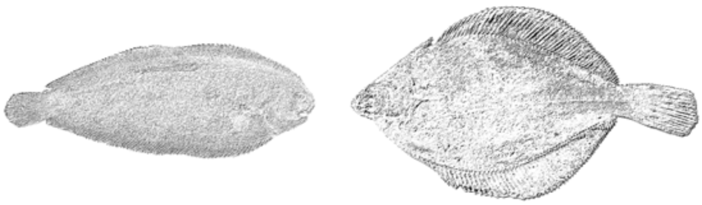
Ex post and *ex ante* evaluation of the long term management plan for sole and plaice in the North Sea (part 2): *ex ante*

Dr. David C. M. Miller, Dr. Jan Jaap Poos

Report number C0104/10



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Client:	Ministerie van Landbouw, Natuur en Voedselkwaliteit Postbus 20401 2500 EK Den Haag
	WOT-05-406-170-IMARES-3
Publication Date:	13-08-2010

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Summary

This report describes the second part of an ex post and ex ante evaluation of the multiannual plan for sole and plaice in the North Sea as laid out in Council Regulation (EC) No 676/2007. This plan has been in place since 2007. The plan aims to ensure, in its first stage, that stocks of plaice and sole in the North Sea are brought within safe biological limits, i.e. above Bpa and below Fpa. Following this, and after due consideration by the Council on the implementation methods for doing so, the plan will ensure that the stocks are exploited on the basis of maximum sustainable yield and under sustainable economic, environmental and social conditions. This report extends work previously carried out by Wageningen IMARES evaluating the multiannual plan for plaice and sole in the North Sea as described in Council Regulation EC 676/2007 (Machiels et al. 2008). That evaluation has been redesigned to take into account comments and criticisms highlighted by two ICES reviewers.

Three different approaches were used to test the effects of the management plan. The first was a yield curve analysis for the two stocks under different stock and recruit relationship assumptions to assess the equilibrium fishing mortality targets in the plan. The second approach is a projection of the two stocks under the rules of the plan, varying only future recruitment under different assumptions. Finally, the third approach is a full feedback MSE approach where in addition to the biology the fisheries system is also modelled. In order to show that the management plan is precautionary for the two species under consideration according to ICES, we use the Criteria agreed during WKOMSE to be applied in the evaluation of Harvest Control Rules/Management Plans in relation to precautionary reference points.

The results presented here suggest that the multiannual plan can be considered to be precautionary for both of the managed stocks according to the criteria described by WKOMSE for the evaluation of multiannual plans. The plan allows for increases in yield to 2015 and in the long term while reducing the current levels of F. There is a very high likelihood of stock growth in terms of SSB for both stocks. Both the simple stock projections and full feedback MSE analysis showed that F is likely to remain at low levels allowing for increases in stock biomass. Caution needs to be taken in the interpretation of the MSE, and stock projection results because future projections take the stock to outside the range of historic observations. But by examining the performance of the plan at the lower ends of the simulation ranges and considering 'worst case' recruitment scenarios the likely risk of a management failure can be considered to be adequately estimated.

The results presented show that the plan is very likely to be precautionary but it is more difficult to assess whether it achieves the goals of long term yields and sustained healthy populations. This is essentially a question over whether the F targets specified for the two stocks are reasonable and whether in practice they can be achieved simultaneously. The former relies of the definition of MSY for these two stocks and the corresponding stock sizes that can deliver these yields while the latter depends on how fisheries behaviour and gear selection changes into the future. Given the uncertainty associated in the estimation of Fmsy reference points and that expert opinion has been incorporated into the determination of target F points, the targets as they stand seem plausible. Regardless, it is clear that both stock growth and long term increases in current yield levels are likely should the multiannual plan be implemented.

1 Introduction

In 2007, the European Commission adopted Council Regulation (EC) No 676/2007, establishing a multiannual plan for fisheries exploiting stocks of plaice and sole in the North Sea (Appendix A). The objective of the plan is to ensure, in its first stage, that stocks of plaice and sole in the North Sea are brought within safe biological limits. This shall be attained by reducing the fishing mortality rate on plaice and sole by 10 % each year, with a maximum TAC variation of 15 % per year until safe biological limits are reached for both stocks. Following this, and after due consideration by the Council on the implementing methods for doing so, the plan will ensure in its second stage that the stocks are exploited on the basis of maximum sustainable yield and under sustainable economic, environmental and social conditions.

Following the establishment of the plan, a simulation study was carried out by Machiels *et al.* (2008) to address an ICES request to test if the management plan could be considered precautionary. ICES subsequently requested a review of the Machiels *et al.* study to "ascertain that the evaluation of the (agreed) flatfish management plan has been carried out appropriately and whether the management plan is in accordance with the precautionary approach." A number of concerns were raised and suggestions for improving the simulation methodology and analysis were suggested. One of the main conclusions was that, based on the simulation study, the plan could not be considered precautionary because the simulated stock assessment estimates of annual fishing mortality rates (F) and Spawning Stock Biomass (SSB) do not show a high probability (>95%) of the plaice stock being within safe biological limits for two consecutive years before 2018. It was then decided that "*depending on the criterion for the precautionary approach that is adopted, this could be seen as non-precautionary*."

In part one of this report, the impact of the management measures on the stocks concerned and the fisheries on those stocks was evaluated (Miller and Poos 2009). According to the available data that evaluation showed:

- Spawning Stock Biomass (SSB) of both species have increased since the implementation of the plan. Plaice has a larger than 95% probability of having reached a stage where the SSB is above B_{pa} for two consecutive years. The XSA stock assessment indicates that this is also the case for sole. An alternative assessment including uncertainty estimates indicate that the probability of being above B_{pa} is not yet larger than 95%.
- The annual fishing mortality rates (*F*) of the two stocks have been declining in recent years. The North Sea plaice stock is now fished at a level below the management regulation target for this stock (<0.3 per year). The annual rate of *F* for the North Sea sole stock remains above the management regulation target for this stock (>0.2 per year).
- According to the latest assessment results, both stocks appear to be within the precautionary zone in 2008, with both SSB and *F* trajectories being indicative of population growth and a move towards more sustainable fishing levels.

In order to ensure sufficient input to the proposed evaluation by the Commission, Wageningen IMARES evaluates the plan, in a study commissioned by the Dutch Ministry of LNV. The evaluation will comprise an *ex post* comparison of the historic performance against the objectives mentioned in the plan (Miller and Poos 2009), and an *ex ante* test of the plan in terms of its sustainability as defined by ICES. The *ex ante* evaluation is presented in this report and aims to find out whether the measures would achieve the objectives stated in the management plan. In addition, the consequences of management actions following the multiannual plan in terms of development of TACs, landings and permitted effort are examined.

2 Assignment

This report extends work previously carried out by Wageningen IMARES evaluating the multiannual plan for plaice and sole in the North Sea as described in Council Regulation EC 676/2007 (Machiels et al. 2008). That evaluation has been redesigned to take into account comments and criticisms highlighted by two ICES reviewers of the previous report and is also updated with the latest available data and assessment models of the stocks. The primary aim of this evaluation is to assess whether or not the management measures specified by the plan constitute a precautionary approach to the management of the two stocks. Further, it aims to evaluate the likelihood of the long term management of the stocks being in line with the principle of managing fisheries for maximum sustainable yield as agreed upon at the World Summit on Sustainable Development in Johannesburg (September 2002). This evaluation includes tests of the robustness of the plan to uncertainty by evaluating its implementation across a range of plausible scenarios of stock dynamics, starting conditions and fisheries dynamics.

3 Materials and Methods

Three different approaches were used to test the effects of the management plan. The first approach is the simplest, where we do yield curve analyses for the two stocks under different stock and recruit relationship assumptions. Such analysis gives the equilibrium results of the fishing mortality targets in the plan. The second approach is a simple projection of the two stocks under the rules of the plan, taking into account only recruitment variability and different assumptions of future mean recruitment. Finally, the third approach is a full feedback MSE approach , including the different uncertainties in the assessment and recruitment. In addition to the biology, the fisheries system is modelled with simple fleet dynamic rules for three different fleets targeting the two species.

All analyses were carried out using the FLR package (Kell et al. 2007), a collection of data types and methods written in the R language (R Development Core Team 2008) as part of the EU EFIMAS-COMMIT-FISBOAT project cluster. All code, data and additional sources for checking, validating and evaluation are freely available upon request.

3.1 The management regulation

The European Commission Council Regulation (EC) No 676/2007 is attached in full in Appendix A. The adopted plan is the main instrument for flatfish fishery management in the North Sea, and was developed with the intention to also contribute to the recovery of other stocks such as cod. In drawing up the multiannual plan, the European Council tried to take into account the fact that the high fishing mortality rate for plaice is to a great extent due to the large discards from beam-trawl sole fishing with 80mm nets in the southern North Sea. The North Sea plaice and sole stocks are currently managed by TACs, days at sea restrictions and technical measures. The stocks are exploited by several fisheries but most of the catch is taken by the mixed beam trawl fisheries. The control of the fishing mortality rates envisaged in the plan is to be achieved by establishing an appropriate method for setting the level of total allowable catches (TACs) of the stocks, and limitations on permissible fishing effort.

The objectives of the first stage of the agreement are to bring the two stocks to within safe biological limits. For plaice, these safe biological limits are a fishing mortality below 0.6 and an estimated spawning biomass exceeding 230 000 ton. For sole the safe biological limits are a fishing mortality below 0.4 and spawning biomass exceeding 35 000 ton. TACs applied will corresponds with fishing mortality that will be reduced by 10% year-on-year until the target levels have been reached, while annual variations in TACs will be kept within 15%. According to Article 5 of the Regulation the Council will amend the agreed plan when the stocks of plaice and sole have returned to within safe biological limits for two years in succession. The council shall decide on the basis of a review proposal from the European Commission that will permit the exploitation of the stocks at a fishing mortality rate compatible with maximum sustainable yield. The proposal for review shall be accompanied by a full impact assessment that takes into account the opinion of the North Sea Regional Advisory Council.

Advice on long term management from ICES indicates that at low target fishing mortalities, low risk to reproduction and high long term yields are achieved simultaneously. In other words there is no conflict between the two main objectives of the multiannual plan. A low fishing mortality will lead simultaneously to high yield and a low risk to reproduction (lower than the 5-10% risk which has generally been considered acceptable by managers).

The management measures were implemented within the models following all of the specifications of the multiannual plan as closely as possible.
However, some of the articles in the plan can only be implemented in a simulation with some interpretation, simply because they are not specified sufficiently to be dealt with in mathematical rules. One example of this is article 18 in the plan, where both the SSB level below which additional TAC reductions shall be taken is not specified, nor is the magnitude of the additional TAC reductions.

3.2 Precautionary criteria

In order to show that the management plan is precautionary for the two species under consideration according to ICES, we use the Criteria agreed during WKOMSE to be applied in the evaluation of Harvest Control

Rules/Management Plans in relation to precautionary reference points (Table 3.2.1). Results were examined to 2015 and beyond and the risk will be evaluated over the ten year period 2011-2020.

Table 3.2.1. Precautionary criteria agreed during WKOMSE for evaluating multiannual plans (ICES 2009a)

Element	Criterion	Notes
Time frame	**2015**: The performance of the HCR (MP) will be evaluated using as time horizon the year 2015 (in agreement with the Johannesburg Declaration)	The simulations will use as starting year the population parameter estimates from the most recent assessment (e.g. from WG or benchmark).
Biological Reference Points	**Limit reference points**: Evaluate the HCR (MP) based on Blim and Flim	If new limit reference points have been accepted (ACOM) these should be used in the evaluation; In the absence of defined limit reference points such as Blim, use proxies (e.g. xlim derived from %SPR, or 0.5Bmsy, or 20%Bo, ….)
Risk	**5%**: The HCR (MP) is considered to be precautionary if the probability of SSB<Blim (or x<xlim) is less than 5%	Criteria for management plan of stocks within safe biological limits to be precautionary: no more than 5% of 10 year simulation runs having one or more years outside of safe biological limits. Criteria for recovery plan qualifying as precautionary: at least 95% of simulation runs recovering by 2015 (the year WSSD committed for rebuilding fish stocks). The 5% will be used unless managers specify another percentage.

3.3 Yield curve analyses

Yield curve analysis based on age structured stock assessment data is a common technique for estimation of the effect of fishing mortality targets. It assumes that the population goes to an equilibrium situation for any chosen F value, with a spawning stock biomass estimate in the equilibrium and a corresponding yield. Here we consider the yield to be the landings. Yield curve analysis for age structured assessment data basically uses two different sources of information: the yield per recruit curve (depending on growth, selectivity and natural mortality), and the stock and recruit curve.

All yield curve analyses were done using FLBRP package 1.0.0, in R version 2.10.1. The analysis of the yield per recruit reference points used selectivity, natural mortality and weight data taken to be the average of the observations and assumptions of the period between 2004 and 2008.
This recent period was chosen as a representation of the current state of the stock and the fishery with respect to general life-history characteristics and fishing patterns. The results obtained here have also been presented in the ICES WKFRAME 2010 group (ICES 2010a).

3.4 Stock projections

The second approach is a simple projection of the two stocks under the rules of the plan, taking into account only variability of future recruitment under different assumptions of future mean recruitment. We show SSB, R, F, and landings, setting the F values according to the rules of the plan. This is done in a forward projection from the ICES WGNSSK 2010 assessment (ICES 2010b).

The forward projection uses a random resampling schedule from historic observed recruitments in the period 1957-2006 . In total, 50 iterations are done in the resampling schedule. The median of the resampled recruitments is within the range of the recruitment in the last 5 to 10 years (Figures 4.2.2a and 4.2.4a). In the forward projection, the standard short term forecast assumptions for these stocks have been made (ICES 2010b), and discards were taken into account. The stock was projected forward for 12 years. All computations were done using the FLSTF 1.99-1 package in R 2.8.1. From the iterations the quantiles are used to derive 95% confidence limits.

3.5 Full management strategy evaluation

3.5.1 Model formulation

The evaluation of the multiannual plan is carried out using a numerical simulation model for the interplay between the biological dynamics of the stocks and the dynamics of the fleet. 'Real' populations and 'real' fleets are simulated from the best information available using simple population and fleet dynamics principles. In the model, the future management of the stocks strictly follows the rules in multiannual management plan, based on observations of the 'real' populations and fleets. The observation uncertainty is modelled by assuming random noise for the landings, discards and surveys, based on historical estimates of uncertainty. Several scenarios are tested as a sensitivity analysis of the implementation uncertainty. Each scenario was simulated 100 times out to 2021 (i.e. fishing mortality estimates out to 2020). FLCore version 3.0 was used in R version 2.8.1.

Biological operating model

The biological operating model consists of age structured population models of the 'real' plaice and sole stocks in the North Sea. The models are conditioned to reflect our current understanding of the states and dynamics of the two stocks. The results presented here are based on two WGNSSK 2009 assessments: the XSA model (Darby and Flatman 1994) and SCA model (Aarts and Poos 2009) for sole and plaice stocks in the North Sea, utilising data up to and including 2008 values.

