ICES WKLIFE V REPORT 2015

ICES ADVISORY COMMITTEE

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Report of the Fifth Workshop on the Development of Quantitative Assessment Methodologies based on Life-history Traits, Exploitation Characteristics and other Relevant Parameters for Data-limited Stocks (WKLIFE V)

5-9 October 2015

Lisbon, Portugal

ICES CIEM
International Council for the Exploration of the Sea
Conseil International pour l'Exploration de la Mer

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Executive summary

The fifth Workshop on the Development of Quantitative Assessment Methodologies based on Life-history traits, exploitation characteristics, and other relevant parameters for data-limited stocks (WKLIFE V), chaired by Carl O'Brien (UK) and Manuela Azevedo (Portugal) met in Lisbon, Portugal, 5–9 October 2015 to identify and develop operational methods for the provision of plausible MSY proxies for all ICES category 3 and 4 stocks.

The European Commission requested that ICES develop quantitative methods to provide advice on data-limited stocks, these activities are considered to have a high priority; both scientifically and for sustainable management. The Commission is preparing long-term management plans for western EU waters (ICES Subareas V to X), and according to Article 10 of Regulation (EU) No 1380/2013 on the Common Fisheries Policy (CFP) a multiannual plan (MAP) shall include quantifiable targets, a time frame to reach the targets, and safeguards to ensure that the quantifiable targets are met.

WKLIFE V developed operational methods for setting reference point proxies for stocks in categories 3 and 4. These methods will be implemented by ICES scientists with expert knowledge of the stocks and fisheries in a subsequent ICES meeting [WKProxy]. Several methodological approaches to data-limited stock assessment were reviewed and applied to both data-limited (e.g. *Nephrops* FUs 28-29 by sex, sea bass in the Bay of Biscay, sole in the Bay of Biscay) and data-rich case studies (e.g. Northern hake) to evaluated strengths and weaknesses of each approach for application to the ICES DLS advisory framework (ICES, 2012). The reviewed approaches included length-based indicators and reference points, spawning potential ratio (SPR), catch and cpue-based methods, and catch-based methods. The prospects of managing other crustaceans and molluscs using minimum legal size was also evaluated. The methods most suitable to the data and expertise available were identified for each of the requested stocks on the western shelf for ICES WKProxy.

1 Introduction

1.1 Terms of reference

The Workshop on the Development of Quantitative Assessment Methodologies based on Life-history traits, exploitation characteristics, and other relevant parameters for data-limited stocks (WKLIFE V), chaired by Carl O'Brien (UK) and Manuela Azevedo (Portugal) met in Lisbon, Portugal, 5–9 October 2015 to identify and develop operational methods for the provision of plausible MSY proxies for all ICES category 3 and 4 stocks. The objectives and outcomes of this workshop complements work-to-date within ICES that provides advice on F_{MSY} ranges for category 1 stocks and is seated within the ICES precautionary approach.

Specifically, two major Terms of Reference (ToRs) were addressed:

1) To develop and test methods to estimate reference point proxies, for F_{MSY} and $MSYB_{trigger}$ as well as precautionary reference points, using the data available and expert judgement.

2) To develop methods that facilitate the classification of stocks in relation to the estimated proxies.

   2.1) Methods should be applicable to the full range of ICES stocks, including crustaceans, molluscs, flatfish, deep-sea fish, elasmobranchs and round fish.

   2.2) Methods should capitalize on available data and information resources including length data, survey data, and statistical models for estimating the maximum sustainable yield.

   2.3) For those stocks or species where this is not possible, describe the current difficulties to the provision of reference point proxies and detail a roadmap to deliver such values as a matter of priority.

Additionally, ACOM requested at their December 2014 meeting that WKLIFE V make further tests of the available software for CC-SRA and CMSY to explore the sensitivity of priors (r-K and depletion level start and end) and to test the method on category 1 stocks (where ACOM already provides advice based on analytical methods). Given the approach taken within the WKLIFE V meeting and the availability of experts, only CMSY was simulation tested and the results are presented and discussed in Section 4.2 (Retrospective analyses) for North Sea plaice and sole.

WKLIFE will report to ACOM no later than 23 October 2015.

1.2 Background

The European Commission requested that ICES develop quantitative methods to provide advice on data-limited stocks, these activities are considered to have a high priority; both scientifically and for sustainable management.

The European Commission is preparing long-term management plans for western EU waters (ICES Subareas V to X). According to Article 10 of Regulation (EU) No 1380/2013 on the Common Fisheries Policy (CFP) a multiannual plan (MAP) shall include quantifiable targets, a time frame to reach the targets and safeguards to ensure that the quantifiable targets are met.

Previous iterations of WKLIFE evaluated performance of the data-limited advisory framework and concluded that F-based harvest control rules did not perform as well as biomass-based methods (ICES, 2010), that data-limited harvest control rules conferred stability, but performance for achieving targets relied on accurate perspective of stock status (ICES, 2012a; 2012b) and that the DLS approach was not always more conservative and led to increased risk when stock are declining and are overexploited (ICES, 2013a; 2013b). Accordingly, the intent was for WKLIFE V to develop operational methods for setting reference point proxies for stocks in categories 3 and 4. These methods will then be implemented by ICES scientists with expert knowledge of the stocks and fisheries in a subsequent meeting: ICES Workshop to develop MSY and precautionary reference point proxies for selected stocks in ICES categories 3 and 4 in Western Waters [WKProxy] to be held at ICES HQ, Copenhagen, Denmark from 3–6 November 2015.

The F_{MSY} proxy corresponds to the exploitation rate that will provide maximum long-term yield. The MSY $B_{trigger}$ proxy corresponds to the stock size that triggers a cautious response; i.e. advice on a reduced fishing mortality relative to the F_{MSY} proxy to allow the stock to rebuild. In this context, a stock with a *desirable status* is being exploited at or below the F_{MSY} proxy with a stock size equal to or larger than MSY$B_{trigger}$ proxy. In turn, stocks are deemed to be in an *undesirable state* if they are either exploited above the F_{MSY} proxy or have a stock size smaller than the MSY $B_{trigger}$ proxy.

The work of these groups will enable the production of assessments and advice for ICES data-limited stocks.

1.3 Conduct of the meeting

WKLIFE V continued with the further investigation of methodologies and guidelines specific to stocks in ICES categories 3 and 4.

The workshop participants were divided into five subgroups during the meeting: a methods subgroup that considered length-based indicators and reference points; a methods subgroup that mainly considered SPR-based approaches; a subgroup that considered approaches using catch and cpue-based methods; a subgroup using only a catch-based method; and a subgroup dealing with crustaceans and molluscs (excluding *Nephrops*).

Within each of the subgroups, a common example was used; namely, *Nephrops* in southwest and south Portugal (FUs 28–29), in order to facilitate discussion and comparison of the methods and approaches.

1.4 Structure of the report

The structure of the report is as follows:

- Section 2 focuses on length-based indicators and methods;
- Section 3 focuses on catch and cpue-based methods;
- Section 4 focuses on catch-based methods and the simulation testing requested by ACOM (see Section 1.1);
- Section 5 focuses on selection of an appropriate method to use;
- Section 6 focuses on issues pertinent to crustaceans and molluscs (other than *Nephrops*); and
- Section 7 provides a provisional date for the next meeting in 2016 subject to ACOM's approval and guidance on suitable ToRs.

1.5 Follow-up process within ICES

The intention was for this meeting of WKLIFE V to develop operational methods for setting reference point proxies for stocks in categories 3 and 4. These methods will then be implemented by ICES scientists with expert knowledge of the stocks and fisheries in a subsequent meeting: ICES Workshop to develop MSY and precautionary reference point proxies for selected stocks in ICES categories 3 and 4 in Western Waters [WKProxy] to be held at ICES HQ, Copenhagen, Denmark from 3–6 November 2015.

1.6 Follow-up process outside ICES

The guidelines and methodologies produced by this group will be of interest to various Advisory Councils (ACs), international scientific and management organizations, ICES clients and observers.

2 Length-based methods

2.1 Length-based indicators and reference points

2.1.1 Screening methods

Length data are relatively inexpensive and straightforward to obtain and usually form one of the datasets from which catch numbers-at-age are derived. Size–frequency data are the primary data collected under the DCF (ICES, 2014). Therefore, size-based methods using length-based indicators explored in WKLIFE IV were validated further through simulation testing. A set of length-based indicators was selected for screening catch/landings–length composition and classify the stocks according to conservation/sustainability, yield optimization and MSY considerations. These indicators require data on the stock catch/landings–length composition and life-history parameters and can be applied systematically to all DLS stocks. The overall perception of stock status can be used to guide experts on the choices for parameters (initial values and/or ranges) used in other methods (e.g. CMSY).

2.1.1.1 Data and information requirements

Information required includes length at maturity (L_{MAT}), von Bertalanffy growth parameters (L_{inf}), catch at length per year (by sex, in case of crustaceans), length–weight relationship parameters (a and b) or mean weights-at-length per year, type (L landings, D discards).

2.1.1.2 Assumptions

A length-based proxy for MSY is $L_{F=M} = 0.75L_c+0.25L_{inf}$ (where L_c is the length at first capture) and the length of optimal yield is $L_{opt}={}^2/_3L_{inf}$. The method assumes that input parameters are known, but life-history parameters L_{MAT}, L_{inf} may be uncertain for data-limited stocks.

2.1.1.3 Outputs expected

Plots of time-series length distributions, indicators and indicators ratios, traffic light table to inform stock status in recent years.

2.1.1.4 Method of operation

Length-based indicators describe length frequencies of landings. Length-based indicators are calculated by sex (e.g. *Nephrops*) and by year from length–frequency distributions. They are compared to appropriate reference points related to conservation, optimal yield and length distribution relative to expectations under MSY assumptions.

Table 2.1.1.4.1 present the selected indicators, reference points, indicator ratios and their expected values. These are grouped in terms of i) conservation/sustainability; ii) optimal yield; and iii) MSY considerations.

Table 2.1.1.4.1. Selected indicators for screening plots. (Indicator ratios in bold used for stock status assessment with traffic light system).

Indicator	Calculation	Reference point	Indicator ratio	Expected value	Property
Lmax5%	Mean length of largest 5%	Linf	Lmax5%/Linf	>0.8	Conservation (large individuals)
L95%	95th percentile		L95%/Linf		
Pmega	Proportion of individuals above Lopt+10%	0.3–0.4	Pmega	>0.3	
L25%	25th percentile of length distribution	Lmat	L25%/Lmat	>1	Conservation (immatures)
Lc	Length at first catch (length at 50% of mode)	Lmat	Lc/Lmat	>1	
Lmean	Mean length of individuals larger Lc	Lopt = 2/3 Linf	Lmean/Lopt	≈1	Optimal yield
Lmaxy	Length class with maximum biomass in catch	Lopt = 2/3 Linf	Lmaxy/Lopt	≈1	
Lmean	Mean length of individuals larger Lc	LF=M = (0.75Lc+0.25Linf)	Lmean/LF=M	≥1	MSY

2.1.1.5 Testing

The indicators $L_{max5\%}$, P_{mega}, L_{mean} were selected from a range of candidate indicators to calculate indicator ratios. In a simulation study (Miethe and Dobby, 2015, Working Document (WD)) other potential indicators were more variable or insufficiently reflected underlying stock status. In addition, to evaluate exploitation of the immature portion of the stock, L_c and L_{25}% were evaluated relative to L_{MAT}. L_c can depend on the choice of bin size of the length distribution, such that $L_{25\%}$ should be considered as well.

2.1.1.6 Caveats

Relative catchability determines catches and catch indicators may not directly reflect stock status. For example, catchability of mature females of *Nephrops* is lower because they spend more time in burrows, and the lower catchability may lead to an underrepresentation in the catches and the impression of overexploitation. The method relies on assumptions on life-history parameters, L_{MAT} and L_{inf}.

2.1.1.7 Software

The R-script *LBIndicators.R* and the output table *stock_sex_IndicatorRatios_table.csv* is available on the WKLIFE V SharePoint.

2.1.2 Application to *Nephrops* in Functional Units (FUs) 28–29

The method was applied to *Nephrops* FUs 28–29, by sex as a case study for demonstration. Input parameters for the analysis are presented in Table 2.1.2.1 and the catch length composition for the period 2000–2014 (males) in Figure 2.1.2.1.

Table 2.1.2.1. Input parameters for *Nephrops* in FUs 28–29.

Input (in mm)	Males	Females
L_{inf}	70	65
L_{MAT}	28.4	30
Start year, end year	2000, 2014	
Sex	M, F	
Type	L	

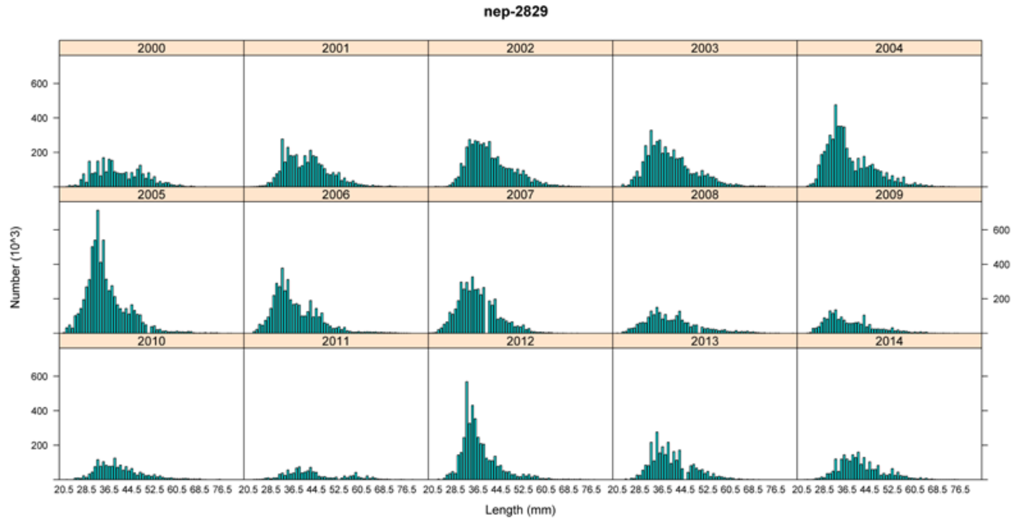


Figure 2.1.2.1. Length distributions over time for male *Nephrops* in FUs 28–29.

Figures 2.1.2.2 and 2.1.2.3 show the indicators and indicator ratios for males.

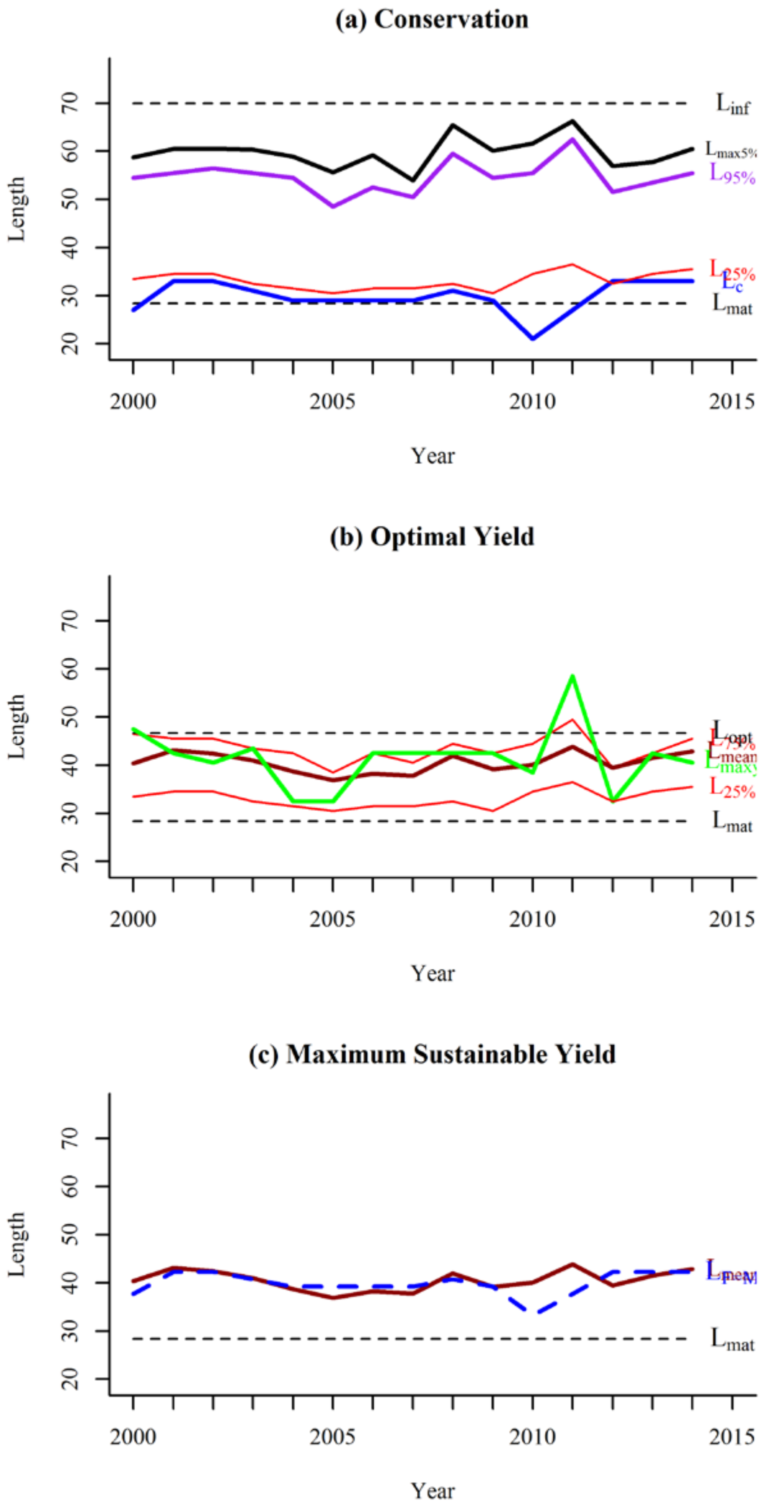


Figure 2.1.2.2 Selected indicators for males, *Nephrops* in FUs 28–29. Screening of length distributions under three scenarios: (a) Conservation, (b) Optimal yield, and (c) maximum sustainable yield.

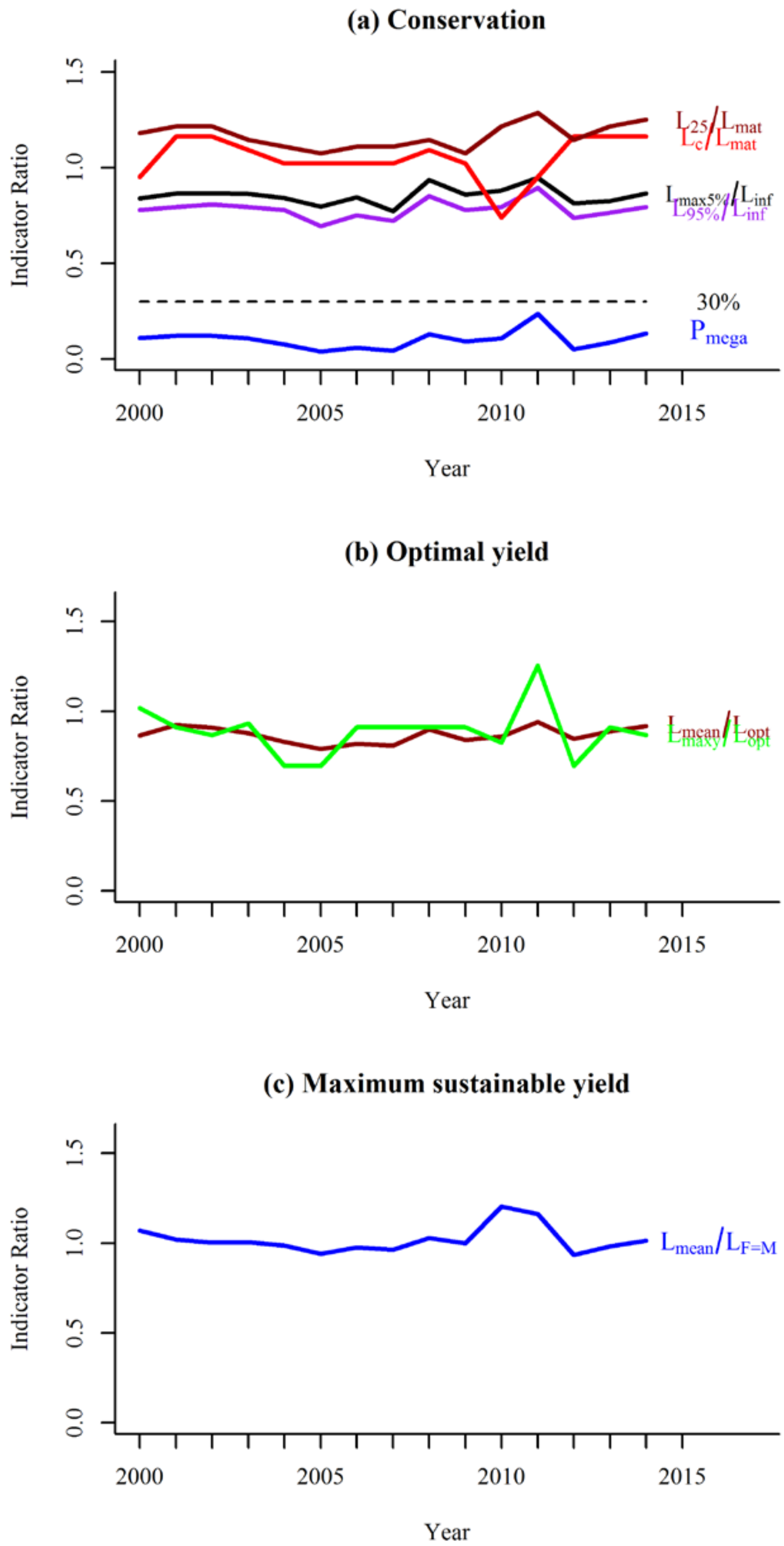


Figure 2.1.2.3. Indicator ratios for male *Nephrops* in FUs 28–29 under three scenarios: (a) Conservation, (b) Optimal yield, and (c) maximum sustainable yield.

Looking at the selected indicator series for male *Nephrops* (Figures 2.1.2.2 and 2.1.2.3), there are no concerns regarding fishing on immature individuals.

In the recent year 2014, as well as across the time-series, a lack of mega-spawners (P_{mega}) in the catches can be observed. $L_{max5\%}$ is relatively close to the lower limit of 0.8. This indicates some truncation in length distribution in catches.

The mean length is stable across the time-series. The catch is close to the theoretical length of optimal yield. However, looking at Figure 2.1.2.2(b) the core distribution (between 25th and 75th percentile) is below the optimal length. The mean length is close to the MSY proxy of $L_{F=M}$.

The results for the most recent year (2014) are presented, by sex, in a traffic light system, according to conservation/sustainability, yield optimization and MSY considerations in Table 2.1.2.2. Reference levels (Ref) for the indicator ratios are indicated. In the case of the Optimizing Yield indicator ratio, with reference level around 1 (≈1), a threshold of 0.9 was adopted for the colour shading.

Table 2.1.2.2. Traffic light indicator example using *Nephrops* in FUs 28–29.

Traffic light indicators						
	Conservation				Optimizing Yield	MSY
	Lc/Lmat	L25%/Lmat	Lmax5%/Linf	Pmega	Lmean/Lopt	Lmean/LF=M
Ref	>1	>1	>0.8	>30%	≈1	≥1
M	1.16	1.25	0.86	0.13	0.92	1.01
F*	1.10	1.12	0.76	0.02	0.89	0.94

*** Berried females stay in burrows leading to lower catchability causing lack of larger individuals compared with males.**

The overall perception from the length-based indicators analysis is that the stock is fished sustainably at levels close to optimum yield and with exploitation at the MSY level for males and slightly above MSY for females.

2.1.3 Application to selected ICES stocks

Sole in the Bay of Biscay

Sole (*Solea solea*) in Divisions VIIIa, b is an ICES category 1 stock with a fully accepted, analytical assessment and forecast, and it was also evaluated as a case study to compare DLS indicators to the perspectives from a data-rich (category 1) stock assessment based on XSA. The length-based indicators analysis was performed using the landings–length composition for the period 2000–2013 (discards assumed negligible) and the following life-history parameters: k=0.33, Linf=48.2, t_0=0.08 (taken from http://www.fishbase.org/ for females), a=0.00482, b=3.175 (the length–weight relationship parameters also from http://www.fishbase.org/, for both sexes), $L_{50\%}$ maturity is taken as 26.0 cm.

Results from the analysis are shown in Figure 2.1.3.1 (for 2013) and in Figure 2.1.3.2 (for the period 2000–2013).

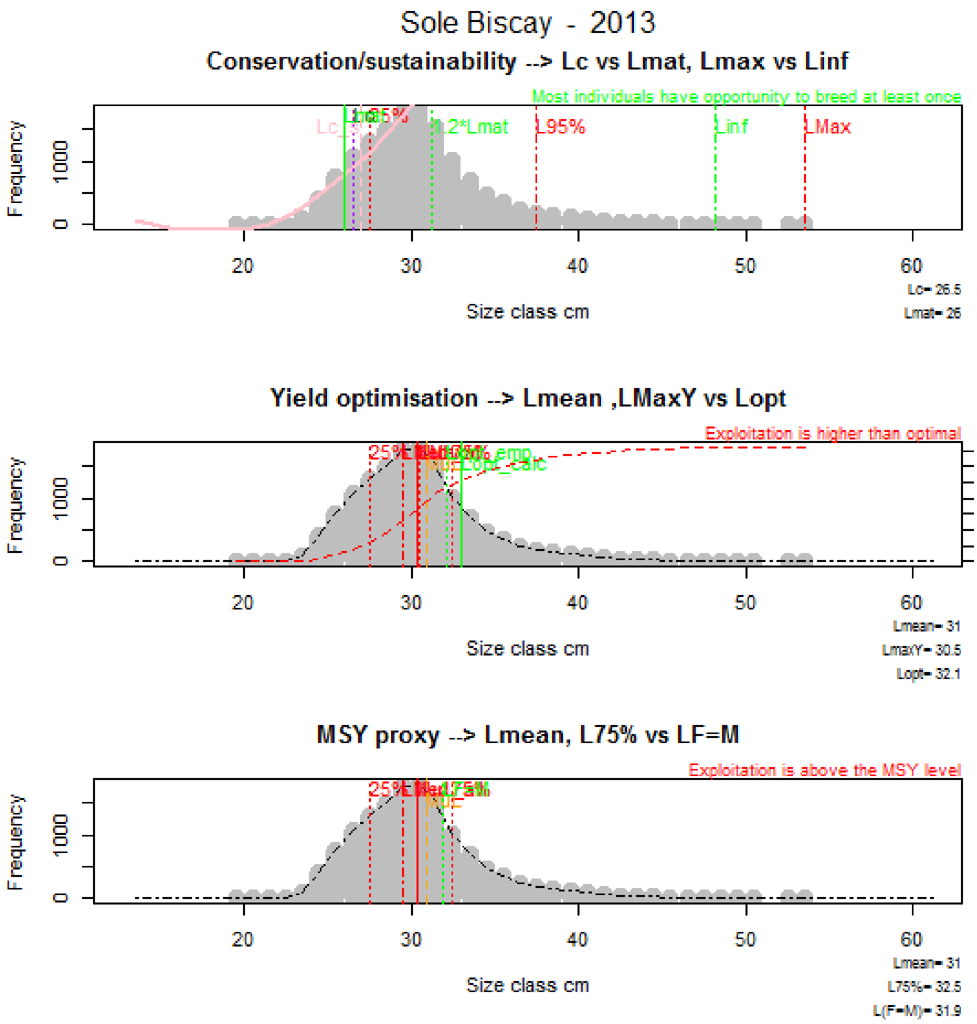


Figure 2.1.3.1. Length-based indicators and reference points for Sole in the Bay of Biscay using the landings–length composition for 2013.

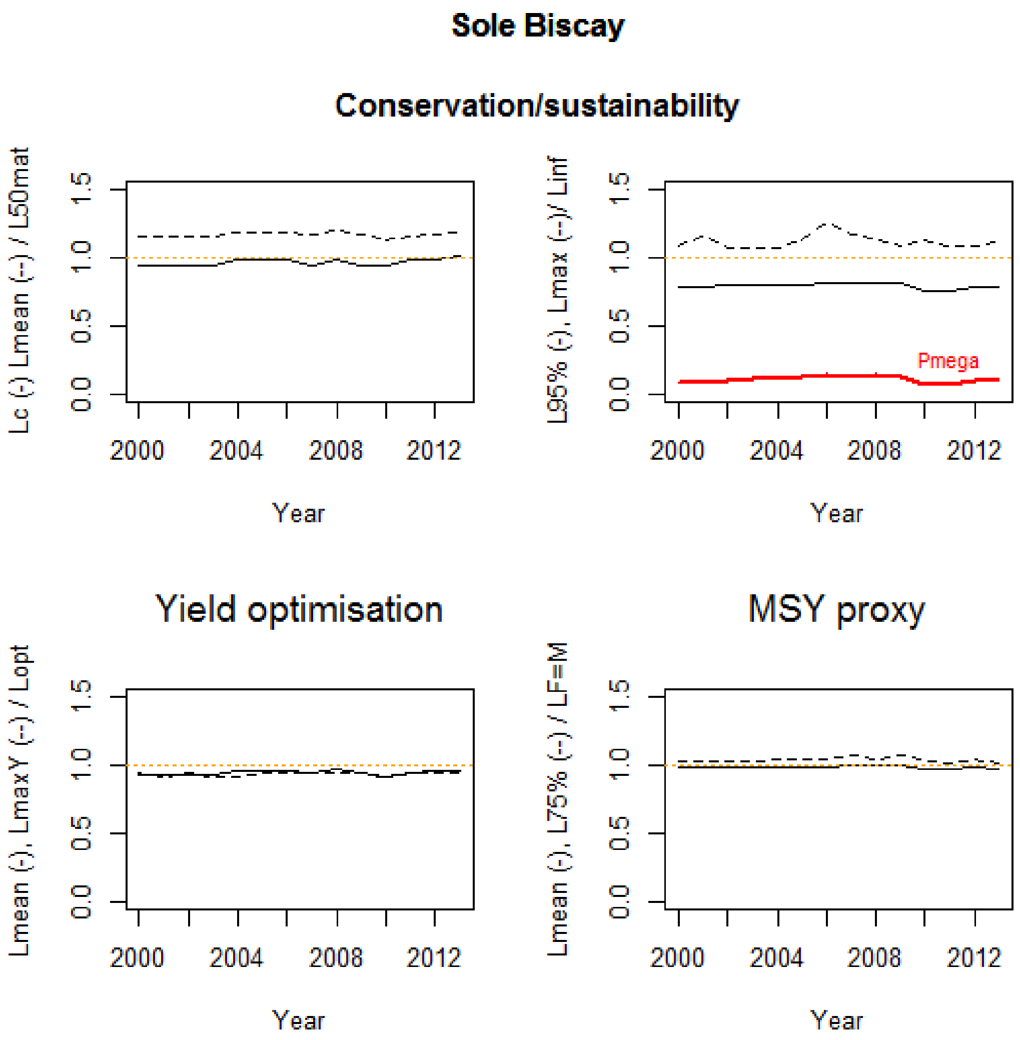


Figure 2.1.3.2. Indicator ratios and reference points for sole in the Bay of Biscay using the landings–length composition for the period 2000–2013.

