Stock assessment of greater silver smelt *(Argentina silus)* in Icelandic waters

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Abstract

The first formal assessment of greater silver smelt in Icelandic waters is presented. The main conclusion had already been brought up before any formal modelling started: there are contradictory trends in the data, which prevent standard assessment models from fitting all data components. An age-based model fails to describe the population with any reliability, but it successfully describes the contradictory data trends in precise terms.

The appropriate course of action is to have experts (this Working Group) discuss possible reasons for the contradictory trends and recommendations on how to improve data or assumptions. Instead of emphasizing numerical output from a model that doesn't fit the data, I list ideas that the expert group can discuss based on their knowledge of this stock.

Contents

1 Introduction

The biology, fishery, and available data regarding greater silver smelt in Icelandic waters (GSS-Va) are described in other working documents. This document contains only plots of data that are needed for the discussion.

For this first formal GSS-Va assessment, several models were considered, including a Schaefer biomass-dynamic model, and a variety of age- and length-based Coleraine models. Exploratory analysis led to the choice of a purely age-based Coleraine model, but an overview of the length data is included in this document, to show that the length data and age data convey the same trends.

2 Data

The main data used in this assessment (Table 1) are annual landings (Fig. 1), commercial catch at age (Fig. 2), survey catch at age (Fig. 4), and an annual biomass index from the autumn survey (Fig. 6).

Table 1. Data overview.

Data	Years	How many
Landings	1988–2009	22
Commercial catch at age	1997–1998, 2002, 2006–2008	6
Survey catch at age	2004–2008	5
Survey biomass index	2000–2009	10

2.1 Landings

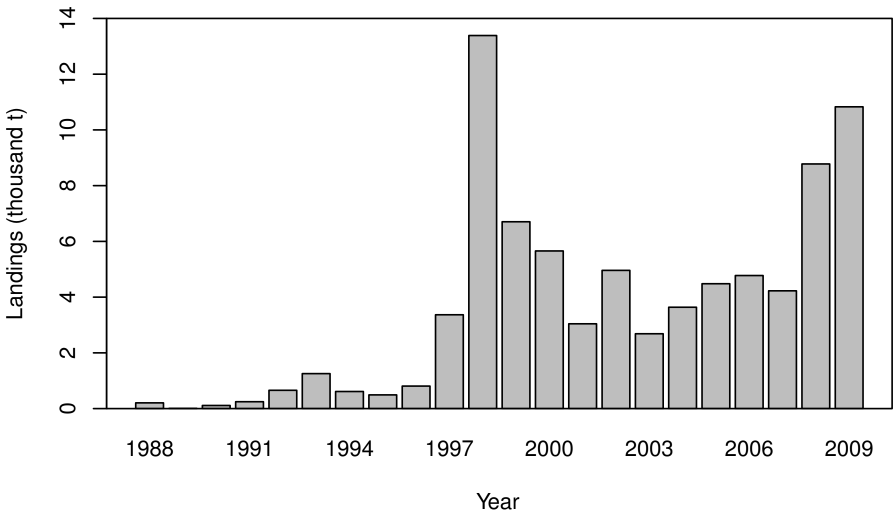

Figure 1. Landings.

2.2 Commercial catch at age

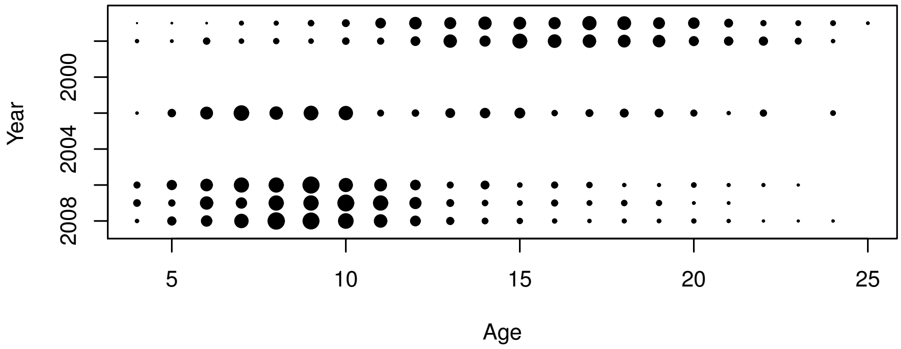

Figure 2. Commercial catch at age.