The simulation was initiated in 2003. The stock numbers at age in the initial year were taken from the assessment results (ICES WGNSSK, 2009b). Landings, discards and survivors of the two stocks were calculated for the years up to 2009 given the model estimated (natural & fishing) mortality rates for the period 2003 to 2009. Recruits up to 2009 were also taken from the assessments results. From 2010 onwards fishing mortality is determined by the multiannual plan and the simulation continues with recruits estimated from the stock-recruitment relationship, given the stock sizes, with random noise added that corresponds to the observed residual variation over the last 25 years.

The historic numbers at age (starting point) and the future stock-recruit relationship are considered to be the primary sources of biological error in the evaluation. There is no variation in future weights at age (mean of the last five years), maturity ogives (knife edge values as used in the assessments of the stocks) or natural mortality (a value of 0.1 for all ages and years for both stocks).

Stock-recruitment functions

The spawning stock biomass (SBB), the biomass of the sexually mature part of the population, determines the number of recruits of the next year.
Stock recruit relationships were examined over the period 1985-2009, the historic period with SSB and recruitment estimates available for both the XSA and SCA models (the SCA model estimates values over a shorter time period due to its reliance on survey indices). Given that neither of the stocks show any clear stock recruit relationship, geometric mean recruitment with error based on that observed in the historic period is used as the 'base case' scenario. The reviewers of the previous evaluation raised doubts over the suitability of the stock recruit relationships considered. So to bound the geometric mean scenario with higher and lower recruitment potential scenarios two alternative functions were considered: Beverton and Holt fits and a 'minimum recruitment' scenario. For the sole stock the Beverton and Holt fit is very flat, hence the behaviour is very similar

to the geometric mean function. The minimum recruitment scenario sets recruitment for all future years to the lowest observed recruitment over the historic period. The probability of this happening, given the statistical distribution of historic recruitment is extremely low.

Starting points

The considered scenarios in the previous *ex ante* evaluation of the multiannual plan put a high degree of confidence in the most recent assessment and failed to consider the possibility of either a healthier or more threatened stock. None of the evaluation scenarios considered accounted for the magnitude of the observed retrospective pattern in plaice. Accounting for the uncertainty about the current stock states this *ex ante* evaluation considers alternative initial stock status scenarios. The SCA model (Aarts and Poos 2009) provides uncertainty estimates of the current stock status and this is incorporated in the alternative scenarios. Incorporating the uncertainty in the current stock status within the process error considered for the stochastic simulations will translate into a lower degree of certainty when evaluating likely success of the management regulations.

We use four distinct starting conditions rather than incorporating uncertainty in starting point into all simulations. The first set of starting values are the results of the XSA assessment done by ICES WGNSSK in 2009. The second set of starting values are pessimistic, alternative and optimistic views of the current situation from the SCA assessment. Namely, the set of starting values associated with the lower 5% SSB estimate, the 50% SSB estimate and the 95% estimate, respectively. It should be noted that the XSA estimate of SSB in 2009 lies well within the range of SCA estimates for the plaice stock, in the case of the sole stock the XSA estimate is towards the lower bounds of the SCA distribution, similar to the 5th percentile. Hence the alternative scenarios are more optimistic in the case of the sole stock.

Fleet dynamics and the fishery

The effects of the fishery on the two stocks is modelled as the combined effect of three different fishing fleets: a Dutch beam trawl fleet, a BT1 fleet for the other countries, and a BT2 fleet for the other countries. This allows for a distinction between OTB (fishing almost exclusively plaice) and TBB (fishing both species) gears. The Dutch fleet is modelled separate from the other two fleets because it has a very high proportion of the North Sea sole and plaice landings (WGNSSK 2009), as well as being a data-rich component of the fishery.

The fleet operating model affects the number at age in the two fish stocks via the fishing mortality rate (F) per year. Conversion from numbers to weights is done using the individual weights at age. These weights are different for the individuals in the population, and between landings and discards, because of differences in the size selectivity of the gear and the discarding process. Fishing mortality rate for each age group is calculated as the product of fishing effort (f), catchability (q) and selectivity. This simplistically implies a linear relationship between catch and fleet effort for each species. The historic selectivity-at-age (Figure 3.5.1) and catchability were estimated from the Fishbase dataset that holds all landings at age for the different international fleets, the international discards data, and the demersal assessment working group stock assessment results. The latter include estimates of fishing mortality by year and age. The total fishing mortalities can be used to create partial fishing mortalities by age and year for the different fleet segments using the discards-at-age and landings-at-age data.

In plaice, a substantial proportion of the catches are discarded, especially for the younger ages that are caught but fall below the minimum landing size. This was dealt with in the simulations by calculating separate discards and landings selectivities and catchabilities for each fleet targeting plaice.
This resulted in a simulated dataset with ‘real’ landings values for the two species and discard values for the plaice stock used in fitting the assessment model (XSA) during each year of the simulations.

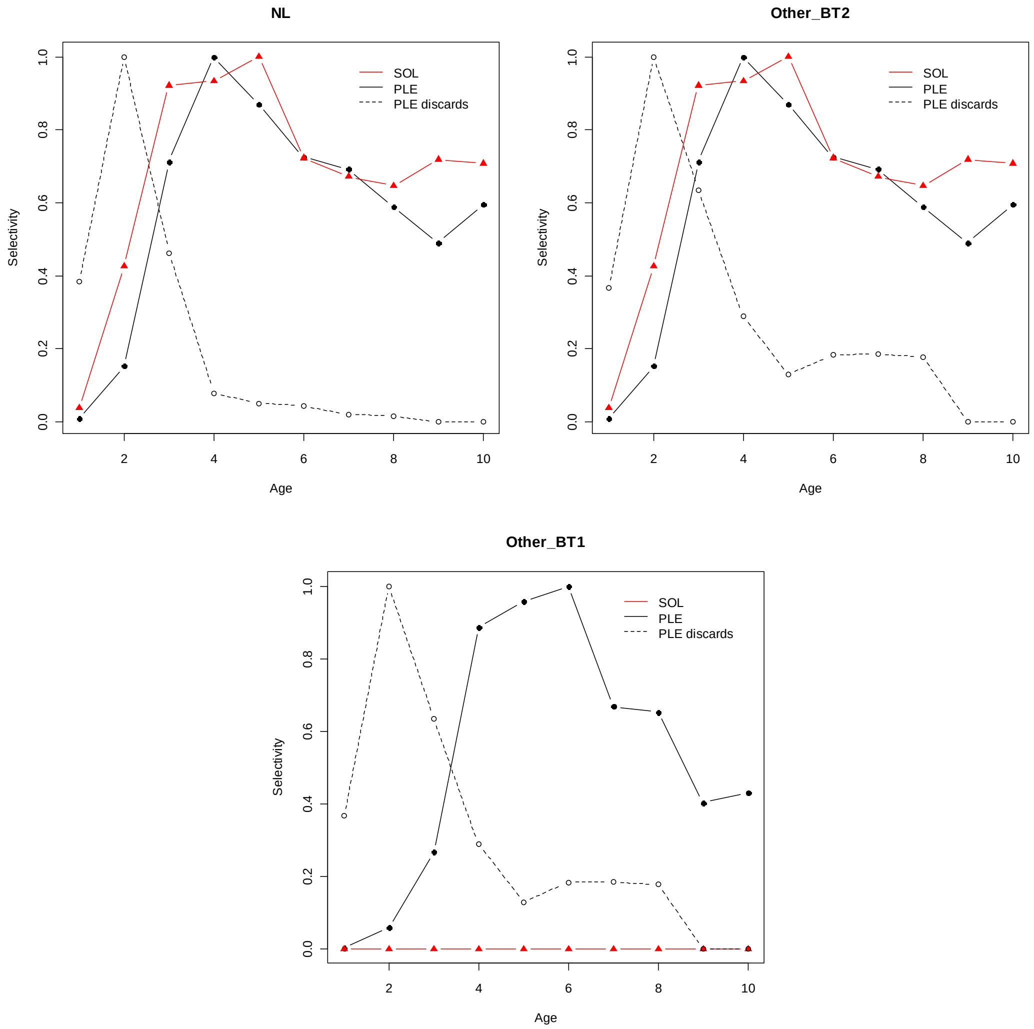

Figure 3.5.1. The selectivities by age (relative to the maximally selected age) of each species by the three fleets used in the MSE simulations.

Possible increase of efficiency of the fleets over time has been taken into account in the current model in the form of technological creep percentages (Rijnsdorp et al., 2006). Estimates of partial fishing mortality rate for sole and plaice were found to increase annually by 2.8% (sole) and 1.6% (plaice) in the recent period. The positive trend was considered to be due to an increase in skipper skills and investment in auxiliary equipment, the replacement of old vessels by new ones and, to a lesser extent, to upgrade engines. These values were used to incrementally increase the catchability of sole and plaice over the simulated period. There are no trend changes in selectivity through time, future selectivity is based on the mean recent historic values (5 years).

All of the scenarios assume that the fleets will fish up both TACs while avoiding catching overquota fish. In other words, no implementation error is assumed in this scenario. The evaluation tests the multiannual plan as if it will be implemented as specified. Given that this is an evaluation of the plan and that none of the articles contained within the plan include any strange or novel concepts that would require special enforcement measures, it seems reasonable to consider any deviations from the application of the plan in reality can not be considered to be a result of the plan itself.

3.5.2 Assessment and forecast

In order to set a management measure for year *y*, assessment data will be available up to year *y*-2 and the assessment itself is carried out in year *y*-1. The stock assessment process results in fishing mortalities estimates until year *y*-2 and survivor estimates and SSB estimates (at the first of January) until year *y*-1. A deterministic short-term forecast procedure then calculates the TAC for year *y*, based on assumptions about F and recruitment in the year *y*-1 and *y*. The assessment output and short-term forecast data might deviate from the real population characteristics as modeled in the biological operating model part because of the introduction of process error, model error, estimation error and observation errors.

The information or perception on the stocks status is generated through the explicit inclusion of a stock assessment in the simulation. Catches, discards and landings of the fleets are "recorded" in the model. Mimicking the assessment procedures, three surveys sample the plaice stock, and two surveys sample the sole stock by fishing with a constant and low fishing effort. Catches per unit of effort are assumed to be linearly related to stock abundance, thus result in two survey indices on the state of the stocks. The implementation of the XSA stock assessment in simulations for use in the multiannual plan HCR means that the MSE explicitly takes into account the impact of error generated by the stock assessment process.

To simulate observation error, the assessment input data were generated from the "real" population with error coefficients. Variance estimates for observations by age (Table 3.5.1) were used to generate log-normal error. The error coefficients for the simulated survey catches are generated from the catchability residuals at age for each survey as estimated by the WGNSSK stock assessment. The error coefficients on the landings and discards are generated from the standard errors estimated by the SCA assessments for sole and plaice. Biological parameters of the stocks in the assessment process are assumed to be equal to the biological parameters set in the operating model.

Table 3.5.1 Variances associated with the generation of observation errors for the catch (landings and discards) and survey indices for use in the annual assessments of the two stocks in the simulation model (observation error component of the simulation).

	Plaice					Sole				
	Catch		Surveys			Catch		Surveys		
Age	Lan	Dis	BTS-Isis	BTS-Tridens	SNS	Lan	Dis	BTS-ISIS	SNS	NL Beam Trawl
1	1.31	0.2	0.22	1.33	0.23	2.13	-	0.06	0.07	-
2	0.25	0.1	0.18	0.38	0.55	0.12	-	0.22	0.29	0.09
3	0.03	0.18	0.2	0.08	0.92	0.02	-	0.31	0.2	0.03
4	0.01	0.24	0.11	0.08	-	0.02	-	0.17	0.43	0.04
5	0.01	0.68	0.28	0.1	-	0.02	-	0.49	-	0.05
6	0.01	0.9	0.32	0.08	-	0.01	-	0.48	-	0.06
7	0.01	1.9	0.39	0.1	-	0.04	-	0.39	-	0.06
8	0.02	8.69	0.75	0.13	-	0.06	-	0.49	-	0.16
9	0.08	-	-	0.1	-	0.2	-	0.39	-	0.05
10	0.08	-	-	-	-	0.2	-	-	-	-
Min	0.01	0.1	0.11	0.08	0.23	0.01	-	0.06	0.07	0.03
Max	1.31	8.69	0.75	1.33	0.92	2.13	-	0.49	0.43	0.16
Mean	0.18	1.61	0.31	0.26	0.57	0.28	-	0.33	0.25	0.07

3.5.3 Simulation of the multiannual plan management measures

Both output and input management measures are included within the plan. The output measures, described in Chapter II (Articles 6-8), consist of setting TACs for each stock based on fishing mortality objectives (annual reductions in F and target Fs for each stock).
The input measures, described in Chapter III (Article 9), are implemented as effort reductions in which the change in effort (days at sea) is proportional to the fishing effort required to land the TACs. In addition to these specified management measures there is also a Special Circumstances clause (Chapter V, Article 18) that allows for a greater reduction in TAC/effort should the SSB of either stock be found to be suffering from reduced reproductive capacity.

In the management part of the model, the perceived fishing mortality (F) from the XSA assessments and the target reference points specified in the multiannual plan are used as inputs to the harvest control rule (HCR). The HCR formulates the advice for setting the TACs according to the intended fishing mortality. The HCR also defines the allowable fishing effort for the fleets based on the F required to land the TAC or effort restrictions that need to be applied when the target F value as not yet been achieved.

Each year the total effort to be applied by the 'real' fishery is calculated as the *maximum* of the amounts needed to land the full TAC of each species (based on the 'real' population and the relationship between *F* and effort). The overquota landings of the species that required less effort to take the total catch are ignored i.e. landings beyond the TAC are not removed from the population. Total effort may be reduced if the HCR sets an upper limit on the total allowable effort (e.g. if *F* remains above F_{tar}, reduce allowable effort by 10%, or the percentage required to get F down to the target value, whichever is lowest), which would obviously reduce overquota and may lead to the TACs not been fully caught. The total effort is converted to *F* for each species.

For article 18 in the plan, the limit reference points were used to determine whether the stocks suffer from 'reduced reproductive capacity'. A 25% TAC reduction would result if they were.

3.5.4 Simulation scenarios

Seven simulation scenarios were run for the evaluation (Table 3.5.2). The simulations are run with 100 stochastic realizations, where the two sources of noise are: (1) process error in the biology part, via random noise around the stock-recruitment relationship and (2) observation error in the management part, by including a random sampling error around the observed fleet and survey catches. In reality there are probably more sources of random noise, like for instance mortality rates. In the simulation model a number of simplifications and assumptions were made.

Table 3.5.2 The seven scenarios run for the evaluation of the multiannual plan.