<u>Conservation:</u> Most individuals have opportunity to breed at least once (LC # LMAT, LMEAN > LMAT)

Large individuals are present but scarce (LMAX > L_{inf}, but L95% < L_{inf})

<u>Yield optimization:</u> Exploitation is (slightly) higher than optimal (LMEAN < L_{opt}, LMAXY < L_{opt})

<u>MSY proxy:</u> Exploitation is (slightly) above the MSY level (LMEAN # < $L_{F=M}$) [but $L_{75\%}$ # > $L_{F=M}$]

Traffic light indicators

	Conservation						Optimizing Yield		FMSY/F	
	Lc/Lmat	L25/Lmat	Lmean/Lmat	Lmax/Linf	L95/Linf	Pmega	Lmean/Lopt	Lmaxy/Lopt	Lmean/$L_{F=M}$	L75%/$L_{F=M}$
Ref	**>1**			**~1**		**>30%**	**~1**		**1**	
Sole VIIIab 2000	0.94	1.02	1.15	1.09	0.78	9%	0.93	0.95	0.98	1.04
Sole VIIIab 2013	1.02	1.06	1.19	1.11	0.78	10%	0.96	0.95	0.97	1.02

The overall perception from length-based indicators: Bay of Biscay sole is fished sustainably at levels close to optimum yield and with exploitation at MSY level.

The length distribution analysis and XSA outputs (Figure 2.1.3.3) give quite similar results over the period 2000–2013; however XSA shows a decrease in F in 2002–2004 that is not apparent in the length distribution analysis.

According to the XSA outputs, F is substantially higher than F_{MSY}, while the length distribution analysis shows that the stock is exploited close to (slightly higher than) F_{MSY} (L_{MEAN} slightly higher than $L_{F=M}$).

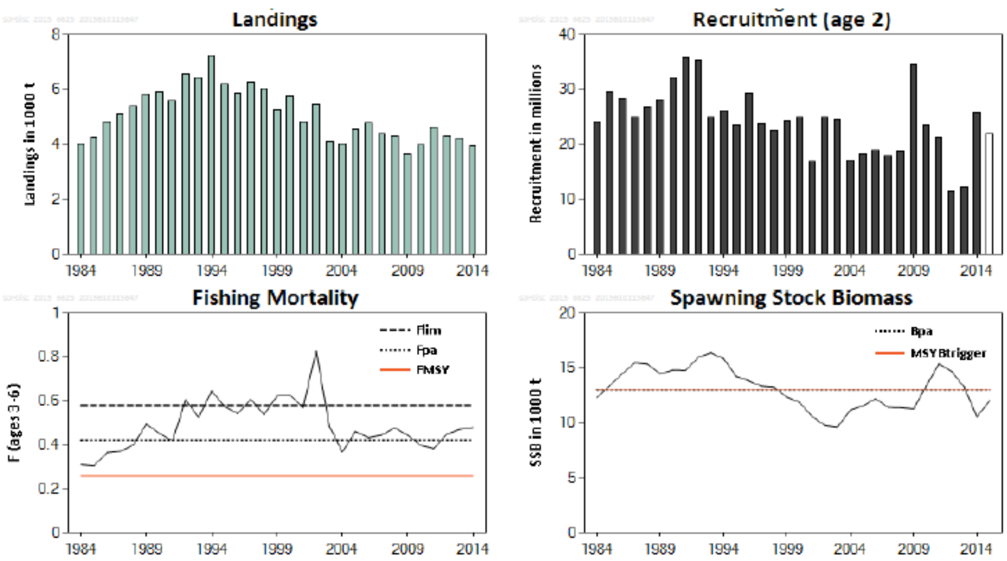


Table 7.3.30.1 Sole in Divisions VIIIa,b. State of the stock and fishery relative to reference points.

	Fishing pressure				Stock size			
		2012	2013	2014		2013	2014	2015
Maximum Sustainable Yield	F_{MSY}	✗	✗	✗ Above	MSY $B_{trigger}$	✓	✗	✗ Below trigger
Precautionary approach	F_{pa}, F_{lim}	O	O	O Increased risk	B_{pa}, B_{lim}	✓	?	? Below B_{pa}
Management plan	F_{MGT}	-	-	- Not applicable	SSB_{MGT}	-	-	- Not applicable

Figure 2.1.3.3. Bay of Biscay sole. Stock development over time and state of the stock and exploitation status from the 2015 ICES advice.

Northern hake

Hake (*Merluccius merluccius*) in Subareas IV, VI, and VII and Divisions IIIa, VIIIa,b,d is a category 1 stock with a fully accepted and assessed and forecast, and it was evaluated as a case study to compare DLS indicators to the perspectives from a data-rich (category 1) stock assessment with stock assessment performed with the length-based model StockSynthesis3. Three length-based indicators analysis was performed using the catch length distribution 2003–2013 and life-history parameters: k=0.17, L_{inf}=130 cm, t_0=0, L_{mat}=42.85 (sexes combined), a=0.00513, b=3.074. Length-based indicators and reference levels are presented for 2003 in Figure 2.1.3.4, and for 2013 in Figure 2.1.3.5. The indicator ratios and reference points for the period 2003–2013 are shown in Figure 2.1.3.6.

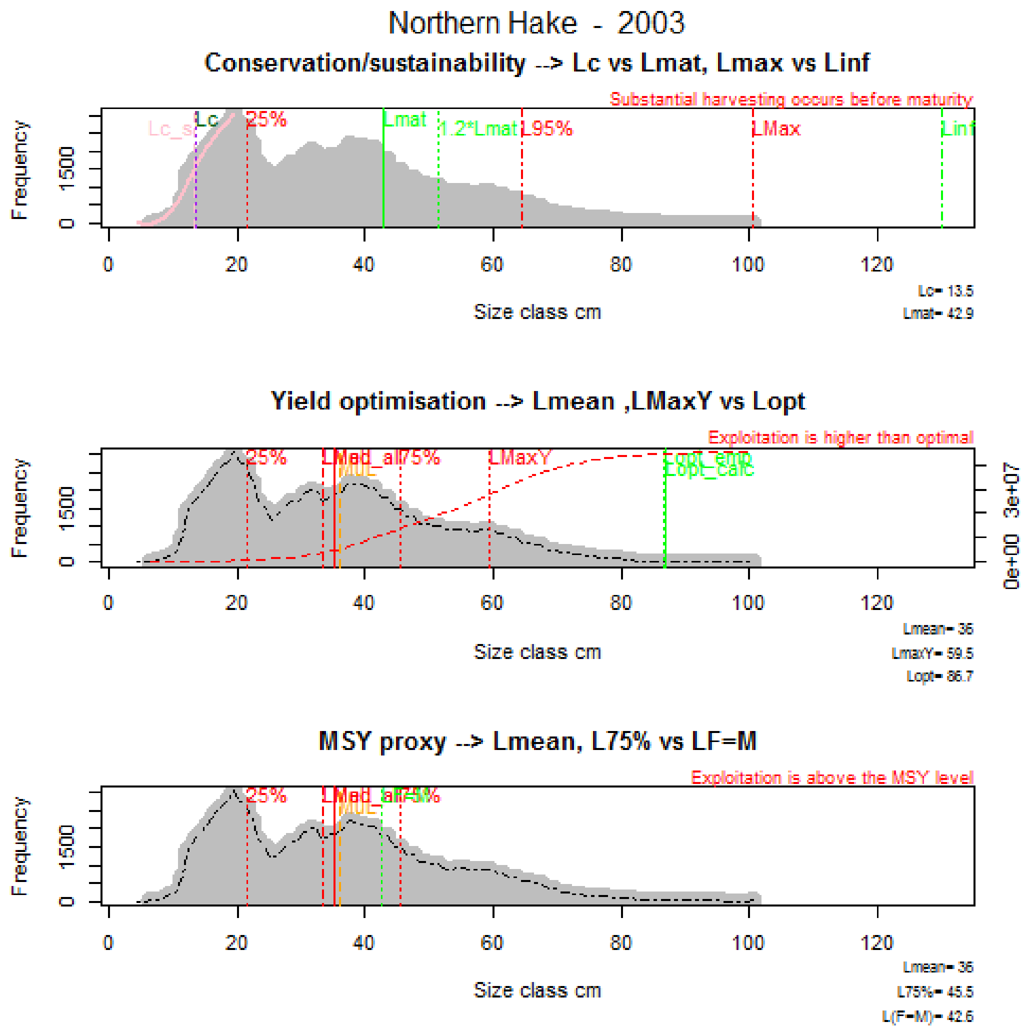


Figure 2.1.3.4. Length-based indicators and reference points for Northern hake using the catch length composition for 2003.

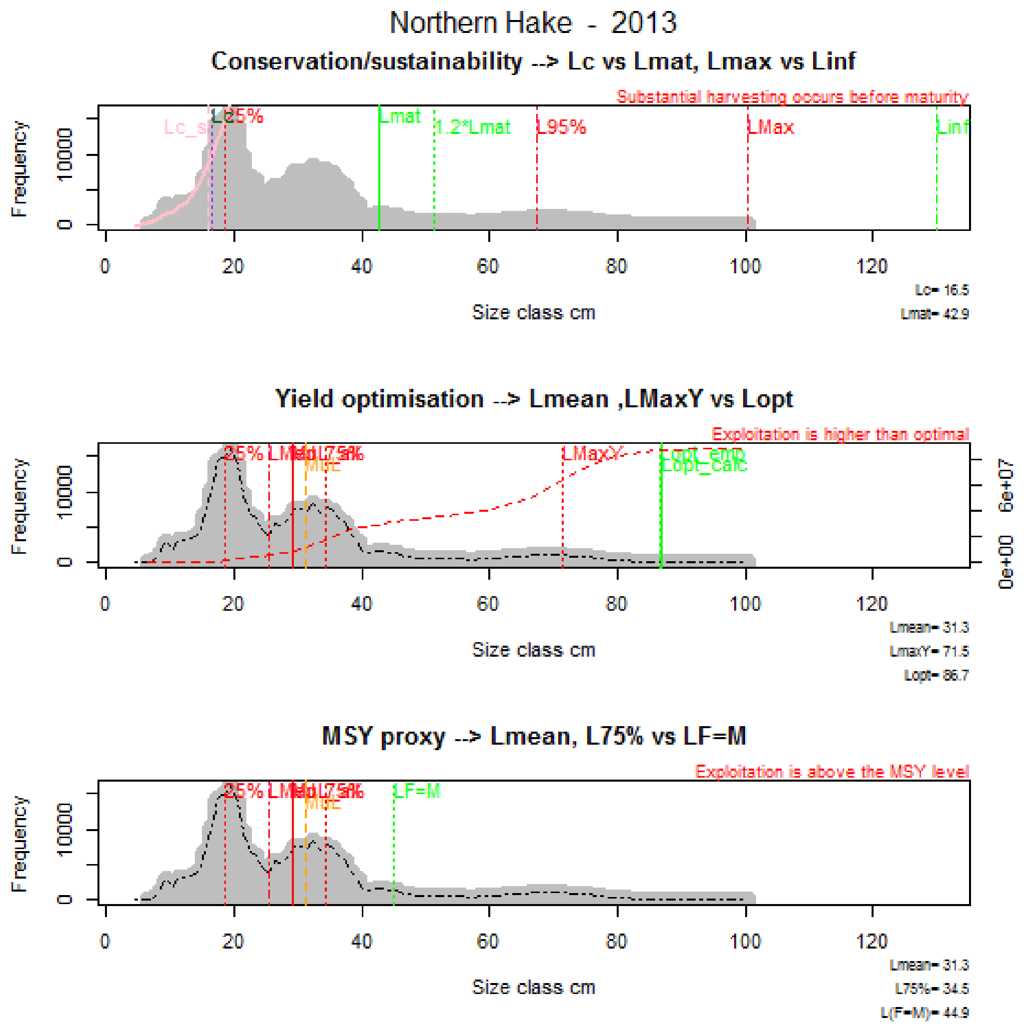


Figure 2.1.3.5. Length-based indicators and reference points for Northern hake using the catch length composition for 2013.

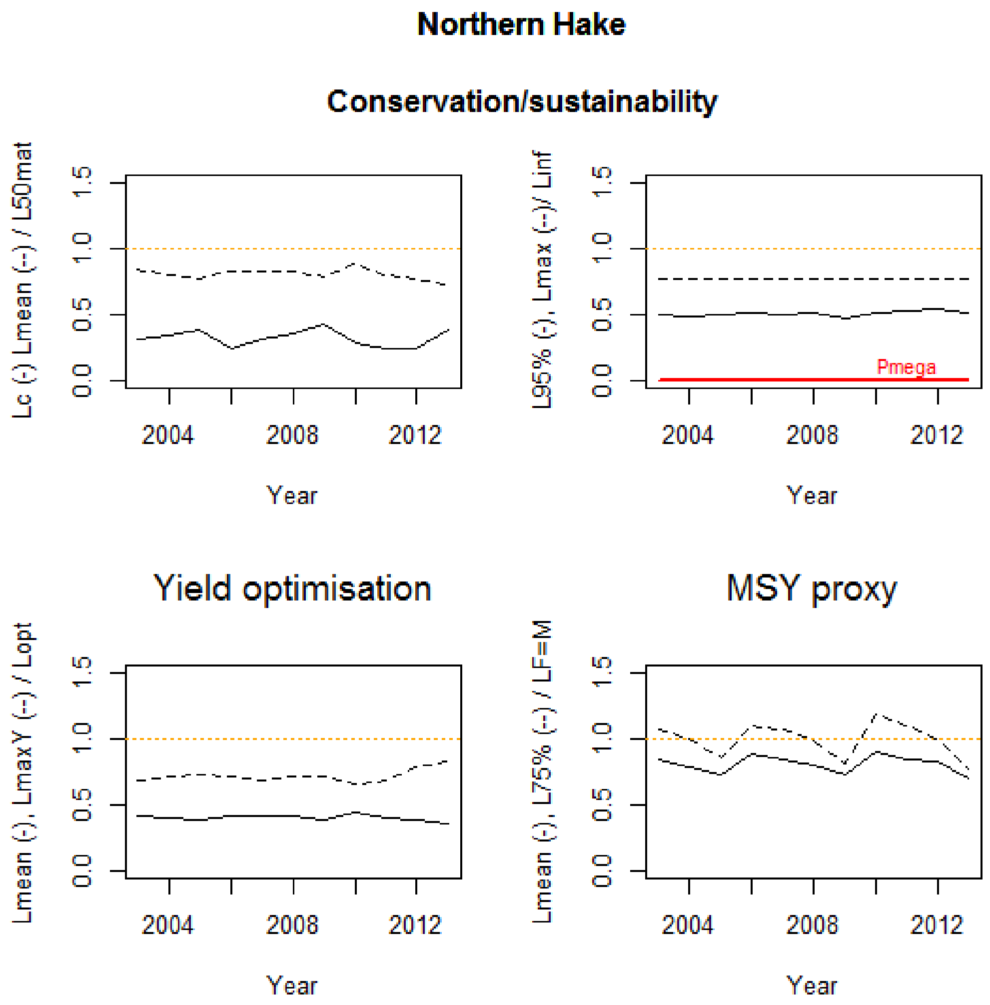


Figure 2.1.3.6. Indicator ratios and reference points for Northern hake using the catch–length composition for the period 2003–2013.

Conservation: Substantial harvesting occurs before maturity ($L_c \ll L_{MAT}$ and $L_{MEAN} < L_{MAT}$)

Since L_{MAX} is a plus group, no interpretation is possible for the bottom two graphs (L_{MAX} related to L_{inf})

Yield optimization: Exploitation is higher than optimal ($L_{MEAN} \ll L_{opt}$, and $L_{MAX}Y < L_{opt}$)

MSY: Exploitation is above the MSY level ($L_{MEAN} < L_{F=M}$) [but $L_{75\%}$ # $L_{F=M}$]

Traffic light indicators

	Conservation						Optimizing Yield		FMSY/F	
	Lc/Lmat	L25/Lmat	Lmean/Lmat	Lmax/Linf	L95/Linf	Pmega	Lmean/Lopt	Lmaxy/Lopt	Lmean/$L_{F=M}$	L75%/$L_{F=M}$
Ref	>1			~1		>30%	~1		1	
N.Hake 2003	0.32	0.50	0.84	-	0.50	0.02%	0.41	0.69	0.84	1.07
N.Hake 2013	0.38	0.43	0.73	-	0.52	0.03%	0.36	0.83	0.70	0.77

Overall perception from length-based indicators: fished unsustainably at levels above optimum yield and with exploitation above MSY level.

The length distribution analysis shows relatively stable parameters over the period (2003–2013) while the assessment model (Figure 2.1.3.7) shows a strong decrease in F since 2005. In 2013, F is estimated by the model relatively close to F_{MSY} (F/F_{MSY}=1.26) while the length distribution analysis gives a ratio of $L_{F=M}$ / L_{MEAN} of 1.43.

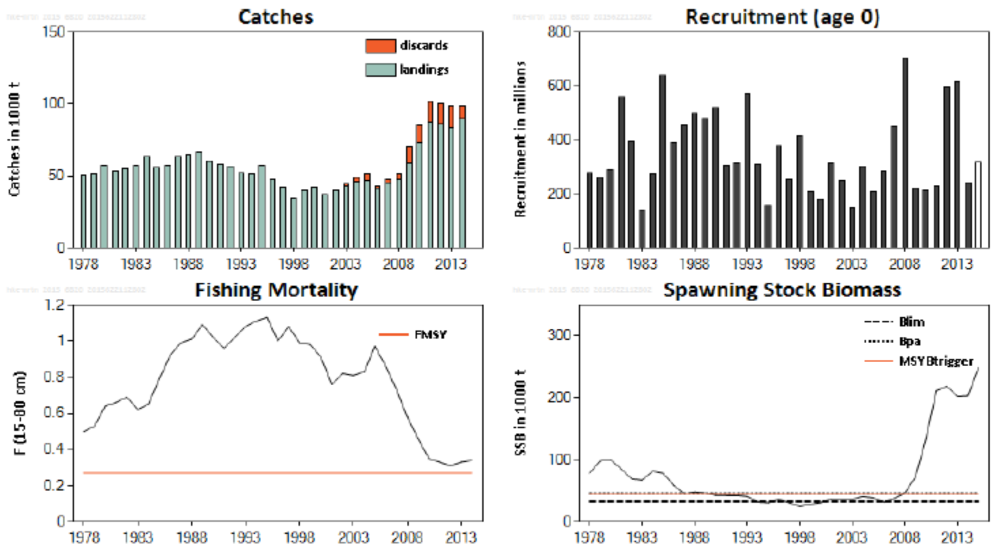


Table 9.3.14.1 Hake in Subareas IV, VI, and VII and Divisions IIIa, VIIIa,b,d (Northern stock). State of the stock and fishery relative to reference points.

	Fishing pressure				Stock size			
		2012	2013	2014		2013	2014	2015
Maximum Sustainable Yield	F_{MSY}	✗	✗	✗ Above	MSY $B_{trigger}$	✓	✓	✓ Above trigger
Precautionary approach	F_{pa}, F_{lim}	?	?	? Undefined	B_{pa}, B_{lim}	✓	✓	✓ Full reproductive capacity
Management plan	F_{MGT}	-	-	- Not applicable	SSB_{MGT}	-	-	- Not applicable

Figure 2.1.3.7. Northern hake. Stock development over time and state of the stock and exploitation status from the 2015 ICES advice.

Sea bass in the Bay of Biscay

Sea bass (*Dicentrarchus labrax*) in Divisions VIIIa,b (Bay of Biscay) is an ICES data-limited category 3 stock. It was used as a case study to demonstrate application of the method. The length-based indicators analysis was performed using the commercial landings in 2014 (discards considered negligible) and the following life-history parameters: k=0.097, L_{inf}=84.55, t_0=0.73, L_{MAT}=40.65, a=0.01244, b=2.95.

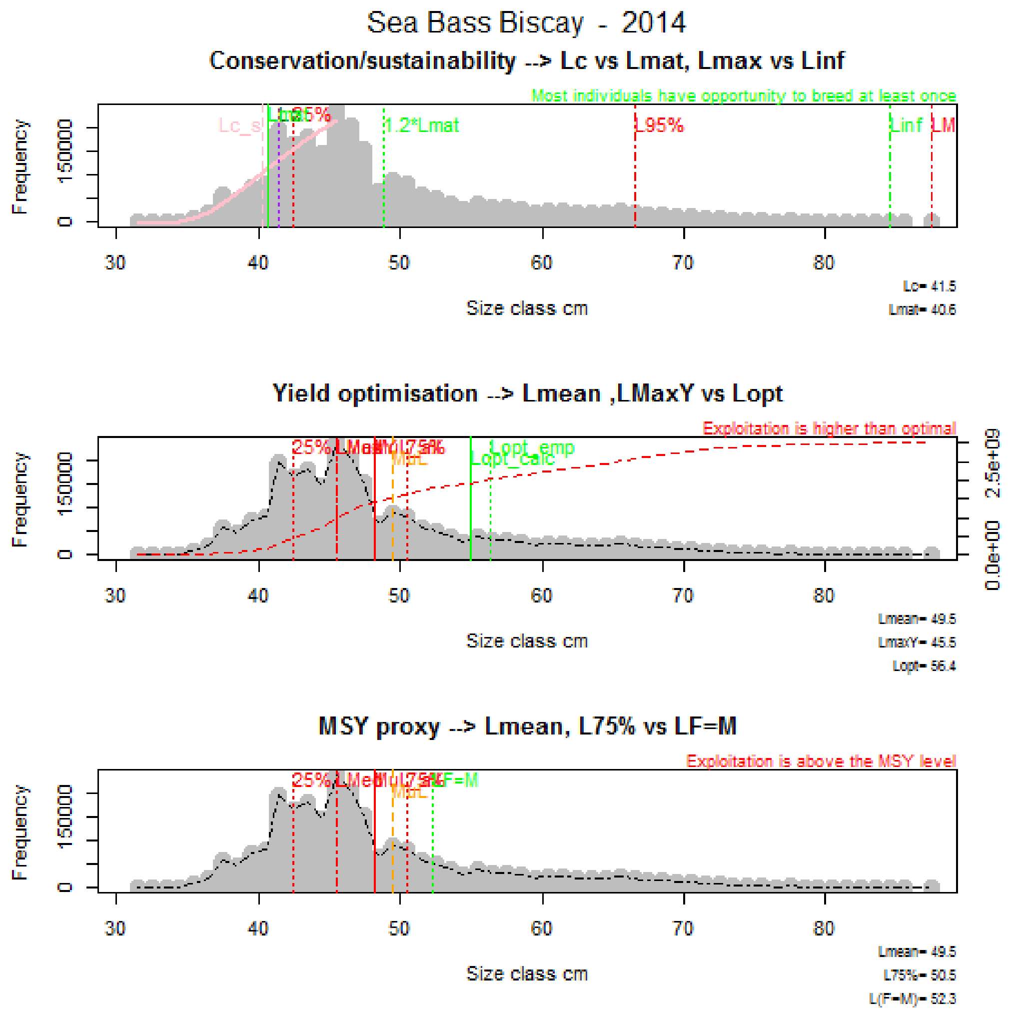


Figure 2.1.3.8. Length-based indicators and reference points for sea bass in the Bay of Biscay using the commercial landings for 2014.

<u>Conservation:</u> Most individuals have opportunity to breed at least once (LC # LMAT, LMEAN > LMAT)

Large individuals are present but scarce (LMAX > L_{inf}, but $L_{95\%}$<L_{inf})

<u>Yield optimization:</u> Exploitation is (slightly) higher than optimal (LMEAN < L_{opt}, LMAXY < L_{opt})

<u>MSY proxy:</u> Exploitation is (slightly) above the MSY level (LMEAN # < $L_{F=M}$, L75% #> $L_{F=M}$)

Traffic light indicators

	Conservation						Optimizing Yield		FMSY/F	
	Lc/Lmat	L25/Lmat	Lmean/Lmat	Lmax/Linf	L95/Linf	Pmega	Lmean/Lopt	Lmaxy/Lopt	Lmean/$L_{F=M}$	L75%/$L_{F=M}$
Ref	>1			~1		>30%	~1		1	
Bass VIII 2014	1.02	1.05	1.22	1.03	0.79	9.1%	0.88	0.81	0.95	0.97

Overall perception from length based indicators: fished sustainably at levels close to optimum yield and with exploitation at (or slightly above) MSY level.

2.2 Mean length-based estimators (Z)

2.2.1 Method

The mean length-based mortality estimator of Gedamke and Hoenig (2006) is a non-equilibrium extension of the Beverton and Holt (1957) mean length mortality estimator. Gedamke and Hoenig (2006) derived the transitional behaviour of the population mean length following a change in instantaneous total mortality (Z) and then generalized the derivation to include length changes due to multiple changes in total mortality. From a time-series of mean length data, total mortality rates are estimated in blocks of time as well as the years in which the mortality changed. The model uses a likelihood approach to obtain parameters that maximize goodness-of-fit to the mean length data. With an external estimate of the natural mortality rate (M), the fishing mortality rate (F) in the most recent time block of the time-series can be derived.

A method to extend the non-equilibrium mean length estimator to incorporate a time-series of fishing effort is described in Then (2014). In this method, the annual total mortality rate is parameterized as the sum of the annual fishing mortality and time and age-invariant natural mortality rate. Assuming that fishing mortality is proportional to fishing effort by the catchability coefficient, the model estimates the catchability coefficient and the natural mortality rate, again with the goodness-of-fit to the mean length data. The use of fishing effort allows for annual estimates of fishing and total mortality. The model requires a specification of the fishing effort prior to the first year of the mean length data. A natural mortality rate obtained from external sources can be fixed in the model if desired.

For both models, the terminal (most recent) fishing mortality rate can be compared with reference points obtained from a length-based per-recruit analysis.

2.2.1.1 Data and information requirements

The mean length-only estimator of Gedamke and Hoenig (2006) requires a time-series of length measurements and von Bertalanffy growth parameters L_∞ and k for the stock. The mean length with effort estimator of Then (2014) also requires a time-series of fishing effort. Often, the effort time-series is derived as the ratio of the catch and a cpue series.

For the per-recruit analysis, natural mortality, weight-at-age is required for both the YPR and SPR analyses, and maturity information is needed for SPR. The value for the natural mortality rate is obtained either externally or estimated using the Then (2014) method.

2.2.1.2 Assumptions

Both models assume (see Gedamke and Hoenig (2006) and Then (2014)):

1) Recruitment is constant over time,
2) Growth is deterministic following a von Bertalanffy growth equation and is time-invariant, and
3) Selectivity is knife-edge above the length of full selectivity (L_c) and is time-invariant.

In addition, for the Then (2014) model, it is assumed:

4) Fishing effort is known without effort and is proportional to fishing mortality.

The mean length-only estimator assumes continuous recruitment; however, the estimator is derived to accommodate annual recruitment by replacing the integrals in Equation A.2.1 of Gedamke and Hoenig (2006) with summations. The mean length with effort estimator can accommodate both types of recruitment numerically: the annual recruitment modelled with an annual time-step and continuous recruitment with a monthly time-step.

2.2.1.3 Outputs expected

The Gedamke-Hoenig (2006) method estimates the number of change points, the years of change, and the total mortality rate in each time block. The method of Then (2014) gives estimates of q and M as well as derived, year-specific fishing and natural mortality rates. Both methods use maximum likelihood estimation and provide asymptotic variances and covariances of the parameter estimates.

2.2.1.4 Method of operation

First, the length of full selectivity (L_c) is obtained from the data. Typically, the L_c is selected to be the peak (mode) of the length–frequency histogram of data combined for all years in the time-series. Then, the annual mean lengths of animals of lengths larger than L_c is calculated. However, annual length–frequency histograms should also be examined to explore trends in the mode of the histogram over time, which would coincide with changing selectivity or possibly trends in recruitment.

For the mean length-only estimator, the number of time blocks is initially specified by the user. The model is fitted multiple times with increasing complexity (more time blocks) until the increase in goodness-of-fit is no longer statistically significant with increasing complexity as judged by an information theoretic criterion such as AIC. Residual analysis of mean length data is also used to diagnose goodness-of-fit. A sensitivity analysis should be performed in which several values of L_c are chosen as a trend in estimates with increasing L_c might indicate failure of the assumption of a knife-edged (flat-topped) selectivity curve.

For the mean length with effort estimator, natural mortality can either be estimated or fixed in the model. Hence, a diagnostic for this model is whether the predicted value of M is consistent with what is known about natural mortality from life-history considerations.

2.2.1.5 Testing

For the Gedamke-Hoenig model, the effects of violating the assumption of constant recruitment were investigated by Gedamke *et al*. (2008). Roughly speaking, they found that a trend of increasing recruitment with a slope of 10% causes about a 10% overestimate of Z, i.e. the increasing recruitment is added to the estimate of Z because both mortality and increasing recruitment reduce the mean length in the population. For the Beverton–Holt estimator, a simplified version of Gedamke-Hoenig model, the effect of a dome-shaped selection curve is known to produce a positive bias in estimated mortality rate, because the observed mean length is reduced by the lack of full selection of large animals (Then *et al*., in press).

Then (2014) provided extensive simulations of the effect of individual variability of growth on the model of mean length and fishing effort. The model was found to be robust to the violation of the assumption deterministic growth.

2.2.1.6 Caveats

Mean length in a population is determined by the mortality history and the recruitment history experienced by the population. Without further information, the effects of changing recruitment and mortality are confounded.

A further complication is that L_c is often assumed to be larger than the true size of full selection to ensure that all fish are fully recruited and meet the assumption of flat-topped selectivity. In this case, to the extent that some animals below the size of L_c are harvested, the recruitment to size L_c will depend on the fishing effort; if fishing effort (or selectivity) changes over time this will induce changes in the recruitment to size L_c.

The use of mean length to estimate mortality rates does not work well for short-lived animals. For example, in a blue crab (*Callinectes sapidus*) fishery in the Chesapeake Bay, USA, the catch is almost entirely age-0 and age-1. If there is a very weak incoming year class (almost no age-0 animals) the mean length will become large (all age-1). The poor year class is bad news yet the mean-length based mortality estimator will falsely interpret this as good news; the total mortality rate has apparently dropped.

2.2.1.7 Software

Software is available for the mean length-only estimator (for both annual and continuous recruitment) in both R and ADMB. The method assuming continuous recruitment is available in the fishmethods package in R (the function name is bhnoneq) and the method for annual recruitment is provided to the meeting organizers and is available on the WKLIFE V SharePoint. Currently, the mean length with effort estimator is available in ADMB. The executable can be called from R. The software is available from Quang Huynh at the Virginia Institute of Marine Science qhuynh@vims.edu.

2.2.2 Application to *Nephrops* in FUs 28–29

Catch-at-size data (2000–2014) and life-history information were available for male and female *Nephrops*. Standardized effort from the fishery (1998–2014) were obtained as the ratio of the catch and the commercial cpue. With considerations to the sex-specific differences in life history, we were able to estimate mortality rates for males and females separately. The life-history information external to the models used in the analysis is provided in Table 2.2.2.1.

Table 2.2.2.1. Life-history information for *Nephrops* in FUs 28–29 used in the analysis.