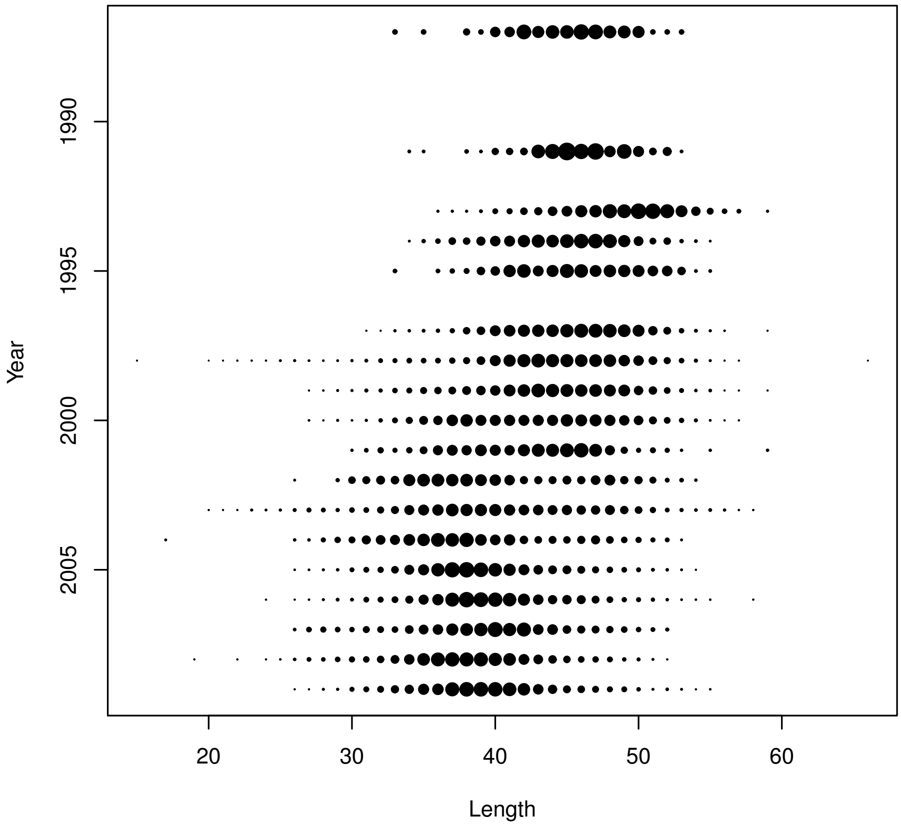

Figure 3. Commercial catch at length.

2.3 Survey catch at age

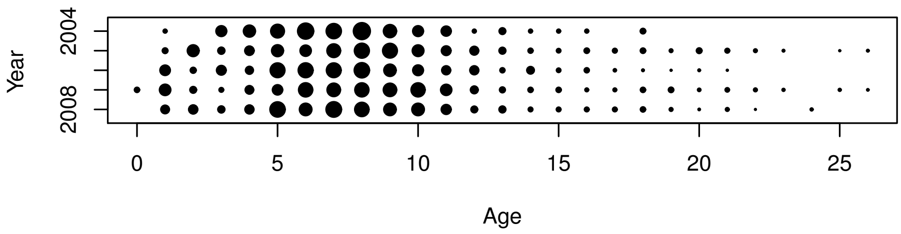

Figure 4. Survey catch at age.

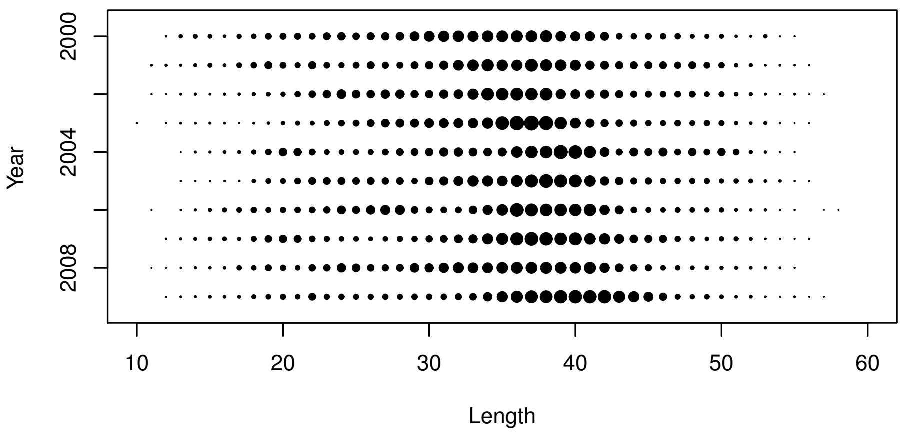

Figure 5. Survey catch at length.

2.4 Survey biomass index

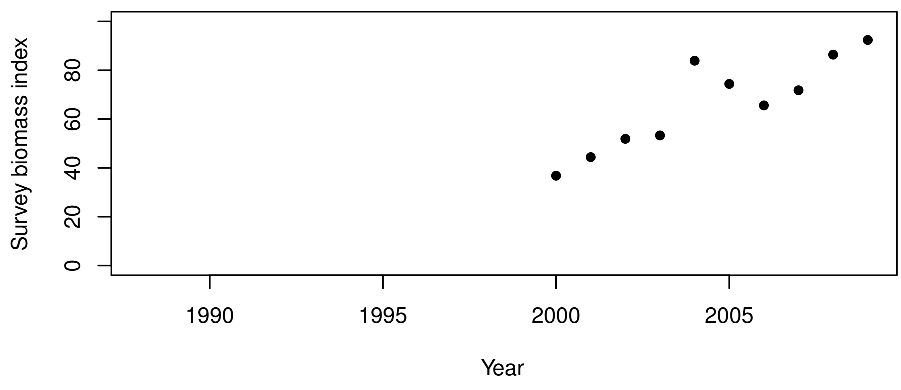

Figure 6. Survey biomass index.