Number	Description	Starting point	Stock recruit relationship
1	BaseCase	XSA	Geometric mean
2	SCA	SCA	Geometric mean
3	SCA_5	SCA 5 percentile	Geometric mean
4	SCA_95	SCA 95 percentile	Geometric mean
5	BevHolt	XSA	Beverton and Holt
6	minRec	XSA	Minimum recruitment
7	worstCase	SCA 5 percentile	Minimum recruitment

Scenarios 1 and 7 (base case and worst case scenarios) are used to assess whether or not the plan can be considered as precautionary. The base case scenario is according to WKOMSE specifications ("*The simulations will use as starting year the population parameter estimates from the most recent assessment*") and strictly speaking the multiannual plan only needs to satisfy criteria under this scenario. However, if the plan is found to be precautionary under the worst case scenario, this will allow greater confidence in the results. The remaining scenarios are presented as checks or sensitivity analyses of the multiannual plan to different starting points (scenarios 2-4) and stock recruit relationships (scenarios 5 and 6).

4 Results

4.1 Yield curve analyses

4.1.1 Plaice

The yield curve analysis for plaice was done for two different stock recruitment relationships: the segmented regression curve, and the Ricker curve. The results critically depend on the assumption that is made with respect to the functional form of these stock recruitment curves.

The historic recruitment series does not indicate a very strong effect of spawning stock biomass on recruitment in the observed ranges. When estimating a segmented regression S/R relation using FLCore 3.0, no breakpoint is found within the observed biomass range (Figure 4.1.1).

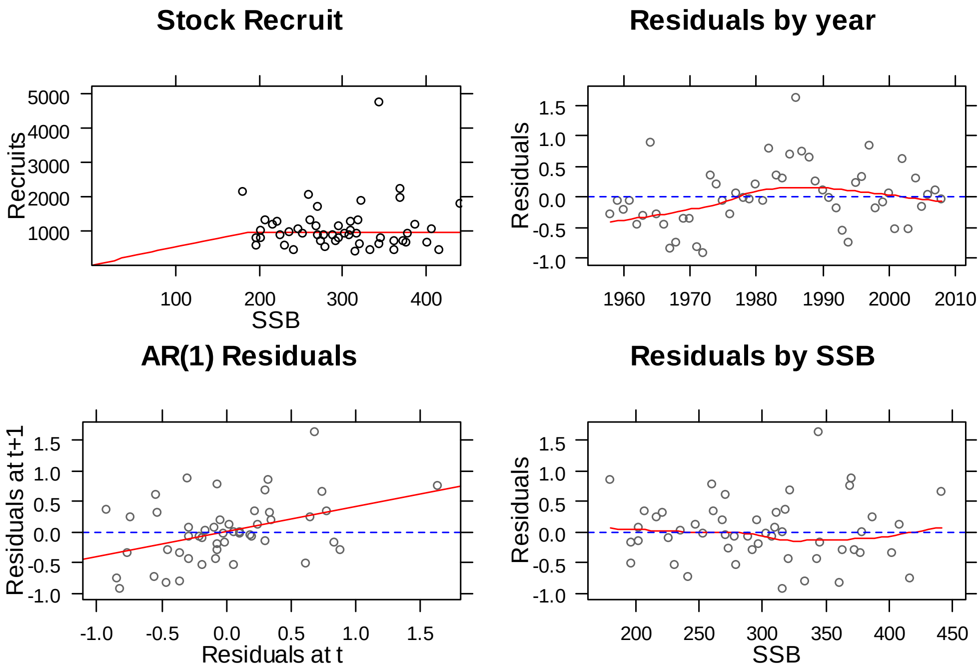

Figure 4.1.1. S/R analysis using a segmented regression model for plaice in area IV. Note that SSB is in 10^3 tons, and recruits are in 10^6.

As a result the breakpoint is put at the lowest SSB estimate in the time series. A Ricker S/R model shows a dome shape with a very flat top, the maximum being within the range of SSB estimates (Figure 4.1.2). A Beverton and Holt curve that was fitted to the data showed an extremely steep origin, and a flat curve at the asymptote through all observations. However there appears to be no information in the data from the assessment hat provides information on the actual slope in the origin. One feature that all fits share is that there are positive residuals in the 1980s. This indicates that there was strong recruitment in those years that is not explained by the stock-recruitment relationship.

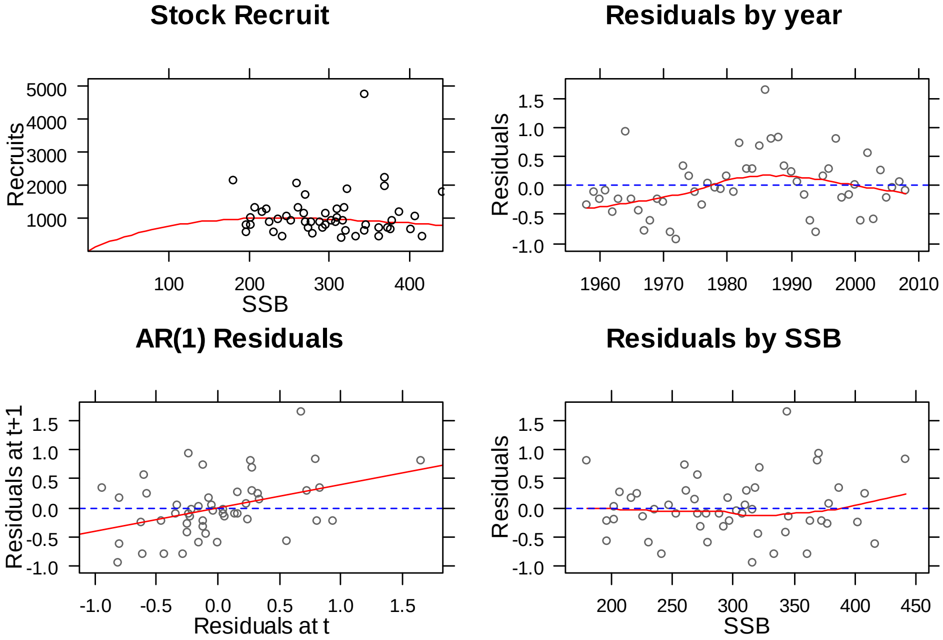

Figure 4.1.2 S/R analysis using a Ricker regression model for plaice in area IV. Note that SSB is in 10^3 tons, and recruits are in 10^6.

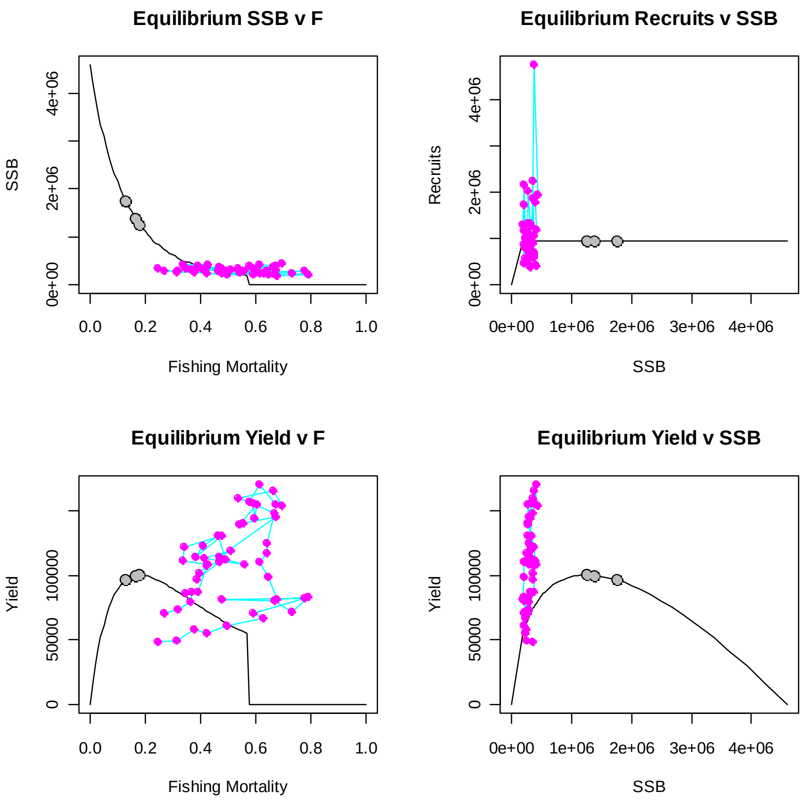

Figure 4.1.3. Results from equilibrium yield curve analysis for plaice in area IV, based on a Ricker S/R curve. Grey dots indicate different reference points, with the rightmost grey dot indicating F_{msy}.. Purple dots indicate the historic observations and estimates.

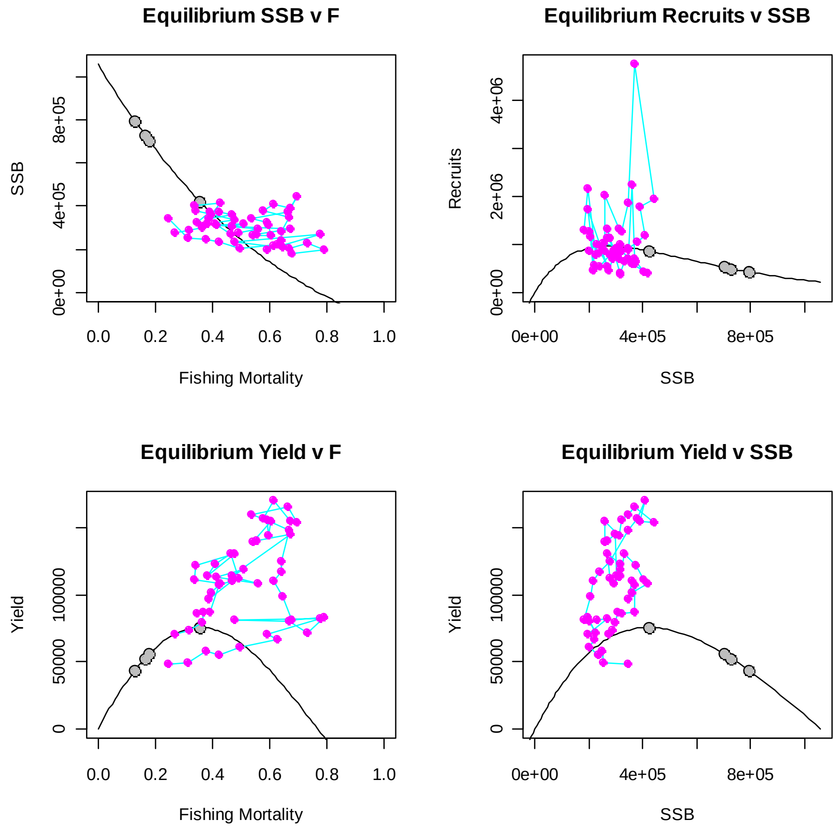

Figure 4.1.4. Results from equilibrium yield curve analysis for plaice in area IV, based on a Ricker S/R curve. Grey dots indicate different reference points, with the rightmost grey dot indicating F_{msy}.. Purple dots indicate the historic observations and estimates.

When using the segmented regression to estimate a yield curve from the YPR and S/R data (Figure 4.1.3) the F_{msy} estimate is at the deterministic F_{max} (0.18 year^{-1}) estimate, simply because in the region of F_{max}, the S/R curve is completely flat. However, the historic estimates of F, SSB, and yield show little correspondence to the equilibrium curves. The equilibrium SSB is far outside of the range of SSBs observed during the last 60 years for this stock. The F_{msy} estimate is quite far from the F_{crash} estimate. It should be noted that this F_{crash} estimate depends entirely on the assumption for the breakpoint in the S/R relation, for which there is no information available in the assessment data. The discrepancy between the equilibrium curves resulting from the yield curve analysis and the historic observations and estimates is the result of changes in growth and recruitment, amongst others.

To show the sensitivity of the deterministic F_{msy} estimate from the YPR and S/R on the assumptions on the S/R curve, an estimate using a Ricker curve is presented in Figure 4.1.4. Here, F_{msy} is estimated at 0.36, and F_{crash} is estimated at approximately 0.8 year-1.

In relation to the F target of 0.3 year^{1} in the multiannual plan, it is clear that at the F target, the spawning stock biomass is expected to be within the range of 400 kt to 1000 kt, depending on the assumed stock and recruitment relation. This is well above the B_{lim} and B_{pa} reference point values calculated by ICES for these stocks. The corresponding landings are between 70 kt and 110 kt.

4.1.2 Sole

The historic recruitment series does not indicate a very strong effect of spawning stock biomass on recruitment in the observed ranges. When estimating a segmented regression S/R relation, no breakpoint is found within the observed biomass range (Figure 4.1.5). As a result the breakpoint is put at the lowest SSB estimate in the time series. A Ricker S/R model shows a dome shape, the maximum being within the range of SSB estimates (Figure

4.1.6). Because there are no SSB and recruitment estimates closer to the origin of the curve, there is no information in these data on the steepness of the curve in the origin.
A Beverton and Holt curve was fitted to the data and showed an extremely steep origin, and a flat curve at the asymptote through all observations. However there appears to be no information in the data from the assessment hat provides information on the actual slope in the origin.

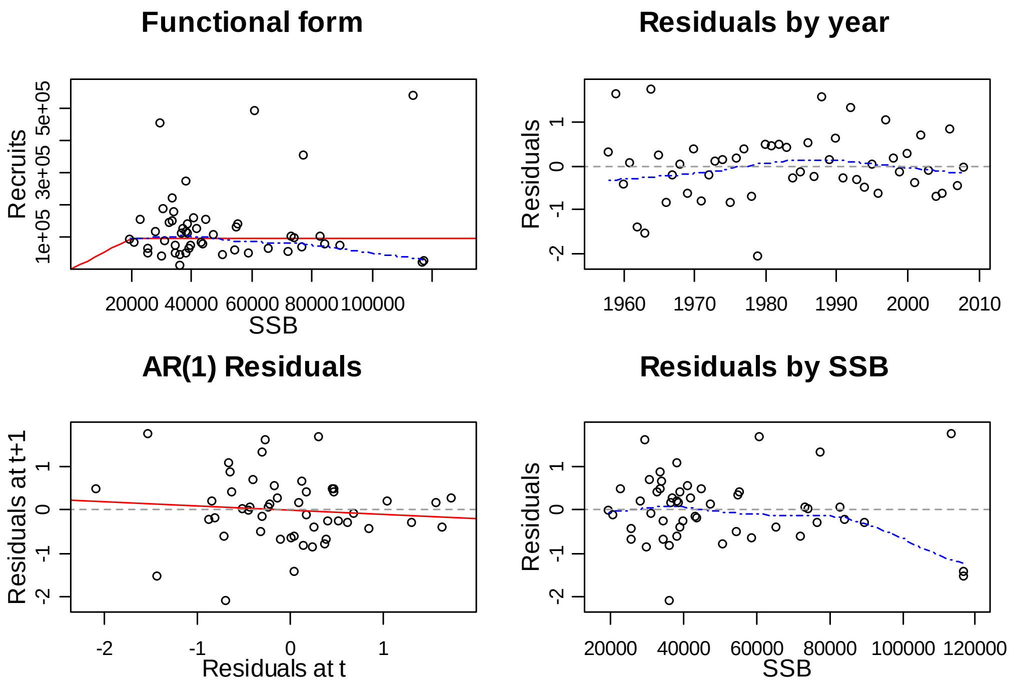

Figure 4.1.5. S/R analysis using a segmented regression model for sole in area IV.