Parameter	Males	Females
Von Bertalanffy L_∞ (mm)	70	65
Von Bertalanffy k ∞ (yr-1)	0.2	0.065
Length–weight a	$2.8\ 10^{-4}$	$5.6\ 10^{-4}$
Length–weight b	3.2229	3.0288
Natural mortality M (yr-1)	0.3	0.2
Length-at-maturity (mm)	28.4	30

Mean length-only estimator

The peak of the time-aggregated length–frequency histogram was at the 32.5 mm length bin for both males and females (Figure 2.2.2.1).

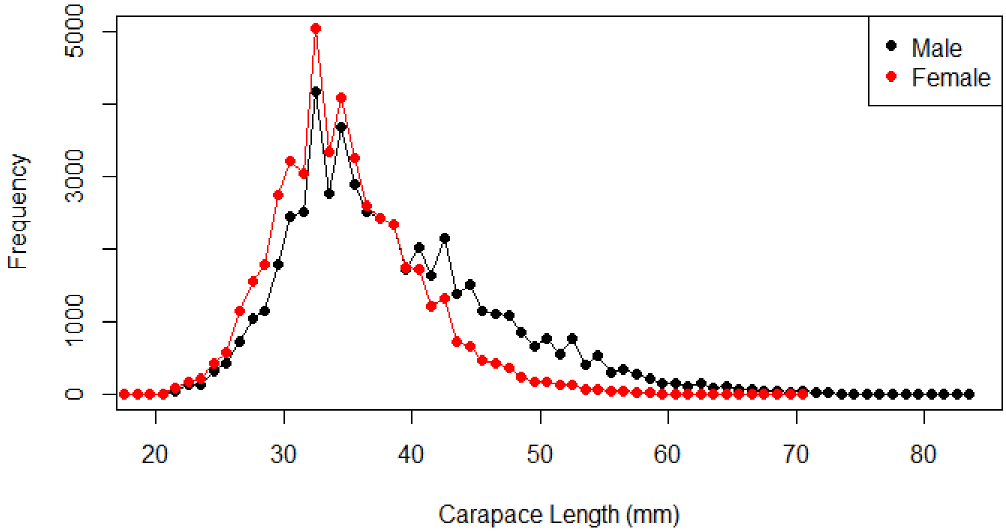


Figure 2.2.2.1. Length–frequency distribution for male and female *Nephrops* in FUs 28–29 aggregated over all years.

The length frequency for individual years suggested that this peak did not systematically shift over time which would be a diagnostic for the problem of changing selectivity over time. Mean lengths above the L_c of 32.5 mm were calculated. Although immature female *Nephrops* have different life history compared to mature animals, the length of full selectivity was above the age of maturity so immature females were not modelled.

The method of Gedamke and Hoenig (2006), modified for annual reproduction, was fit to each sex separately with no change in mortality over time and with one change over time. There was little support for including a change in mortality in the model (ΔAIC = 7), so only the results for the constant mortality rate scenario are presented. The estimate of Z for males is 0.46 and for females is 0.29 for the observed time-series (Figure 2.2.2.2). Using the sex-specific natural mortality rates in Table 2.2.2.1, the derived F for males is 0.16 and for females is 0.09. The results were stable to alternative specifications of L_c above the value of 32.5 mm used in the analysis shown above.

Reference points for the fishing mortality rate were obtained using the Length-Based Yield per Recruit program (http://nft.nefsc.noaa.gov/YPRLEN.html) with the requisite life-history information in Table 2.2.2.1. From the Yield per Recruit (YPR) analysis, the $F_{0.1}$ was estimated to be 0.26 for males and 0.29 for females. From the Spawning Potential Ratio (SPR) analysis, the F_{35} was estimated to be 0.33 for males and 0.55 for females. From the mean length-only analysis, it is inferred that overfishing is not occurring on this *Nephrops* stock.

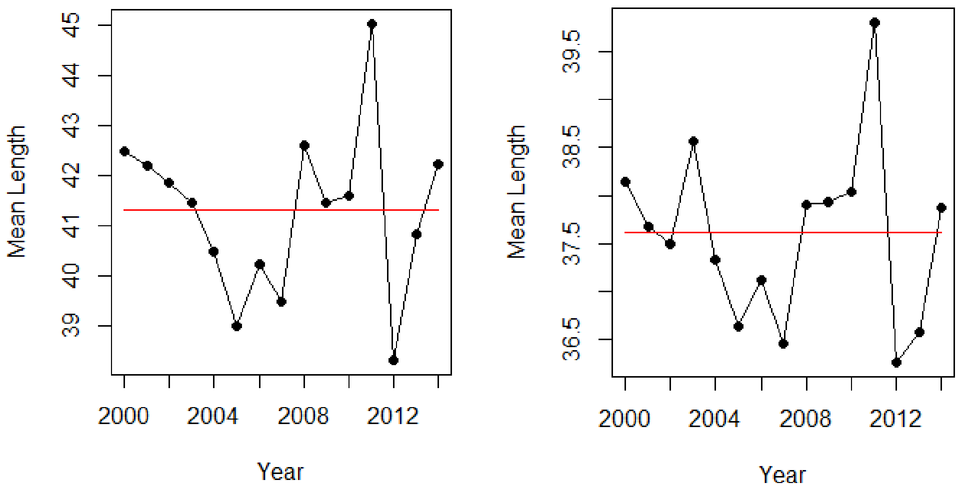


Figure 2.2.2.2. ***Nephrops*** **in FUs 28–29. Observed and fitted mean lengths for males (left) and females (right).**

Mean length and effort estimator

The method of Then (2014) modifies the Gedamke-Hoenig model by replacing the period specific total mortality rate Z with the year-specific formulation $Z_t = F_t + M = q f_t + M$ where Z_t is the total mortality rate in year t, F_t is the fishing mortality rate in year t, q is the catchability coefficient, f_t is the fishing effort in year t, and M in the instantaneous natural mortality rate. This allows for the estimation of q and M (or, alternatively, the value of M can be fixed and just q is estimated). Year specific fishing and total mortality rates can then be calculated. It is necessary to specify the fishing effort values for the years prior to the first observation on mean length so that the expected mean length in the first year can be predicted by the model. Typically, one assumes either that there was no effort prior to the start of collection of length data or, more likely, that the fishing effort in the years immediately before the collection of length data was the same as the fishing effort at the start of the time-series of effort data. The latter assumption was adopted here.

For *Nephrops*, standardized effort from 1998 to 2014 and mean lengths (L_c = 32.5 mm) from 2000–2014 were available. Effort prior to 1998 was assumed to be the same as the effort in 1998.

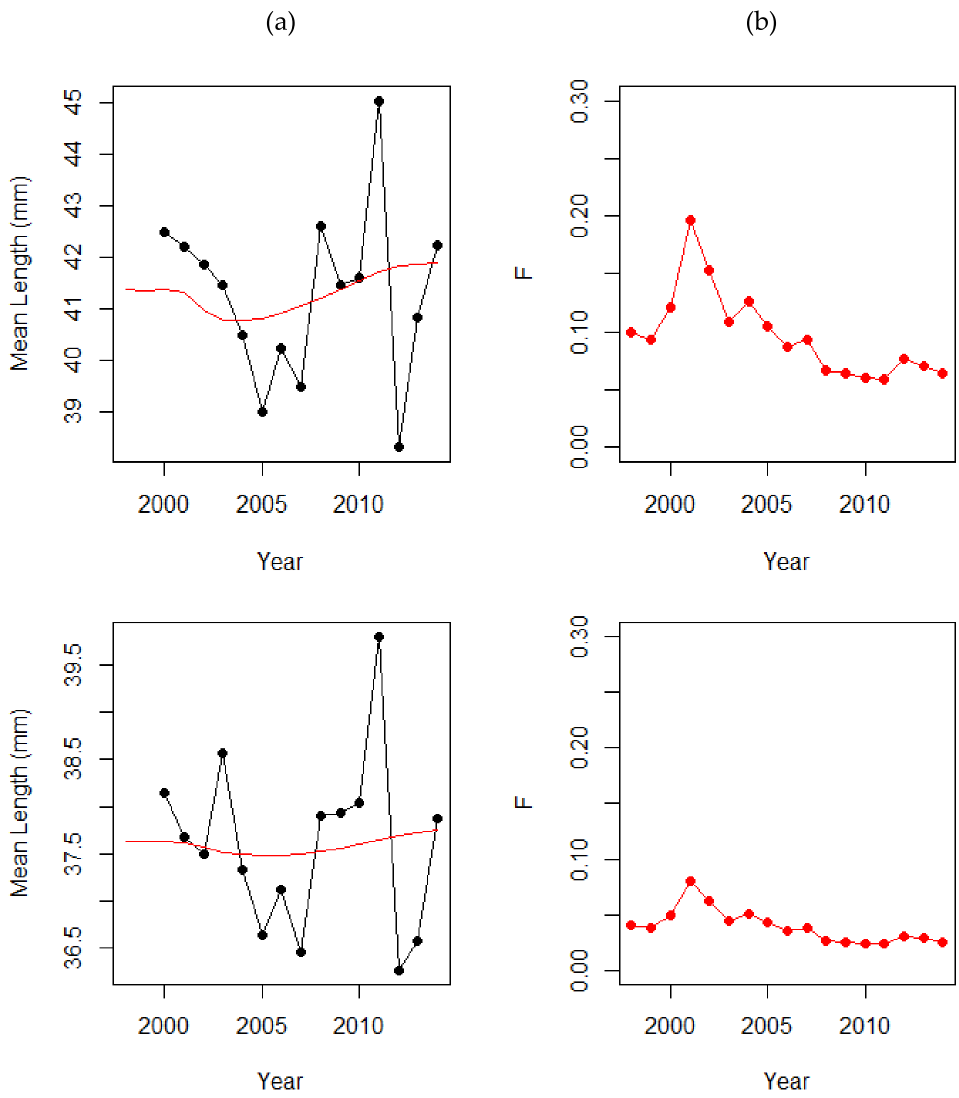


Figure 2.2.2.3. *Nephrops* in FUs 28–29. Results of fitting the Then (2014) model to males (first row) and females (second row). The observed (black line with dots) and predicted (red lines) mean lengths are shown in the left column (a). The estimated fishing mortalities are shown in the right column (b).

The estimates of M were 0.35 yr^{-1} for males and 0.23 yr^{-1} for females. These are slightly greater than the values 0.3 and 0.2 used in the assessment. The estimates of fishing mortality in the most recent year (2014) were F = 0.06 for males and F = 0.03 for females.

Reference points for the fishing mortality rate were again obtained using the Length-Based Yield per Recruit program. For this analysis, the natural mortality rate estimated in this model was instead of the values in Table 2.2.2.1. From the yield-per-recruit (YPR) analysis, the $F_{0.1}$ was estimated to be 0.30 for males and 0.33 for females. From the Spawning Potential Ratio (SPR) analysis, the F_{35} was estimated to be 0.39 for males and 0.66 for females. From the mean length and effort analysis, it is again inferred that overfishing is not occurring on the *Nephrops* stock.

Conclusions

The Then (2014) model produced estimates of M that are slightly higher than the values of M used in the stock assessment. Fixing the value of M in the Then model to the value used in the assessment results in slightly higher estimated fishing mortality rates.

Both mean length estimators predict small changes in mean length over the course of the time-series, and both models predict small values of F. The two approaches are thus consistent with each other in the conclusions they afford.

2.3 SPR approach

2.3.1 Method

Reference points that are comparable to and consistent with size-based estimators are needed to derive catch advice in the ICES data-limited stock advisory framework, either for perceptions of stock status or as thresholds in ICES advice rules. Traditional approaches compared size-based estimates of fishing mortality (*Z*, Beverton and Holt, 1956) with sized-based yield-per-recruit reference points (F_{max} or $F_{0.1}$, Beverton and Holt, 1957), both of which assumed knife edged selectivity at L_c. Alternative selectivity functions can be assumed if the yield-per-recruit analysis is based on length at relative age (Cadima, 2003), and the size-based yield-per-recruit can be extended to spawning biomass per recruit (http://nft.nefsc.noaa.gov/).

For size based YPR and spawning biomass per recruit reference points, information is needed on:

- Growth, usually expressed as von Bertalanffy parameters, L_∞ and κ:
- $L_t = L_\infty(1 - e^{-\kappa(t-to)})$
- Length–weight relationship
- Natural mortality rate (*M*)
- Selectivity-at-length, either knife-edged, logistic or domed (double-logistic)
- Maturity-at-length (for spawning biomass per recruit)

The -per recruit analysis will derive YPR and spawning biomass per recruit as a function of F, maximum spawning potential (at F=0), and *F* reference points for maximum YPR (F_{MAX}), $^1/_{10th}$ of the initial rate of increase in YPR (F0.1), and maintaining a portion of maximum spawning potential (%MSP, with 40%MSP being a common proxy for MSY). The primary assumption of -per recruit models is that the stock is in equilibrium (i.e. constant recruitment, growth and mortality, including M and F at size).

Beverton and Holt (1957) found that the ratio of *M/κ* largely determines productivity, resilience and overfishing limits. This life-history ratio is known to be relatively consistent between closely related stocks, and less variable between species than either of the individual parameters in the ratio (Beverton, 1992; Prince, 2015). Hordyk *et al*. (2015a, b) developed a size-based estimator that is based on the ratio *M/κ*, for application to data-poor situations with no reliable age data or local estimates of growth or mortality. The method develops links between life-history ratios and the expected equilibrium size composition of the catch, and by comparing this expected size composition to the observe size composition, the method is able to estimate both *F/M* and selectivity parameters (assuming logistic selection). By further inclusion of information on maturity, the model estimates Spawning Potential Ratio (SPR), which can be used as a metric of stock status (similar to %MSP). The method incorporates variation in length-at-age by introducing a CV on L_∞ under the assumption that variation in length-at-age follows a Normal distribution and is due to variation in L_∞ alone.

2.3.1.1 Data and information requirements

- Length composition data of the catch
- M/κ ratio
- L_∞
- CV[L_∞] (software default: 0.1)
- Maturity-at-length (software default: logistic parameters L_{MAT50} and L_{MAT95})
- b, the allometric exponent from the length–weight relationship (software default: 3)
- P, the proportion of animals surviving to maximum age (software default: 0.01)

2.3.1.2 Assumptions

- Equilibrium-based method
- Differences between observed and expected length distributions are not due to variability of recruitment or mortality (i.e. method assumes constant recruitment and fishing pressure)
- Growth is adequately described by von Bertalanffy equation with known L_∞, CV[L_∞], M/κ, and t_0=0
- Length structure of the catch is representative (i.e. not subject to biased sampling)
- Commercial selectivity follows a logistic curve (although the method is not limited to this, and will take alternative forms, including domed selection; however, this requires knowledge of the shape of the selectivity curve, information that may not be readily available in data-poor situations)

2.3.1.3 Outputs expected

- Estimates of F/M and selectivity parameters (e.g. L_{sel50} and L_{sel95}) for logistic selection)
- Estimates of SPR, which can be compared to and SPR target (e.g. SPR = 35%)
- A time-series of these estimates if length–frequency distributions available for consecutive years (although estimation is independent year-on-year)

2.3.1.4 Method of operation

A description of the LB-SPR method developed by Hordyk *et al*. (2015a, b, c), as it has been implemented during WKLIFE V, is given below. The method essentially involves fitting the expected length distributions, given life history, selectivity parameters and levels of exploitation, to observed length distributions, with values for F/M and the selectivity parameters (L_{sel50} and L_{sel95}) adjusted (using a maximum likelihood approach) to obtain the closest match between these two length distributions. The calculation of $\overline{S}_x$ (equations 2.3.7, 2.3.8, 2.3.10 and 2.3.14) was not included in the Hordyk *et al*. papers, and its derivation is therefore also included here.

Objective function to minimise

$$\text{NLL} = \sum_i O_i \ln\left(\frac{P_i}{O_i^P}\right)$$

Where:

O_i = observed numbers in the catch in length class *i*

O_i^P = observed proportion in the catch in length class *i*

P_i = expected proportion in the catch in length class *i*, given life-history parameters, selectivity and F/M

Observations

Length classes to be defined relative to L_∞ (i.e. $\tilde{\ell}_i = \ell_i / L_\infty$). Length classes number *i* = 1, 2,…, *I*, and associated with relative lengths $\tilde{\ell}_1^{lo}, \tilde{\ell}_2^{lo}, \ldots, \tilde{\ell}_I^{lo}$, which represent the lower bound of the length classes.

The observed length composition, converted to proportions-at-length, a choice of number of length classes, and the length classes defined relative to L_∞, are needed as inputs.

Construct age–length transition matrix

Mean length (relative to L_∞) at relative age is give as:

$$\text{E}[\tilde{L}_x] = 1 - P^{x/(M/\kappa)} \qquad 2.3.1$$

With associated standard deviation:

$$\sigma_{\tilde{L}_x} = \text{CV}[L_\infty]\left(1 - P^{x/(M/\kappa)}\right) \qquad 2.3.2$$

With the age–length transition matrix defined as:

$$P_{x,i} = \begin{cases} \Phi\left(\dfrac{\tilde{\ell}_2^{lo} - \text{E}[\tilde{L}_x]}{\sigma_{\tilde{L}_x}}\right) & , i = 1 \\ \Phi\left(\dfrac{\tilde{\ell}_{i+1}^{lo} - \text{E}[\tilde{L}_x]}{\sigma_{\tilde{L}_x}}\right) - \Phi\left(\dfrac{\tilde{\ell}_i^{lo} - \text{E}[\tilde{L}_x]}{\sigma_{\tilde{L}_x}}\right) & , 1 < i < I \\ 1 - \Phi\left(\dfrac{\tilde{\ell}_I^{lo} - \text{E}[\tilde{L}_x]}{\sigma_{\tilde{L}_x}}\right) & , i = I \end{cases} \qquad 2.3.4$$

Here you need to assume a value for P (0.01 used in the Hordyk *et al*. papers) and have M/κ and CV[L_∞] as inputs, and need to decide how many relative age classes to have (at least 50 is recommended).

Expected relative numbers-at-age in the population

Selection at relative length:

$$\tilde{S}_i = \frac{1}{1+e^{-(\ln 19)(i-\tilde{L}_{sel50})/(\tilde{L}_{sel95}-\tilde{L}_{sel50})}} \qquad 2.3.5$$

so that selection at relative age becomes:

$$\tilde{S}_x = \sum_i P_{x,i}\tilde{S}_i \qquad 2.3.6$$

where $P_{x,i}$ is from equation 2.3.4.

Relative numbers-at-age in the population is then given by:

$$\tilde{N}_x = \left(1-\mathrm{E}[\tilde{L}_x]\right)^{M/\kappa+(M/\kappa)(F/M)\bar{S}_x} \qquad 2.3.7$$

where

$$\bar{S}_x = \frac{1}{(\sum_{j\le x} 1)}\sum_{j\le x}\tilde{S}_j \qquad 2.3.8$$

with $\tilde{S}_j$ from equation 2.3.6. [See below for derivation of equation 2.3.7, which did not appear in any of the Hordyk *et al*. papers (and will shortly to be submitted for publication, for the record).]

Here you need M/κ as input, and F/M, $\tilde{L}_{sel50}$ and $\tilde{L}_{sel95}$ are quantities to be estimated.

Expected relative numbers-at-length in the catch

Selection for the catch needs to be accounted for:

$$C_{x,i} = P_{x,i}\tilde{S}_i \qquad 2.3.9$$

calculated for all *x* and *i*,

The expected relative numbers-at-length are then

$$\tilde{N}_i^{catch} = \sum_x \left(1-\mathrm{E}[\tilde{L}_x]\right)^{M/\kappa+(M/\kappa)(F/M)\bar{S}_x} C_{x,i} \qquad 2.3.10$$

with $\bar{S}_x$ as defined in equation 2.3.8.

Expected proportion-at-length in the catch

$$P_i = \begin{cases} 0 & , \sum_i \tilde{N}_i^{catch} = 0 \\ \dfrac{\tilde{N}_i^{catch}}{\sum_i \tilde{N}_i^{catch}} & , \sum_i \tilde{N}_i^{catch} > 0 \end{cases} \qquad 2.3.11$$

Calculation of SPR

Maturity at relative length:

$$\tilde{Q}_i = \frac{1}{1 + e^{-(\ln 19)(i - \tilde{L}_{mat50})/(\tilde{L}_{mat95} - \tilde{L}_{mat50})}} \qquad 2.3.12$$

so that maturity at relative age becomes:

$$\tilde{Q}_x = \sum_i P_{x,i} \tilde{Q}_i \qquad 2.3.13$$

and SPR is calculated as follows:

$$SPR = \frac{\sum_x \tilde{Q}_x \left(1 - \mathrm{E}[\tilde{L}_x]\right)^{M/\kappa + (M/\kappa)(F/M)\bar{S}_x} \left(\mathrm{E}[\tilde{L}_x]\right)^b}{\sum_x \tilde{Q}_x \left(1 - \mathrm{E}[\tilde{L}_x]\right)^{M/\kappa} \left(\mathrm{E}[\tilde{L}_x]\right)^b} \qquad 2.3.14$$

Here input values are required for b (the Hordyk *et al*. papers used the usual value of 3) and the maturity parameters $\tilde{L}_{mat50}$ and $\tilde{L}_{mat95}$.

Derivation of Equation 2.3.7 for the LB-SPR method

Starting from the exponential decay equation:

$$\tilde{N}_a = \frac{N_a}{N_0} = e^{-\sum_{j=0}^{a-1} Z_j} = e^{-\sum_{j=0}^{a-1}(M + FS_j)}$$

$$= e^{-aM - F\sum_{j=0}^{a-1} S_j}$$

$$= e^{-aM - aF\bar{S}_a}$$

where

$$\bar{S}_a = \tfrac{1}{a} \sum_{j=0}^{a-1} S_j$$

Introducing relative age in the same way as Hordyk *et al*. (2015a, b), where $x = a / a_{\max}$, and using (see Hordyk *et al*. 2015a for derivations):

$$a_{\max} = (-\ln P) / M$$

and

$$x = \frac{M}{\kappa} \frac{\ln(1-\tilde{L}_x)}{\ln P}$$

we have:

$$\begin{aligned} \tilde{N}_x &= e^{-xa_{\max}M - xa_{\max}F\bar{S}_x} \\ &= (1-\mathrm{E}[\tilde{L}_x])^{M/\kappa + F\bar{S}_x/\kappa} \end{aligned}$$

where:

$$\bar{S}_x = \frac{1}{(\sum_{j \le x} 1)} \sum_{j \le x} \tilde{S}_j$$

so that:

$$\tilde{N}_x = (1-\mathrm{E}[\tilde{L}_x])^{M/\kappa + (M/\kappa)(F/M)\bar{S}_x}$$

2.3.1.5 Testing

Hordyk *et al*. (2015b) evaluated the utility of LB-SPR for assessing data-poor and small-scale stocks. Their approach was to test the main assumptions (robustness to recruitment variability and dome selection), examine sensitivity to errors in model inputs, and apply the method to data from a well-studied species. The simulation model was based on four species with a diverse range of life histories (*M/κ* ratios varying from ~0.5 to ~3). A total of twelve tests were explored for each of these species:

1) Assumed M/κ ratios ± 25% of true value

2) Assumed L_∞ ± 25% of true value

3) Assumed CV[L_∞] ± 25% of true value

4) Number of age bins ranging from 10 to >200

5) Sample size reduced to 100, 500, 1000, 5000, 10 000

6) Length-at-birth ranging from 0 to 0.25 L_∞

7) True F/M ranging from 0.001–5

8) Recruitment variability = 0.1, 0.3, 0.6, 0.9

9) Test 8 with auto correlated recruitment variability

10) Test 8 with episodic recruitment failure

11) M/κ, L_∞ and CV[L_∞] drawn from triangle distributions and recruitment variability = 0.6

12) Increased dome selection and recruitment variability = 0.6

Results from these tests showed that:

- The model passed self-tests (i.e. estimates closely match true values when assumptions were correct)
- The estimation model was relatively insensitive to misspecified CV[L_∞], but highly sensitive to misspecified L_∞.
  - F/M appeared to be more sensitive to misspecified input values for M/κ and CV[L_∞] than SPR, but both showed high sensitivity to misspecified input values for L_∞.
- The model was completely insensitive to the number of age bins, as long as there were at least 25, and produced reasonably precise estimates for sample sizes of 1000 fish or more.
- The method was successful at correctly estimating parameters for recruitment variability up to 0.6, with SPR consistently well estimated for all four life histories tested; model performance deteriorated when recruitment autocorrelation was included, particularly for recruitment variability of 0.6 or more, with SPR being greatly overestimated in some cases.
- The low M/κ species was most sensitive to simultaneous error in all three inputs, with the model tending to overestimate F/M and underestimate SPR
- The model underestimated SPR in the face of dome selection for all four life histories tested, with the lower M/κ species being most sensitive to this

In general, the method appeared to work well for species with M/κ > 0.53, but is likely to be increasingly biased for species with lower M/κ than this, because the method relies on detecting the signal of fishing mortality in the right-hand side of the length composition; lower M/κ species will have length compositions with many adults of widely varying ages, but similar (near asymptotic) sizes. Fishing is therefore not likely to have a visible impact on the length composition until fishing mortality is very high and SPR very low (Hordyk *et al*., 2015b).

The method was also coupled with Harvest Control Rules (HCR) based on effort, and the combination tested within a Management Strategy Evaluation framework by Hordyk *et al*. (2015c) to evaluate performance under a range of scenarios. The HCRs adjusted effort (in various ways) based on comparing current SPR estimates with a given SPR target, with the aim of iteratively driving fishing pressure towards a level consistent with the target SPR. The scenarios included low and high initial stock equilibrium, and for the low scenarios, increased or auto correlated recruitment variability and a catchability trend. Generally, HCRs were able to guide the stocks tested towards the target SPR, but with the time taken to reach the target dependent on the M/κ ratio.

2.3.1.6 Caveats

- Method is equilibrium-based
  - if this assumption is a problem, it can be ameliorated by aggregating size data over generational time periods
- Method most likely limited to cases where asymptotic selectivity is a reasonable assumption (given difficulty of establishing the presence of doming for data-poor stocks)

- Method cannot fit multimodal length compositions well, leading to unrealistic estimates of F/M, selectivity and SPR in these cases
  - traditional length-based methods may be more suitable
  - problem could be tackled by collecting data at a higher temporal resolution
- Number of age classes need to be high enough to approximate continuous dynamics well
- Validity of assumptions need careful examination

2.3.1.7 Software

The software for LB-SPR is a reasonably short R-script, and is available on the WKLIFE V SharePoint site.

2.3.2 Application to *Nephrops* in FUs 28–29

The LB-SPR approach was run separately for males and females, because adults of the species are relatively sedentary and differential fishing mortality, as well as different life-history parameters, cause an imbalance between the sexes. Furthermore, successful mating may rely on males and females being a similar size, so fewer males being available at particular size may affect the number of females that are able to reproduce at these sizes. So in this case, male SPR may be as important as female SPR.

The analysis was run separately for each year and sex, so there are independent estimates for the estimable (F/M, L_{sel50} and L_{sel95}) and derived (SPR) parameters by year and sex. For this reason, these estimates are not linked by lines in the plots shown. Life-history parameters were taken from the stock annex and references therein, and are summarized in Table 2.3.2.1.

The fits to the catch–length frequency distributions for males and females are shown in Figure 2.3.2.1. The fit to the 2011 length distribution for males stands out as a poor fit because of the strong bi-modality in the data for that year. Figure 2.3.2.2 plots two measures of the mean length in the catch, one for the total catch and one weighted by selection (referred to below as mean selected length), to get a proxy for the mean length above length-at-first-capture (for comparability to similar metrics used by other methods presented). These plot show mean length varying within a range of ~8 mm for males and ~6 mm for females. Estimates of the selectivity parameters (L_{sel50} and L_{sel95}) are given in Figure 2.3.2.3, indicating considerable variation in selection from year to year.

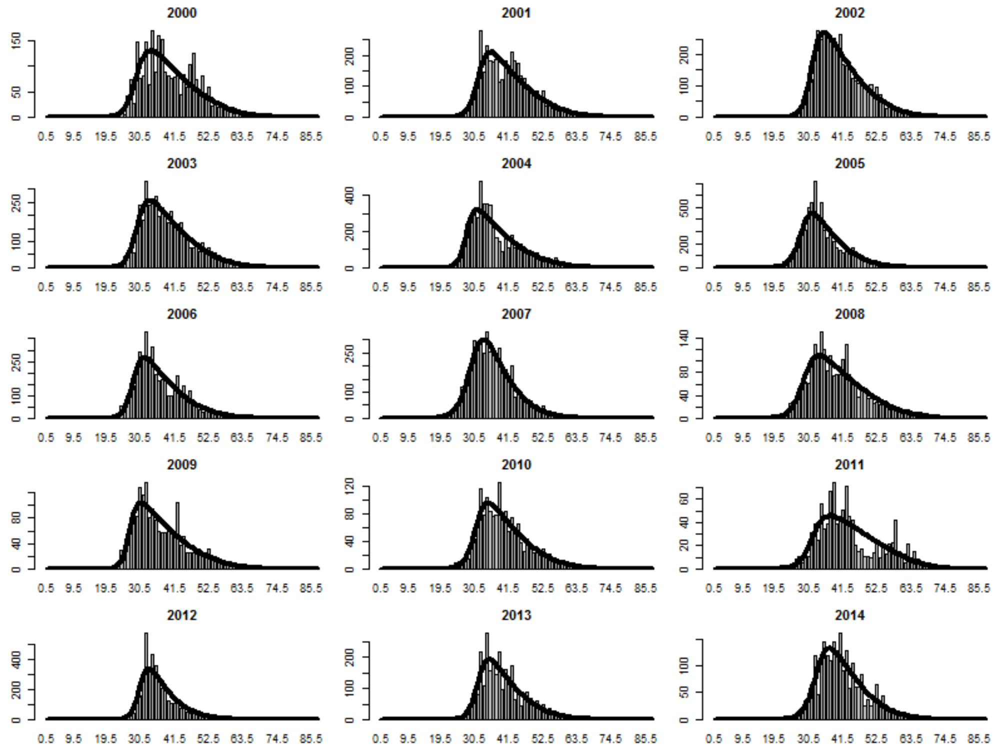
F/M and SPR are given in Figure 2.3.2.4, indicating heavier exploitation for males compared to females during the earlier years, but with similar levels of exploitation for both sexes in recent years (although uncertainty for recent years appears to be greater for females). Omitting the problematic 2011 fit for males, SPR for males has been at or below 30–40%, while SPR for females has been at or above this range. In case the contribution for population-level SPR differs by sex (e.g. males may not be as valuable for producing young as females) this range, if used as a "safe zone" target, would be different between the sexes (e.g. lower for males.

Figure 2.3.2.5 plots the change in mean selected length against the corresponding change in SPR, showing that the two are linked, as would be expected, with the correlation for the males being much clearer than for females (although note, the poorly fitted 2011 values for males was omitted from the regression).

Table 2.3.2.1. LB-SPR for *Nephrops* in FUs 28–29. Life-history parameters used in the model. Quantities used by the method but not shown below take on their default values (see Section 2.3.1.1). [Note that males are subject to knife-edge maturity, which is approximated by setting L_{mat50} and L_{mat95} to be close together.]