3 Model

Coleraine (Hilborn et al. 2003) is a versatile environment for single-species statistical catch-at-age modelling. It can incorporate a combination of catch at age, catch at length, and abundance indices from different fisheries and surveys, allowing for missing years. Data and parameters can be sex- and gear-specific. Future projections can be used to evaluate a range of harvest policies. The model is implemented in AD Model Builder (ADMB Project 2008), supporting maximum likelihood or Bayesian estimation, using the delta method and/or Bayesian MCMC to analyze the uncertainty.

Optional software for working with Coleraine include an Excel spreadsheet interface and two R packages, 'scape' and 'scapeMCMC', for plotting and diagnosing model fits and MCMC output (Magnusson 2005). Several variations of simple age-based Coleraine models have been described and analyzed in detail by Magnusson and Hilborn (2007), while diverse examples of sex- and gear-specific age- and length-based model output can be found in Magnusson (2005).

The model used in this assessment is a simple age-based Coleraine model. Due to the apparent low variability in recruitment, as well as the overall limited amount of data, annual recruitment is not estimated as free parameters, but deterministic Beverton-Holt predictions are used, based on spawning stock biomass and a steepness (Francis 1992) of $h = 0.6$. The stock is assumed to be in unfished condition in 1988, and landings are known without error. All parameters are assigned wide bounds that are used as flat priors in the Bayesian uncertainty analysis, where 1 000 draws were saved out of 1 000 000 MCMC iterations.

3.1 Dynamics

The population dynamics are governed by the equation:

$$N_{t+1,a+1} = N_{t,a}\, e^{-M}(1 - {}_C S_a u_t) \tag{1}$$

where $N_{t,a}$ is population size at time t and age a, M is the rate of natural mortality, ${}_C S$ is the selectivity of the commercial fishery, and u is harvest rate. The oldest age group, age A, is treated as a plus group:

$$N_{t+1,A} = N_{t,A-1}\, e^{-M}(1 - {}_C S_{A-1} u_t) \; + \; N_{t,A}\, e^{-M}(1 - {}_C S_A u_t) \tag{2}$$

Selectivity is asymptotic, shaped like a normal curve on the left:

$$S_a = \begin{cases} \exp\left(\dfrac{-(a - S_{\text{full}})^2}{\exp(S_{\text{left}})}\right), & a \le S_{\text{full}} \\ 1, & a > S_{\text{full}} \end{cases} \tag{3}$$

where S_{full} is the age at full selectivity and S_{left} describes the left-hand slope of the curve. Harvest rate is defined as the fraction removed from the vulnerable biomass in the middle of the fishing year,

$$u_t = Y_t \,/ V_t \tag{4}$$

where Y is catch, vulnerable biomass is

$$V_t = \sum_a ({}_C S_a\, N_{t,a}\, w_{t,a})e^{-M/2} \tag{5}$$

and w is body weight.

The population size at the start of the first year is

$$
\begin{aligned}
N_{1,1} &= R_0 \\
N_{1,a} &= R_0\, e^{-(a-1)M} \\
N_{1,A} &= R_0\, e^{-(A-1)M} / \,(1 - e^{-M})
\end{aligned} \tag{6}
$$

for one-year-olds, intermediate ages, and the plus group, where R_0 is the average virgin recruitment. Recruitment is deterministic, using a reparametrized Beverton-Holt function (Francis 1992):

$$
N_{t+1,1} \;=\; \frac{4hR_0(B_t/B_0)}{1-h+(5h-1)(B_t/B_0)} \tag{7}
$$

where $B_t = \sum_a N_{t,a}\Phi_{t,a}w_{t,a}$ is spawning biomass,

$$
B_0 = \sum_{a=1}^{A-1} R_0 e^{-(a-1)M}\Phi_a w_{1,a} + R_0\, e^{-(A-1)M}\Phi_A w_{1,A}/(1-e^{-M}) \tag{8}
$$

is average virgin spawning biomass, h is steepness of the stock-recruitment curve, and Φ is maturity at age.

3.2 Parameters

A total of 7 parameters are estimated (Table 2).

Table 2. Estimated parameters.

Parameter	Meaning
R_0	Average virgin recruitment
M	Natural mortality rate
${}_CS_{\text{full}}$	Age at full selectivity in the commercial fishery
${}_CS_{\text{left}}$	Left slope of commercial selectivity curve
${}_SS_{\text{full}}$	Age at full selectivity in the survey
${}_SS_{\text{left}}$	Left slope of survey selectivity curve
q	Survey catchability coefficient

3.3 Estimation

The objective function for the parameter estimation is the sum of three components:

$$
f \;=\; -\log L_C - \log L_S - \log L_I \tag{9}
$$

The survey biomass index likelihood component is lognormal:

$$
-\log L_I \;=\; \sum_t \frac{(\log I_t - \log \hat{I}_t)^2}{2\sigma_I^2} \tag{10}
$$

where I and $\hat{I}$ are observed and fitted abundance indices,

$$
\hat{I}_t \;=\; qV_t \tag{11}
$$

and σ_I is the standard error of the log residuals, one value across all years.