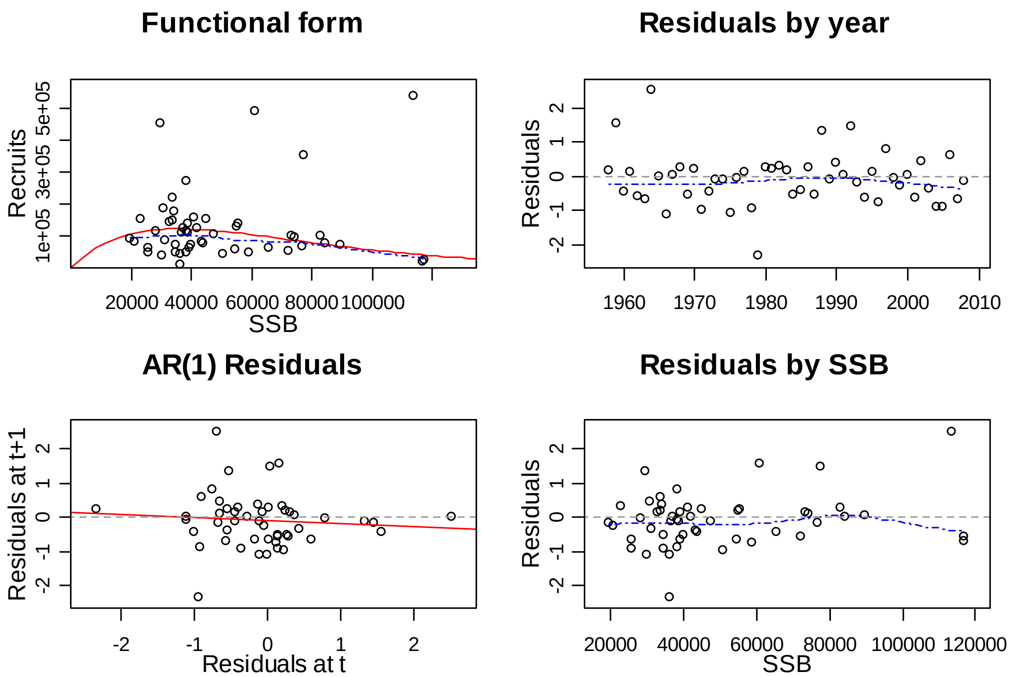

Figure 4.1.6. S/R analysis using a Ricker model for sole in area IV

One feature that all fits share is that there are positive residuals in the 1980s, but the effect is less pronounced as it is in plaice. This indicates that there was strong recruitment in those years that is not explained by the stock-recruitment relation.

When using the segmented regression to estimate a Yield curve from the YPR and S/R data (Figure 4.1.7), the F_{msy} estimate is close to the deterministic F_{max} (0.59 year^{-1}). However, the F_{msy} estimate is very close to the F_{crash} estimate. It should be noted that this F_{crash} estimate depends entirely on the assumption for the breakpoint in the S/R relation, for which there is no information available in the assessment data.

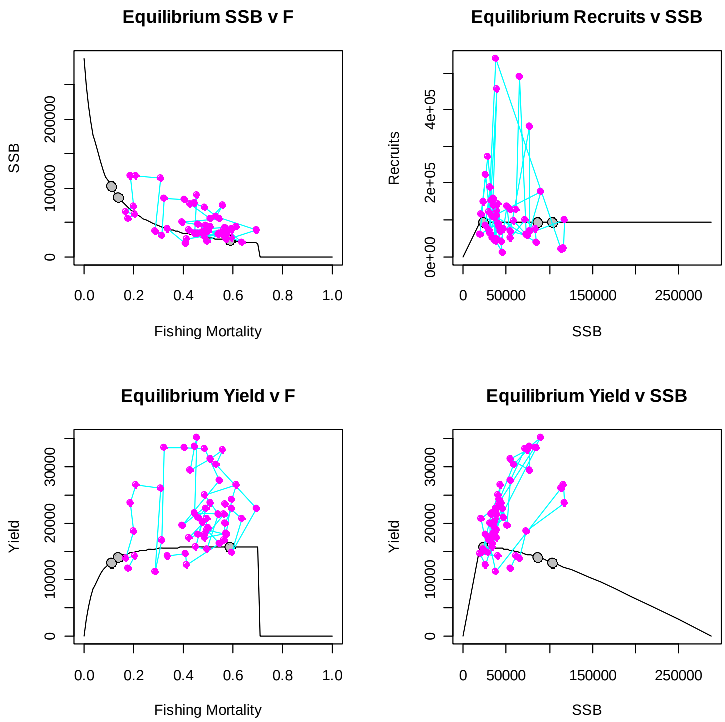

Figure 4.1.7. Results from equilibrium yield curve analysis sole in area IV, based on a segmented regression S/R curve.

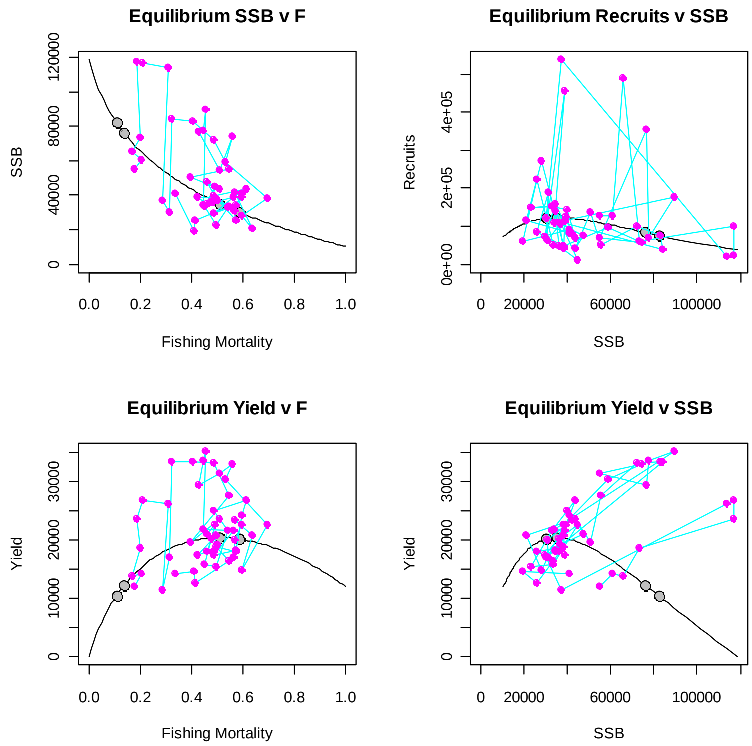

Figure 4.1.8 Results from equilibrium yield curve analysis sole in area IV, based on a Ricker S/R curve.

The historic estimates of F, SSB, and yield show better correspondence to the equilibrium curves for the sole stock compared to the plaice stock. The equilibrium SSB is far outside of the range of SSBs observed during the last 60 years for this stock. One of the reasons for this is probably that the equilibrium analysis here estimates the yield curve based on the average recruitment, while the historic estimates stem also from the period when recruitment was high in the 1980s. Also, growth has changed substantially over the entire time period.

To show the sensitivity of the deterministic F_{msy} estimate from the YPR and S/R on the assumptions on the S/R curve, an estimate using a Ricker curve is presented in Figure 4.1.8. Here, F_{msy} is estimated at 0.51, and F_{crash} is estimated to be higher than 1.0 $year^{-1}$.

In relation to the F target of 0.2 $year^{-1}$ in the multiannual plan, it is clear that at the F target, the spawning stock biomass is expected to be approximately 60 kt. This is well above the B_{lim} and B_{pa} reference point values calculated by ICES for these stocks. The corresponding landings are approximately 15 kt.

4.2 Stock projections

4.2.1 Plaice

The results indicate that the SSB will likely increase (Figure 4.2.1a). The lower 95% confidence limit stays approximately at level at which SSB is now, being above 400 000 tonnes. This is substantially higher than B_{lim}. Thus, there is a <5% probability of SSB falling below B_{lim} before 2020. None of the 10 year simulation runs have years outside of safe biological limits.

The fishing mortalities that result from the plan are around the target F in the plan (0.3 $year^{-1}$; Figure 4.2.1b). The lower confidence interval is substantially lower, resulting from the 15% TAC change constraint and occasional large recruitments (Fig. 4.2.2a). These large recruitments are the result of drawing the exceptionally large 1986 year class in the sampling procedure. In that case, the TAC cannot increase fast enough to keep F at 0.3 $year^{-1}$.

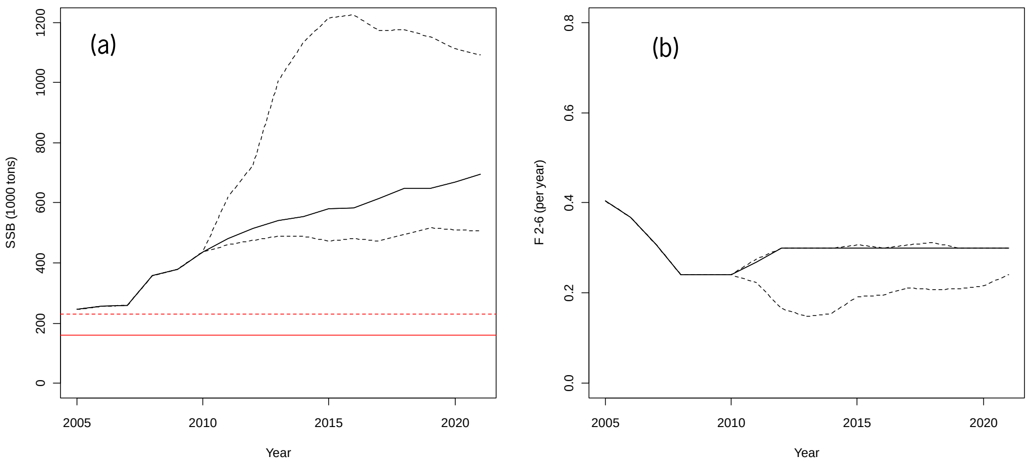

Figure 4.2.1. Time series of spawning stock biomass (a) and fishing mortality (b) for plaice in the North Sea. The time series comprise of the stock assessment results prior to 2010, and the projected 95% confidence intervals (- - -) and median (—) after 2010. In the SSB panel, the red line drawn line indicates B_{lim}, and the red dashed line indicates B_{pa}.

The median landings in the projection of the plan increase to values in the range of 80-100 kt. (Figure 4.2.2b). However, the 95% confidence interval is very large. The increase in the upper confidence limit is defined entirely by the 15% TAC change constraint.

In the context of the plan being in line with the precautionary approach, the probability of the plan bringing the SSB < B_{lim} within the next 10 years is substantially smaller than 0.05, with none of the 50 simulations being below B_{lim}. The plan thus has a very small (<<5%) probability of bringing F above F_{pa} and F_{lim} in the period up to 2020 and SSB < B_{lim}.

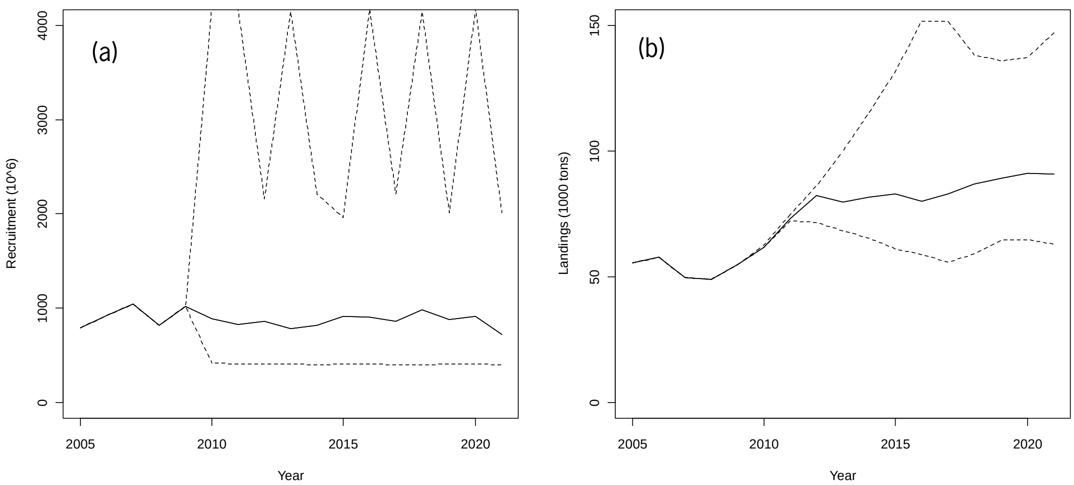

Figure 4.2.2. Time series of recruitment (a) and landings (b) for plaice in the North Sea. The time series comprise of the stock assessment results prior to 2010, and the projected 95% confidence intervals (- - -) and median (—) after 2010.

4.2.2 Sole

The results indicate that the SSB will likely increase as a result of the rules in the plan (Figure 4.2.3a). The lower 95% confidence limit is approximately at B_{lim} for a number of years, mainly caused by those realizations where recruitment is low in the period 2010-2012. In those cases, the fishing mortality does not decrease by 10% per year because of the 15% TAC change limits. After the fishing mortality has successfully been decreased, the stock increases, and SSB becomes increasingly unaffected by recruitment strength. The lower confidence limit then increases to approximately B_{pa}, being 35 000 tonnes. Of the 50 realizations, only 2 bring the SSB below B_{lim}. Thus, there is a <5% probability of SSB falling below B_{lim} before 2020.

The fishing mortalities that result from the plan decrease to the target F in the plan (0.2 $year^{-1}$; Figure 4.2.3b). The lower confidence interval is substantially lower, resulting from the 15% TAC change constraint and occasional large recruitments. In that case, the TAC cannot increase fast enough to keep F at 0.2 $year^{-1}$. Finally, none of the realizations results in an $F > F_{pa}$ after 2011. Thus, the plan has a very small (<<5%) probability of bringing F above F_{pa} in the period up to 2020.