Parameter	Males	Females
M/κ	1.5	3.08
L∞	70 mm	65 mm
Lmat50	28.4 mm	28.1 mm
Lmat95	28.5 mm	38.1 mm
b	3.229	3.03

(a) Males


2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
0.5 9.5 19.5 30.5 41.5 52.5 63.5 74.5 85.5

(b) Females

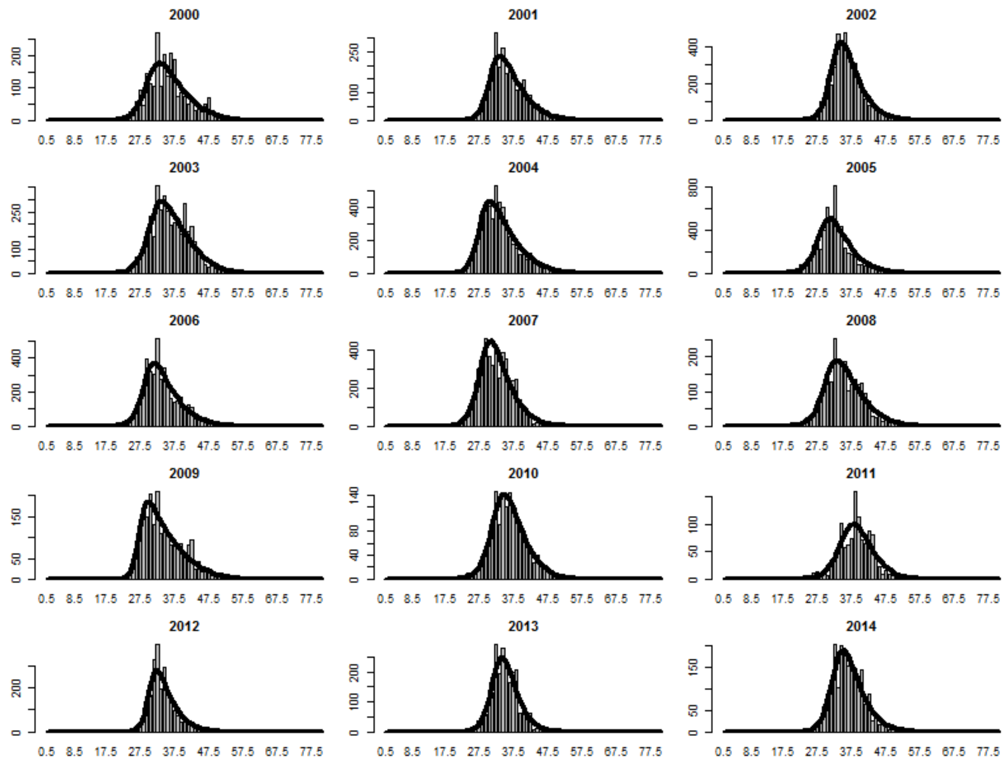


Figure 2.3.2.1. LB-SPR for *Nephrops* FUs 28–29. Model fits (solid lines) to the length–frequency distributions from the catch (vertical bars) for (a) males and (b) females.

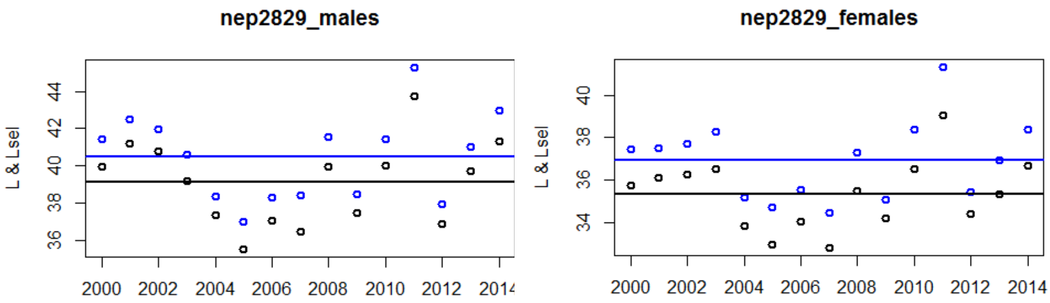


Figure 2.3.2.2. LB-SPR for *Nephrops* FUs 28–29. Mean length in the catch for males (left) and females. The lower black circles are weighted means using the midpoints of length bins weighted by the frequency of the bins for the entire catch. The upper blue circles apply a similar calculation, but with the midpoint of a length bins weighted by the product of the frequency and selection for that length bin (derived from the estimated selection parameters given in Figure 2.3.2.3). The horizontal lines give the corresponding overall mean for each mean length calculation.

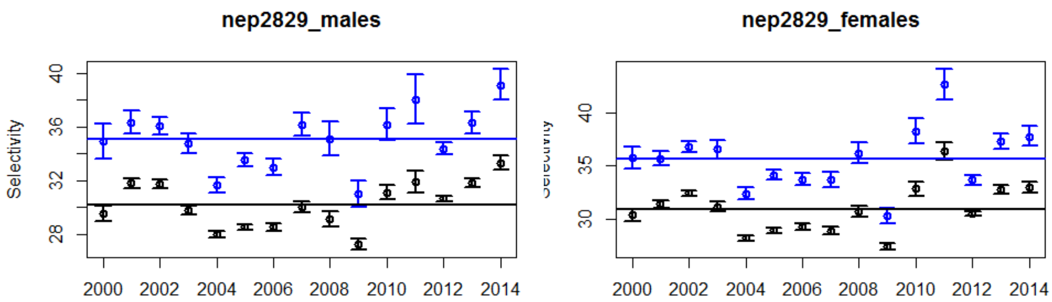
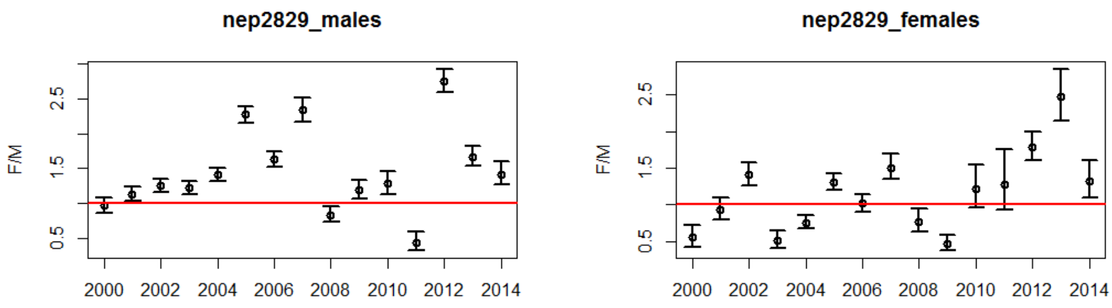


Figure 2.3.2.3. LB-SPR for *Nephrops* FUs 28–29. Estimates of the selectivity parameters (L_{sel50} in black and L_{sel95} in blue) with 95% confidence intervals for males (left) and females (right). The horizontal lines indicated the means across all years.

(a) F/M



(b) SPR

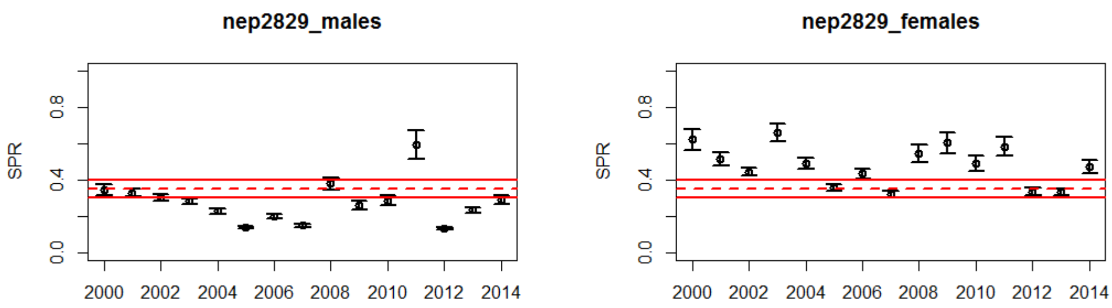


Figure 2.3.2.4. LB-SPR for *Nephrops* FUs 28–29. Estimates of (a) F/M and (b) SPR with 95% confidence intervals for males (left) and females (right). In (a) the horizontal red line reflects F=M, while in (b) the top solid red line reflects SPR=40%, the middle dashed red line SPR=35%, and the bottom solid red line SPR=30%.

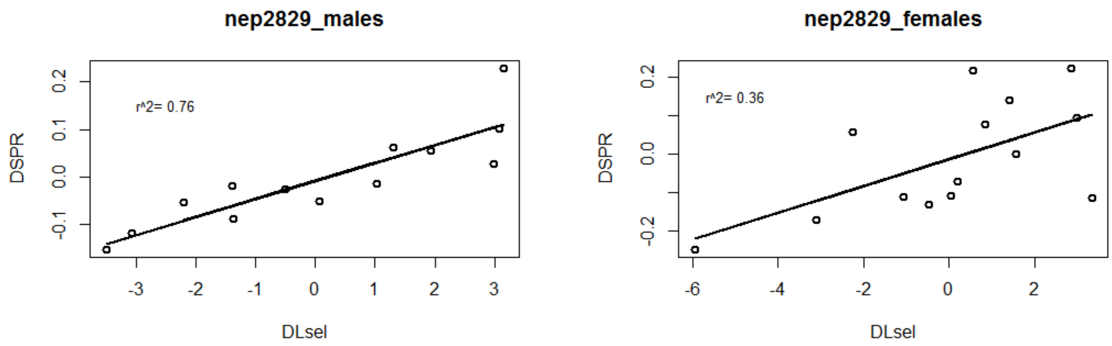


Figure 2.3.2.5. LB-SPR for *Nephrops* FUs 28–29. Interannual changes in SPR (DSPR) plotted against the corresponding interannual changes in mean selected length (DLsel; these correspond to the blue circles in Figure 2.3.2.2) for males (left) and females (right). Positive values indicate an increase from one year to the next, and negative values a decrease, moving forward in time. A regression line is plotted in each case, with the corresponding r^2 given in the plots. [Note, in the case of the males, the poor fit in 2011 is omitted, and the change accounting for that omission was between 2012 and 2010 (the only case where the difference was not interannual).]

2.3.3 Application to northern hake

The length–frequency data were grouped into 5 cm length bins to reduce the effects of bimodality. The LB-SPR analysis was run separately for each year, so there are independent estimates for the estimable (*F/M*, L_{sel50} and L_{sel95}) and derived (SPR) parameters. For this reason, these estimates are not linked by lines in the plots shown. Life-history parameters were taken or derived from values in the most recent working group report (ICES, 2015) and are summarized in Table 2.3.3.1.

The fits to the catch length–frequency distributions are shown in Figure 2.3.3.1. The fits to the length distributions for some years, particularly later years, stand out as a poor fits because of strong bi-modality in the data for those years. Figure 2.3.3.2 plots two measures of the mean length in the catch, one for the total catch and one weighted by selection (referred to below as mean selected length) to get a proxy for the mean length above length-at-first-capture (for comparability to similar metrics used by other methods presented). These plots show mean length varying within a range of ~25 cm and mean selected length within a range of ~38 cm. Estimates of the selectivity parameters (L_{sel50} and L_{sel95}) are given in Figure 2.3.3.3, indicating considerable variation in selection from year to year with a sharp increase in selection towards the end of the time-series.

F/M and SPR are given in Figure 2.3.3.4. SPR has been below the SPR range of 30–40% for the entire time-series. This is somewhat consistent with the latest assessment of northern hake, where SSB is very low (around B_{lim}) between the mid-1990s and mid-2000s. However, the assessment shows a significant increase in SSB from 2006 that is not reflected by an increase in SPR using the LB-SPR method. The F/M in 2012 has a large confidence interval and is over five times higher than other values in the time-series, indicating a poor fit to the length data for this year. This is confirmed by Figure 2.3.3.1, which shows strong bimodality in 2012. F/M roughly follows the trends of the assessment in the middle of the time-series but again fails to capture the strong decline in F/M that is apparent in the assessment in recent years.

Figure 2.3.3.5 plots the change in mean selected length against the corresponding change in SPR, omitting the poorly fitted 2012 value from the regression. The regression line is likely not significantly different from zero, suggesting that there is no link between the two. This is likely a consequence of poor fits to the data in years where the length distributions show strong bimodality, and indicates that the method may not be suitable for this stock because of a violation of the constant recruitment assumption. One way to deal with this would be to combine several length–frequency distributions (similar to the idea of a running mean), and then apply the methodology to provide annual estimates of F/M and SPR. This was not attempted during the meeting.

Table 2.3.3.1. LB-SPR for northern hake. Life-history parameters used in the model. Quantities used by the method but not shown below take on their default values (see Section 2.3.1.1).

PARAMETER	VALUE
M/K	2.255
L∞	130 cm
Lmat50	42.9 cm
Lmat95	57.6 cm
b	3.074

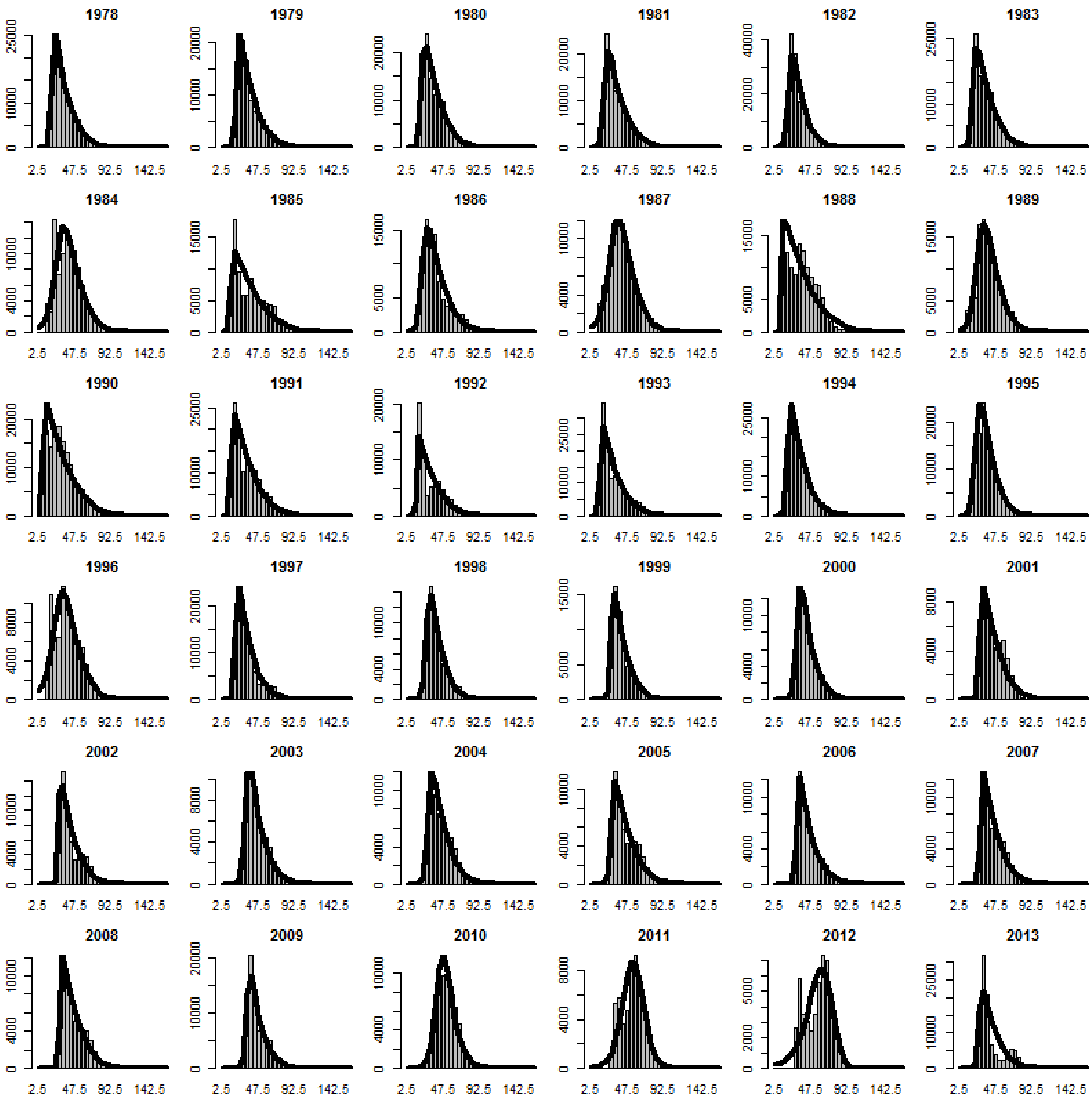


Figure 2.3.3.1. LB-SPR for northern hake. Model fits (solid lines) to the length frequency distributions from the catch (vertical bars).

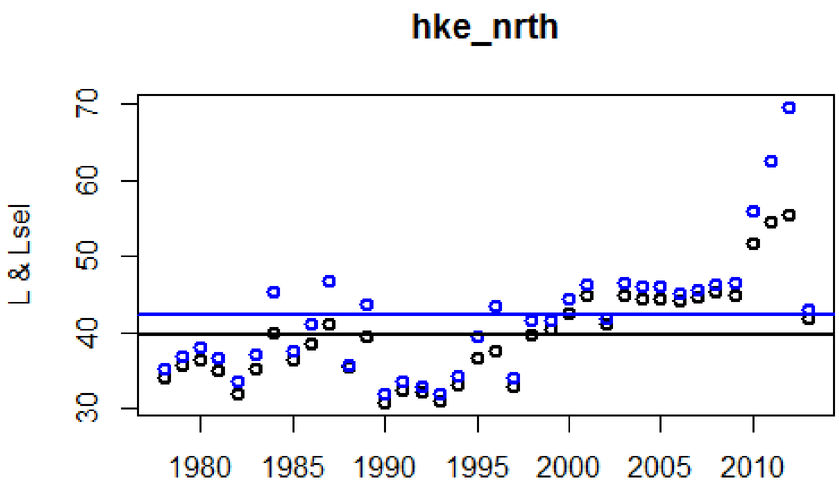


Figure 2.3.3.2. LB-SPR for northern hake. Mean length in the catch. The lower black circles are weighted means using the midpoints of length bins weighted by the frequency of the bins for the entire catch. The upper blue circles apply a similar calculation, but with the midpoint of a length bins weighted by the product of the frequency and selection for that length bin (derived from the estimated selection parameters given in Figure 2.3.3.3). The horizontal lines give the corresponding overall mean for each mean length calculation.

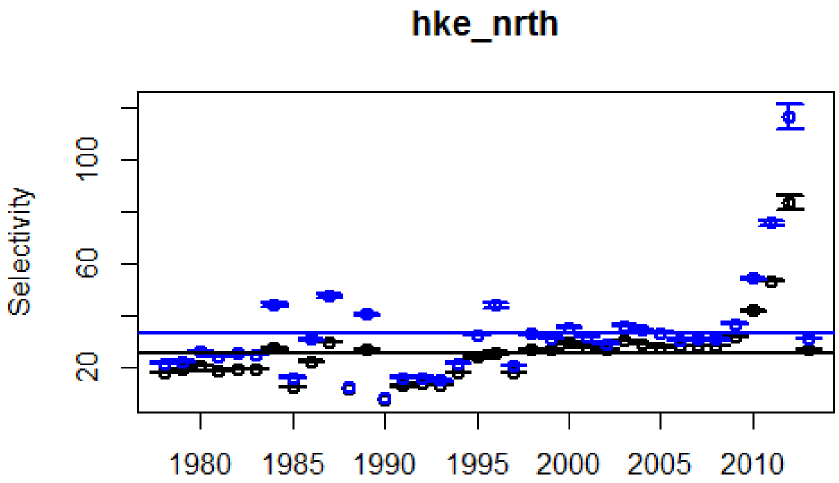
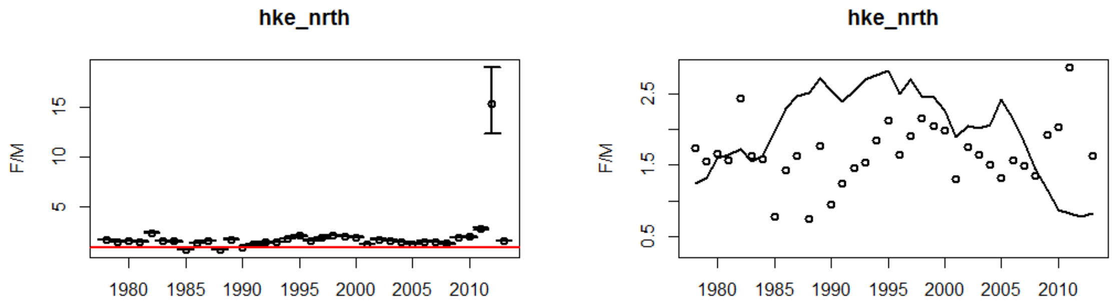


Figure 2.3.3.3. LB-SPR for northern hake. Estimates of the selectivity parameters (L_{sel50} in black and L_{sel95} in blue) with 95% confidence intervals. The horizontal lines indicated the means across all years.

(a) F/M



(b) SPR

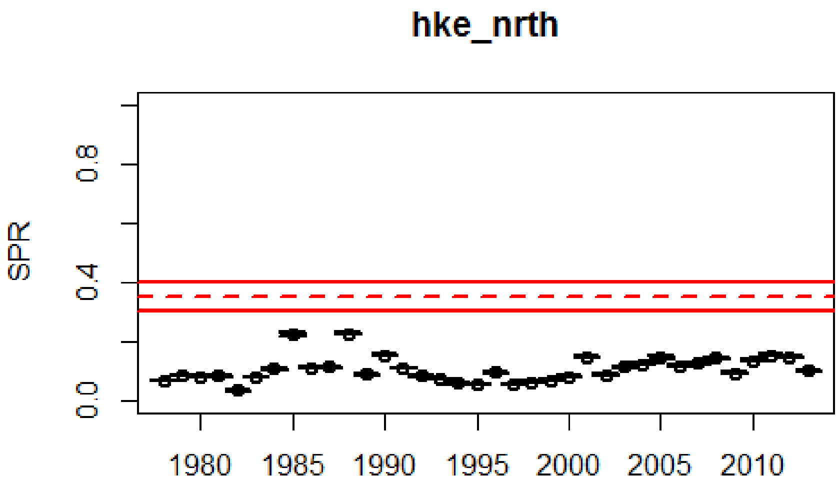


Figure 2.3.3.4. LB-SPR for northern hake. Estimates of (a) F/M with 95% confidence intervals (left) and compared to F/M from the assessment (right) and (b) SPR with 95% confidence intervals. In (a right) the horizontal red line reflects F=M, while in (b) the top solid red line reflects SPR=40%, the middle dashed red line SPR=35%, and the bottom solid red line SPR=30%. In (a left) the points are the estimates from the LB-SPR method while the solid line is F/M from the assessment. Note the poor fit in 2012 is omitted in this plot.

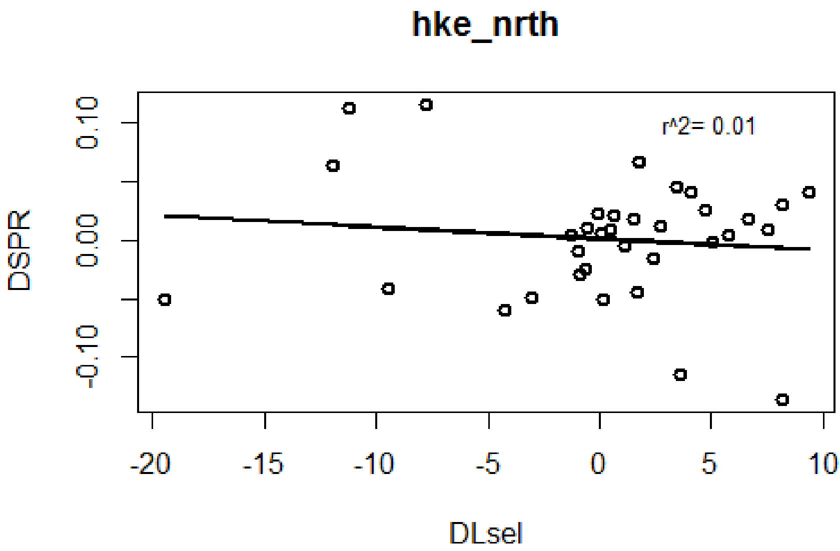


Figure 2.3.3.5. LB-SPR for northern hake. Interannual changes in SPR (DSPR) plotted against the corresponding interannual changes in mean selected length (DLsel; these correspond to the blue circles in Figure 2.3.3.2). Positive values indicate an increase from one year to the next, and negative values a decrease, moving forward in time. A regression line is plotted in each case, with the corresponding r^2 given in the plots. [Note the poor fit in 2012 is omitted, and the change accounting for that omission was between 2013 and 2011 (the only case where the difference was not interannual).]

2.4 S6model

2.4.1 Method

Size-based estimation of the fishing status of stocks is important in situations where ageing is not possible or inaccurate. The s6model is a single-species, size-based data-limited assessment method in steady state. Two applications of the method are shown, the *Nephrops* functional units 28–29 and the northern hake. The method requires only size frequencies from the catch and provides the fishing status of the stock, F/F_{MSY}. The method is based on a theoretical framework describing the demography and recruitment of an exploited population characterized by the asymptotic weight trait and a set of life-history invariants.

At the individual level, the available energy, growth and mortality are size-dependent. After maturation, some energy is allocated to reproduction. The total mortality is the sum of natural mortality and the mortality due to fishing. A sigmoid selectivity pattern for fishing mortality is assumed, a pattern consistent with many trawl and longline fisheries. Scaling up to the population level is achieved using the McKendrick–von Foerster conservation of mass equation. In steady state, an analytical solution of the partial differential equation leads to the theoretical size-spectrum of the population.

The model is parameterized using Beverton–Holt life-history invariants, reducing the number of model parameters and making the results insensitive to the choice of most of them. The results are mostly influenced by the choice of physiological mortality (relative to the M/k Beverton–Holt invariant). For more information on the theoretical framework see Andersen and Beyer (2013) and for a simulation analysis looking into sensitivity of the method to parameter input see Kokkalis *et al*. (2015). The method is being validated using data-rich stocks and comparing the outputs with official assessments. Preliminary results show that the method is able to capture the trends of fishing pressure with some issues in the level, constantly higher or lower F/F_{MSY} estimations compared to the official assessments for all years.

2.4.1.1 Data and information requirements

Minimum required information

- Size composition from the catch from one year
- If length frequencies are available, a weight–length relationship is needed

Default values from data-rich stocks are used for life-history invariants that are not estimated, preferably from similar stocks, e.g. same species from other regions or other species from the same region.

Extra information

- M/k ratio, single value or a distribution (as mean and standard deviation)
- 50% maturation size, W_{MAT}
- Asymptotic weight, W_∞

2.4.1.2 Assumptions

- Equilibrium-based method assumes that stock size and productivity components (recruitment, survival, growth) are approximately constant
- Size distributions from the catch are assumed to be representative (i.e. no biased sampling)
- Growth similar to von Bertalanffy, but with added reproduction costs
- Beverton–Holt stock–recruitment relationship
- Commercial selectivity follows a sigmoid curve (inflection point w_{50} is estimated). Alternative selectivity shapes can be used if sigmoid is inappropriate

2.4.1.3 Outputs expected

- Estimates of fishing status: quantified by the ratio F/F_{MSY}
- Estimates of W_∞ (asymptotic weight) and W_{50} (50% retainment size)
- If catch (or landings) data are available the spawning–stock biomass (SSB) and recruitment, but not relative to a reference point
- A time-series of estimates if size–frequency distributions are available for more years (estimation is independent for each year)

2.4.1.4 Method of operation

Weight is used as a measure of size. Thus, weight frequencies from the catch are expected. Alternatively, a weight–length relationship can be used to transform length–weight-frequencies. The default relationship W = 0.01 L ^ 3 can be used, when such information is not available. When length is transformed to weight, an appropriate bin size has to be chosen, so that enough weight classes are available for estimation without too many classes with zero value. As a rule of thumb, 30–100 weight classes are appropriate to most cases. The method operates on the available data from each year separately. Default values are available for all life-history invariants (Andersen and Beyer, 2013) but alternative values can be used if stock-specific information is available. The physiological mortality (corresponds to M/k life-history invariant) influences the results the most. Thus, a lognormal distribution (mean and standard deviation in the log scale) can be used instead of just a constant, resulting in uncertainty intervals of the estimates. The method is estimating three parameters, the fishing mortality F, the asymptotic weight W_∞ and the 50% retainment size w_{50}. The counts of each size class are assumed to follow a Poisson distribution given the theoretical size distribution. The F/F_{MSY} is then derived using the estimated size spectrum (N(w)) and maximizing the yield function $Y(F)$ over F:

$$Y(F) = \int_{w_r}^{W_\infty} F\ \psi_F(w)\ N(w)\ w\ dw$$

$$F_{msy} = argmax_F\ \{Y(F)\},$$

where F is the fishing mortality, $\psi_F(w)$ is the selectivity-at-weight.

Confidence intervals for all estimates can be calculated using the standard error provided for each quantity. Nevertheless, confidence intervals due to uncertainty of the physiological mortality are preferred.

2.4.1.5 Testing

Simulation testing of the method (Kokkalis *et al.*, 2015) showed that the method was mostly sensitive to the value of physiological mortality (a). This parameter is closely related to the Beverton–Holt life-history invariant M/k ($a = \frac{M}{3K}\eta_m^{(1-n)}$, where η_m is the relative maturation weight and n the exponent of consumption assumed equal to ¾).

2.4.1.6 Caveats

- Equilibrium method - aggregation of data over consecutive year can be used to produce steady-state snapshots of the size-distribution, e.g. to eliminate multimodal distributions
- Sigmoid selectivity shape is assumed - Violation of this assumption (e.g. domed selectivity) will have impact to the results. If the true selectivity of a stock is domed and sigmoid selectivity is assumed, the stock will appear to be in worse condition than in reality
- Results are sensitive to M/k inputs. The distribution of this parameter among similar stocks can be used if no information is available.

2.4.1.7 Software

An open source R package is being under development and is available under https://github.org/alko989/s6model

2.4.2 Application to *Nephrops* in FUs 28–29

The method was applied to the *Nephrops* functional units 28–29, separately on males and females, because of differences in growth and natural mortality between sexes. The size–frequency from each sex and each year were treated separately. The weight–length relationships and life-history parameters that were used in the assessment are shown in Table 2.4.2.1. For females the physiological mortality corresponding to M/k and given, was equal to 0.57. The model predicts that for asymptotic size the population is crashed, even without fishing pressure, for physiological mortality greater than 0.52. Thus, the assessment was done using a lower value for physiological mortality, i.e. 0.4. The available length frequencies from the catch were transformed to weight and binned in 5 g weight classes. The asymptotic weight W_∞ was not estimated.

The estimates of the fishing status F/F_{MSY} are shown in Figure 2.4.2.1 for females and males. Both sexes appear to be exploited close to F_{MSY}. The males have higher fishing mortality than females in all years. The estimates of 50% retainment size (w_{50} and L_{50}) are shown in Figure 2.4.2.2 for females and males. The mean across all years was 29 mm for females and 30 mm for males.

Table 2.4.2.1. Life-history parameters and weight–length relationship parameters for *Nephrops* in FUs 28–29 by sex.