Catch-at-age data are provided to the model in the form of proportions at age. The robust normal likelihood for proportions (Fournier et al. 1990) is assumed for the commercial catch-at-age data,

$$
-\log L_C = -\sum_t \sum_a \log\left[\exp\left(\frac{({}_CP_{t,a} - {}_C\hat{P}_{t,a})^2}{2\big[{}_CP_{t,a}(1-{}_CP_{t,a}) + 0.1/A\big]\,{}_Cn_t^{-1}}\right) + 0.01\right] \tag{12}
$$

as well as the survey catch-at-age data:

$$-\log L_S = -\sum_t \sum_a \log \left[\exp\left(\frac{({}_SP_{t,a} - {}_S\hat{P}_{t,a})^2}{2\left[{}_SP_{t,a}(1 - {}_SP_{t,a}) + 0.1/A\right] {}_Sn_t^{-1}} \right) + 0.01 \right] \tag{13}$$

where P and $\hat{P}$ are observed and fitted catch at age,

$$\hat{P}_{t,a} = \frac{S_a N_{t,a}}{\sum_a S_a N_{t,a}} \tag{14}$$

and n_t is the year-specific effective sample size.

The magnitude of the observation noise (σ_I, ${}_Cn_t$, ${}_Sn_t$) is estimated iteratively as

$$\hat{\sigma}_I = \sqrt{\frac{\sum(\log I_t - \log \hat{I}_t)^2}{T-1}} \tag{15}$$

for the abundance index, where T is the number of abundance index datapoints, and

$$\hat{n}_t = \frac{\sum_a \hat{P}_{t,a}(1 - \hat{P}_{t,a})}{\sum_a (P_{t,a} - \hat{P}_{t,a})^2} \tag{16}$$

for commercial and survey catch at age (McAllister and Ianelli 1997). Initially, the effective sample size in each year is set to the number of tows where otoliths were sampled and read. In later iterations, all years are scaled by the same multiplier so that their average matches the average of the empirical (Eq. 16) multinomial sample size. This means that if twice as many otoliths were sampled and read in year t_2 than in year t_1, then the effective sample size in year t_2 will always be two times greater than in year t_1, although both will be scaled up or down depending on how closely the model fits the catch-at-age data.

4 Results

4.1 Key quantities

Table 3. Estimated key quantities with 90% confidence intervals.

Quantity	Value	Lower	Upper
Parameters			
R_0	94.41	70.78	189.54
M	0.22	0.20	0.26
${}_CS_{\text{full}}$	9.63	9.12	10.14
${}_CS_{\text{left}}$	1.87	1.58	2.14
${}_SS_{\text{full}}$	10.66	9.75	11.78
${}_SS_{\text{left}}$	3.15	2.86	3.42
q	1.83×10^3	1.08×10^3	2.42×10^3
Recruitment			
R_{1988}	94.41	70.78	189.54
R_{2008}	84.29	61.50	178.17
Spawning biomass			
B_{1988}	67 900	63 600	97 900
B_{2009}	36 300	30 000	69 600
Vulnerable biomass*			
V_{1988}	49 200	45 800	64 900
V_{2009}	21 300	18 100	40 700
Harvest rate*			
u_{1988}	0.00	0.00	0.00
u_{2009}	0.51	0.27	0.60

*: Defined in Eqs. 4 and 5.

Table 4. Estimates of observation noise. 'Tows' are the initial likelihood weights and 'Estimate' are the final likelihood weights.

Quantity	Estimate	Tows
${}_Cn_{1997}$	193	19
${}_Cn_{1998}$	241	24
${}_Cn_{2002}$	44	4
${}_Cn_{2006}$	102	10
${}_Cn_{2007}$	81	8
${}_Cn_{2008}$	312	31
${}_Cn_{\text{avg}}$	162	16
${}_Sn_{2004}$	22	18
${}_Sn_{2005}$	161	132
${}_Sn_{2006}$	168	139
${}_Sn_{2007}$	193	159
${}_Sn_{2008}$	173	144
${}_Sn_{\text{avg}}$	143	118
σ_I	0.39	

4.2 Selectivity

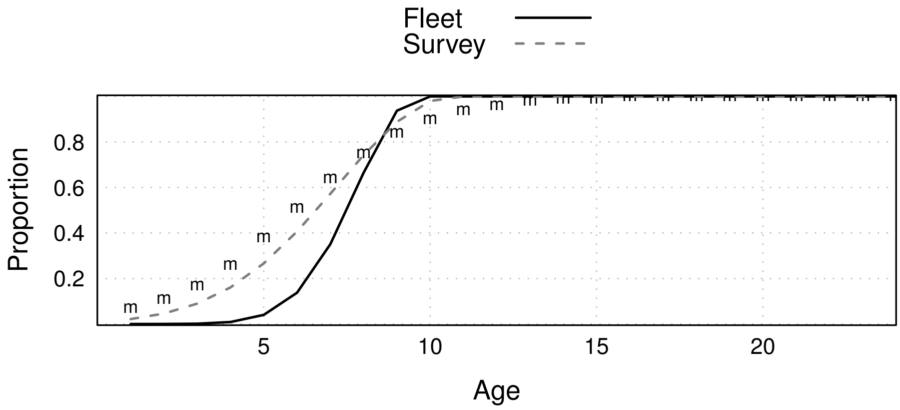

Figure 7. Selectivity and maturity (m).