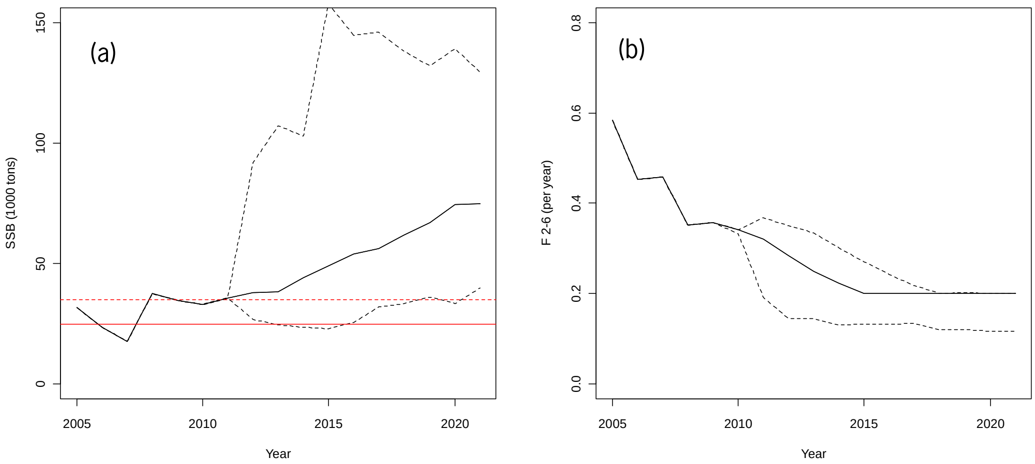

Figure 4.2.3. Time series of spawning stock biomass (a) and fishing mortality (b) for sole in the North Sea. The time series comprise of the stock assessment results prior to 2010, and the projected 95% confidence intervals (- - -) and median (—) after 2010. In the SSB panel, the red line drawn line indicates B_{lim}, and the red dashed line indicates B_{pa}.

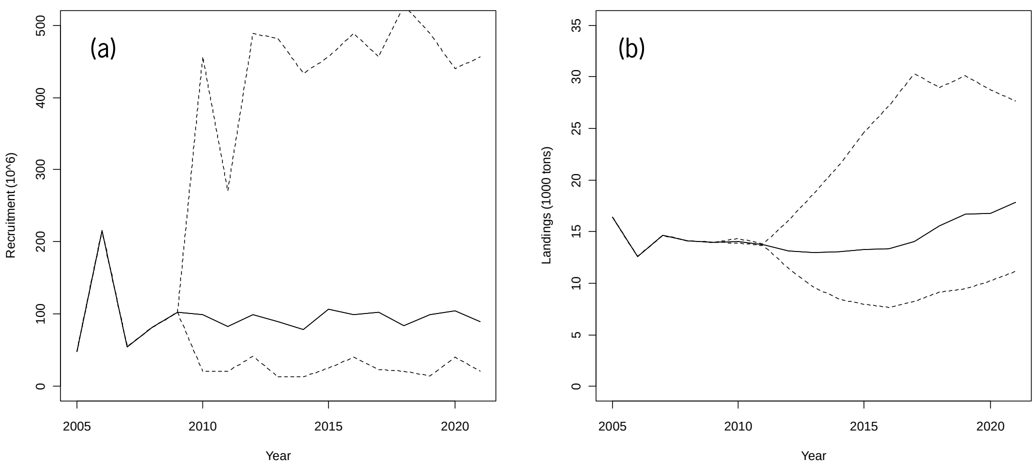

Figure 4.2.4. Time series of recruitment (a) and landings (b) for sole in the North Sea. The time series comprise of the stock assessment results prior to 2010, and the projected 95% confidence intervals (- - -) and median (—) after 2010.

The median landings in the projection of the plan slightly decrease in the period up to 2013, as a result of the decrease in fishing mortality. The decrease is followed by an increase as the stock increases and fishing mortality is more or less constant at the target F. Then the median landings increase to values in the range of 15 to 20 kt. (Figure 4.2.4b). However, the 95% confidence interval is very large. The increase in the upper confidence limit is defined entirely by the 15% TAC change constraint.

4.3 Full management strategy evaluation

4.3.1 Base case and worst case scenarios

Under both scenarios an initial large reduction in effort is followed by a slowly decreasing trend in HP days (Figure 4.3.1). There is a greater initial reduction in effort observed in the base case scenario because of the reduction in F required for the sole stock. Effort does not subsequently increase as stock recovery means that less effort is required to land the TACs. Under the worst case scenario, poorer stock recovery means that more effort is required to land the TACs.

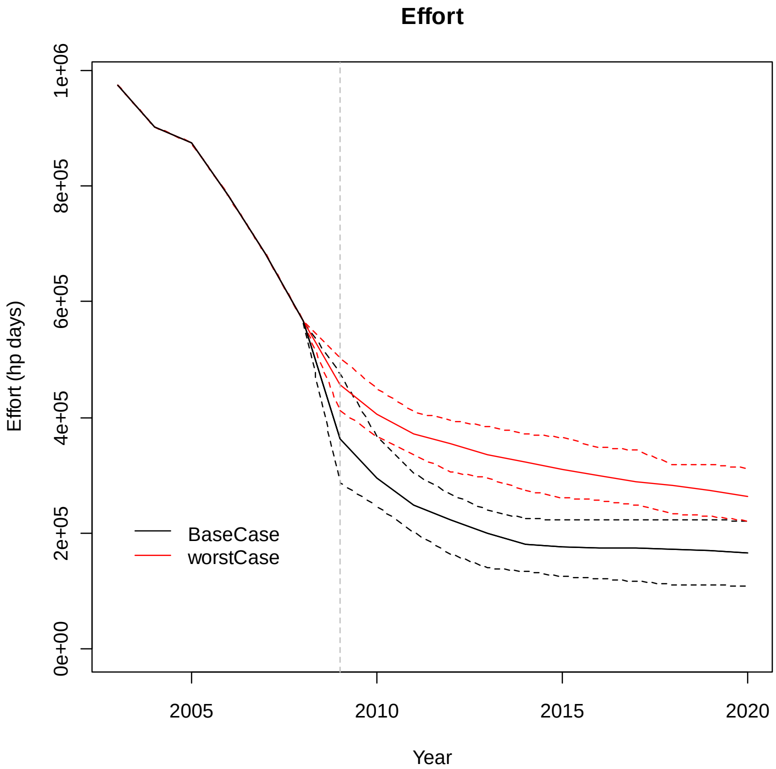

Figure 4.3.1. Total effort in HP days of the Fleet fishing the North Sea sole and Plaice stocks.

Plaice
Fishing mortality for plaice starts below the target level of 0.3 and decreases for about 5 years before stabilizing in the region of 0.2 (Figure 4.3.2). Under the multiannual plan, if current F is below the target level, F should increase towards the target. However in the simulations F initially decreases by more than 10%. This is because the already healthy stock continues to increase while the 15% limit prevents the TAC from increasing accordingly. In addition, restriction to the effort that can be applied on the sole stock impact on the ability of the fleet to utilize the full plaice quota (Figure 4.3.3). Discards decrease with the reduction in effort and remain stable at low levels. At these low F levels, SSB, which starts above Bpa, is likely to increase steadily. This is also the case under the minimum recruitment scenario.

Sole
For the sole stock, the initial stock status from the 5th percentile of the SCA distribution represents a stock in healthier condition than the XSA estimates it to be. However, the minimum recruitment scenario still represents a more pessimistic view of stock dynamics and can still be viewed as the worst case scenario. In both cases F continues the sharp decrease observed in the recent past reaching the target level before around 2013 (Figure 4.3.2). The decrease in F exceeds 10% for the first three years as a result of a mismatch between ‘real’ F and the perceived F used in the determination of the TAC. This, in combination with effort restrictions, is also the reason why F stabilizes slightly below the F target. SSB starts near Bpa and increases steadily under the base case scenario, though with larger uncertainty bounds. Yields increase slowly at first then quicker once target F is reached (Figure 4.3.3) and these are likely to increase further as the stock recovers. In the worst case scenario there is no increase in SSB, despite the stabilizing of F levels in the range of the target, suggesting at those low levels of recruitment the stock is near the equilibrium biomass and yield for the target F value.

Probability of achieving management goals/being precautionary
In the 10 years following 2010 (future simulation period) none of the 100 stochastic runs had SSB levels below B_{lim} or above F_{lim} for any of the years for both the plaice and sole stocks (Table 4.3.1). This was also true for the stock projection for plaice, but not for sole which had 4% of the simulations dropping below B_{lim} at one point. This

implies that by ICES precautionary criteria, the management plan can be considered precautionary for both stocks.

Table 4.3.1. Performance of the multiannual plan for North Sea sole and plaice according to WKMOSE criteria for the stock projection and MSE results.

Stock	Analysis	*N* simulations	*N* simulations with B < B_{lim} for 1 or more years	% Risk level
Sole	Projection	50	2	<5%
	MSE	100	0	<1%
Plaice	Projection	50	0	<1%
	MSE	100	0	<1%

4.3.2 Sensitivity to stock recruit relationship

The alternative recruitment scenarios represent a greater range of future stock dynamics for the plaice stock than for the sole stock (Figure 4.3.4). For plaice, the Beverton and Holt scenario shows a massive increase is recruitment compared to the base case geometric mean function while the minimum recruitment scenario obviously represents a much lower potential future recruitment. The impact of this on future SSB and F values is as would be expected, with greater recruitment leading to greater recovery in SSB and, through reduction in effort required to land TACs, slightly lower F values. In all scenarios SSB increases and F decreases, but at different rates. For sole, the Beverton and Holt scenario is identical to the base case geometric mean scenario. This is because the Beverton and Holt curve for this stock is flat-topped as described above in section 4.1. In the minimum recruitment scenario, very poor recruitment leads initially to a slight decline in stock size, but this then stabilizes in the range of Bpa.

4.3.3 Sensitivity to starting point

Both the rate of recovery (increase in SSB and decrease in F) as well as the pattern of recovery over time relative to the initial starting conditions are very similar across the range of starting points for both stocks. The 'poorer' starting points show a greater degree of recovery at a slightly more rapid rate.

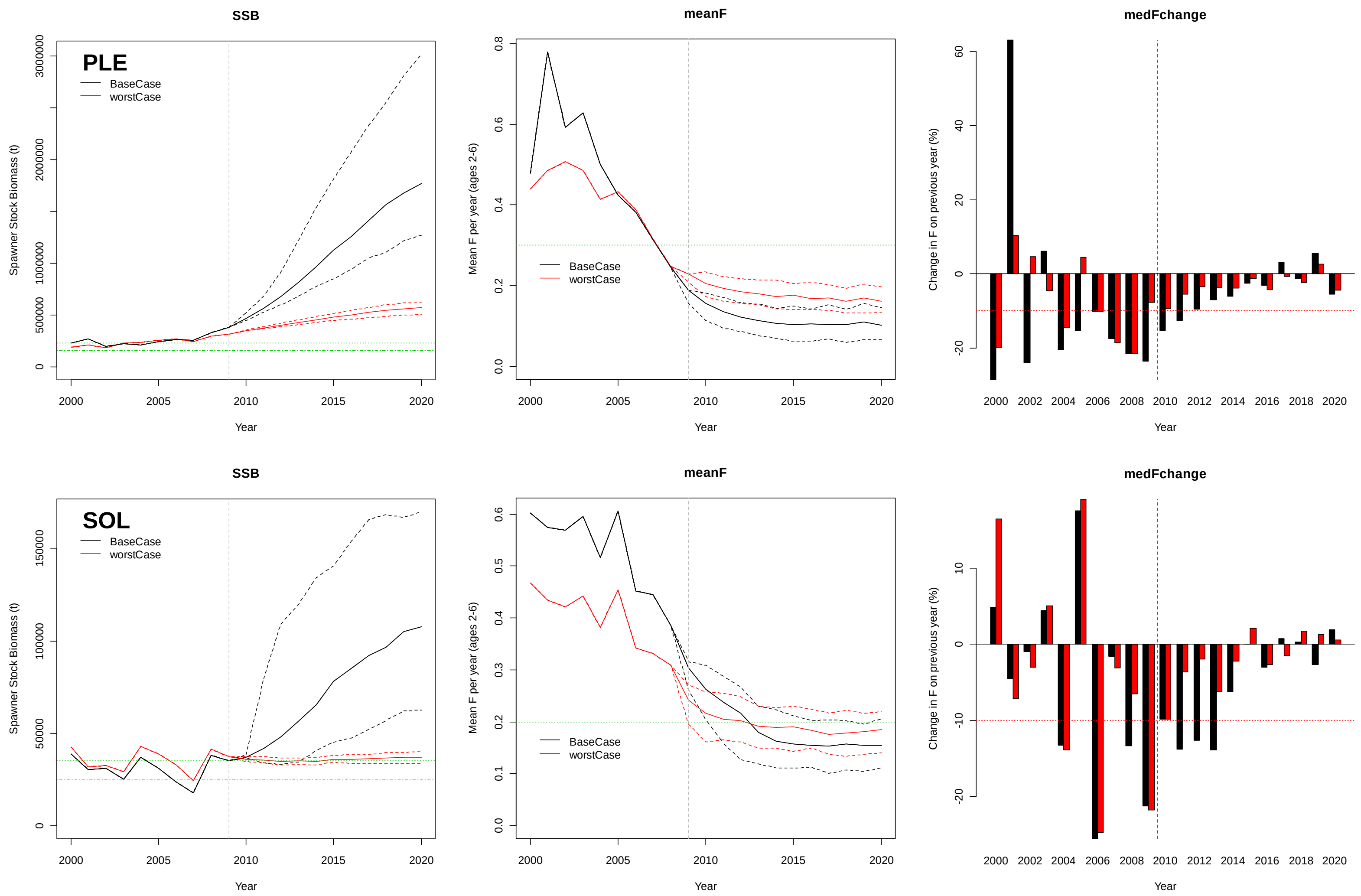

Figure 4.3.2. 'Base case' and 'worst case' scenarios: time series of SSB (left, with B_{lim} and B_{pa} marked), mean fishing mortality for ages 2-6 (centre, with target F marked) and median annual change in mean F (right) for the North Sea plaice (top) and sole (bottom) stocks. Time series comprise stock assessment results prior to 2010, and the 90% confidence intervals (- - -) and median (—) thereafter.