Parameter	Males	Females
A	0.00028	0.00056
B	3.2229	3.0288
Lmat (Wmat)	28.4 mm (13.5 g)	30 mm (16.7 g)
Linf (Winf)	70 mm (247.6 g)	65 mm (173.4 g)
M/k (phys. mortality)	1.5 (0.24)	3.08 (0.4)

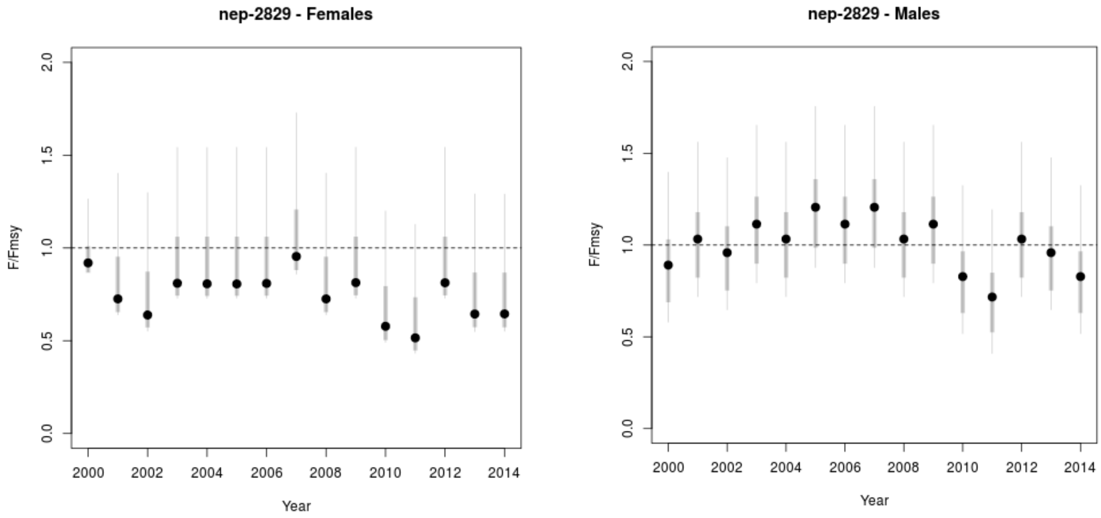


Figure 2.4.2.1. Estimates of F/FMSY of nep-2829 for females (left) and males (right). The thick grey lines show 50% confidence intervals and the thin grey lines 95% confidence intervals.

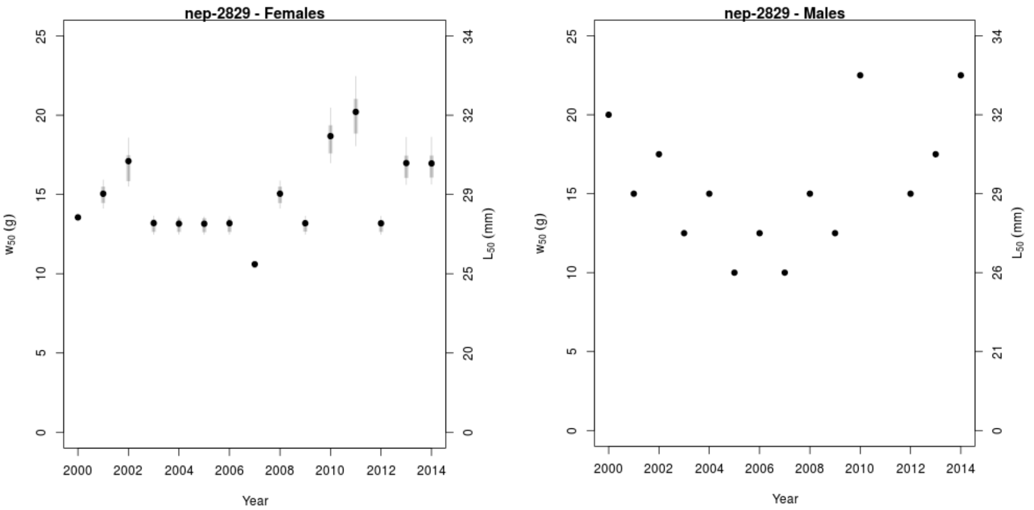


Figure 2.4.2.2. Selectivity parameter estimates for *Nephrops* FUs 28–29 females (left) and males (right). The 95% confidence intervals are shown as grey lines. In some cases they are narrower than the size of the dots. There are two y-axes the left one shows the size as weight and the right one as length.

2.4.3 Application to northern hake

The northern hake is a category 1 stock, i.e. it has an analytical assessment based on the length-based model StockSynthesis3. This makes it valuable as a validation example for new data-limited stock assessment methods. Life-history parameters and length–weight relationship are taken from the most recent working group report and is shown in Table 2.4.3.1. The length was transformed to weight and the data were binned in 100 g weight classes. The fishing mortality, 50% retainment size and asymptotic weight were estimated. The information about M/k and size-at-maturation was used in the assessment.

The results of the assessment (F/F_{MSY} and SSB) are compared to those from the benchmark assessment method and presented in Figure 2.4.3.1. Both methods indicate that fishing mortality was far above F_{MSY} for all years. The SS3 assessment shows a decreasing trend in fishing mortality, but the trend is not apparent in the assessment done using *s6model*. The trends and level of spawning–stock biomass (SSB) are similar in both assessments. The general conclusion about the stock status in the recent years is that the fishing pressure is high and the spawning–stock biomass is increasing. There are selectivity changes over time, the size at 50% retainment seems to be increasing (Figure 2.4.3.2).

Table 2.4.3.1. Life history and weight–length relationship parameters for the northern hake.

Parameter	Value
a	0.00513
b	3.074
Lmat (Wmat)	42.85 cm (533 g)
Linf (Winf)	130 cm (16157 g)
M/k (phys. mortality)	2.26 (0.32)

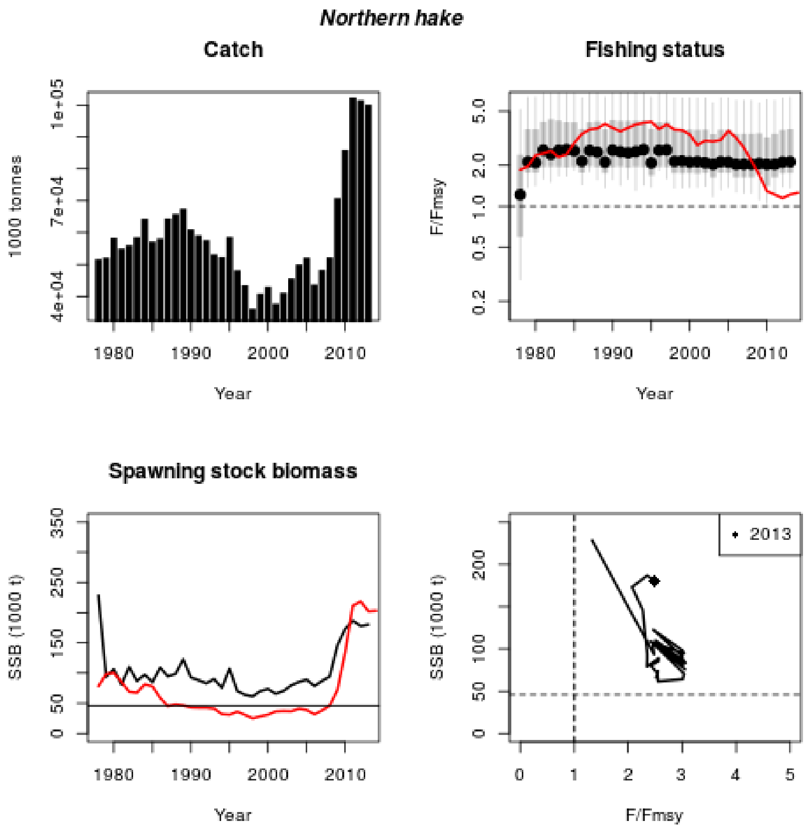


Figure 2.4.3.1. Assessment of northern hake using the s6model. The catch (upper left) is used to get the correct level of spawning–stock biomass (lower left). The red line shows the official assessment. The fishing status (F/FMSY, upper right) as estimated by s6model (dots: median, thick grey lines: 50% CI, thin grey lines: 95% CI) is compared to the official assessment (red line). The general perception of the stock status is shown in the SSB over F/FMSY plot (lower right).

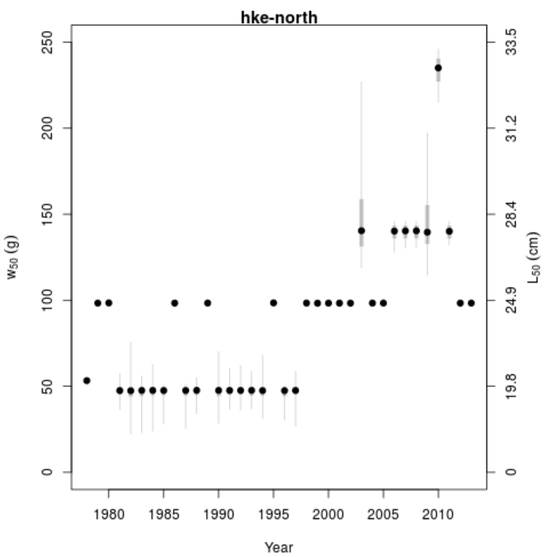


Figure 2.4.3.2. Selectivity parameter estimates for the northern hake (dots: median, grey lines: 95% CI). There are two y-axes, the left one shows size as mass and the right one as length.

2.5 Separable Length cohort Analysis

2.5.1 Method

Separable Cohort Analysis (SCA) is a statistical model which estimates recruitment, selectivity and fishing mortality by fitting to catch (and discards) by length and sex. It was originally devised as a method for use in conjunction with the underwater TV surveys used in many North Atlantic *Nephrops* stocks and can take the TV survey as an additional data point to constrain population size estimates. SCA works on the same general principles as Length Cohort Analysis (Jones, 1981) although LCA starts with the largest length classes and working backwards, whereas SCA estimates recruitment and works forwards. The main functional difference between the SCA and LCA is SCA's assumption of a parameterised selection pattern and the simultaneous fitting to male and female length distributions (assumption of equal recruitment). SCA is not a dynamic assessment model, because it operates on length frequencies under the assumption of equilibrium (just as LCA does) and residuals from the model should be examined for evidence of gross departure from this assumption before any results are presented.

There are a number of similarities to LCA in terms of the equations governing the time spent in each length class and some of the key assumptions.

- Growth is continuous;
- Population is in equilibrium;
- Landings are taken throughout year;
- The change in availability with respect to length only affects females and is a function of size at first maturity.

In addition to these common assumptions, there are two other assumptions specific to the *Nephrops* application.

- Recruitment is equal between sexes;
- Recruitment occurs at smallest size in data on 1 January;Selection functions for both the fishery and the TV survey follow a sigmoid curve and is flat topped;
- Survey represents an instantaneous snapshot in time.**Model**

It is possible to rewrite the von Bertanalaffy growth equations to give the length of time spent in any given length interval (equation 2.5.4). Assuming all recruits enter the system at the same size, it is then straightforward to project the decay of that cohort through time using the standard Baranov catch equations to give both population and catch numbers-at-length. As the population is assumed to be in equilibrium and has constant recruitment, the resulting length frequency of the catch from this cohort is equivalent to the expected length frequency of the catch in any given year.

$$N_{s,l+1} = N_{s,l} \times \exp^{-Z_{s,l}} \quad 2.5.1$$

$$Z_{s,l} = F_{s,l} + M_{s,l} \quad 2.5.2$$

$$C_{s,l} = N_{s,l} \times \frac{F_{s,l}}{Z_{s,l}} \times \left(1 - \exp\left(-Z_{s,l}\right)\right) \quad 2.5.3$$

$$\Delta t_{l,s} = \frac{1}{VBK_{l,s}} \times \log\left(\frac{L.INF_{l,s}}{L.Inf_{l,s} - l_{l+1}}\right) \qquad 2.5.4$$

Fishing mortality on a particular length class therefore becomes the product of the selection ogive, the fishing mortality at full selection and the time expended in that length class.

$$F_{l,s} = \Delta t_{l,s} \times \frac{f_s}{1 + \exp\left(\frac{s.50 - l}{s.50 - s.25}\right)} \qquad 2.5.5$$

s is sex, *l* is length, *f* is annual fishing mortality at full selection and s.25 and s.50 are the selection model parameters giving length at 25% selection and 50% selection, respectively.

Immature female *Nephrops* were considered to have the same characteristics as male *Nephrops* and therefore utilised common parameters. For females, maturity-dependent changes to parameters governing growth, natural mortality and availability to the fishery were modelled as a sigmoid function of length (eqn 2.5.6). Changes to growth and natural mortality parameters have previously been knife-edge at 50% maturity resulting in sharp discontinuities in survivorship and leading to difficulties in subsequent model fitting, smoothing these changes in line with the proportion mature at length alleviates such problems (eqn 2.5.7).

$$Mat = \frac{1}{1 + \exp\left(\frac{L.50_{mat} - l}{L.50_{mat} - L.25_{mat}}\right)} \qquad 2.5.6$$

$$p_{l,female} = \left(P_{male} \times (1 - Mat_l)\right) + \left(P_{female} \times Mat_l\right) \qquad 2.5.7$$

Where *P* is the parameter for growth, natural mortality or fishing mortality.

Discarding practice is also included in the model. The inputs to the model include landings and discards by length and sex. A discard ogive is fitted to the input data prior to the main parameter estimation section of the model. This ogive is then used to split the predicted numbers caught into landings and discard components.

In order to compare the modelled population to the estimates of abundance observed in the TV surveys, a total population index was constructed. The modelled length frequency represents the continuous evolution of the population through time, whereas the TV survey is a snapshot of population size at a particular point within the year subject to a survey selectivity function (same formulation as equation 2.5.6). The estimate of the population abundance at the time of the survey is therefore:

$$\hat{P} = \sum_{t=0.8,1.8,2.8....} N_{s,t}$$

As the basic unit of the model was length rather than time, some form of interpolation of population numbers was required to determine the population size at the exact time of the survey and a smooth spline function was used to this effect.

The objective function used for parameter estimation was the log likelihood of the predicted length frequencies (landings and discards) plus a penalty function for deviation from the observed TV abundance (equation 2.5.8). As the penalty function comprised just a single observation there was no estimable variance term for this part of the objective function so a manual weighting term was added. The first was the difference between the observed and predicted catch-at-length while the second was the difference between the observed TV survey abundance and the estimated abundance at the time of the survey.

$$ll = \frac{1}{2}\sum_{l,s}\left[\frac{\left(L_{l,s}-\hat{L}_{l,s}\right)^2}{\sigma_L^2}+\ln\left(2\pi\sigma_L^2\right)+\frac{\left(D_{l,s}-\hat{D}_{l,s}\right)^2}{\sigma_D^2}+\ln\left(2\pi\sigma_D^L\right)\right]+\alpha\left(N_{obs}-\sum_{t,s}\hat{N}_{t,s}\right)^2 \qquad 2.5.8$$

$$\sigma_x^2 = \frac{1}{n}\sum_{l,s}\left(X_{l,s}-\hat{X}_{l,s}\right)^2 \qquad 2.5.9$$

where α is a weighting factor for the fitting to TV abundance and *t* is the point in the year at which the survey takes place.

The model was fitted using the OPTIM function of R, and employed the "L-BFGS-B" fitting method to constrain the parameter estimates. Estimates of standard errors for the parameters were obtained from the inverse Hessian matrix.

The model had five parameters to estimate; initial population size at the smallest length class (equal sex distribution assumed), two selection parameters and two fishing mortalities at full selection, one for males and immature females, the other for mature females. Initial population size was estimated to be 5* the total numbers caught (TNC) and the bounds on population size were TNC to 10 000*TNC. Selection parameter L.25 was constrained at between 10 and 40 mm while L.50 was fitted as a multiplier on L.25, ranging from 1.000001 to 10. The range of the f multipliers for males, immature females, and mature females was constrained between 0.01 and 2.00. For the purposes of model fitting, population numbers were scaled to bring the estimates of recruits into the same order of magnitude as the estimates of F.

Data

The model requires landing and discard numbers by length and sex, typically a three year average to remove strong year-class effects. Additional parameters required are the von Bertalanffy growth parameters, natural mortality and weight–length parameters by sex. Parameters for ogives governing female maturity and the selectivity of the TV survey are also required (using the same formulation as equation 6).

Once the model has finished fitting to the length distributions, it then performs a yield and spawner per recruit calculation in order to estimate the three potential reference points used in Northeast Atlantic *Nephrops* stocks, $F_{0.1}$, $F_{35\%SpR}$ and F_{MAX}.

2.5.2 Application to *Nephrops* in FUs 28–29

The length–frequency data for FU28–29 *Nephrops* were compiled into running averages of three years in order to better satisfy the equilibrium assumptions. The model was then run sequentially through the 13 combined length distributions.

The model expects some discard data, so one individual was introduced as a discard at the smallest observed length.

Model parameters were as follows:

VBK.Female=0.065, L.INF.Female=65,

M.Female=0.2,

VBK.Male=0.2, L.INF.Male=70,

M.Male=0.3,

Length–weight Female=0.00056, 3.0288,

Length–weight Male=0.00028, 3.0288,

DISCARD.SURVIVAL=0

Female.Maturity.Ogive L25=24.8, L50= 28.1

Male.Maturity.Ogive, L25=28.3, L50=28.4

In addition to the three reference point estimates the model usually exports, we have also calculated the Spawning Potential Ratio to facilitate direct comparisons with the model described in Section 2.3. This was calculated as the spawner per recruit estimate for the observed fishing mortality rate divided by the spawner per recruit expected with no fishing. SPR was determined for each sex at each year.

Results

An example output is given in Figure 2.5.1 showing the model fit, estimated selection patterns, residuals and yield-per-recruit curves (males, females and combined). The length distributions appear to follow the exponential decay expected under the assumption of equilibrium conditions, and there are no systematic deviations in the residuals. The full exploitation F estimate is around 0.2 for females and 0.5 for males. F_{BAR} calculations are performed over the range 25–55 mm, hence F_{BAR} is generally lower than the plateau F.

The reconstructed time-series of model fits is shown in Figure 2.5.1. Recruitment is estimated to be generally declining through time and has quite tight 95% confidence intervals. Selection parameters are also estimated with low variance, having declined by about 4 mm until about 2008 and have risen again since. The greatest uncertainty comes from the estimates of fishing mortality, but despite the wider confidence intervals there appears to be a significant difference between the sexes and a significant change in fishing mortality through time. Although not formally tested, there would appear to be no obvious correlation between the different parameter estimates.

The spawning potential ratio estimates differ from those estimated in section 2.3 (LB-SPR) in both pattern and magnitude to some extent. The SPR estimates from SCA are correlated between the sexes, which is expected given that they share a selection pattern and recruit estimate. The overall pattern from SCA is more similar to the pattern observed for males in LB-SPR, possibly reflecting that the SCA fitting algorithm is biased towards the length distribution with the largest values (males outnumbering females in this case). There are, however, no indications from the model fit plots and diagnostics that female length distributions are systematically of a poorer fit. The smoothing introduced by the three year averaging process does not explain why the SPR estimate of SCA is decreasing in the terminal year (2012–2014 length distributions) while the LB-SPR indicators are level or increasing.

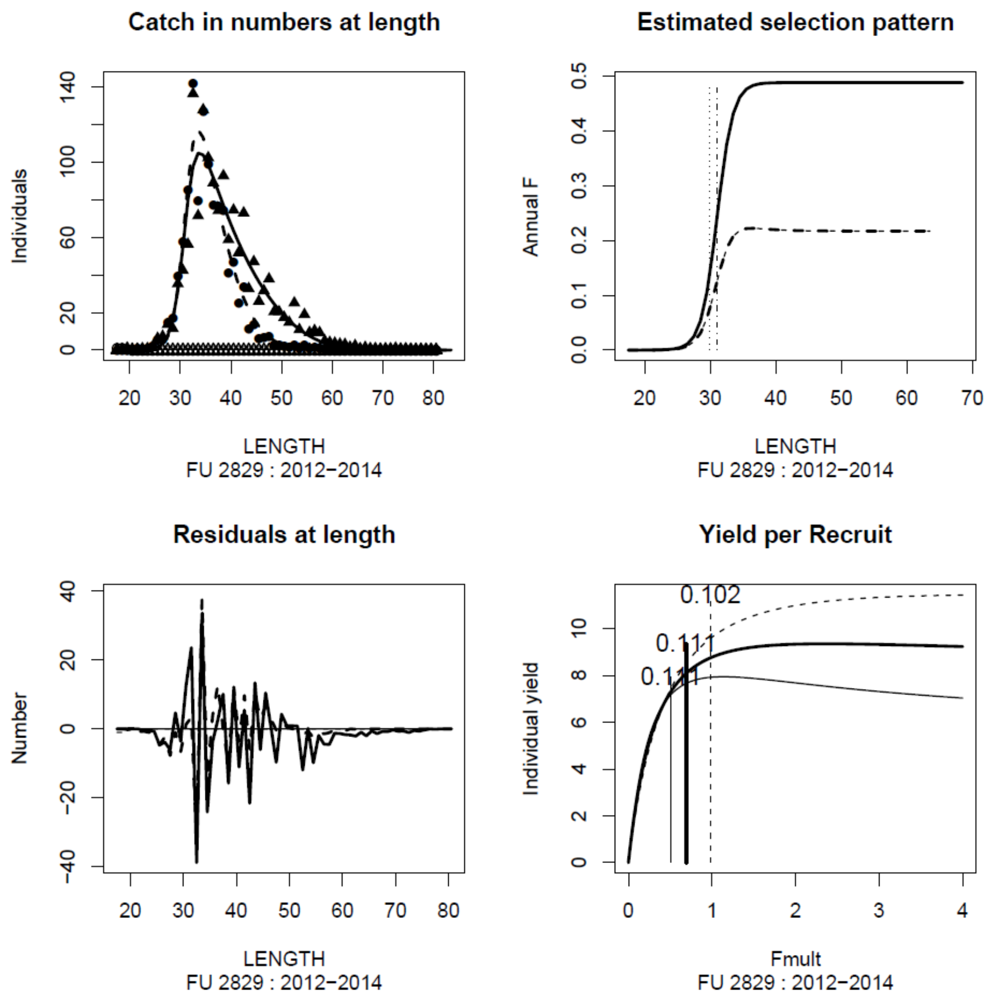


Figure 2.5.1. SCA for *Nephrops* FUs 28–29. Example plot from the SCA model showing fits to data, residuals and the estimate of $F_{0.1}$ for the 2012–2014 averaged length distributions. A) Fits to the length distribution, circles are observed females, dashed line is the fit, triangles are males and the solid line the fit. B) Realised selection pattern – solid line is males and dashed line is mature females. C) Residuals, solid line=males, dashed line=females. D) Yield-per-recruit curves, solid line=males, dashed line=females, thick line = combined with estimates of $F_{0.1}$ indicated.

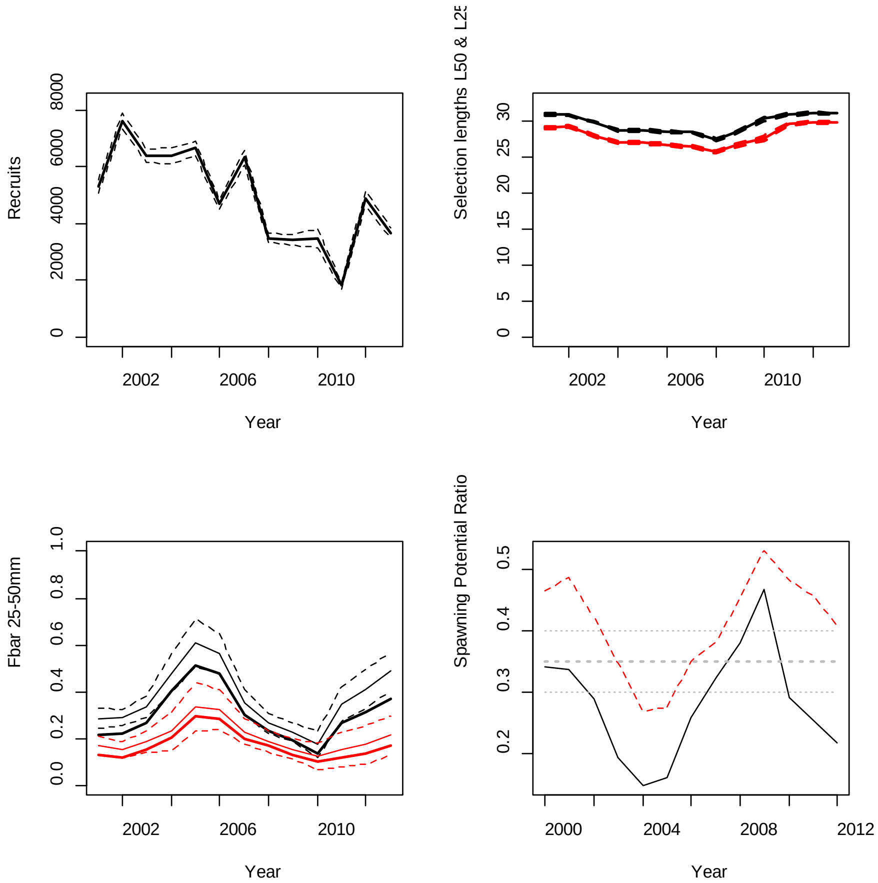


Figure 2.5.2. SCA for *Nephrops* FUs 28–29. Reconstructed time-series of model estimates. A) Recruitment with 95% CI, B) Selection parameters L50 (black) and L25 (red) with 95% CI. C) Fishing mortality, fully selected=thin lines with 95% CI and the FBAR value as the thicker line, black is males, red is females. D) Spawning Potential Ratio, black is males, red is females.

2.6 Empirical estimates of FMSY from life-history traits

2.6.1 Method

Production model theory relates the intrinsic (maximum) rate of population increase r to the fishing mortality rate producing maximum sustainable yield. Thus, under a logistic production model, FMSY = $r/2$. The intrinsic rate of increase is correlated with life-history traits. It follows that if we could develop a model to predict r, and thus FMSY, from easy to obtain life-history parameters we would have a simple method to estimate FMSY for use with data-limited stocks.

Past studies have related *r* maximum body size (Blueweiss *et al.*, 1978; Pauly, 1982; 1984) and generation time (Heron, 1972) using linear regression. Currently, the Hoenig laboratory at Virginia Institute of Marine Science is developing a database with values of r, and the corresponding values of maximum age and asymptotic weight for a variety of marine stocks including crustaceans, molluscs, elasmobranchs, teleosts and marine mammals. The *r* values are being collected from non-equilibrium surplus production models, observed population growth of invasive species and observed recovery of depleted species. The estimates of *r* in this database will be independent from life-history traits, for example, an estimate of r from the results of a statistical catch-at-age model that assumes of value of natural mortality rate (M) would not be used. No Bayesian approaches are intended to be used unless it can be shown that the estimate of r is insensitive to the prior. The choice of maximum weight and maximum age as predictor variables was made on the basis of these parameters being widely available and known to be related to population growth rate. This work is patterned after the study by Then *et al*. (2015) who related natural mortality rate to maximum age and growth parameters.

The simple method of using life-history traits to estimate F_{MSY} will be useful for data-poor stocks. In addition, this method can be used to evaluate the plausibility of estimates from other methods and provide information for priors for other models. The database is in the process of being expanded, and this method is still in the development stage so results here are exploratory.

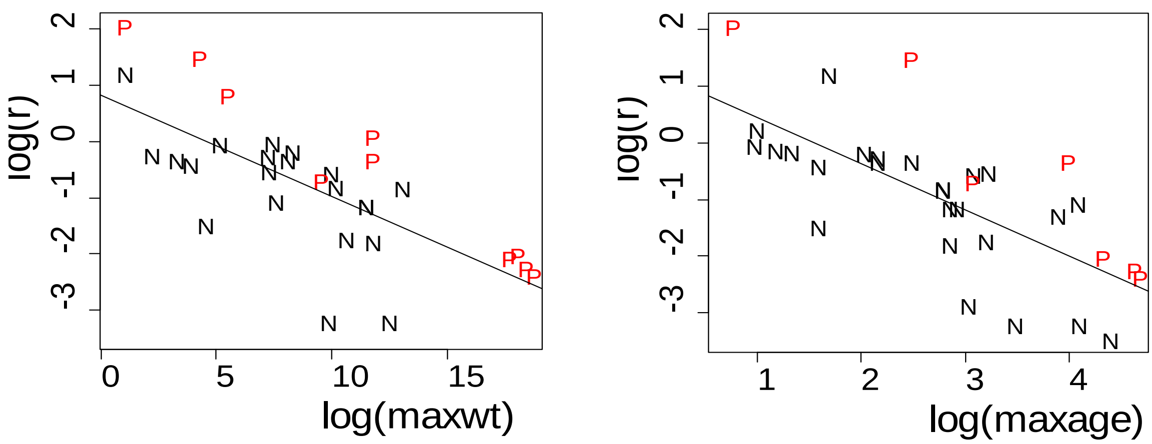


Figure 2.6.1. Plots of log(r) vs. log(max weight) and log(max age) with collected metadata (indicated by N) and Pauly, 1982; 1984 (indicated by P).

2.6.1.1 Data and information requirements

This method only requires an estimate of maximum recorded age and/or maximum weight (w_∞).

2.6.1.2 Assumptions

It is assumed that most of the deviation of the observed r values from the regression line is due to measurement error rather than species to species variability of r values given the value of the predictor variable (i.e. due to process error).

2.6.1.3 Outputs expected

This method at present produces four estimates of *r*. Two equations use maximum recorded age (T_{MAX}) to produce *r* estimates with one equation using only information in our database and the other equation using our information and data from Pauly (1982, 1984). The second set of equations use w_∞ to estimate *r* with one equation using information from our database only and the other additionally using the Pauly data.

2.6.1.4 Method of operation

The following are the preliminary equations for estimating log(*r*) from log(w_∞) and log(T_{MAX}) using the data from our database with and without data from Pauly, 1982; 1984.

Max weight with data from Pauly (1982; 1984)

$\log(r) = 0.8362 – 0.1804 * \log(w_\infty)$ (goodness-of-fit: r = -0.71)

Max weight without data from Pauly (1982; 1984)

$\log(r) = 0.5379 – 0.1803 * \log(w_\infty)$ (goodness-of-fit: r = 0.63)

Max age with data from Pauly (1982; 1984)

$\log(r) = 1.2806 – 0.8176 * \log(T_{MAX})$ (goodness-of-fit: r=-0.71)

Max age without data from Pauly (1982; 1984)

$\log(r) = 1.1091 – 0.8464 * \log(T_{MAX})$ (goodness-of-fit: r=-0.72)

2.6.1.5 Testing

The methods have not been tested yet.

2.6.1.6 Caveats

The models currently produce large prediction intervals and the equations are in preliminary stages. Data have not been verified and models are still in development. The equations are being updated as more life history and *r* values are added to the database.

2.6.1.7 Software

Not applicable.

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3 Catch and cpue-based methods (SPiCT)

3.1 Stochastic Production model in Continuous-Time (SPiCT)

Stochastic Production model in Continuous-Time (SPiCT) (Pedersen and Berg, submitted) was presented to WKLIFE as a traditional surplus production model with several advancements. SPiCT is formulated as a state–space model and incorporates dynamics related both to the fisheries (F) and to the biomass (B) in the form of Pella and Tomlinson (1969). These two latent processes are then related to the observed data (catches and Catch per Unit of Effort: cpue - either commercial or from surveys) via observation equations, which include error terms.

The equations of the model are defined:

Process equations (random effects):

- Biomass: $dB_t = rB_t\left(1 - \left[\frac{B_t}{K}\right]^{n-1}\right)dt - F_tB_tdt + \sigma_B B_t dW_t$.
- Fishing: $d\log(F_t) = f(t, \sigma_F)$,

where W_t is Brownian motion (noise term).