4.3 Fit to data

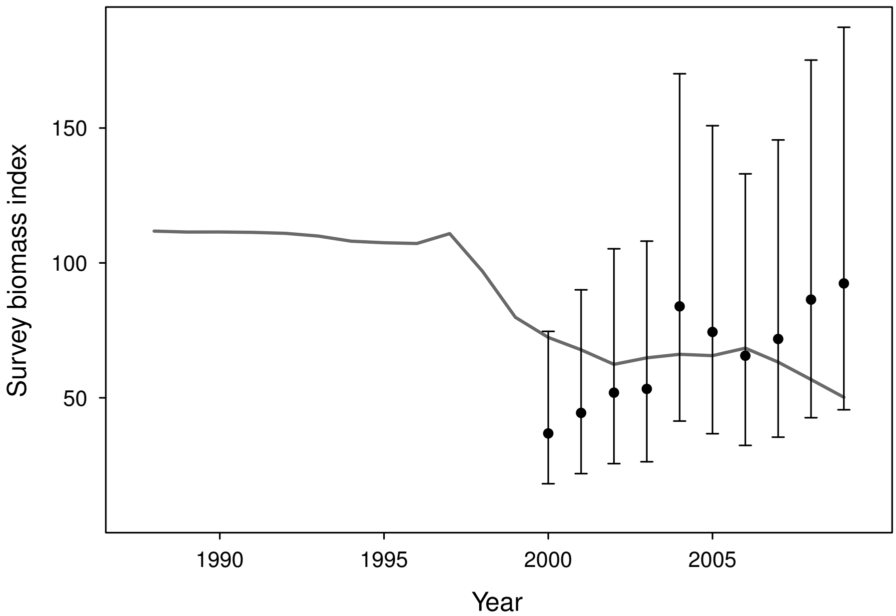

Figure 8. Model fit (line) to survey biomass index, shown with 90% error bars.

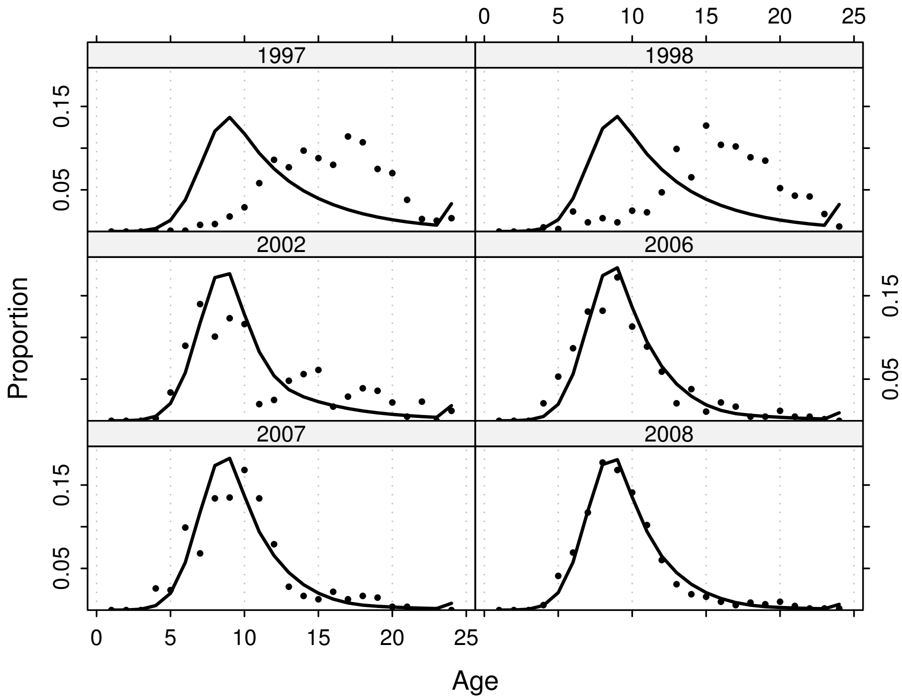

Figure 9. Model fit (line) to observed commercial catch at age (dots).