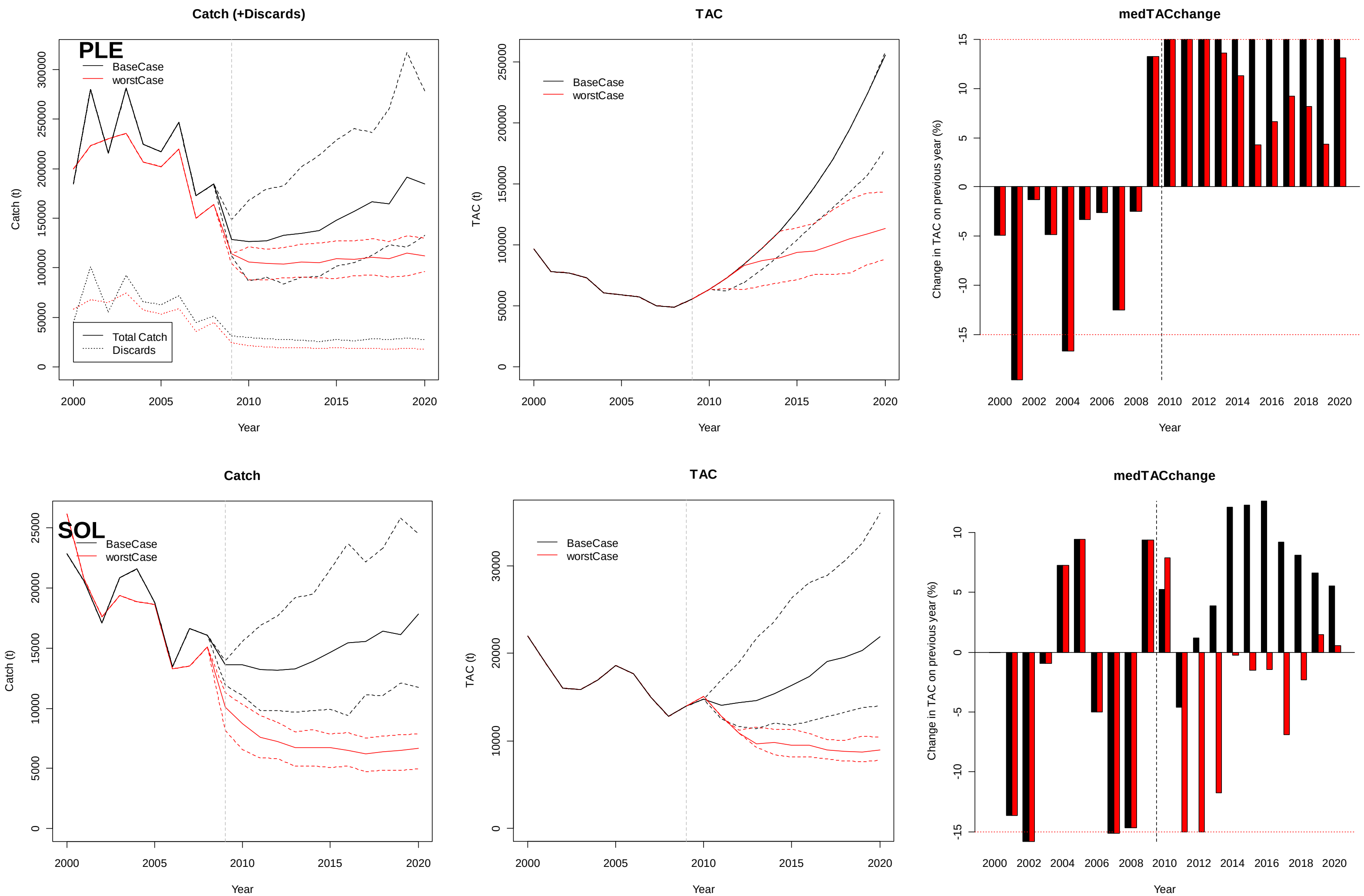

Figure 4.3.3. 'Base case' and 'worst case' scenarios: time series of Catch (left), TAC (centre) and median annual TAC change (right) for the North Sea plaice (top) and sole (bottom) stocks. Time series of catch and TAC comprise stock assessment results prior to 2010, and the 90% confidence intervals (- - -) and median (—) thereafter.

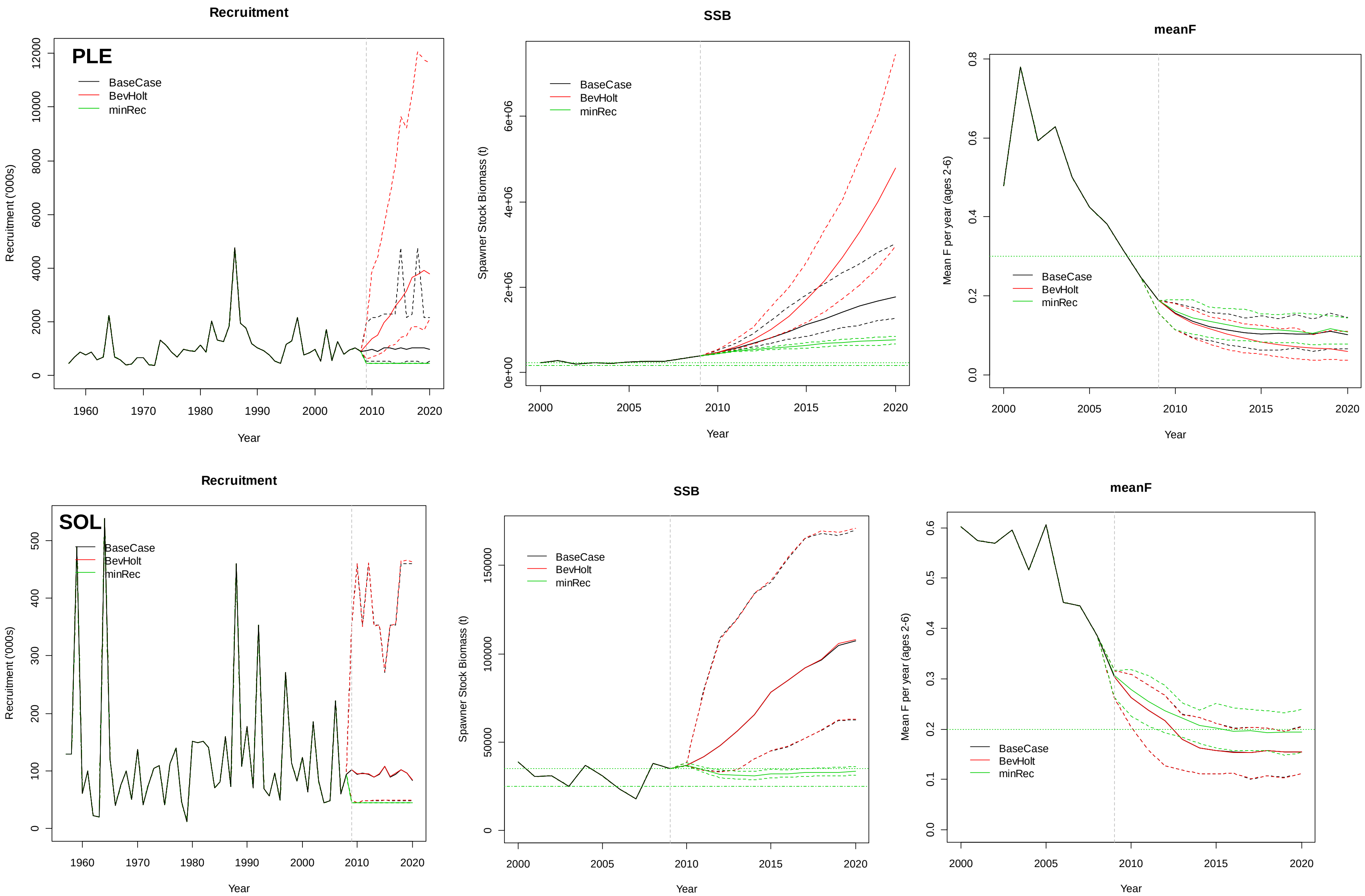

Figure 4.3.4. Alternative stock-recruitment relationship scenarios: time series of recruitment (left), SSB (centre, with B_{lim} and B_{pa} marked) and mean fishing mortality for ages 2-6 (right, with target F marked) for the North Sea plaice (top) and sole (bottom) stocks. Time series comprise stock assessment results prior to 2010, and the 90% confidence intervals (- - -) and median (—) thereafter.

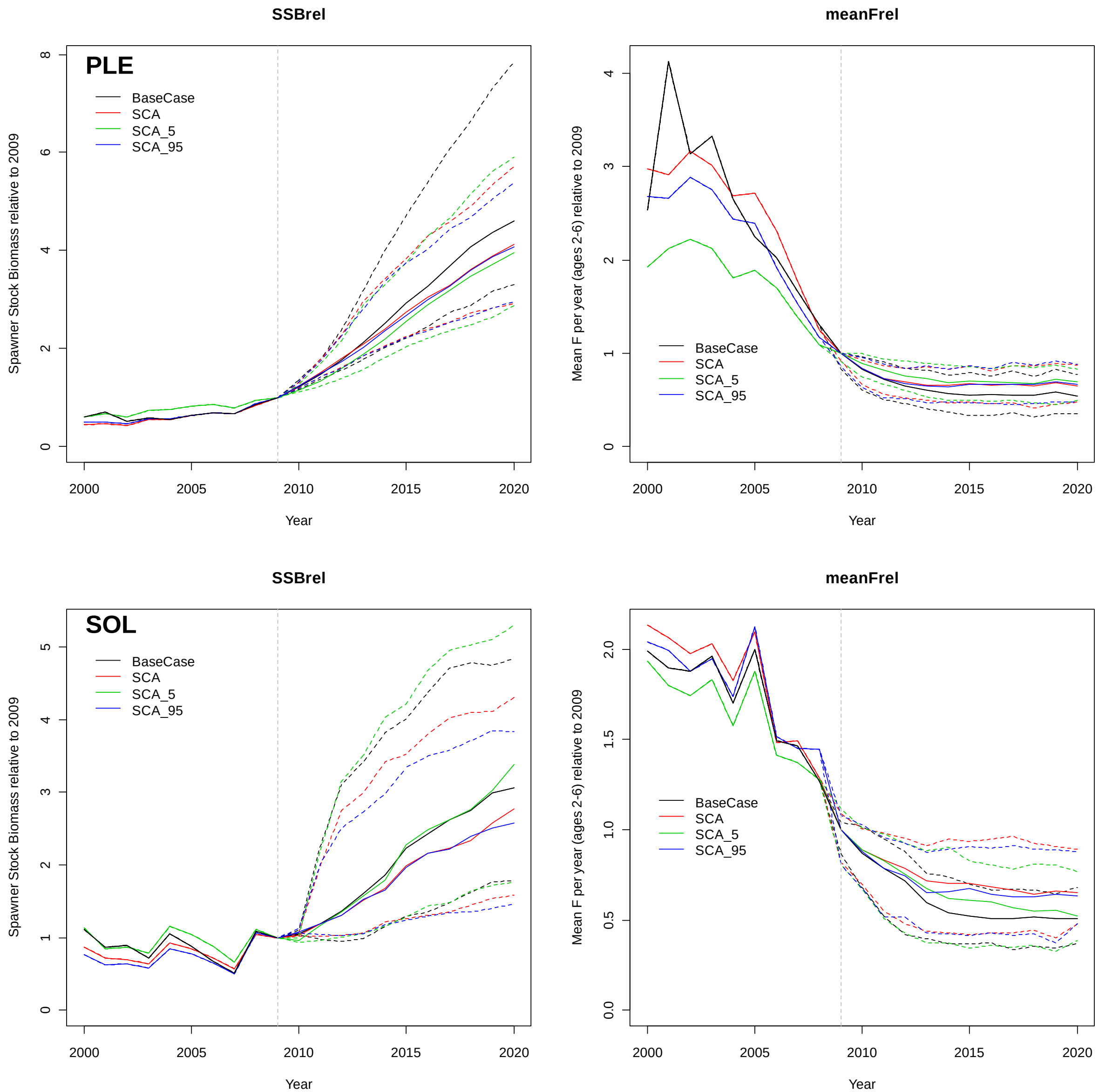

Figure 4.3.5. Alternative starting point scenarios: time series of SSB (left) and mean fishing mortality for ages 2-6 (right) relative to the median value in 2009 for the North Sea plaice (top) and sole (bottom) stocks. Time series comprise stock assessment results prior to 2010, and the 90% confidence intervals (- - -) and median (—) thereafter.

5 Discussion

The multiannual plan through its two stage process leads to a change in management strategy from a risk avoidance strategy (to get within safe biological limits) to a strategy of optimal harvesting of the resource. The aims of stage two of the plan are in accordance with the commitments made at the World Summit on Sustainable Development at Johannesburg (2002), the approach that is currently being implemented by ICES for the provision of advice for the management of fish stocks. The proposed management means a change from conservation or limit reference points to target reference points that are intended to meet management objectives. The primary driver for management advice under the multiannual plan is the estimated fishing mortality, but this output control is also complemented by effort restrictions. The fishing mortality targets have been chosen such that they will ensure that the biomass of the two stocks is kept at a high level within safe limits without the need for specific reactionary measures to the biomass status of the stocks. However, included within the plan is a clause that allows for more reactionary management measures should the stocks be found to be suffering from reduced reproductive potential that may result from insufficient biomass levels.

We used three different approaches to study the effects of the long term management plan for sole and plaice. Each of these approaches has pros and cons in terms of the level of complexity and the assumptions made in the analysis. In general, the three different approaches lead to similar conclusions about the effects of the plan on the spawning stock biomasses and yields.

The results presented here suggest that the multiannual plan can be considered to be precautionary for both of the managed stocks according to the criteria described by WKOMSE (ICES 2009a) for the evaluation of multiannual plans. The plan allows for increases in yield in the long term while reducing the current levels of F. There is a very high likelihood of stock growth in terms of SSB for both stocks. Both the simple stock projections and full feedback MSE analysis showed that F is likely to remain at low levels allowing for increases in stock biomass. The fact that the projections incorporated no effort control and therefore allowed for the full utilisation of both TACs lead to some slight differences in future stock status. For the sole stock, some of the projected runs allowed for a slight increase in F in the first few years of the simulation causing 2 of the 50 iterations to drop below B_{lim} for a short period before full recovery began. This did not occur in the MSE simulations, where none of the iterations dropped below B_{lim}, because the reductions in effort applied by the HCR prevented any increases from the initial starting F value thereby allowing for more immediate stock recovery.

Caution needs to be taken in the interpretation of the MSE, and stock projection, results because future projections take the stock to outside the range of historic observations. It is likely that in reality such changes in stock status would not proceed unchecked. Density-dependent growth or mortality would impact on the stock at such sizes and fishing patterns and selectivity would likely change. This evaluation does not aim to predict exactly what would happen if the multiannual plan continues to be implemented in the long term. The evaluation aims to assess whether the plan is robust to future process error and various assumptions of stock dynamics. It further aims to assess the degree of certainty with which we can accept that it is likely to be both precautionary and allow for the high long term yields while maintaining healthy stocks. The models should be used as indications more than absolute projections into the future. By examining the performance of the plan at the lower ends of the simulation ranges and considering 'worst case' recruitment scenarios the likely risk of a management failure can be assessed. This is embodied in the WKOMSE criteria used to evaluate the results.

A number of simplifying assumptions were required for the implementation of the MSE.
For both plaice and sole stocks it has been assumed that productivity of the marine ecosystem in the projected period will remain within the same range as has been observed in the past 50 years. Though this assumption is likely to be flawed, it is the most reasonable assumption to make given the availability of data and the fact that incorporating potential future regime shifts would be largely speculative. Observations of changes in the species composition in the North Sea towards more southern species and observation on changes in stock dynamics of some other stocks may indicate that external factors, such as climate change, do also affect the ecosystem. In the evaluation, it has also been assumed that annual decisions will be made using certain assessment methods (the present assessment procedures) with their associated uncertainties. It can be envisaged that other methods may be used in the future and this may affect (improve or deteriorate) the effect of the measures. In the current model spatial variation in fish abundance and fishing effort is not included.

