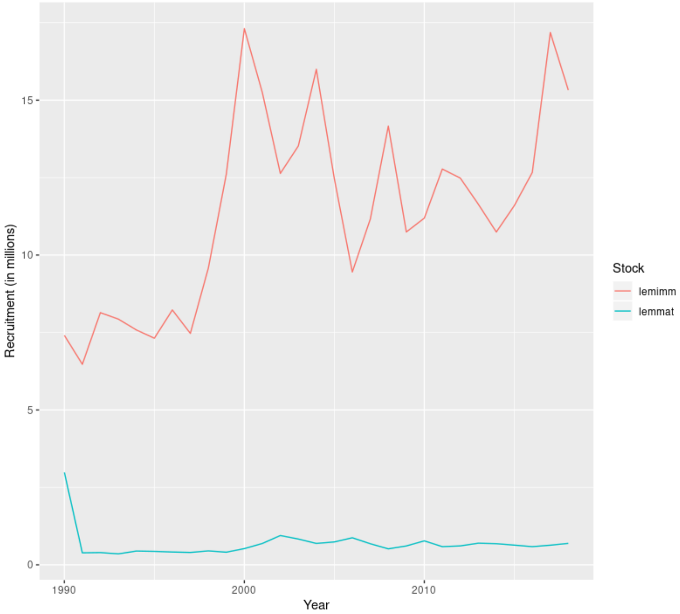

Figure 22. The recruitment of lemon sole, lemimm refers to immature lemon sole, lemmat refers to mature lemon sole.

# 5 DISCUSSION

## 5.1 Effectiveness of Gadget in analyzing lemon sole population dynamics in Iceland

For stock dynamic assessment and further fisheries management, fish age determination is important worldwide (Morison, Coutin, & Robertson, 1998). It gives the results of population dynamics with time series, spawning stock biomass and recruitment impairment. Some age-based models do not allow for years of missing data. The accuracy of model assessments is highly dependent on age estimates. Ageing error can cause bias in numbers-, catch-, maturity-, selectivity- and weight-at age, and growth rate over time. And the age of most fish is difficult to determine. To read the age of the fish, otoliths (ear-stones) or scales are needed. For lemon sole, it is always difficult to read the otolith to determine the age. The otoliths are small, at the maximum of 2–4 mm width, and difficult to break through the nucleus (Smith, 2014). Gadget model as one kind of integrated stock assessment models combined kinds of limited data (size based-, age based-, survey indices and catch, etc.). It will propagate error appropriately. In this model, catch data of lemon sole was collected since 1990 and length data was collected since 1995 and relatively reliable age date was collected after 2000 in Icelandic water. However, no stock assessment model was made to estimate the stock dynamics of lemon sole. In this work, the length data and age data, and maturity data was input to Gadget model, and some estimations were achieved. The catch data of different fleets, the length data, age data, and the maturity situation were used in this model. Every year, 6-10 thousand fish were measured from the commercial catch and during the survey. The age samples were not enough before (but around 2000 otoliths per year have been collected and read in recent years). The model showed an overall close output. Although it is not exactly accurate, it fit to the observed data relatively well. Diagnostic figures with the estimated and the observed survey indices were showed in this project, including estimated total catches, maturation proportion, size distributions, age composition, fishing mortality and biomass with the time series.

In general, the Gadget model is effective in analyzing lemon sole population dynamics in Iceland. In the model developed in this study, the age-, length- distribution and growth fit well with the observed data. It propagated error appropriately as discussed above. Other estimated parameters look reasonable too, which means that the Gadget model is effective in analyzing lemon sole population dynamics in Iceland. It also means the sampling method, the length determination method, and the otolith reading are fine in general. The estimated length distribution fit best with the observed data. The quality of length data is good. Before 2000, the quality of age data is not so good, and the estimation does not fit well. In the modelling, the age of small fish does not fit well with the observed data in many years. The reason is that the small fish ages are hard to read and might be inaccurate. For the growth curve, the growth was simulated without specifying the gender and there were not too many samples of bigger fish in the survey. So, the growth curve of the survey data does not fit as well as the catch data, especially for the larger fish. As Kélig M. (Kélig, Romain, Cécile, & et.al, 2010) reported females of lemon sole appeared to grow more rapidly than males. So, in the future, the gender should be considered.

## 5.2 Population dynamics of Icelandic lemon sole

According to the biomass and catch data, the fishing mortality was low and stable and was kept at 0.25-0.3 since 2013, which responds to around 1,700 tonnes every year. The biomass of mature lemon sole increased rapidly from 2,500 tonnes in 1990 to about 11,000 tonnes in 2018. Although there was fluctuation in past years, it increased rapidly since 2010 till now, similarly to the biomass of immature lemon sole which had increased since 2016. The policy of the lemon sole fishing is good in last five years. It kept a healthy increase of the lemon sole biomass. In the past using a simpler method suggesting that the present assessment and harvest rate is not harming the population.

## 5.3 Applicability for developing fisheries research in China

In recent years, many traditional fisheries resources have declined in China. For the sustainable use of fisheries resources, scientific management has been implemented. For example, there are five provinces which are now piloting a catch quota management system. Due to the relative lack of fisheries data obtained through scientific surveys in China, commercial fisheries data is the main source of fishery assessment data in China at present.

In the past, the Chinese government paid more attention to the environmental quality. Regular testing is conducted annually or monthly for parameters such as water quality, Chlorophyll a, fish eggs (number, species), juveniles (number, species), phytoplankton, zooplankton, etc.. In December 2019, National Marine Fisheries Resources Assessment Expert Committee was established in China, which will provide technical support for the formulation of marine fishery resources protection-related management systems, policy plans, standards and norms. They will guide and carry out the investigation and monitoring for marine fishery resources. They will carry out marine stock assessment nationwide, to put forward advice for the management and control of total marine fishery resources, guide the implementation of the total quantity management and quota fishing system, and give final evaluation about the implementation.

In other words, fish survey work will start soon along with systematic stock assessment. We need more effective suggestions about how to invest and which kind of data, even which kind of assessment methods can be used for the future stock assessment work in China. As mentioned above, because of the limited and poor data, the main stock assessment methods used in China mainly include catch-MSY model, GLM, GAM, Fox model and Bayesian model. Gadget model, as a flexible, simple, and with many successful examples, especially where age data are missing or form an incomplete series, will be useful and helpful to apply in stock assessment work in China.

ACKNOWLEDGEMENT

I would like to express my special thanks for my supervisors Dr. Pamela Woods and Dr. Guðjón Már Sigurðsson, thank them for teaching me a lot and helping me accomplish this work. As well as, I also wish to express my sincere thanks to the staff of UNESCO (Tumi Tómasson , Julie Ingham, Þór Heiðar Ásgeirsson, Mary Frances Davidson, Beata Wawiernia ) who gave me the golden opportunity to join this fisheries training programme and help us in this half year.

I am also thankful to Jónas Jónasson and Bjarki Elvarsson for their help in my project. Additionally, I owe my gratitude to all my friends (Shigen Ye, Anthony Ansu Yokie, Sahr Patrick Sandi, Alhaji Lamin Daboh, Owen Mbokigwe Kibona, Thapeetha Yoganathan, Kameral Ba and other friends) for giving me their company, friendship, moral support and advice.

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