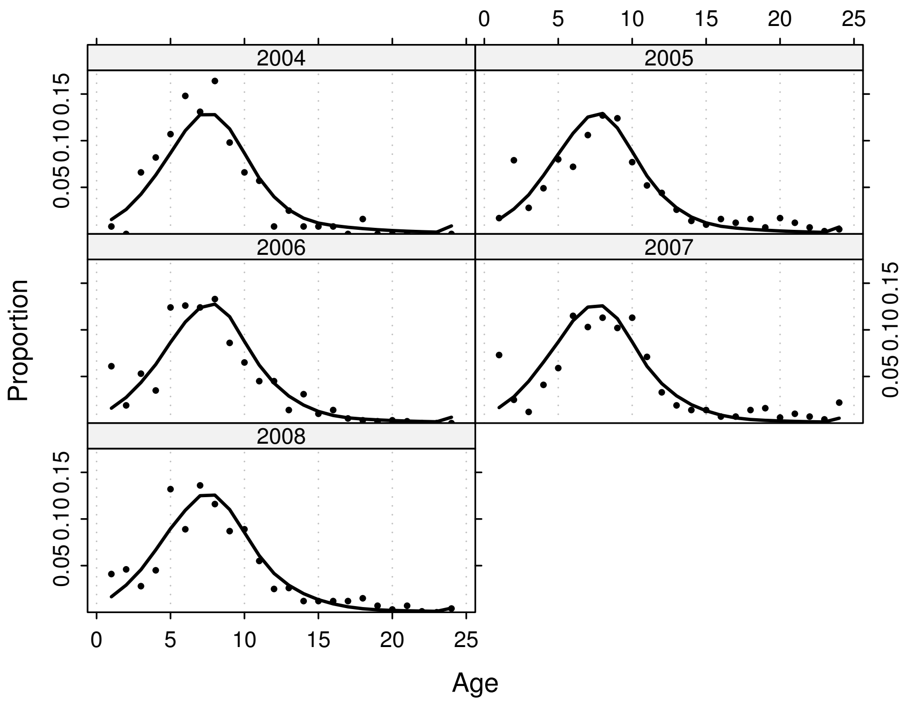

Figure 10. Model fit (line) to observed survey catch at age (dots).

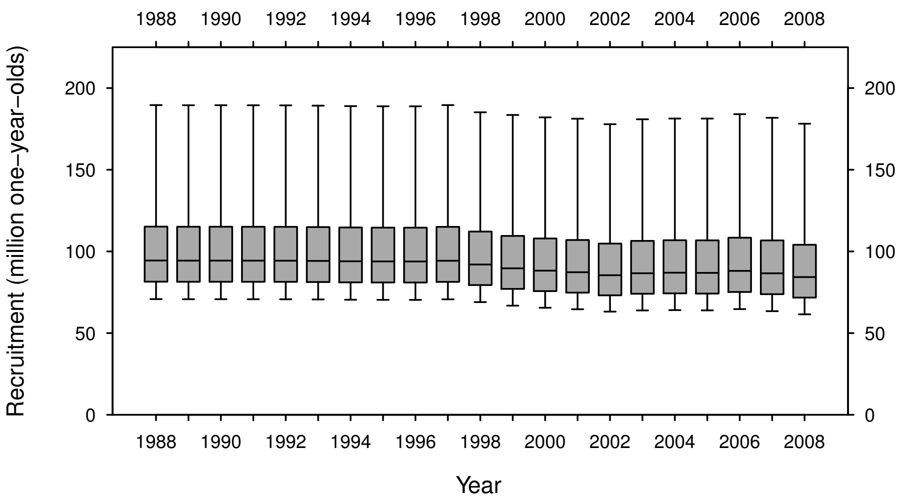

Figure 11. Recruitment with 50% and 90% confidence intervals.

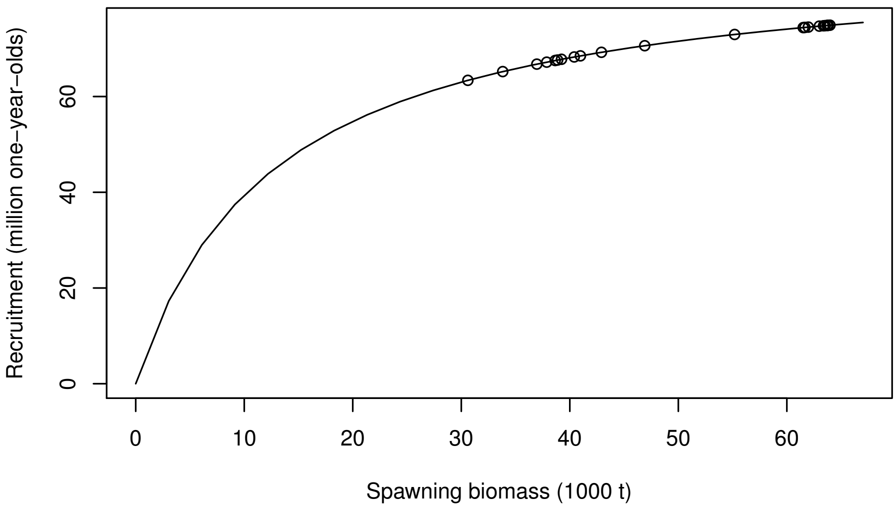

Figure 12. Recruitment, following deterministic Beverton-Holt.

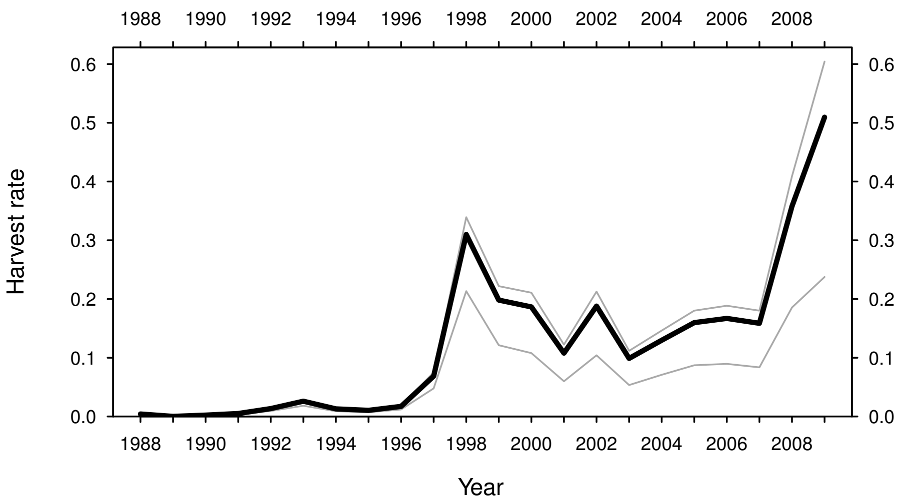

Figure 13. Harvest rate with 90% confidence intervals.