Conditioning of a model with spatial differentiation is complicated (Pastoors et al. 2006; Poos et al. 2006) and the (XSA) observation model to which the results are compared don't include spatial variation either. When evaluating the model, assumptions had to be made at different levels in the process. If these assumptions are very different from the true situation, the effect of the measures may be different than indicated by the evaluation. Two major assumptions that were identified for this analysis were the initial starting condition of the two stocks and the form of the stock recruit relationship. By assessing ranges of these two factors in different scenarios it was possible to determine the plan is sensitive to assumptions about them. The present results suggest that the multiannual plan is effective across a broad range of stock conditions, as simulated in the 7 scenarios (Table 3.5.2), for both plaice and sole, maintaining a healthy stock while keeping F levels low in all cases. It also performed effectively at even the lowest likely future recruitment. These results show the multiannual plan to be robust to uncertainty in initial starting condition and future recruitment.

The current MSE implementation has addressed a number of the main concerns addressed by the previous ICES reviewers: for example (i) the issue of unrealistic uncertainty estimates for surveys, landings and discards has been dealt with by using estimates from the most recent stock assessments, (ii) the model does not generate systematic, large overestimates of plaice landings in the conditioning period compared with observed landings, (iii) the evaluation correctly simulates the forecasting procedure necessary for implementation of the plan. Because the multiannual plan has been applied for a number of years now, less interpretation was required in devising the HCR to be used in accordance with the plan. The current implementation of the plan in the simulations is believed to be in strict accordance with the regulations detailed in the multiannual plan. Some assumptions still needed to be made for the incorporation of Article 18 (actions to be taken when the stocks show reduced reproductive potential), though in none of the simulations did this clause ever come into affect. Fleet dynamics have been improved, though still in a simplified form due to limitations in data available for all métiers of the fleet. The estimation of observation error in landings and discards has also improved by using the outputs from the SCA model. Additionally, improved criteria to evaluate the precautionary nature of the plan were used. By assessing performance against the WKOMSE criteria, the evaluation of results is in accordance with both ICES and STECF standards.

The results presented show that the plan is very likely to be precautionary but it is more difficult to assess whether it achieves the goals of long term yields and sustained healthy populations. This is essentially a question over whether the F targets specified for the two stocks are reasonable and whether in practice they can be achieved simultaneously. The Yield curve analyses presented show that F_{msy} for plaice should be in the region of 0.18-0.36 and sole from 0.51-0.59, depending on the assumption of stock recruit relationship. In the case of sole, these high F values are close to F_{crash} in the segmented regression case. Also, the F_{msy} estimate using the Ricker functional form differs substantially from the estimates in the demersal assessment working group report. While the target for plaice lies within the bounds indicated by the different yield curves, the target F for sole is substantially lower.
However, because of the lack of any clear functional form in stock-recruit data of either of the two stocks these values have a high degree of uncertainty attached to them. In 2005, the ICES ad hoc Group on Long Term Advice (AGLTA; ICES CM 2005/ACFM:25) concluded that with regards to plaice "*if the objective is to obtain a high long term yield in combination with a low risk to B_{lim}, the preferred level of human consumption fishing mortality could be in the area of Ft=0.2 to Ft=0.3.*". It is also stated within the EU multiannual plan that "*advice from a committee of experts examining multiannual management strategies indicates that the highest yield of sole can be taken at a fishing mortality rate of 0,2 on ages two to six years.*" Hence, given the uncertainty associated in the estimation of F_{msy} reference points and that expert opinion has been incorporated into the determination of possible target F points, the targets as they stand seem plausible. Whether or not the two targets can be achieved simultaneously depends on future fisheries behaviour and gear selection. The results suggest greater and more rapid recovery of the plaice stock compared to the sole stock. This will open up greater opportunities in the plaice fishery in future that would require potential shifts in fishing location (to grounds further north) and gear (to more 100mm trawls). However, economic reasons such as fuel prices and market prices of sole and plaice are likely to have an impact on future fishery behaviour and this is not easy to predict in simulations. Regardless, it is clear that both stock growth and long term increases in yield levels are likely should the multiannual plan be implemented.

6 Conclusions

Despite the known limitations of the approaches applied in this evaluation to assess the effectiveness of the multiannual plan for sole and plaice in the North Sea, it appears that the plan is in line with the ICES precautionary approach.

7 Quality Assurance

IMARES utilises an ISO 9001:2000 certified quality management system (certificate number: 57846-2009-AQ-NLD-RvA). This certificate is valid until 15 December 2012. The organisation has been certified since 27 February 2001. The certification was issued by DNV Certification B.V. Furthermore, the chemical laboratory of the Environmental Division has NEN-AND-ISO/IEC 17025:2005 accreditation for test laboratories with number L097. This accreditation is valid until 27 March 2013 and was first issued on 27 March 1997. Accreditation was granted by the Council for Accreditation.

8 References

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9 Justification

Rapport Number: C0104/10
Project Number: 4301217006

The scientific quality of this report has been peer reviewed by the a colleague scientist and the head of the department of IMARES.

Approved: N.T. Hintzen M.Sc
Research scientist

Signature:

Date: 13-08-2010

Approved: Drs. J. Asjes
Head of Fish department

Signature:

Date: 13-08-2010

Number of copies: 15
Number of pages 44
Number of tables: 4
Number of graphs: 18
Number of appendix attachments: 2

Appendix A. Council Regulation EC No 676/2007

19.6.2007 EN Official Journal of the European Union L 157/1

I

(Acts adopted under the EC Treaty/Euratom Treaty whose publication is obligatory)

REGULATIONS

COUNCIL REGULATION (EC) No 676/2007

of 11 June 2007

establishing a multiannual plan for fisheries exploiting stocks of plaice and sole in the North Sea

THE COUNCIL OF THE EUROPEAN UNION,

Having regard to the Treaty establishing the European Community, and in particular Article 37 thereof,

Having regard to the proposal from the Commission,

Having regard to the opinion of the European Parliament [1],

Whereas:

(1) Recent scientific advice from the International Council for the Exploration of the Sea (ICES) has indicated that the stocks of plaice and of sole in the North Sea have been subjected to levels of mortality by fishing which have exceeded the level determined by ICES as being consistent with the precautionary approach, and the stocks are at risk of being harvested unsustainably.

(2) Advice from a committee of experts examining multi-annual management strategies indicates that the highest yield of sole can be taken at a fishing mortality rate of 0,2 on ages two to six years.

(3) The Scientific, Technical and Economic Committee for Fisheries (STECF) has advised that the precautionary biomass for the stock of plaice in the North Sea should be 230 000 tonnes, that the fishing mortality rate necessary to produce the highest yield from the stock of plaice in the North Sea in the long term is 0,3 and that the precautionary biomass for the stock of sole in the North Sea should be 35 000 tonnes.

(4) Measures need to be taken to establish a multiannual plan for fisheries management of the stocks of plaice and sole in the North Sea. Such measures, where they concern the stock of plaice in the North Sea, are to be established in the light of consultations with Norway.

(5) The objective of the plan is to ensure, in a first stage, that stocks of plaice and sole in the North Sea are brought within safe biological limits, and in a second stage and after due consideration by the Council on the implementing methods for doing so that those stocks, are exploited on the basis of maximum sustainable yield and under sustainable economic, environmental and social conditions.

(6) Council Regulation (EC) No 2371/2002 of 20 December 2002 on the conservation and sustainable exploitation of fisheries resources under the Common Fisheries Policy [2] requires, *inter alia*, that to achieve that objective, the Community is to apply the precautionary approach in taking measures to protect and conserve the stock, to provide for its sustainable exploitation and to reduce to a minimum the impact of fishing on marine ecosystems.

[1] Opinion of the European Parliament delivered on 28 September 2006 (not yet published in the Official Journal).

[2] OJ L 358, 31.12.2002, p. 59.

I

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REGULATIONS

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(2) Advice from a committee of experts examining multiannual management strategies indicates that the highest yield of sole can be taken at a fishing mortality rate of 0,2 on ages two to six years.

(3) The Scientific, Technical and Economic Committee for Fisheries (STECF) has advised that the precautionary biomass for the stock of plaice in the North Sea should be 230 000 tonnes, that the fishing mortality rate necessary to produce the highest yield from the stock of plaice in the North Sea in the long term is 0,3 and that the precautionary biomass for the stock of sole in the North Sea should be 35 000 tonnes.

(4) Measures need to be taken to establish a multiannual plan for fisheries management of the stocks of plaice and sole in the North Sea. Such measures, where they concern the stock of plaice in the North Sea, are to be established in the light of consultations with Norway.

(5) The objective of the plan is to ensure, in a first stage, that stocks of plaice and sole in the North Sea are brought within safe biological limits, and in a second stage and after due consideration by the Council on the implementing methods for doing so that those stocks, are exploited on the basis of maximum sustainable yield and under sustainable economic, environmental and social conditions.

(6) Council Regulation (EC) No 2371/2002 of 20 December 2002 on the conservation and sustainable exploitation of fisheries resources under the Common Fisheries Policy [2] requires, *inter alia*, that to achieve that objective, the Community is to apply the precautionary approach in taking measures to protect and conserve the stock, to provide for its sustainable exploitation and to reduce to a minimum the impact of fishing on marine ecosystems.

[1] Opinion of the European Parliament delivered on 28 September 2006 (not yet published in the Official Journal).

[2] OJ L 358, 31.12.2002, p. 59.

(7) This Regulation should aim at a progressive implementation of an ecosystem-based approach to fisheries management, and should contribute to efficient fishing activities within an economically viable and competitive fisheries industry, providing a fair standard of living for those who depend on fishing North Sea plaice and sole and taking into account the interest of consumers. The Community bases its policy partly on the policy recommended by the appropriate Regional Advisory Council (RAC). A large part of the catches of plaice in the North Sea are taken together with catches of sole. The management of plaice cannot be addressed independently of the management of sole.

(8) Consequently, in drawing up the multiannual plan, account should also be taken of the fact that the high fishing mortality rate for plaice is due to a great extent to the large discards from beam-trawl sole fishing with 80mm nets in the southern North Sea.

(9) Such control of the fishing mortality rates can be achieved by establishing an appropriate method for the establishment of the level of total allowable catches (TACs) of the stocks concerned, and a system including limitations on permissible days at sea whereby fishing efforts on those stocks are restricted to levels at which the TACs and planned fishing mortality rates are unlikely to be exceeded, but are sufficient to catch the TAC allowed on the basis of the fishing mortality rates established in the plan.

(10) The plan should cover all flatfish fisheries having a significant impact on the fishing mortality of the plaice and sole stocks concerned. However, Member States whose quotas for either stock are less than 5 % of the European Community's share of the TAC should be exempted from the provisions of the plan concerning effort management.

(11) This plan should be the main instrument for flatfish management in the North Sea, and should contribute to the recovery of other stocks such as cod.

(12) Control measures in addition to those laid down in Council Regulation (EEC) No 2847/93 of 12 October 1993 establishing a control system applicable to the Common Fisheries Policy [1] need to be included in order to ensure compliance with the measures laid down in this Regulation.

(13) In 2006 the Commission initiated a debate concerning a Community strategy for a gradual reduction in fishing mortality in all major fisheries by means of a communication concerning the attainment of the maximum sustainable yield objective by 2015. The Commission has submitted this communication to the RACs for their opinion.

(14) The Commission has requested STECF to report on key aspects of impact assessment in relation to the management of plaice and sole, which should be based on accurate, objective and comprehensive biological and financial information. That impact assessment will be annexed to the Commission's proposal concerning the second stage of the multiannual plan.

(15) The multiannual plan should be deemed to be a recovery plan during its first stage and a management plan during its second stage, within the meaning of Articles 5 and 6 of Regulation (EC) No 2371/2002,

HAS ADOPTED THIS REGULATION:

CHAPTER I

SUBJECT-MATTER AND OBJECTIVE

Article 1

Subject-matter

1. This Regulation establishes a multiannual plan for the fisheries exploiting the stocks of plaice and sole that inhabit the North Sea.

2. For the purposes of this Regulation, 'North Sea' means the area of the sea delineated by the International Council for the Exploration of the Sea as Sub-area IV.

Article 2

Safe biological limits

1. For the purposes of this Regulation, the stocks of plaice and sole shall be deemed to be within safe biological limits in those years in which, according to the opinion of the Scientific, Technical, and Economic Committee for Fisheries (STECF), all of the following conditions are fulfilled:

(a) the spawning biomass of the stock of plaice exceeds 230 000 tonnes;

[1] OJ L 261, 20.10.1993, p. 1. Regulation as last amended by Regulation (EC) No 1967/2006 (OJ L 409, 30.12.2006, p. 11).

(b) the average fishing mortality rate on ages two to six years experienced by the stock of plaice is less than 0,6 per year;

(c) the spawning biomass of the stock of sole exceeds 35 000 tonnes;

(d) the average fishing mortality rate on ages two to six years experienced by the stock of sole is less than 0,4 per year.

2. If the STECF advises that other levels of biomass and fishing mortality should be used to define safe biological limits, the Commission shall propose to amend paragraph 1.

Article 3

Objectives of the multiannual plan in the first stage

1. The multiannual plan shall, in its first stage, ensure the return of the stocks of plaice and of sole to within safe biological limits.

2. The objective specified in paragraph 1 shall be attained by reducing the fishing mortality rate on plaice and sole by 10 % each year, with a maximum TAC variation of 15 % per year until safe biological limits are reached for both stocks.

Article 4

Objectives of the multiannual plan in the second stage

1. The multiannual plan shall, in its second stage, ensure the exploitation of the stocks of plaice and sole on the basis of maximum sustainable yield.

2. The objective specified in paragraph 1 shall be attained while maintaining the fishing mortality on plaice at a rate equal to or no lower than 0,3 on ages two to six years.

3. The objective specified in paragraph 1 shall be attained while maintaining the fishing mortality on sole at a rate equal to or no lower than 0,2 on ages two to six years.

Article 5

Transitional arrangements

1. When the stocks of plaice and sole have been found for two years in succession to have returned to within safe biological limits the Council shall decide on the basis of a proposal from the Commission on the amendment of Articles 4(2) and 4(3) and the amendment of Articles 7, 8 and 9 that will, in the light of the latest scientific advice from the STECF, permit the exploitation of the stocks at a fishing mortality rate compatible with maximum sustainable yield.

2. The Commission's proposal for review shall be accompanied by a full impact assessment and shall take into account the opinion of the North Sea Regional Advisory Council.

CHAPTER II

TOTAL ALLOWABLE CATCHES

Article 6

Setting of total allowable catches (TACs)

Each year, the Council shall decide, by qualified majority on the basis of a proposal from the Commission, on the TACs for the following year for the plaice and sole stocks in the North Sea in accordance with Articles 7 and 8 of this Regulation.

Article 7

Procedure for setting the TAC for plaice

1. The Council shall adopt the TAC for plaice at that level of catches which, according to a scientific evaluation carried out by STECF is the higher of:

(a) that TAC the application of which will result in a 10 % reduction in the fishing mortality rate in its year of application compared to the fishing mortality rate estimated for the preceding year;

(b) that TAC the application of which will result in the level of fishing mortality rate of 0,3 on ages two to six years in its year of application.

2. Where application of paragraph 1 would result in a TAC which exceeds the TAC of the preceding year by more than 15 %, the Council shall adopt a TAC which is 15 % greater than the TAC of that year.