Observation equations:

- Index: $\log(I_t) = \log(qB_t) + e_t, \quad e_t \sim N(0, [\alpha\sigma_B]^2)$.
- Catch: $\log(C_t) = \log\left(\int_t^{t+\Delta} F_sB_sds\right) + \epsilon_t$,
  $\epsilon_t \sim N(0, [\beta\sigma_F]^2)$.

The model for the fishing mortality represented by $f(t, \sigma_F)$ is, when using annual data, a random walk (or diffusion). If subannual data are available a model for F incorporating a seasonal pattern is applied. The model parameters are defined:

- B_t: Exploitable stock biomass.
- F_t: Fishing mortality.
- r: Intrinsic growth rate: growth, recruitment, natural mortality.
- K: Carrying capacity or equilibrium biomass or virgin stock biomass.
- n: Parameter determining the shape of the production curve.
- q: Catchability.
- σ_B: Standard deviation of B_t.
- σ_F: Standard deviation of F_t.
- α: Ratio of standard deviation of I_t to standard deviation of B_t.
- β: Ratio of standard deviation of C_t to standard deviation of F_t.

With limited information, it is often difficult to estimate n, in which case n is set to 2 resulting in the Schaefer model. Similarly it is not always possible to estimate α and/or β, in which case they are set to 1, which is a common assumption (Thorson *et al.*, 2013). However, this default assumes equal error in catch and cpue, which deviates from simpler observation error models that assume no error in the catch but may be appropriate to data-limited stocks.

The SPiCT formulation is a generalisation of previous surplus production models in that it includes the dynamics of the fishery and the uncertainty of the observed catches, which are commonly omitted in similar models. The SPiCT is therefore able to make short-term projections of biomass as well as both fishing mortality and catch including uncertainty.

The continuous-time formulation of SPiCT, as opposed to constant fixed time-steps, enables the model to accommodate arbitrary and irregular data sampling without a need for catch and index observations to match temporally. It is therefore straightforward to fit SPiCT to data containing a mix of annual, biannual and quarterly data. Such increased sampling frequencies will typically lead to a large sample size than the corresponding annual dataset. While autocorrelation between observations likely also increases at higher sampling frequencies, simulations have shown that increased sample size leads to increased precision on certain model parameters, in particular noise parameters.

3.1.1 Data/information requirements

The model uses observed data on landings or catches and cpue indices either commercial or from surveys. The model can handle several cpue time-series. The model does not include stock demographic data.

3.1.2 Assumptions

Important model assumptions shared by all production models include:

1) No migration takes place in and out of the stock as changes in biomass only occur through growth via r and K and through fishing.

2) No lagged effects in the dynamics of the biomass as caused by variability of the size/age-distribution.

3) Constant catchability i.e. no change in technology of fishing technique that changes q.

4) Gear selectivity is not part of this model and would require and extension to be included; e.g. to a stage-based form.

5) No knowledge of natural mortality is required because it's included in the intrinsic growth rate, r.

3.1.3 Outputs expected

In addition to parameter estimates, the model provides estimates of management reference points B_{MSY}, F_{MSY}, and MSY (maximum sustainable yield), where B_{MSY} is the biomass that leads to maximum surplus production (i.e. MSY), similarly F_{MSY} is the fishing mortality leading to MSY. All estimates of reference points include uncertainty (95% confidence intervals). A further benefit of the TMB package (Template Model Builder, see below) is that one-step-ahead residuals are provided automatically, which should be independent and standard normally distributed for the model output to be valid.

3.1.4 Method of operation

The SPiCT is implemented as an R-package and uses the Template Model Builder (TMB) package to obtain fast and efficient model estimation.

3.1.5 Testing

The R-package had been tested prior to WKLIFE V on two stocks which were presented in plenary during the meeting in Lisbon, South Atlantic albacore and Norway pout in ICES Subarea IV and Division IIIa.

In addition, the estimation performance of SPiCT has been tested with simulation in terms of estimation stability (proportion of converged runs), estimation precision (expressed by the coefficient of variation of parameter estimates), and the reliability of 95% CIs (proportion containing the true parameter). These quantities were evaluated for the full model, and for models with certain parameters fixed ($n=2$, $\alpha=1$, $\beta=1$). Data were, in all cases, generated and estimated by the same model. Results generally showed expected behaviour; namely, that i) proportion of converged runs was higher for simpler models and increasing number of datapoints, ii) estimation precision improved for increasing number of datapoints for all models, and iii) the proportion of 95% confidence intervals containing the true parameter approached 0.95 for increasing datapoints for all models.

3.1.6 Caveats (including problems, difficulties and issues with application)

Departures from independence and standard normality of residuals indicate that model assumptions have been violated. It is therefore important to report residual diagnostics together with model results such that correct interpretations can be made.

3.1.7 Software

The SPiCT is implemented as an R-package and uses the Template Model Builder (TMB) package to obtain fast and efficient model estimation.

3.2 Application to *Nephrops* in Southwest and South Portugal (FUs 28–29)

SPiCT run: Official landings and catch per unit of effort (cpue – kg hour^{-1}) from the crustacean trawl survey (PT-CTS).

SPiCT settings: Observation equation parameters ($\alpha = \beta = 1$). Process equation parameters (t = 0.2 based on YPR $F_{0.1}$ calculated in 2011, assumed $\sigma_F = 0.5$).

Stock and exploitation status (inferred from SPiCT):

Fishing pressure				
	2012	2013	2014	
MSY (F_{MSY})	✓	✓	✓	Appropriate
Precautionary approach (F_{PA},F_{lim})	?	?	?	Undefined

Stock size				
	2013	2014	2015	
MSY ($B_{trigger}$)	✓	✓	✓	Above trigger
Precautionary approach (B_{PA},B_{lim})	?	?	?	Unknown

Stock development over time:

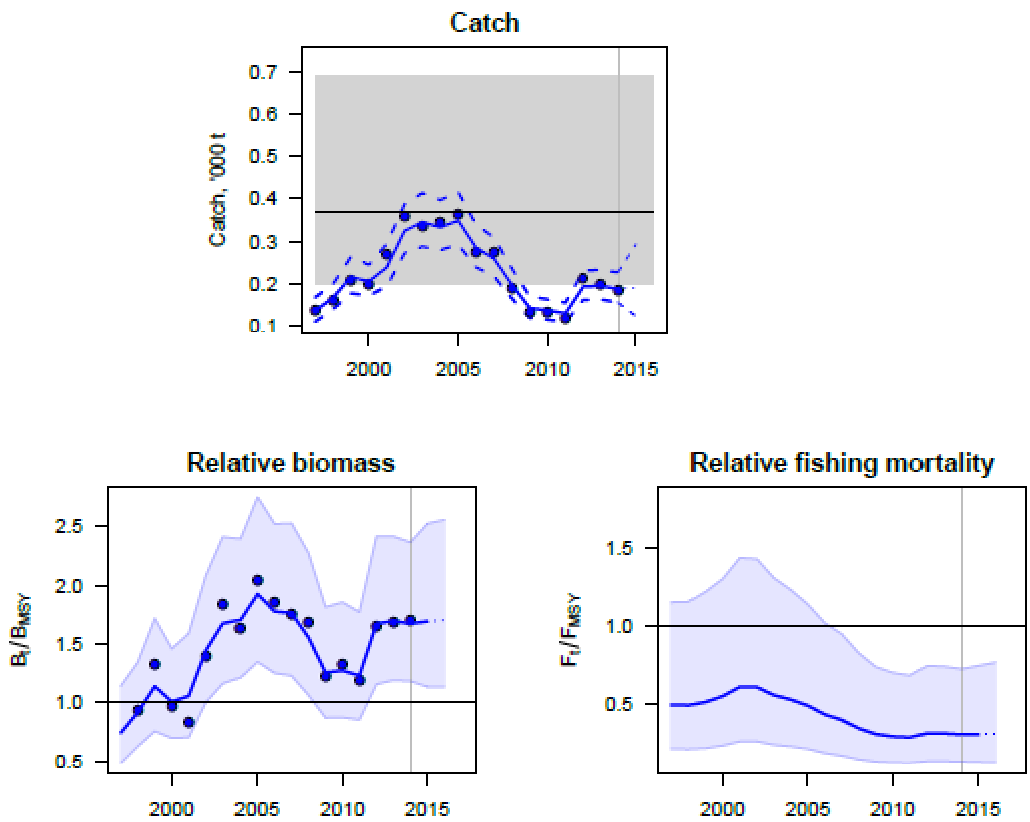


Figure 3.2.1. SPiCT model output (top left: time-series of catch used, bottom left: relative biomass estimates over time, bottom right: relative fishing mortality over time).

Reported residual diagnostics from the SPiCT model are appropriate.

3.3 Application to selected ICES category 3 stocks

Additionally to the application to the common stock used throughout this workshop, three further stocks were considered and are presented below:

- cod (*Gadus morhua*) eastern Baltic stock in Subdivisions 25–32 (Eastern Baltic Sea) and Subdivision 24
- dab (*Limanda limanda*) in Subdivisions 22–32 (Baltic Sea)
- cod (*Gadus morhua*) in Division IIIa East (Kattegat)

3.3.1 Cod (*Gadus morhua*) eastern Baltic stock in Subdivisions 25-32 (Eastern Baltic Sea) and Subdivision 24

SPiCT run: Commercial catch (landings and discards) and catch per unit of effort (cpue – kg hour^{-1}) from the Baltic International Trawl Survey (BITS-Q1+Q4) of fish larger than or equal to 30 cm.

SPiCT settings: Observation equation parameters ($\alpha = \beta = 1$).

Stock and exploitation status (inferred from SPiCT):

Fishing pressure				
	2012	2013	2014	
MSY (F_{MSY})	✓	✓	✓	Appropriate
Precautionary approach (F_{PA},F_{lim})	?	?	?	Undefined

Stock size				
	2013	2014	2015	
MSY ($B_{trigger}$)	✓	✓	✓	Above trigger
Precautionary approach (B_{PA},B_{lim})	?	?	?	Unknown

Stock development over time:

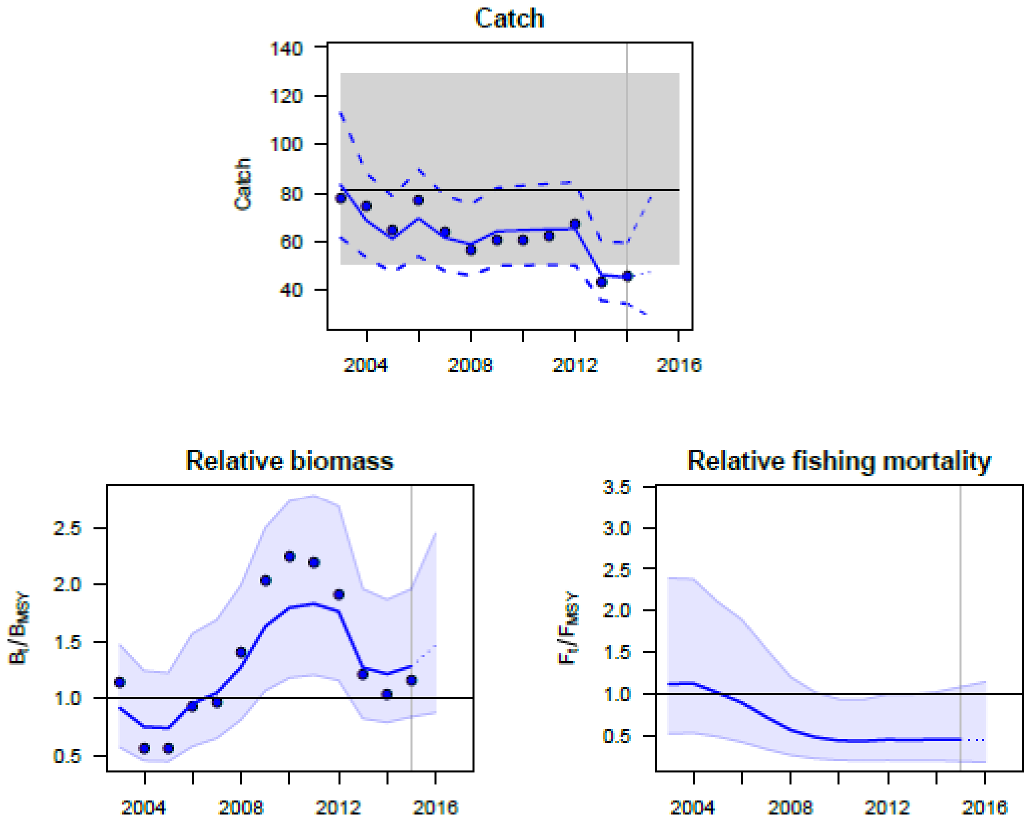


Figure 3.3.1. SPiCT model output (top left: time-series of catch used, bottom left: relative biomass estimates over time, bottom right: relative fishing mortality over time).

Reported residual diagnostics from the SPiCT model are appropriate.

3.3.2 Dab (*Limanda limanda*) in Subdivisions 22–32 (Baltic Sea)

SPiCT run: Official landings and catch per unit of effort (cpue – kg hour^{-1}) from the Baltic International Trawl Survey (BITS-Q1+Q4) of fish larger than or equal to 15 cm.

SPiCT settings: Observation equation parameters ($\alpha = \beta = 1$).

Stock and exploitation status (inferred from SPiCT):

Fishing pressure				
	2012	2013	2014	
MSY (F_{MSY})	✓	✓	✓	Appropriate
Precautionary approach (F_{PA},F_{lim})	?	?	?	Undefined

Stock size				
	2013	2014	2015	
MSY ($B_{trigger}$)	✓	✓	✓	Above trigger
Precautionary approach (B_{PA},B_{lim})	?	?	?	Unknown

Stock development over time:

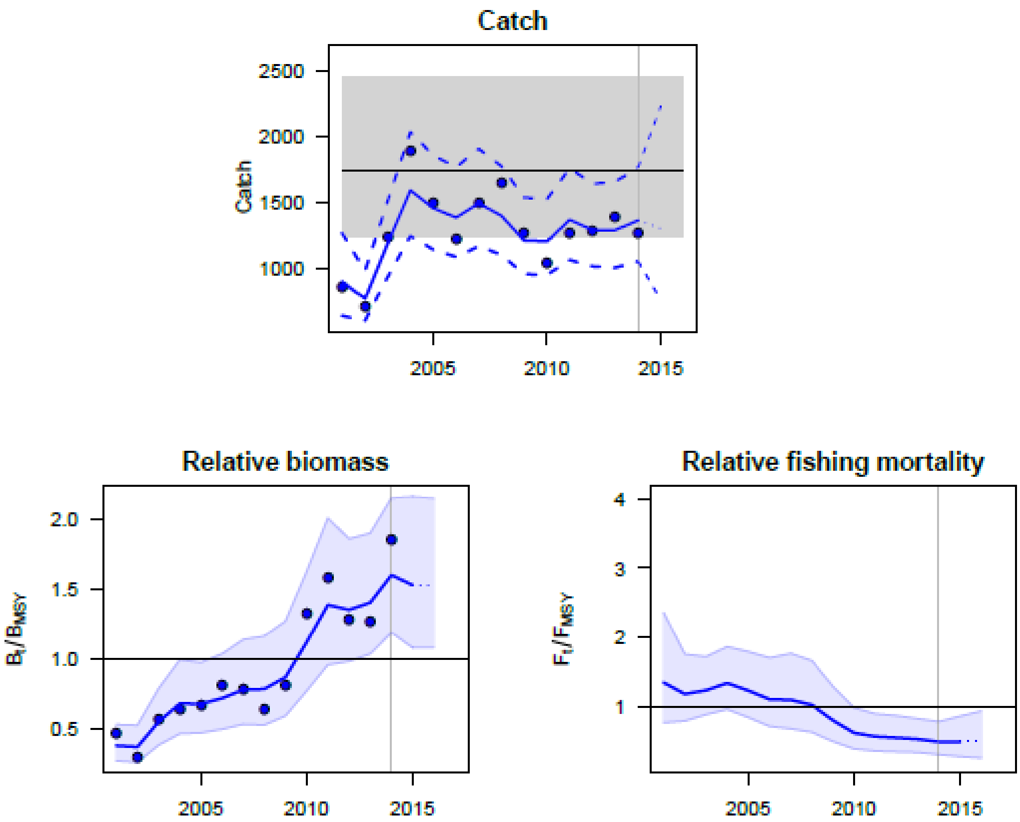


Figure 3.3.2. SPiCT model output (top left: time-series of catch used, bottom left: relative biomass estimates over time, bottom right: relative fishing mortality over time).

Reported residual diagnostics from the SPiCT model are appropriate.

3.3.3 Cod (*Gadus morhua*) in Division IIIa East (Kattegat)

SPiCT run: Commercial catch (landings and discards) and catch per unit of effort (cpue – kg hour-1) from five bottom-trawl surveys (IBTS-Q1, IBTS-Q3, Havfisken-Q1, Havfisken-Q4 and cod survey for 2008–2014).

SPiCT settings: Observation equation parameters (α estimated, β = 1).

Stock and exploitation status (inferred from SPiCT):

Fishing pressure				
	2012	2013	2014	
MSY (F_{MSY})	✔	✔	✔	Appropriate
Precautionary approach (F_{PA},F_{lim})	?	?	?	Undefined

Stock size				
	2013	2014	2015	
MSY ($B_{trigger}$)	✘	✔	✔	Above trigger
Precautionary approach (B_{PA},B_{lim})	?	?	?	Unknown

Stock development over time:

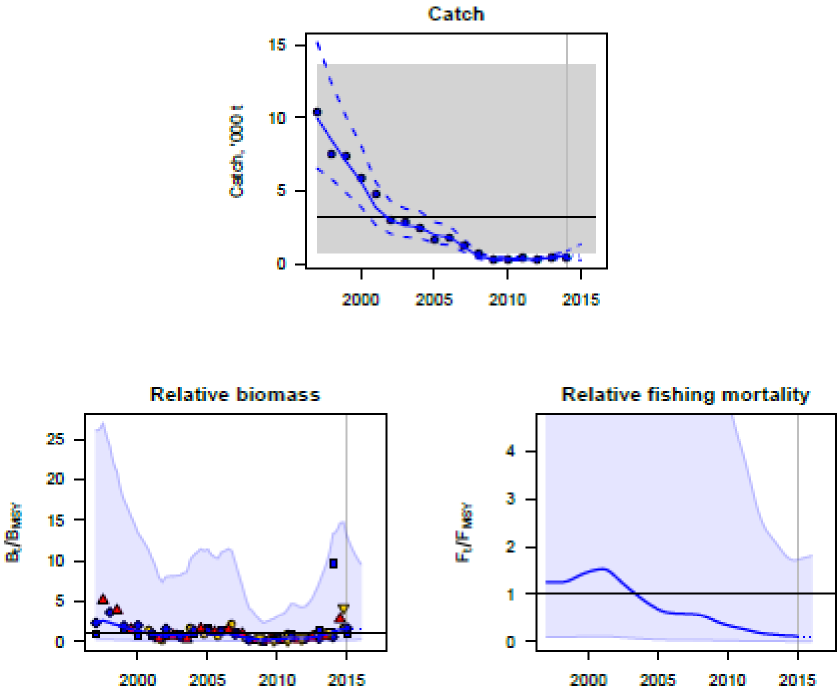


Figure 3.3.3. SPiCT model output (top left: time-series of catch used, bottom left: relative biomass estimates over time, bottom right: relative fishing mortality over time).

Reported residual diagnostics from the SPiCT model are appropriate.

3.4 References

Pedersen, M.W. and Berg, C.W. 2015. A stochastic surplus production model in continuous-time. Submitted.

Pella, J. J. and Tomlinson, P. K. 1969. A generalized stock production model. *Bulletin of the Inter-American Tropical Tuna Commission*, **13**: 421–458.

Thorson, J.T., Minto, C., Minte-Vera, C.V., Kleisner, K.M. and Longo, C. 2013. A new role for effort dynamics in the theory of harvested populations and data-poor stock assessment. *Canadian Journal of Fisheries and Aquatic Sciences*, **70(12)**: 1829–1844.

4 Catch-based method (CMSY)

4.1 Method

C_{MSY} is a method for estimating maximum sustainable yield (MSY) and related fisheries reference points (B_{MSY}, F_{MSY}) from catch data and information on resilience. It is an advanced implementation of the Catch-MSY method of Martell and Froese (2013). C_{MSY} was developed by R. Froese, G. Coro, H. Winker, N. Demirel and K. Kleisner. It was tested and found satisfactory at the WKLIVE IV workshop in Lisbon, October 2014 (ICES, 2014) and at an ICCAT workshop on data-limited stocks in Madrid, June 2015 (Froese, 2015). If managers, experts or stakeholders have a perception about the depletion history and the current status of a given stock, then C_{MSY} can test such hypotheses against observed catches and the known resilience of the species. If combinations of productivity and stock size are found that are compatible with catches and resilience, then the stock status and exploitation rate are presented in an MSY-framework. C_{MSY} has been tested against simulated data, where the "true" parameter values were known, and against over one hundred fully assessed stocks, with good agreement between C_{MSY} predictions and "true" or observed data (Froese *et al.*, in press, pending revision). A more detailed description of C_{MSY} and application to nine ICES stocks is presented as report from the C_{MSY} breakout group, as Annex 3 to this report.

With the C_{MSY} method, prior parameter ranges for the maximum intrinsic range of population increase (*r*) and for unexploited population size or carrying capacity (*K*) are filtered with a Monte Carlo approach to detect 'viable' *r-K* pairs. A parameter pair is 'viable' if the corresponding biomass trajectories calculated with a Schaefer model are compatible with the observed catches, in the sense that predicted biomass does not overshoot carrying capacity nor crash the stock. Also, predicted biomass shall be compatible with prior estimates of relative biomass ranges for the beginning and the end of the respective time-series. Optionally, a third intermediate prior biomass range can be provided to reflect extraordinary year classes or stock depletions. Also optionally, an indication whether the stock is likely to crash within three years if current catches continue can be given. This will improve the estimation of biomass in the final years.

4.1.1 Data and information requirements

C_{MSY} requires a time-series of catches, preferably longer than ten years, an indication of the resilience of the species, and qualitative estimates of stock status (good or bad) at the beginning and the end of the time-series.

Landings data can also be used if discards are negligible or more or less constant. In the latter case the output estimate of MSY will refer to landings and only relative biomass estimates should be considered for management.

If in addition time-series of total biomass, cpue or stock size index are available, then these data will be analyzed by a full Bayesian state–space Schaefer model (BSM), for comparison with C_{MSY} results, or for direct use.

Table 1 reports a set of questions that can help to determine the prior information needed by C_{MSY} (and possibly BSM). Please note that answers can also rely on the output of other stock assessment methods, such as length-based analyses.

Table 4.1. Example of questions to be put to experts to establish priors for C_{MSY} analysis.

PRIOR	QUESTION TO EXPERTS
Start year for catch time-series	From what year onward are catch data deemed reliable?
Relative start and end biomass B/B_0	What was the most likely stock status at the beginning and end of that time-series: light, full, or overfishing? Given this exploitation level, what was the most likely status of the stock, good or bad?
Relative intermediate biomass B/B_0	Is there an intermediate year where biomass is considered to have been particular low or high, e.g. exploitation changed from light to full, or where an extraordinarily large year class entered the fishery?
Resilience prior	What is your best guess for the range of values including natural mortality of adults (M)? Considering the relationship $M \approx r/2$
Resilience prior	What is your best guess for the range of values including maximum sustainable fishing mortality (F_{MSY})? Considering the relationship $F_{MSY} \approx r/2$ Use this question to reinforce or change the answer to previous question
FutureCrash: Possible / No	If current catches continue, is it likely that the stock will be outside safe biological limits within the next three years? E.g. $B/B_0 < 0.2$?

Table 4.2 suggests ranges for relative biomass to be used as input parameters, depending on the depletion status of the stock. Alternatively, you can get preliminary estimates of r from the following empirical relations:

$$r \approx 2\ M \approx 2\ F_{MSY} \approx 3\ K \approx 3/t_{gen} \approx 9/t_{MAX}$$

where r is the intrinsic rate of population increase, M is the rate of natural mortality, F_{MSY} is the maximum sustainable fishing mortality, K is the somatic growth rate (from the von Bertalanffy growth equation), t_{gen} is generation time, and t_{MAX} is maximum age. If point estimates are very close to each other, assume a range of uncertainty of +/- 50%.

Table 4.2. Prior relative biomass (b/K) ranges for C_{MSY}.

POINT IN TIME-SERIES	STRONG DEPLETION	LOW DEPLETION
Beginning	0.1–0.5	0.5–0.9
Intermediate	0.01–0.4	0.3–0.9
End	0.01–0.4	0.4–0.8

Table 4.3 reports the r ranges automatically associated by C_{MSY} with the resilience parameter values.

Table 4.3. Prior ranges for parameter *r*, based on classification of resilience.

Resilience	prior r range
High	0.6–1.5
Medium	0.2–0.8
Low	0.05–0.5
Very low	0.015–0.1

When setting an intermediate biomass, it often improves the C_{MSY} analysis if the end of a period with low biomass is indicated by setting the intermediate year to the last year with low biomass, and indicating a respective relative range, e.g. as 0.01–0.4. Similarly, indicate a period of large biomass by setting the intermediate year to the last year with high biomass and indicate a respective range, e.g. as 0.4–0.8. In general, the width of relative biomass windows should not be less than 0.4, as in the previous examples. Setting a range of 0 to 1 is also possible, and would indicate no information at all about stock status, which is, however, unlikely. If a stock is fished it must be smaller than 1. If it is delivering decent catches, it must be larger than 0.01. See Table 1 for guidance on how to get priors from interviews with fishers or experts (or your-self).

Note that if Biomass/cpue values are provided, part of the C_{MSY} analysis is also an analysis with a Bayesian state–space implementation of a Schaefer model (BSM). These results are shown in red in the graphical output. You can change the minimum number of years with total biomass or cpue required for BSM analysis (variable 'nab' in the "General settings for the analysis" section, see row 46 of the code), but it should not be much less than the recommended nine years. You can also change the uncertainty associated with catch data (variable 'dataUncert' in the "General settings for the analysis" section of the code), in row 38, but it should not be much higher than 0.2, because without reliable catch data, C_{MSY} makes no sense. The default uncertainty is 0.1 (i.e. 10%).

4.1.2 Outputs expected

Outputs of C_{MSY} (and BSM) are standard fisheries reference points (MSY, $F_{MSY} = 0.5\ r$, $B_{MSY} = 0.5\ k$) and time-series of predicted relative biomass (B/B_{MSY}) and exploitation rate (*u*/*u.msy*), all with indication of uncertainty. If BSM is applied to cpue data it will provide an estimate of catchability *q*. Other examples of outputs are reported in this section as well as in the Annex to this report.

4.1.3 Method of operation

R-code that runs C_{MSY} and BSM analyses is available together with a manual on the WKLIFE V SharePoint. Catch data and optional total biomass or cpue data are made available in a csv file and read by the R-code. The settings for the analysis are provid-ed in a second csv file. The method of operation is described at the link given in Sec-tion 4.1.6 of this report. Examples of application to nine ICES stocks are given in Annex 3, too.

Additionally, Annex 4 presents a comparison of the Depletion-Corrected Average Catch (DCAC) method and C_{MSY} method undertaken for pollack in Subareas VI and VII which was undertaken prior to the WKLIFE V meeting but presented in plenary for discussion and feedback.

4.1.4 Sensitivity of C_{MSY} to depletion patterns and resilience of stocks

C_{MSY} assessments of 48 simulated stocks were analysed to detect the sensitivity of the C_{MSY} method to different patterns and contrast in stock biomass and to different levels of resilience of the species. Resilience ranges of Very low, Low, Medium and High resilience were analysed (Table 3). The simulations covered a range of biomass scenarios, including strongly as well as lightly depleted stocks, with monotone stable or monotone changing (i.e. steadily decreasing or increasing) or with alternating biomass trajectories: patterns of high-high (HH), high-low (HL), high-low-high (HLH), low-low (LL), low-high (LH), and low-high-low (LHL) biomass trends.

The details of the testing are described in the Annex to this report. For many stocks, C_{MSY} provided similar perspectives of stock status as BSM, but for others, the perspective was considerably different. The conclusions were the following: C_{MSY} analysis appears to be less well suited for lightly exploited stocks where the catches have very little impact on biomass, and for species with very low resilience, such as sharks or deep-sea species, where sustainable levels of exploitation represent a very small fraction of biomass.

4.1.5 Caveats

C_{MSY} analysis appears to be less well suited for lightly exploited stocks where the catches have very little impact on biomass, and for species with very low resilience, where sustainable levels of exploitation represent a very small fraction of biomass.

4.1.6 Software

The software is available on the WKLIFE V SharePoint and at the following link, which contains a detailed guide:

http://data.d4science.org/uri-resolver/id?fileName=CMSY_-_Windows_OS_-_Package.zip&smp-id=56150c97e4b02e1b6570e0fe&contentType=application%2Fzip

4.2 Testing ICES stocks

4.2.1 Eastern Baltic cod and Western Baltic dab

We tested C_{MSY} on nine stocks provided by the participants to the meeting and by ICES. The complete report is presented in the Annex reporting the SG2 activity.

In the following we report the output of C_{MSY} on two data-limited stocks: cod-25–32 and dab-22–32.