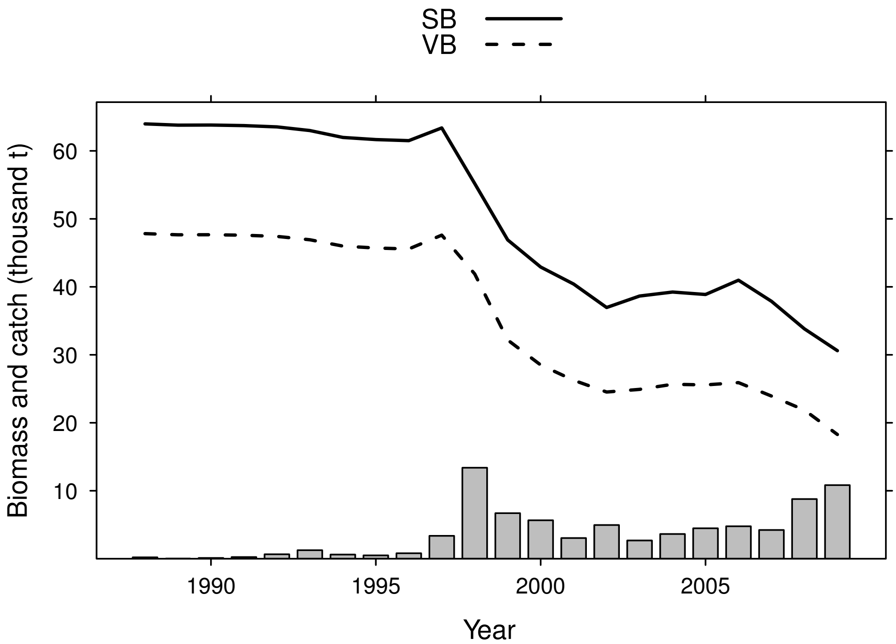

Figure 14. Spawning biomass, vulnerable biomass, and landings.

5 Discussion

The base case model presented here does not fit the upward trend in the autumn survey biomass index. Several attempts were made to find a model where the population grows fast enough to fit the survey index, but it was found that such a model would require two features. First, the population in 1988 would need to be start in a heavily overfished condition, which goes against the documented history of this fishery. Secondly, the strong recruitment pulse needed for the population to grow this fast would show up clearly in age and length compositions, but the observed age compositions indicate no such pulse.

In fact, the observed age compositions (Figs. 9 and 10) show a distinct lack of variable cohort strengths. The deepwater is a stable habitat which may lead to less variable recruitment than for most groundfish species.

The only model that can fit the fast biomass growth is a simplistic model using only landings and survey biomass index, ignoring all age and length compositions (Schaefer or Schaefer-like), starting at a very low level, but long-term biomass predictions of those models can exceed a billion tons. This is because the biomass index does not respond to years of relatively large catch removals.

The base case model estimates M without much uncertainty. This makes sense, since the data include age compositions from early years of the fishery, when the age structure is largely determined by M alone. Conversely, h, the steepness of the Beverton-Holt curve, could not be estimated reliably. When h is estimated, it goes straight to the upper bound of 1, because the model starts in an unfished condition in 1988, so recruitment will gradually decrease as the fishery develops (Fig. 12). With $h = 1$, recruitment would remain stable, resulting in a slightly improved fit to the survey biomass index, but recruitment overfishing can never take place when recruitment is independent of stock size. The simple approach of fixing h at 0.6 was taken, since a more complex model involving a Bayesian prior leads to similar conclusions. The main conclusions are not sensitive to the exact value of h.

The small data set does not provide enough degrees of freedom to estimating a free recruitment parameter for every year. In any event, the age compositions show clearly that one or more enormous cohorts are not plausible reasons for the recent biomass growth. The current stock consists of many cohorts of similar size.

5.1 Contradictory data

The main conclusion after exploring the data with many variations of Coleraine models, including the base case run presented here, is that no model was found that can fit all the data components. The data seem to violate model assumptions (e.g. cohorts growing instead of decaying in the survey data), which severely undermines traditional statistical statements, required for managing the Icelandic greater silver smelt fishery.

Instead of detailed residual diagnostics, future projections, and MCMC diagnostics, it is necessary to examine the contradictory data components (Richards 1991, Schnute and Hilborn 1993) and have experts (this Working Group) discuss possible reasons and recommendations.

In a nutshell, the declining age and length distributions observed in the fishery indicate very high fishing mortality rates, while the autumn survey indicates that the stock biomass has been growing rapidly.

5.2 Fishery data

A closer look at the commercial catch-at-age data (Figs. 2, 3, and 9) shows a sharp divide between 1998 and 2002, when the mean age fell from 14.5 years (averaging 1997–1998) to 9.6 years (averaging in 2002 and 2006–2008). This does not appear to be a regional effect, since the sampling locations during these years are comparable (Fig. 15).