3. Where application of paragraph 1 would result in a TAC which is more than 15 % less than the TAC of the preceding year, the Council shall adopt a TAC which is 15 % less than the TAC of that year.

Article 8

Procedure for setting the TAC for sole

1. The Council shall adopt a TAC for sole at that level of catches which, according to a scientific evaluation carried out by STECF is the higher of:

(a) that TAC the application of which will result in the level of fishing mortality rate of 0,2 on ages two to six years in its year of application;

(b) that TAC the application of which will result in a 10 % reduction in the fishing mortality rate in its year of application compared to the fishing mortality rate estimated for the preceding year.

2. Where the application of paragraph 1 would result in a TAC which exceeds the TAC of the preceding year by more than 15 %, the Council shall adopt a TAC which is 15 % greater than the TAC of that year.

3. Where the application of paragraph 1 would result in a TAC which is more than 15 % less than the TAC of the preceding year, the Council shall adopt a TAC which is 15 % less than the TAC of that year.

CHAPTER III

FISHING EFFORT LIMITATION

Article 9

Fishing effort limitation

1. The TACs referred to in Chapter II shall be complemented by a system of fishing effort limitation established in Community legislation.

2. Each year, the Council shall decide by a qualified majority, on the basis of a proposal from the Commission, on an adjustment to the maximum level of fishing effort available for fleets where either or both plaice and sole comprise an important part of the landings or where substantial discards are made and subject to the system of fishing effort limitation referred to in paragraph 1.

3. The Commission shall request from STECF a forecast of the maximum level of fishing effort necessary to take catches of plaice and sole equal to the European Community's share of the TACs established according to Article 6. This request shall be formulated taking account of other relevant Community legislation governing the conditions under which quotas may be fished.

4. The annual adjustment of the maximum level of fishing effort referred to in paragraph 2 shall be made with regard to the opinion of STECF provided according to paragraph 3.

5. The Commission shall each year request the STECF to report on the annual level of fishing effort deployed by vessels catching plaice and sole, and to report on the types of fishing gear used in such fisheries.

6. Notwithstanding paragraph 4, fishing effort shall not increase above the level allocated in 2006.

7. Member States whose quotas are less than 5 % of the European Community's share of the TACs of both plaice and sole shall be exempted from the effort management regime.

8. A Member State concerned by the provisions of paragraph 7 and engaging in any quota exchange of sole or plaice on the basis of Article 20(5) of Regulation (EC) No 2371/2002 that would result in the sum of the quota allocated to that Member State and the quantity of sole or plaice transferred being in excess of 5 % of the European Community's share of the TAC shall be subject to the effort management regime.

9. The fishing effort deployed by vessels in which plaice or sole are an important part of the catch and which fly the flag of a Member State concerned by the provisions of paragraph 7 shall not increase above the level authorised in 2006.

CHAPTER IV

MONITORING, INSPECTION AND SURVEILLANCE

Article 10

Fishing effort messages

1. Articles 19b, 19c, 19d, 19e and 19k of Regulation (EEC) No 2847/93 shall apply for vessels operating in the area. Vessels equipped with monitoring systems in accordance with Articles 5 and 6 of Commission Regulation (EC) No 2244/2003 of 18 December 2003 laying down detailed provisions regarding satellite-based vessel monitoring systems [1] shall be excluded from hailing requirements.

2. Member States may implement alternative control measures to ensure compliance with the obligation referred to in paragraph 1 which are as effective and transparent as these reporting obligations. Such measures shall be notified to the Commission before being implemented.

[1] OJ L 333, 20.12.2003, p. 17.

Article 11

Margin of tolerance

1. By way of derogation from Article 5(2) of Commission Regulation (EEC) No 2807/83 of 22 September 1983 laying down detailed rules for recording information on Member States' catches of fish [1], the permitted margin of tolerance, in estimation of quantities in kilograms live weight of each of plaice and sole retained on board of vessels that have been present in the North Sea shall be 8 % of the logbook figure. In the event that no conversion factor is laid down in Community legislation, the conversion factor adopted by the Member State whose flag the vessel is flying shall apply.

2. Paragraph 1 shall not apply concerning a species of aquatic organism if the quantity of that species retained on board is less than 50 kg.

Article 12

Weighing of landings

The competent authorities of a Member State shall ensure that any quantity of sole exceeding 300 kg or of plaice exceeding 500 kg, caught in the North Sea shall be weighed before sale using scales that have been certified as accurate.

Article 13

Prior notification

The master of a Community fishing vessel that has been present in the North Sea and who wishes to land any quantity of plaice or sole in a port or a landing location of a third country shall inform the competent authorities of the flag Member State at least 24 hours prior to landing in a third country, of the following information:

(a) the name of the port or landing location;

(b) the estimated time of arrival at that port or landing location;

(c) the quantities in kilograms live weight of all species of which more than 50 kg is retained on board.

The notification may also be made by a representative of the master of the fishing vessel.

[1] OJ L 276, 10.10.1983, p. 1. Regulation as last amended by Regulation (EC) No 1804/2005 (OJ L 290, 4.11.2005, p. 10).

Article 14

Separate stowage of plaice and sole

1. It shall be prohibited to retain on board a Community fishing vessel in any individual container any quantity of plaice or any quantity of sole mixed with any other species of marine organisms.

2. The masters of Community fishing vessels shall give inspectors of Member States such assistance as will enable the quantities declared in the logbook and the catches of plaice and of sole retained on board to be cross-checked.

Article 15

Transport of sole and plaice

1. The competent authorities of a Member State may require that any quantity of plaice exceeding 500 kg or any quantity of sole exceeding 300 kg caught in the geographical area referred in Article 1(2) and first landed in that Member State is weighed before being transported elsewhere from the port of first landing using scales that have been certified as accurate.

2. By way of derogation from Article 13 of Regulation (EEC) No 2847/93, quantities of plaice exceeding 500 kg and quantities of sole exceeding 300 kg which are transported to a place other than that of landing shall be accompanied by the declaration provided for in Article 8(1) of that Regulation. The exemption provided for in Article 13(4)(b) of Regulation (EEC) No 2847/93 shall not apply.

Article 16

Prohibition of transhipments of sole and plaice

A Community fishing vessel that is present in the North Sea shall not tranship any quantity of plaice or sole to any other vessel.

CHAPTER V

FOLLOW-UP

Article 17

Evaluation of management measures

1. The Commission shall, on the basis of advice from STECF, evaluate the impact of the management measures on the stocks concerned and the fisheries on those stocks, in the second year of application of this Regulation and in each of the following years.

2. The Commission shall seek scientific advice from the STECF on the rate of progress towards the objectives of the multiannual plan in the third year of application of this Regulation and each third successive year of application of this Regulation. The Commission shall, if appropriate, propose relevant measures, and the Council shall decide by qualified majority on alternative measures to achieve the objectives set out in Articles 3 and 4.

Article 18

Special circumstances

In the event that STECF advises that the spawning stock size of either or both plaice or of sole is suffering reduced reproductive capacity, the Council shall decide by qualified majority on the basis of a proposal from the Commission on a TAC for plaice that is lower than that provided for in Article 7, on a TAC for sole that is lower than that provided for in Article 8, and on levels of fishing effort that are lower than those provided for in Article 9.

CHAPTER VI

FINAL PROVISIONS

Article 19

Assistance under the European Fisheries Fund

1. During the first stage foreseen in Article 3 of this Regulation, the multiannual plan shall be deemed to be a recovery plan within the meaning of Article 5 of Regulation (EC) No 2371/2002, and for the purposes of Article 21(a)(i) of Council Regulation (EC) No 1198/2006 of 27 July 2006 on the European Fisheries Fund [1].

2. During the second stage foreseen in Article 4 of this Regulation, the multiannual plan shall be deemed to be a management plan within the meaning of Article 6 of Regulation (EC) No 2371/2002, and for the purposes of Article 21(a)(iv) of Regulation (EC) No 1198/2006.

Article 20

Entry into force

This Regulation shall enter into force on the 20th day following its publication in the *Official Journal of the European Union*.

This Regulation shall be binding in its entirety and directly applicable in all Member States.

Done at Luxembourg, 11 June 2007.

For the Council
The President
H. SEEHOFER

[1] OJ L 223, 15.8.2006, p. 1.

Appendix B. The Statistical Catch at Age (SCA) model

Model description

The model is elaborately described in Aarts and Poos (2009). Here we present the text from Aarts and Poos (2009), changing parts to make the text more concise, and to describe the differences between the sole and plaice assessment. For an in-depth description we refer to Aarts and Poos (2009). In short, the model is a traditional discrete-time age-structured population dynamics model

$$N_{a+1,t+1} = N_{a,t}\mathrm{e}^{-Z_{a,t}},$$

where Na,t are the numbers at age a at time t, and Za,t the total mortality, which is composed of the instantaneous natural mortality rate M and the fishing mortality rate Fa,t.

Natural and fishing mortality

Natural mortality is assumed to be constant (0.1) in time and equal for all ages. Fishing mortality Fa,t is the result of catchability q, annual fishing effort et, and the selectivity pattern fa,t , such that

$$F_{a,t} = qe_t f_{a,t}.$$

Catchability q is the extent to which a stock is susceptible to fishing. The fishing effort et is the total amount of fishing in a year. With the available data, it is only possible to estimate the product of these two. The selectivity pattern fa,t defines the relative likelihood that an individual of age a in the population is caught and is constrained to have a maximum of 1. A smooth function of age is used, constructed using four b-spline basis functions hk(a). Each b-spline basis function is a cubic polynomial of the explanatory variable, but it is only non-zero within a certain range (defined by so-called knots) of the explanatory variable. Next, each basis function hk(a) is weighted by a constant bk, t. Summing these weighted functions results in the complex smooth function of age:

$$f_{a,t} = \mathrm{logit}^{-1}\left(\sum_{k=1}^{4} b_{k,t}h_k(a)\right).$$

In this function, logit-1 is exp(.)/(1 + exp(.)) and ensures that fa,t takes values between 0 and 1. Because of the local nature of the basis function, the fit of the smooth function in one range of the data (e.g. at low ages) is independent of its fit at the other extreme (e.g. at high ages). Similar to many other assessment techniques, we assume that the fishing mortality of the last age class is equal to the fishing mortality of the preceding age. Temporal changes in the spatial overlap between fishing effort and the different age classes of the fish population can result in changes in the selectivity pattern. This is captured by modelling the weighting constants as a function of time, hence the subscript t in bk,t. To prevent overparameterization, only a linear function for the temporal changes in selectivity was inspected, i.e.

$$b_{k,t} = \beta_{0,k} + \beta_{1,k}t.$$

Discards and landings

The expected catch Ca, t for age a and year t is calculated from

$$C_{a,t} = \frac{F_{a,t}}{Z_{a,t}}N_{a,t}(1 - \mathrm{e}^{-Z_{a,t}}).$$

For plaice, the catch consist of discards Da,t and landings La,t.We assume that an age-dependent fraction da,t of the catch is discarded, such that

$$D_{a,t} = d_{a,t}C_{a,t},$$
$$L_{a,t} = (1 - d_{a,t})C_{a,t}.$$

Although landings data are generally available, discard data are often lacking or, as in our study, only available for the most recent years.

For sole, we assume that the landings are equal to the catches, and there in no discarding. For plaice, we assume that the discard fraction da,t is a smooth function of age where each smooth parameter is modeled as a second-order orthogonal polynomial function of time.

Tuning series

The tuning series data for plaice are collected over a short period (August–September) of each year. Because the survey vessel catches are a very small part of the population, it is assumed that these catches do not affect the mortality of the population as a whole. The population size Na,t represents the population size on 1 January of year t. When the scientific survey takes place later in the year, the population size may be reduced considerably by fishing and natural mortality. To correct for this, the mean population size during the time of the survey is estimated as

$$N_{a,t}^{U} = N_{a,t}\frac{\mathrm{e}^{-\kappa Z_{a,t}} - \mathrm{e}^{-\lambda Z_{a,t}}}{(\lambda - \kappa)Z_{a,t}},$$

where κ and λ are the start and end, respectively, of each survey expressed as a fraction of a year. Consequently, the catch of survey Ua,t of age a in year t can easily be calculated as

$$U_{a,t} = s_{u,a}N_{a,t}^{U}q_u,$$

where qu is the efficiency, which is survey vessel u-specific, and su,a the age-specific selectivity of the survey vessel u. Again, we model su,a as a smooth function of age. Survey selectivity su,a is assumed to remain constant in time. It should be noted that for sole, the commercial LPUE series of the Dutch beam trawl fleet is used in the assessment (similar to the ICES WGNSSK assessment). Here, the assumption of constant qu may be violated. Because the LPUE series span the entire year, κ and λ are set to 0 and 1, respectively.

Likelihood function

The available datasets for parameter estimation are (i) landings-at-age, (ii) discards-at-age, and (iii) tuning series from three surveys. Conforming with most other statistical catch-at-age assessment, the data are assumed to be lognormally distributed, with means and age-specific standard deviations predicted by the model. Zero values were replaced by half of the lowest value observed in the dataset where each occurred. This approach guards against zeros in the likelihood function by taking account of the scale of the data. The total log-likelihood is then

$$\begin{aligned} \ell &= \ell_D + \ell_L + \ell_U, \\ \text{where } \ell_D &= \sum_{a,t} \mathrm{n}(\log(D_{a,t}); \log(\hat{D}_{a,t}), \sigma_a^D), \\ \ell_L &= \sum_{a,t} \mathrm{n}(\log(L_{a,t}); \log(\hat{L}_{a,t}), \sigma_a^L), \\ \ell_U &= \sum_{a,t} \mathrm{n}(\log(U_{a,t}); \log(\hat{U}_{a,t}), \sigma_a^U). \end{aligned}$$

The values of σa are modelled as the exponent of an orthogonal polynomial function of age, with 2 d.f. The standard deviations are constrained to be at least 0.05, to facilitate convergence of the minimizer used to find the maximum likelihood. For sole, the likelihood function for the discards observations is removed from the total likelihood function, because we assume there are no discards.

Parameter estimation and model selection

All model fitting was done using the FLR package. The negative of the likelihood function was minimized using the BFGS quasi-Newton or variable metric algorithm. Several starting values were selected randomly from a uniform distribution within appropriate boundaries, leading to different parameter estimates. This suggests that the likelihood function had several local maxima. We therefore selected the parameter estimates corresponding to the highest maximum likelihood among >50 runs. The model often converged to these parameter estimates, and we assumed that these correspond to the global maximum.

Also, all eigenvalues of the numerically differentiated Hessian matrix at the parameter values presented here were positive, indicating that the parameter values indeed represented a maximum of the log-likelihood function.

Quantifying uncertainty

Maximizing the log-likelihood function results in maximum likelihood parameter estimates and the variance–covariance matrix that is derived from the inverse of the Hessian. For estimating parameter uncertainty, we selected 10 000 random values from a multivariate normal distribution with those parameter means and variance–covariances. The resulting random realizations are then used to estimate 95% confidence intervals for population and fisheries characteristics of interest, using the percentile method.