Species: *Gadus morhua*, stock: cod-2532

Name and region: Eastern Baltic, Areas 25–32

Catch data used from years 2003–2014, biomass = cpue

Prior initial relative biomass = 0.1–0.5

Prior intermediate rel. biomass= 0.1–0.9 in year 2007

Prior final relative biomass = 0.01–0.4

If current catches continue, is the stock likely to crash within three years? Possible

Prior range for r = 0.2–0.8, prior range for k = 95.6–1147

Prior range of q = 0.000733–0.00293

Results from Bayesian Schaefer model using catch & cpue

r = 0.51, 95% CL = 0.462–0.607, k = 619, 95% CL = 390–1052

MSY = 80.5, 95% CL = 50.3–136

q = 0.000841, lcl = 0.000656, ucl = 0.00113

Biomass in last year from cpue/q = 150 or 0.242 k

Results of C_{MSY} analysis

Altogether 5817 viable trajectories for 2675 r-k pairs were found

1665 r-k pairs above r = 0.376 and 2610 trajectories within r-k CLs were analyzed

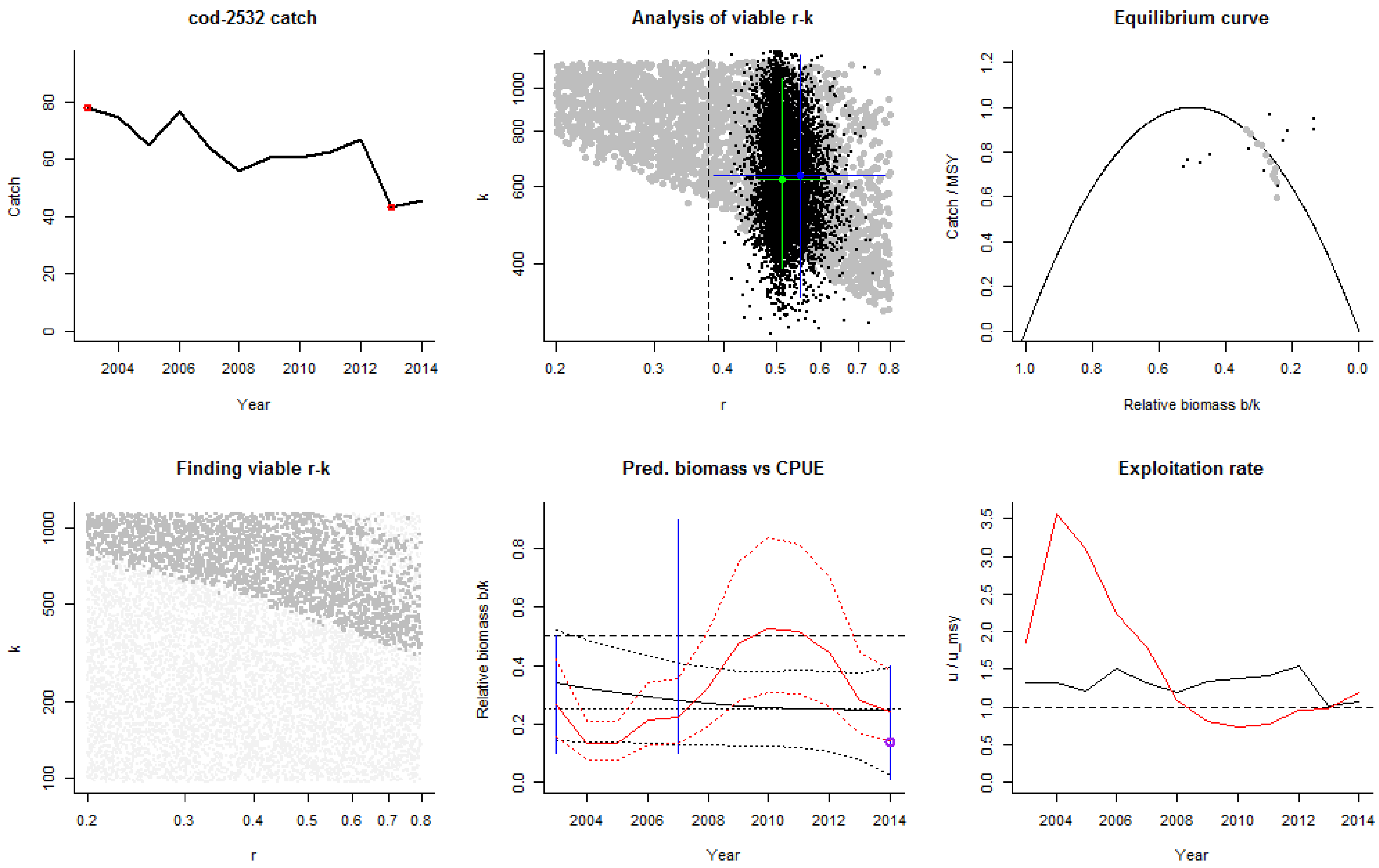
r = 0.549, 95% CL = 0.384–0.784, k = 632, 95% CL = 336–1191

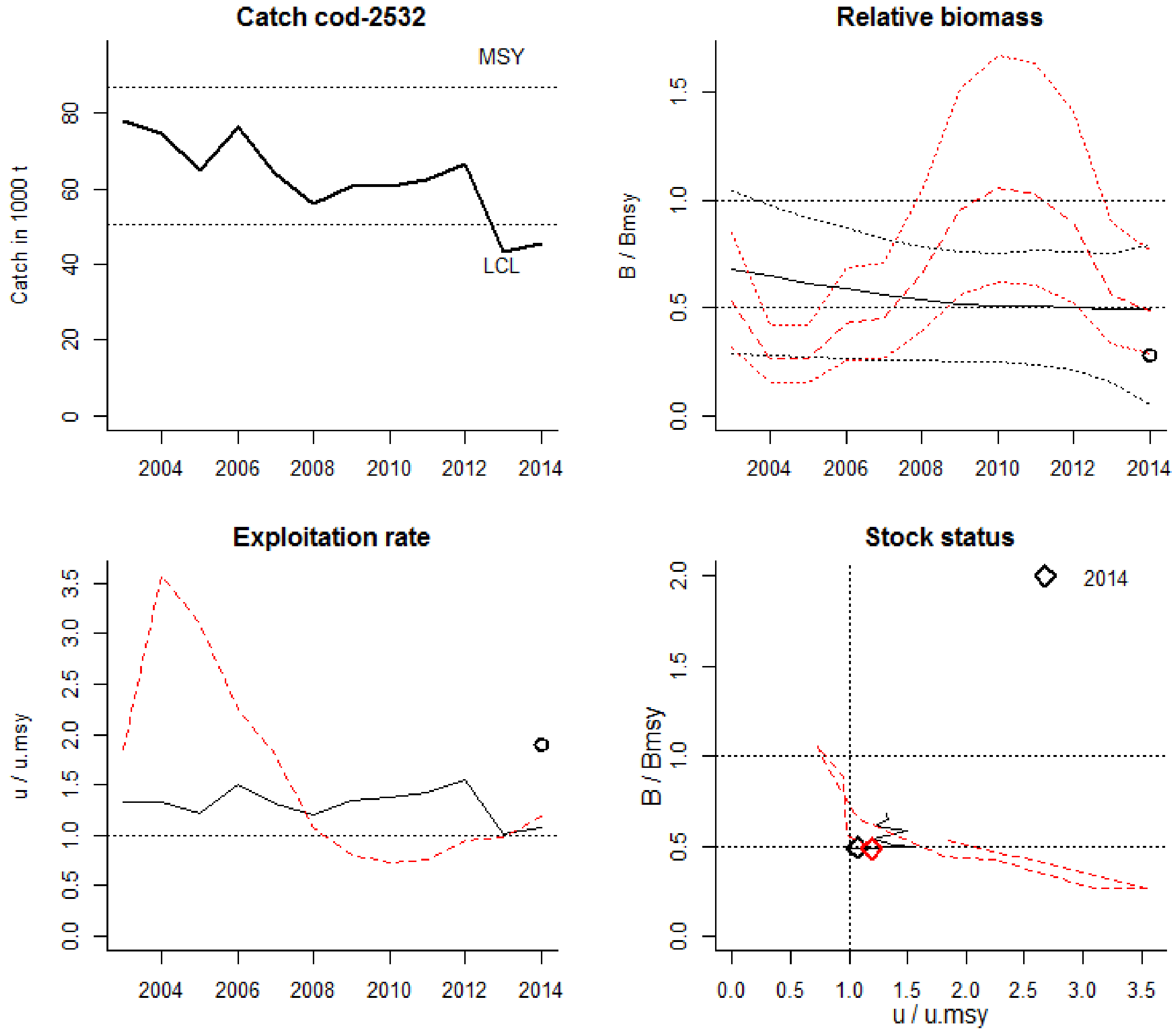
MSY = 86.8, 95% CL = 50.4–149

Predicted biomass in last year = 0.246, 2.5th perc = 0.0247 25th perc = 0.138 97.5th perc = 0.395

Predicted biomass in next year = 0.256, 2.5th perc = -0.0544 25th perc = 0.111, 97.5th perc = 0.451

Predicted exploitation rate in last year= 1.07, 25th = 1.904


cod-2532 catch
Catch
Year
Analysis of viable r-k
k
r
Equilibrium curve
Catch / MSY
Relative biomass b/k
Finding viable r-k
k
r
Pred. biomass vs CPUE
Relative biomass b/k
Year
Exploitation rate
u / u_msy
Year


Catch cod-2532
MSY
LCL
Catch in 1000 t
0
20
40
60
80
2004
2006
2008
2010
2012
2014
Relative biomass
B / Bmsy
0.0
0.5
1.0
1.5
Exploitation rate
u / u.msy
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
Stock status
2014
u / u.msy
2.0

The grey dots stem from CMSY analysis based on catch and the black dots stem from BSM analysis based on catch and stock size index. Estimates of the most probable r-k (middle upper panel) are similar between the methods. The blue vertical lines in the lower middle graph show the prior biomass window. The black curves are predicted by CMSY and the red curves by BSM. The dotted lines are the 2.5th and 97.5th percentiles.

These four panels are suggested for management advice. The upper left panel shows the short time-series of catches relative to MSY. CMSY does not capture the variability of stock index data as scaled by BSM, but gives similar median results for final biomass and exploitation rate. The black circles indicate relative biomass and relative exploitation rate if the 25th percentile of predicted biomass is used in the last year, instead of the median.

Species: *Limanda limanda*, stock: dab-22–32

Name and region: Western Baltic

Catch data used from years 1970–2014, biomass = cpue

Prior initial relative biomass = 0.2–0.8

Prior intermediate rel. biomass= 0.1–0.9 in year 2005

Prior final relative biomass = 0.2–0.8

If current catches continue, is the stock likely to crash within three years? No

Prior range for r = 0.2–0.8, prior range for k = 3.68–44.1

Prior range of q = 0.00809–0.0324

Results from Bayesian Schaefer model using catch & cpue

r = 0.509, 95% CL = 0.461–0.597, k = 14.2, 95% CL = 9.49–19.6

MSY = 1.83, 95% CL = 1.22–2.48

q = 0.0119, lcl = 0.00899, ucl = 0.0156

Biomass in last year from cpue/q = 12.2 or 0.858 k

Results of CMSY analysis

Altogether 9005 viable trajectories for 1308 r-k pairs were found

629 r-k pairs above r = 0.342 and 3819 trajectories within r-k CLs were analyzed

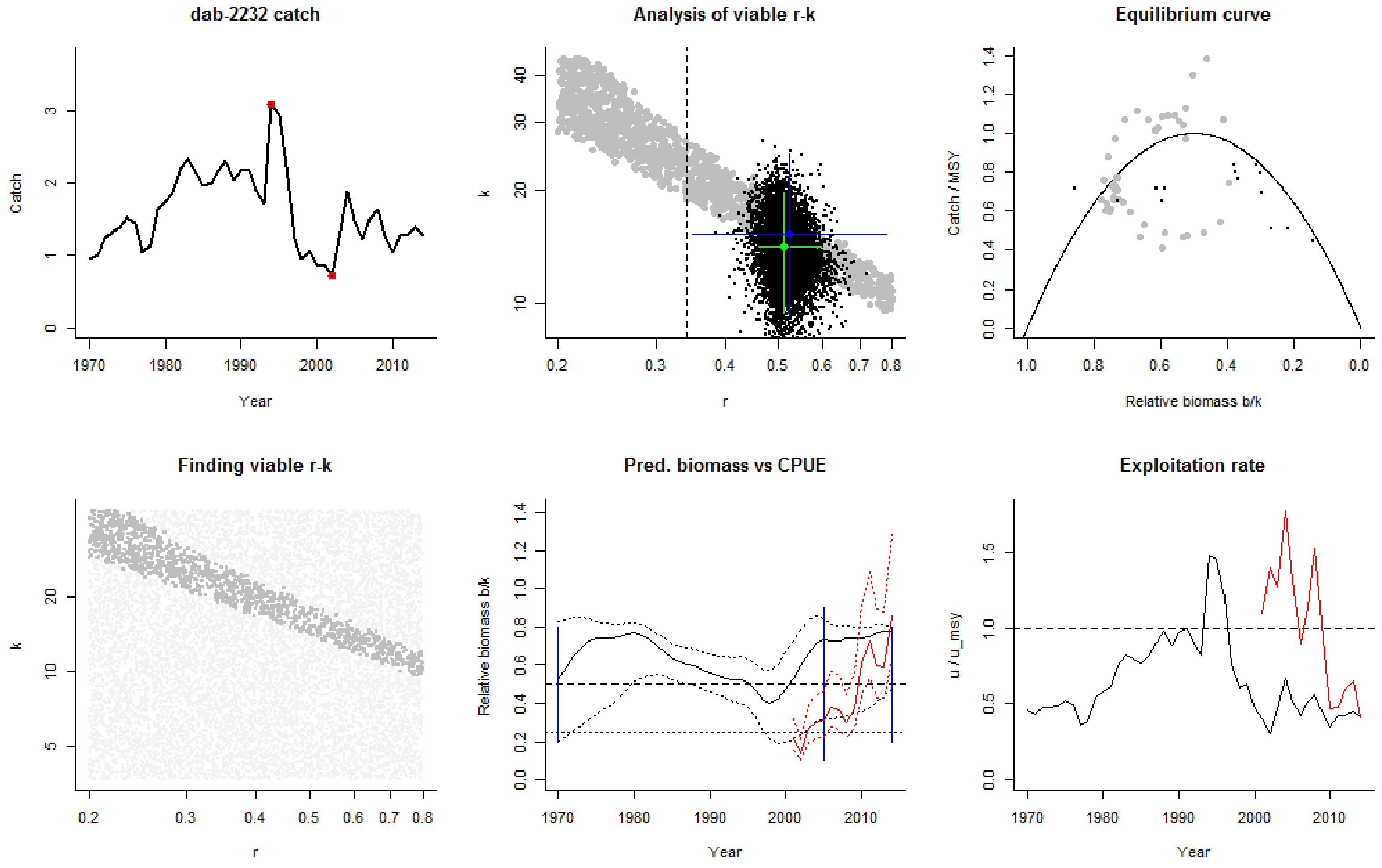
r = 0.522, 95% CL = 0.349–0.782, k = 15.3, 95% CL = 9.39–24.8

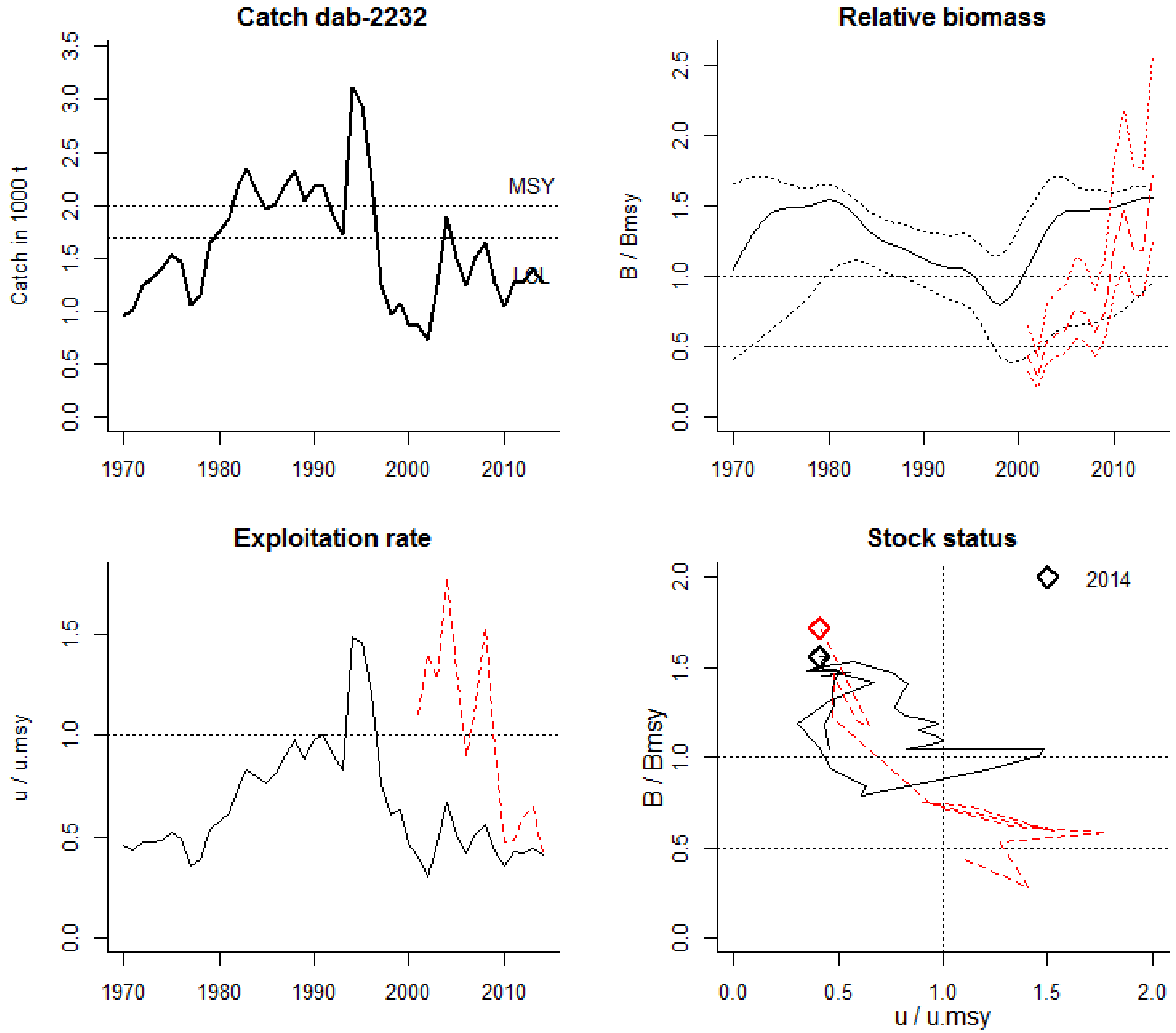
MSY = 1.99, 95% CL = 1.7–2.34

Predicted biomass in last year = 0.778, 2.5th perc = 0.475 25th perc = 0.749 97.5th perc = 0.799

Predicted biomass in next year = 0.78, 2.5th perc = 0.501 25th perc = 0.753, 97.5th perc = 0.813

Predicted exploitation rate in last year= 0.409


dab-2232 catch
Catch
Year
Analysis of viable r-k
k
r
Equilibrium curve
Catch / MSY
Relative biomass b/k
Finding viable r-k
k
r
Pred. biomass vs CPUE
Relative biomass b/k
Year
Exploitation rate
u / u_msy
Year


Catch dab-2232
Catch in 1000 t
MSY
LCL
Relative biomass
B / Bmsy
Exploitation rate
u / u.msy
Stock status
B / Bmsy
u / u.msy
2014

Landings data were used for this analysis, although discards may be substantial. There was no good prior idea of stock size, so very wide prior biomass windows (0.2–0.8) were used. There is no good agreement between C_{MSY} and cpue as scaled by BSM, although trends are similar and estimates converge in the last years. The methods agree in the assessment of good relative stock status. Also, both C_{MSY} and BSM agree in the estimate of r ~ 0.5, so an estimate of F_{MSY} ~ 0.25 seems reasonable.

4.2.2 North Sea sole and plaice stocks

ACOM agreed at the December 2014 meeting to request WKLIFE make further tests of … C_{MSY} to explore:

- The sensitivity of results to prior assumptions (r-K and depletion level start and end);
- Test the method on cat 1 stocks (where we know the answer).

Some exploratory runs were applied to the North Sea sole and plaice stocks, assessed by WGNSSK (Figures 4.2.1 and 4.2.2; ICES, 2015). It should be noted that all models can provide incorrect results if poor quality data or incorrect assumptions are made. However, by definition data-limited stocks will require more subjective decisions on the appropriateness of data and assumptions made. Therefore it is useful to understand how influential particular decisions in the settings of C_{MSY} could be on the results that would form the basis for advice for such stocks.

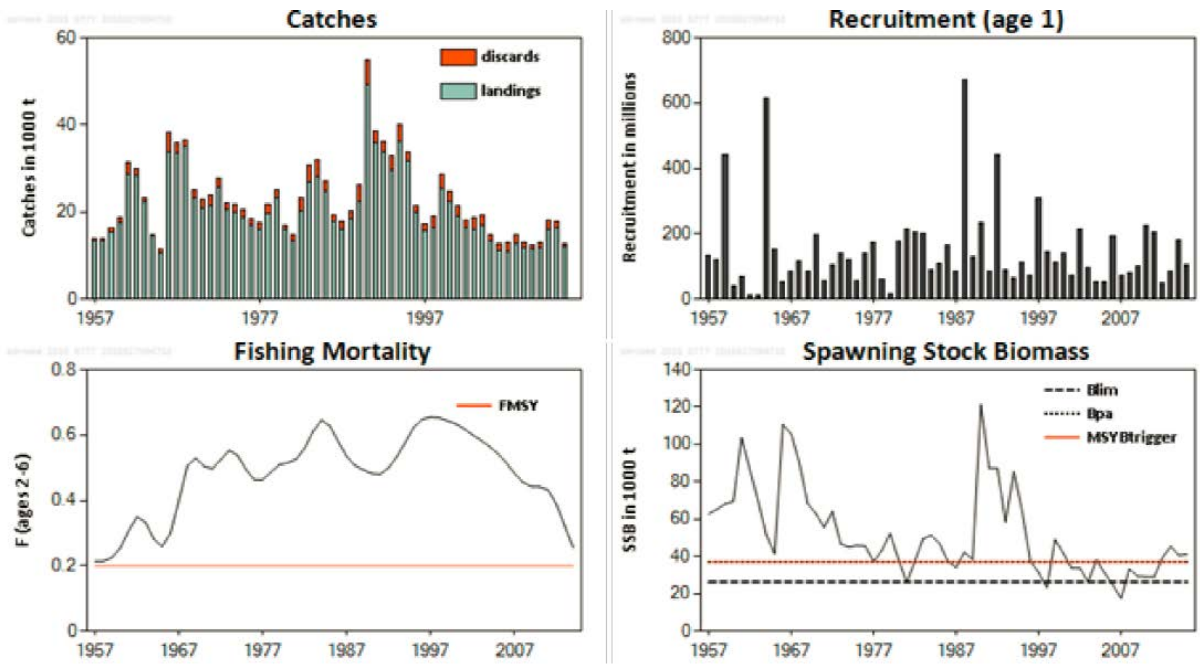


Figure 4.2.1. Latest ICES stock assessment results for sole in the North Sea (SOL-IV).

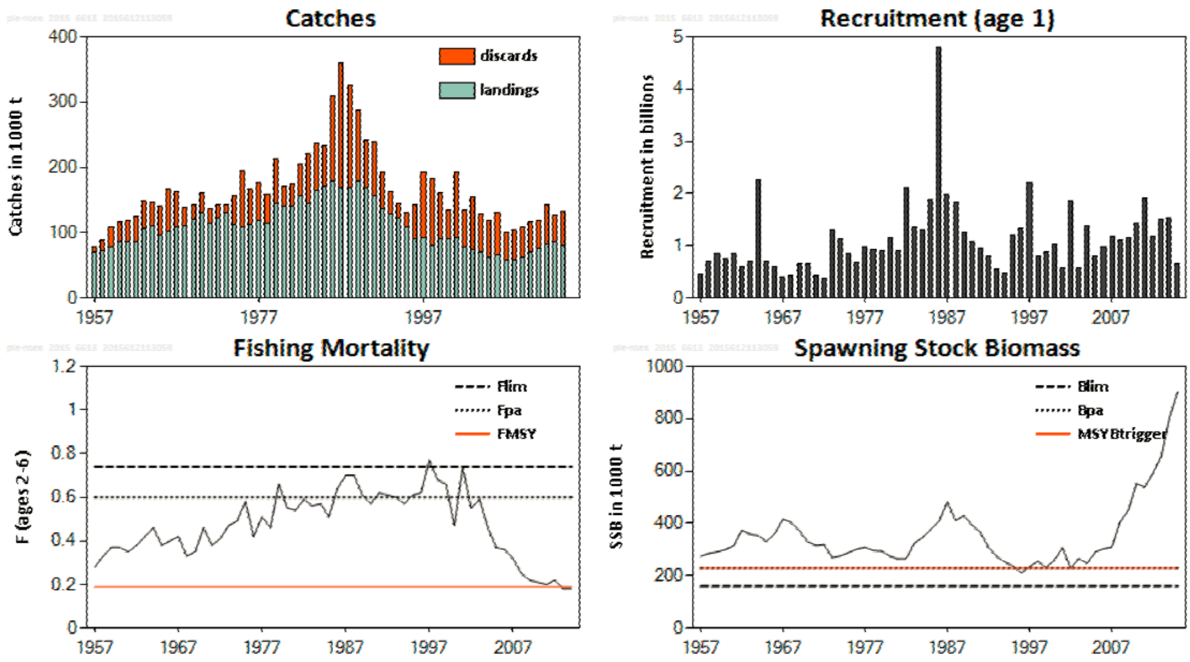


Figure 4.2.2. Latest ICES stock assessment results for plaice in the North Sea (PLE-IV).

Input data

C_{MSY} is proposed as a method to use for Category 4 stocks i.e. stocks where only catch data are available. However this method also includes the option to fit a Bayesian Schaeffer model to total biomass or cpue (commercial or survey) data. For sole and plaice in the North Sea, catch data back to 1957 (Figure 4.2.3) were used and Schaeffer fits were done using estimates of total biomass from the most recent ICES stock assessments of these stocks (ICES, 2015).

Sole and plaice in the North Sea are largely caught by the same mixed fishery and hence show a similar pattern over time: increasing from the start of the time-series to peak values in the late 1980s and early 1990s, and decreasing thereafter to lower values similar to those at the start of the time-series.

A number of factors have changed over time impacting on the level of (estimated) catch:

- Changes in fishing technology, both technological creep and step changes in technology (e.g. advent of the beam trawl, changes in mesh size, change to pulse trawl gears in recent years);
- Changes in fleet capacity, increasing to high levels in the 1990s, and decreasing thereafter following a number of decommissioning schemes in various countries;
- Limits on fishing effort coming from the North Sea cod management plan have impacted on the fleets fishing on sole and plaice in some recent years;
- The EU Data Collection Framework (DCF) since 2002 has led to more complete reporting of discarding levels, prior to this discard numbers are model estimated based on discarding rates observed since 2002, year-class size and weights-at-age.

Hence the quality of the catch data, and the impact different levels of catch have had on the stock, varies over time.

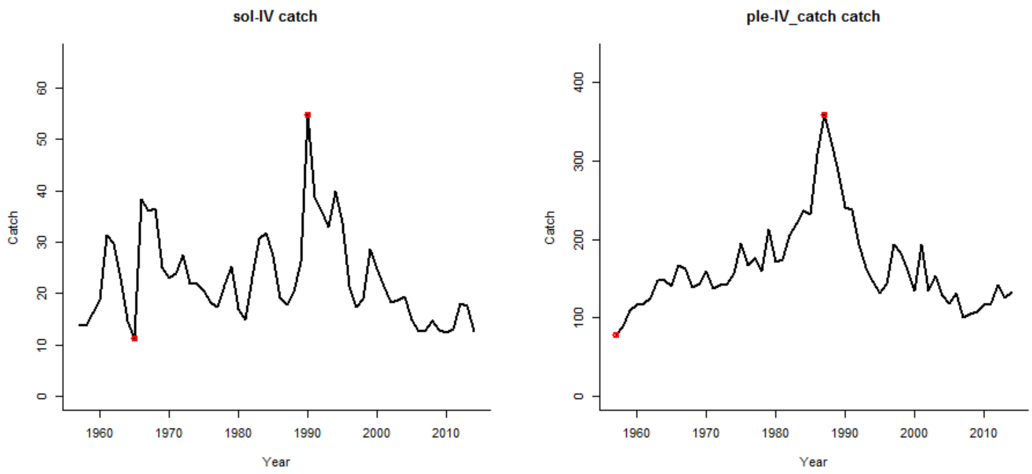


Figure 4.2.3 Catch (landings + discards) time-series for North Sea sole (SOL-IV, left) and plaice (PLE-IV, right).

'Best' analysis prior assumptions

The first fits of the CMSY model were done using the most likely settings that would be applied without prior knowledge of stock assessment results (i.e. as if the stocks truly were data-limited).

Sole settings: Years: 1957–2014; Medium resilience; start B/K = 0.2–0.8; end B/K = 0.1–0.5; Intermediate year = default (CMSY chose low biomass for lowest catch year, 1965).

Fishing pressure increased in the 1950s following WWII, but the reasonably high catches at the beginning of the time-series suggest that the stock was not severely depleted, hence a broad prior on initial starting biomass. Following heavy fishing pressure in the 1980s and 1990s, the stock would not be considered to be very large at the end of the time-series, most likely below BMSY, hence the low end biomass prior range.

The CMSY model corresponds fairly well with the Schaffer model fit (Figure 4.2.4). Trends in biomass over time are in agreement, though smoother in the CMSY outputs. Likewise the trend in exploitation over time is similar, and the CMSY outputs show a similar trend (though not level) of exploitation in recent years compared to the F estimated by the ICES assessment (Figure 4.2.1).

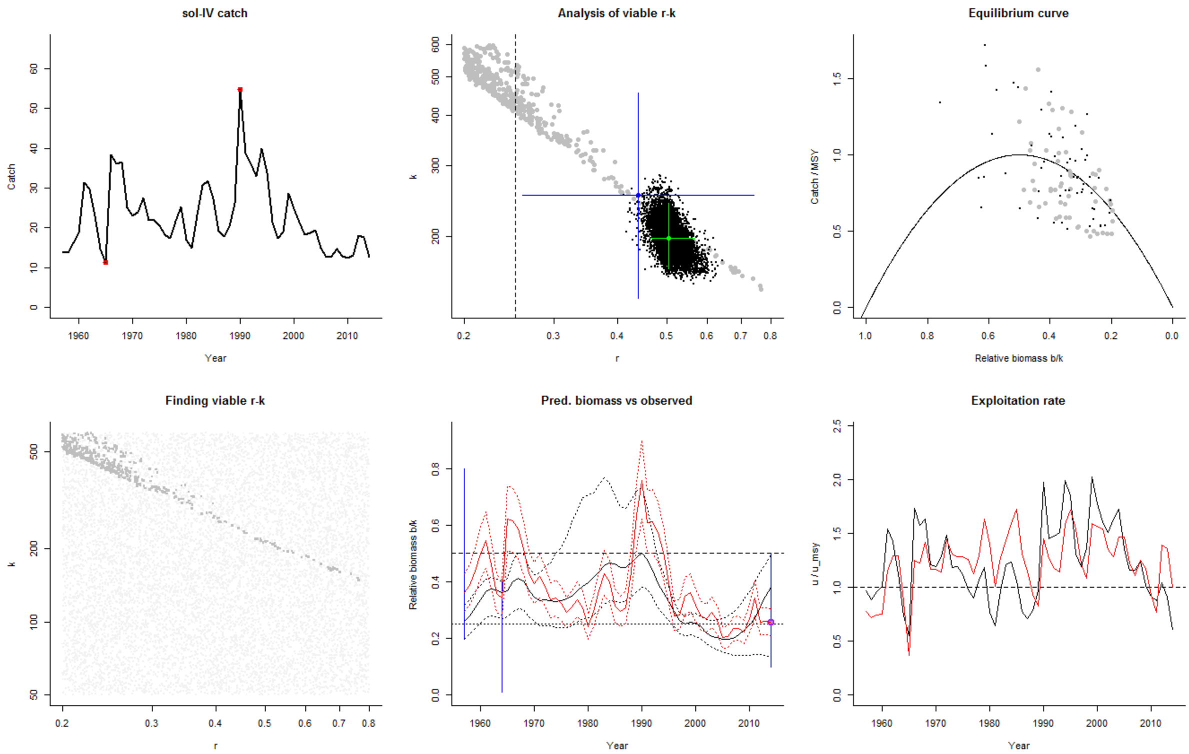


Figure 4.2.4. First attempt at fitting the CMSY model to North Sea sole.

Plaice settings: Years: 1957–2014; Medium resilience; start B/K = 0.2–0.8; end B/K = 0.2–0.6; Intermediate year = default (CMSY chose high biomass for highest catch year, 1987).