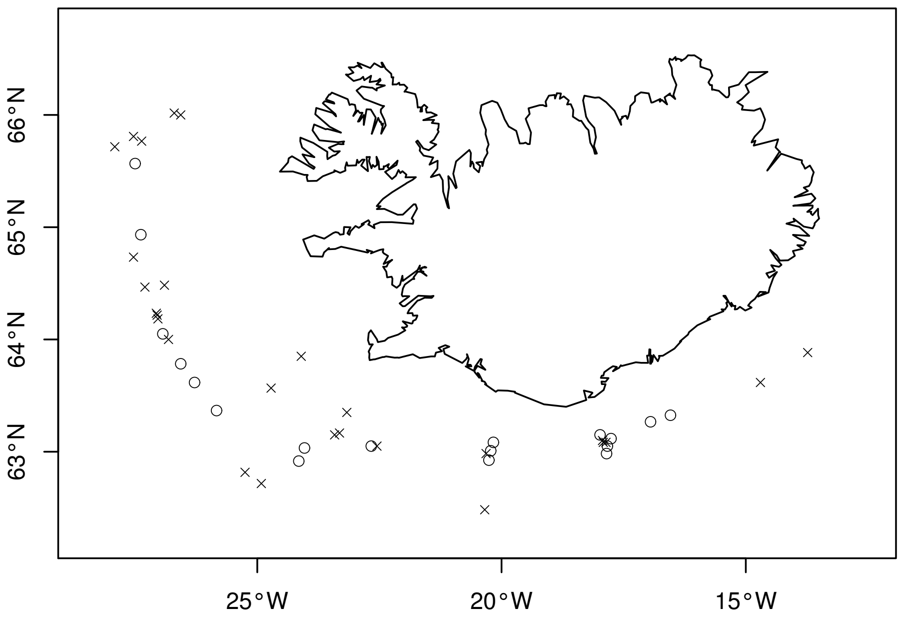

Figure 15. Geographical distribution of otoliths sampled and read from the autumn survey in 1997 (o) and 2008 (x).

In isolation, the fishery data indicate that in 1998–1999, enough older individuals (ages 15–20) were caught to cause a considerable shift in the age distribution towards younger ages. The length data show the same trend on a finer time scale (Fig. 3), with the mean length declining from 48 cm to 40 cm between 1993 and 2009. When all the age data are combined in the base case model, it is not possible to explain this sudden age shift between 1998 and 2002 with the amount of catches, since catches of the same magnitude in later should then have caused some further decrease in age and length, but the age and length composition has been steady or expanding since 2002.

It seems quite plausible that the selectivity changed during those years, but the degrees of freedom that would cost to model is equivalent to throwing out the 1997 and 1998 age distributions. This would lead to a model very similar to the base case, which does not fit the 1997 and 1998 age distributions.

5.3 Survey data

A closer look at the survey data (Figs. 6 and 8) shows that the biomass index has increased rapidly, almost threefold between 2000 and 2009 after Winsorizing outliers, and the observed increase is even greater before Winsorizing. Weight at age has remained stable during this time. The stability of the age (2004–2008, Fig. 4) and length (2000–2009, Fig. 5) distributions in the survey imply that the increasing survey biomass index is not explained by young fish entering the population. Rather, the biomass increase is across all ages.

The simplest scenario explaining the survey data is that a considerable part of the current stock was previously outside the survey area, but has in recent years (since 2000) gradually shifted its distribution into the survey area. This theory is supported by the fact that much of the survey biomass comes from the outermost stations, at the southern and western edges of the survey area.

If such a geographic shift/immigration is taking place, areas outside the autumn survey area would need to be investigated in a special survey. Modelling exercises cannot describe or predict this phenomenon using only the current data set. The absence of significant immigration or emigration is a fundamental assumption underlying traditional stock assessment methodology, even more so when the overall amount of data is limited.

5.4 Recommendations

It would seem that the current level of fishing is sustainable in the short term, at least while the survey biomass index increases. At the same time, the base case stock assessment model presents an alarming picture (Figs. 13 and 14) of a collapsing stock. The stock may be growing, steady, or declining, and when all the data components are incorporated in one model, the pessimistic scenario has the highest likelihood, following indications from the fishery data. Survey data, on the other hand, are generally better balanced and randomized, and therefore more reliable in stock assessment, but in this case the autumn survey does not cover the greater silver smelt distribution very well. First and foremost, this data set is a case of extreme uncertainty and appears to violate standard modelling assumptions.

The stock needs to be monitored closely, due to the contradictory data components, where age and length composition in the fishery indicates a rapidly declining stock, while the autumn survey indicates a rapidly growing stock. There may be a geographic shift/immigration event currently taking place, possibly via the Faroe Islands or the Reykjanes Ridge. Alternatively, the life history involves spatial shifts that are not yet understood. A one-time survey dedicated to cover the entire distribution of this stock could greatly reduce the range of plausible scenarios.

There is a considerable collection of otoliths that have been sampled but not read. An effort to read those otoliths would sharpen the picture somewhat, but probably not add fundamental pieces of information, compared to the added information from a one-time dedicated survey, since the existing age data already convey the main trends seen in the length data.

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