Fishing pressure increased in the 1950s following WWII, but the reasonably high catches at the beginning of the time-series suggest that the stock was not severely depleted, hence a broad prior on initial starting biomass. Following heavy fishing pressure in the 1980s and 1990s, the stock would not be considered to be very large but would be considered to have recovered more than the sole stock at the end of the time-series, hence a slightly higher, but still low, end biomass prior range.

The CMSY model corresponds fairly well with the Schaffer model fit (Figure 4.2.5) in the period following the peak in catches, but differs substantially in the period prior to that. It appears that the prior assumption of starting biomass may have been set too high, though without prior knowledge this assumption would not have been an unreasonable one. It also appears that the intermediate year assumption has a large impact on the fit for the period prior to the peak in catches. Froese *et al.* (submitted) assumed lower starting and end biomass and used an alternative intermediate year assumption (low biomass a few years prior to the peak in catches) that produces a closer fit to the Schaeffer model in the initial period with similar trends after that (Figure 4.2.6). The recent trend in exploitation over time is similar for both fits, and corresponds well with the exploitation in recent years compared to the F estimated by the ICES assessment (Figure 4.2.2). However, the different prior assumptions on biomass lead to difference in the estimation of *r* (median values of ~0.5 vs.~0.3, with overlap in confidence ranges) and hence U_MSY.

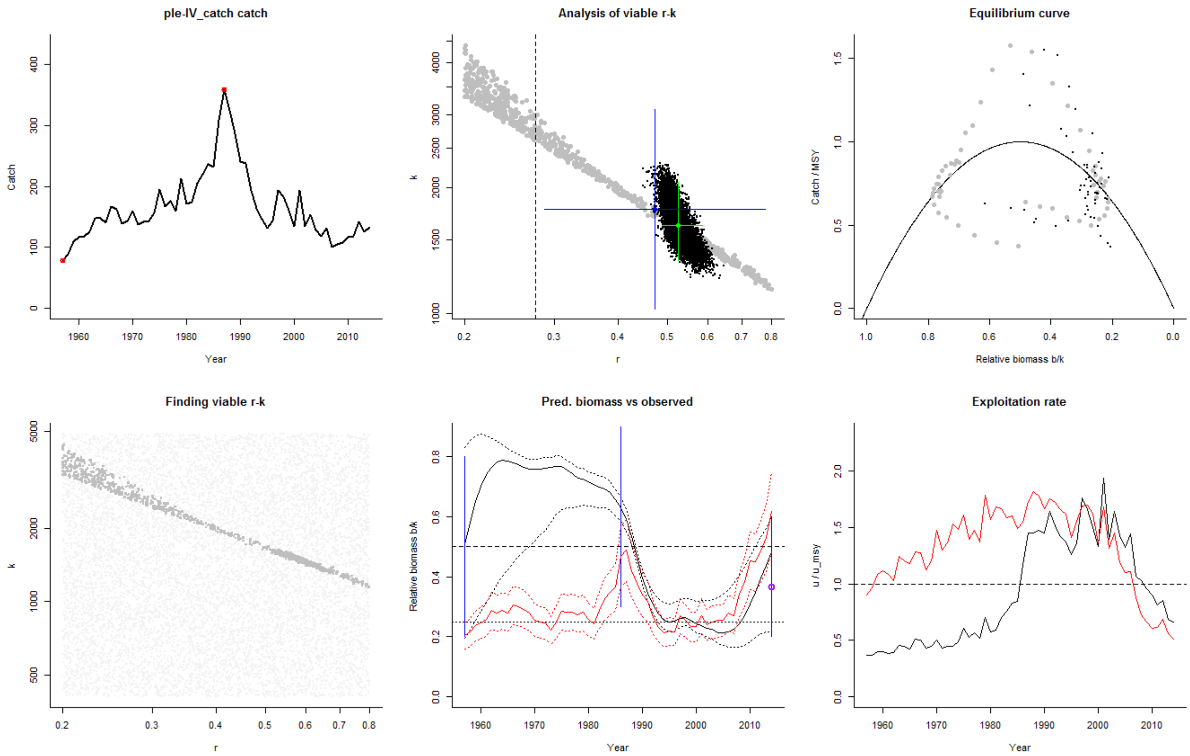


Figure 4.2.5. First attempt at fitting the CMSY model to North Sea plaice.

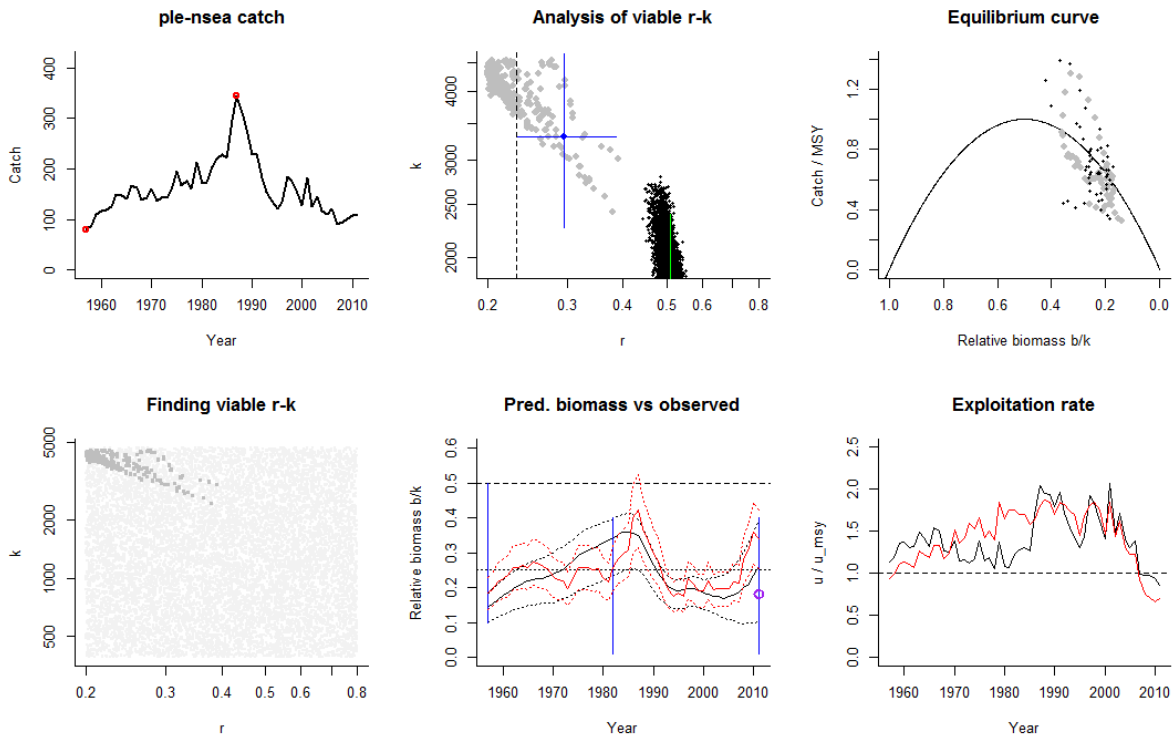


Figure 4.2.6. First attempt at fitting the CMSY model to North Sea plaice.

Part of the explanation for the difficulties in fitting to the initial part of the time-series could be down to changes in the quality of catch data over time. With long time-series it could also be more difficult to make accurate predictions of stock status in the start and intermediate years. In such cases it is probably more appropriate to use a shorter, more consistent quality, time-series of catch. An alternative fit (Figure 4.2.7) using the settings below was done for plaice that resulted in more consistent trends and levels of biomass compared with the Schaeffer model and ICES stock assessment. The estimate of *r* is larger in this fit and hence while the pattern of exploitation over time is likely realistic, the level of exploitation in relation to U_MSY is estimated to be lower than that from the full stock assessment.

Alternative plaice settings (short time-series): Years: 2000–2014; Medium resilience; start B/K = 0.1–0.5; end B/K = 0.2–0.8; Intermediate year = default (CMSY chose low biomass for lowest catch year, 2007).

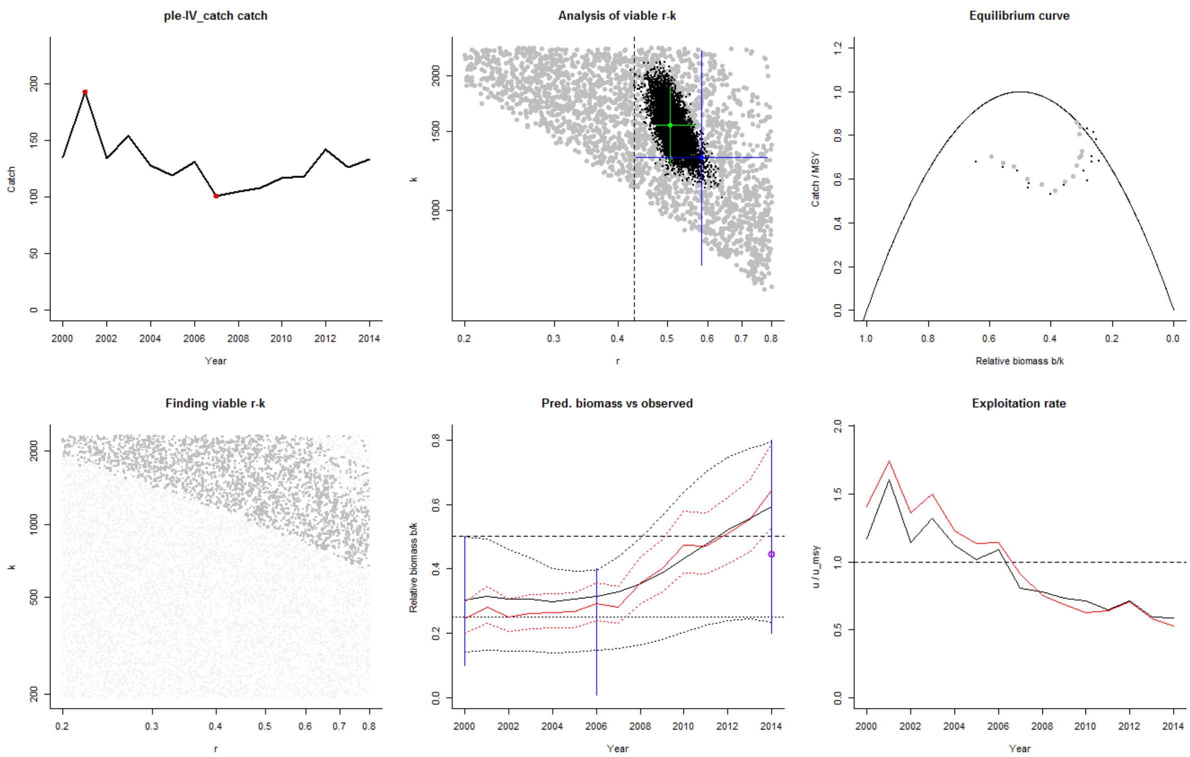


Figure 4.2.7. First attempt at fitting the CMSY model to North Sea plaice.

Sensitivity of estimates of current stock status (biomass) to prior assumptions

Current stock status is an important consideration when applying advice, so sensitivity to assumptions likely to impact on this was examined. Results are shown for sole only, though tests done using the plaice data show similar results.

Assuming high, medium or low resilience obviously has an impact on the estimation of *r*, and in turn on the smoothness of the biomass trend over time (Figure 4.2.8). Following from this, the lower the assumed resilience, the higher the estimated exploitation in relation to U_MSY.

Not surprisingly the assumption on the prior of biomass at the end of the time-series has a significant impact on the estimated biomass in the final year (Figure 4.2.9).

While there are only slight differences in the estimate *r* (slightly higher for large end biomass), the trend in biomass over the last TEN years differs as the model tries to force biomass to alternative levels at the end of the time-series. This impact is more influential than the assumed resilience (Figure 4.2.10). Likewise the starting biomass assumption has less impact on the estimate biomass in the final year (results not shown), though this is to be expected given the long time-series of catch.

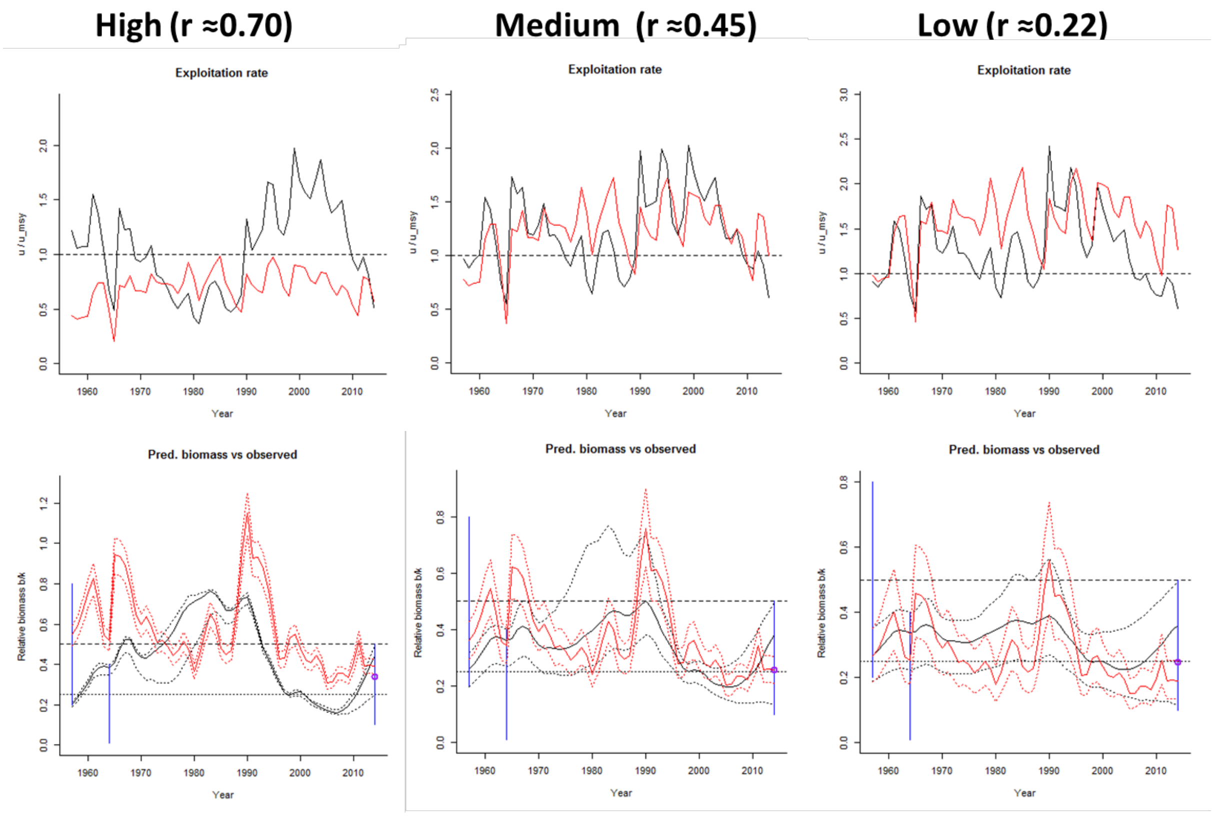


Figure 4.2.8. Results of the C_{MSY} for SOL-IV with different assumptions on the resilience of the stock.

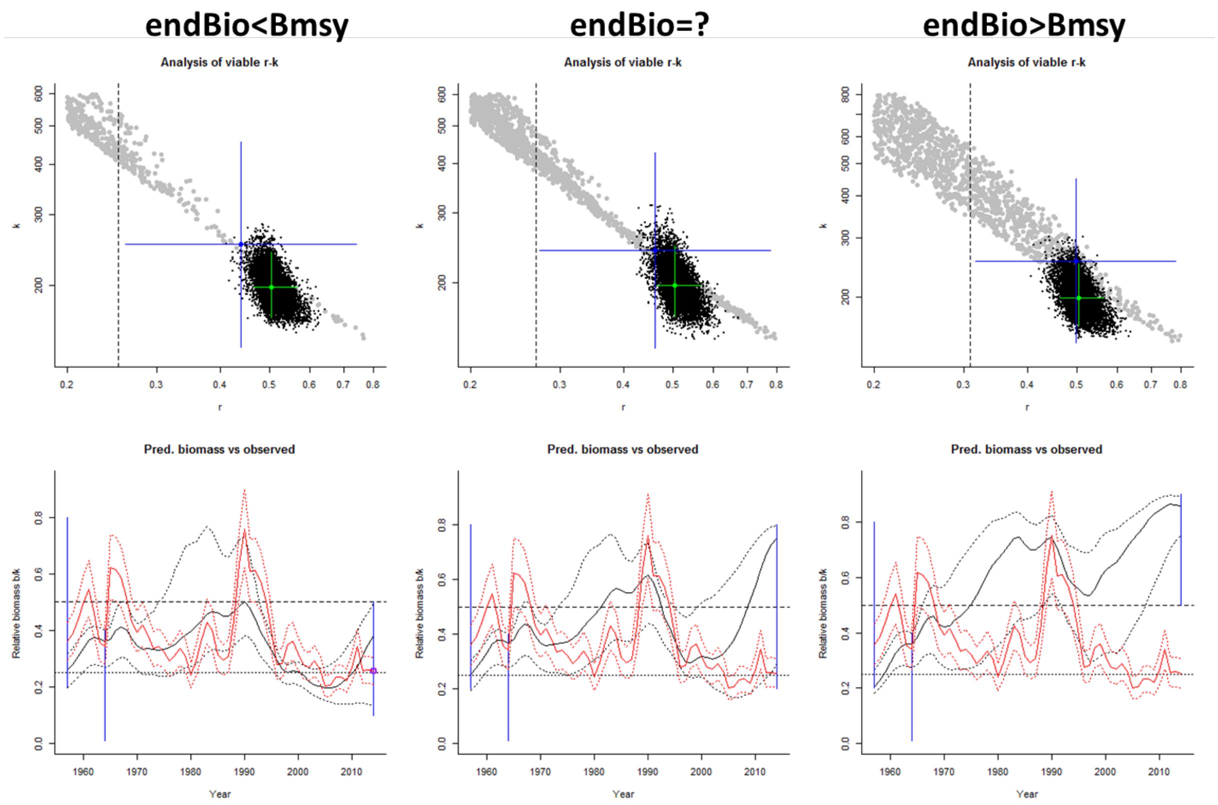


Figure 4.2.9. Results of the C_{MSY} for North Sea sole (SOL-IV) with different assumptions on the end biomass.

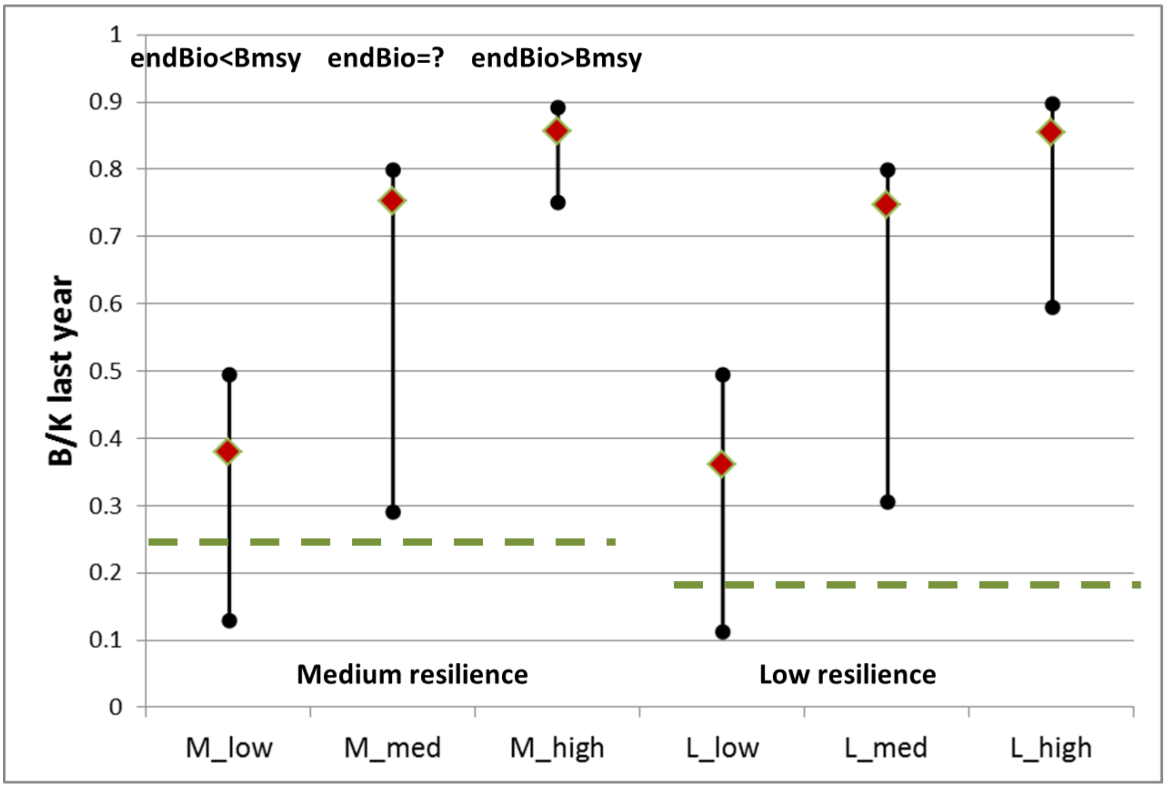


Figure 4.2.10. Estimates of the ratio of North Sea sole (SOL-IV) biomass to B0 (K) in the last year of the CMSY analyses (2014). Results show median values (red diamonds) and 95% confidence intervals (black lines and dots) for an initial assumption of medium resilience (left three) or low resilience (right three) and alternative priors on end biomass (less than BMSY (0.1–0.5), uncertain (0.2–0.8) or greater than BMSY (0.5–0.9)). The dashed green lines show the approximate values from the Schaeffer model fits.

Retrospective analyses

Retrospective analyses were conducted on the CMSY runs starting in 2000 (settings below) and end on each year from 2009 to 2014. The same prior assumptions were made for each run, which is likely an overly simplistic assumption, though the prior end biomass ranges are considered likely for all end years used. The results are shown in Figures 4.2.11 and 4.2.12.

Retrospective settings (short time-series): Years: 2000–(2009:2014); Medium resilience; start B/K = 0.1–0.5; end B/K = 0.2–0.8 (plaice) or 0.1–0.5 (sole); Intermediate year = default.

The estimated values of *r* (and therefore U_MSY) and MSY were very similar for each retrospective peel, with a very slight downward trend in MSY level. For both stocks the relative trend in U:U_MSY showed a consistent pattern of underestimation, possibly because both stocks were recovering from a low biomass over this period so the assumption of average stock productivity could be violated. The final year estimates of each consecutive peel following the pattern of catch over the years 2009–2014 i.e. higher final year exploitation for years with higher catch in the final year, and lower final year exploitation in years with lower final year catch.

The retrospective patterns for relative biomass differed between stocks. Sole, which had a more restrictive low prior of end year B/K, estimated the same median relative biomass in each of the retrospective peels with slight differences in the lower end of the estimated range and 25th percentile. Plaice, which had a broader prior of end year B/K, showed a downward step change after 2010 with very little retrospective changes thereafter. The initial step change could be due to the very short time-series use for the first two retrospective peels (nine and ten years).

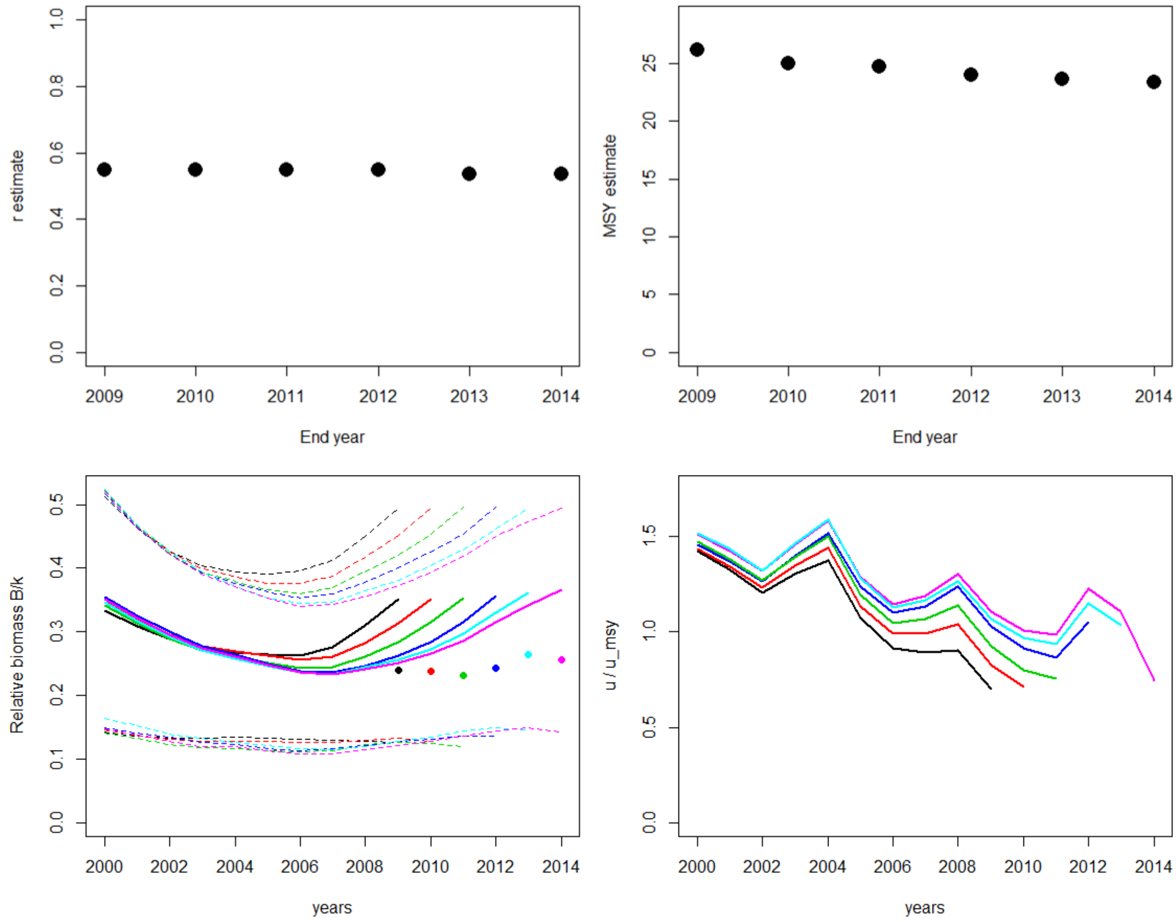


Figure 4.2.11. Results of a retrospective analysis on the CMSY for North Sea sole (SOL-IV): median r estimate (top left), MSY estimate (top right), relative biomass (bottom left) and relative exploitation rate (bottom right). Catch time-series starts in 2000 and ends in each of the years from 2009 to 2014. The same prior assumptions are made in each case.

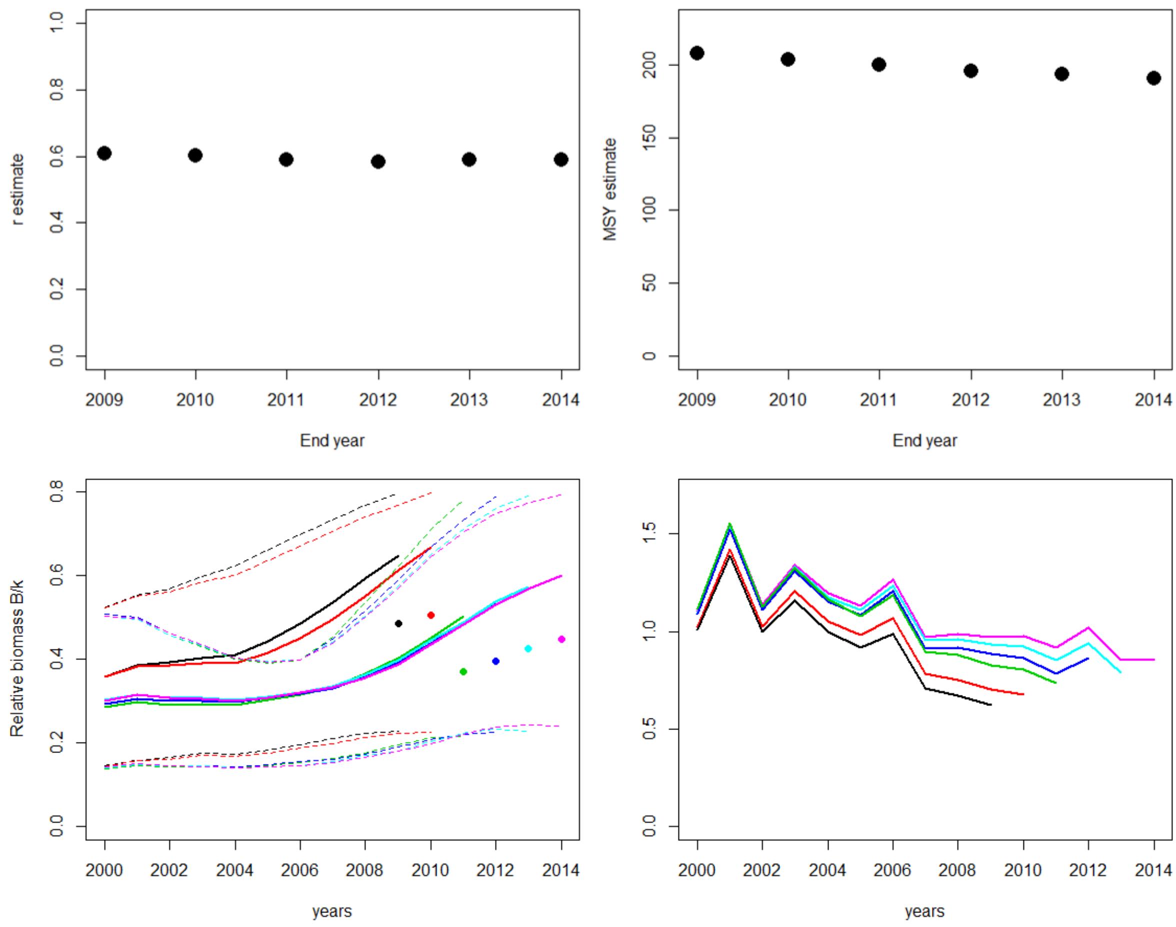


Figure 4.2.12. Results of a retrospective analysis on the C_{MSY} for North Sea plaice (PLE-IV): median r estimate (top left), MSY estimate (top right), relative biomass (bottom left) and relative exploitation rate (bottom right). Catch time-series starts in 2000 and ends in each of the years from 2009 to 2014. The same prior assumptions are made in each case.

Discussion

C_{MSY} with appropriate assumptions estimates similar recent trends in biomass and exploitation for both North Sea sole and plaice. Not surprisingly, assumptions on end year B/k, and to a lesser degree intermediate year B/k, have a significant impact on the estimation of current stock status. The assumption on end B/k, if too restrictive, could additionally lead to retrospective estimation problems for current stock status. This problem was compounded for these stocks because both are currently in a recovering phase from low biomass levels. However, C_{MSY} can recover to produce reasonable estimates of current stock status if the prior on start biomass is set wrongly or is uninformative (e.g. 0.2–0.8).

It may not be easy for stock assessors to have the necessary information on the prior biomass assumptions for very data-limited or poorly understood stocks, and it is likely that without good guidance the application of the method may vary between ICES stocks depending on the expert group doing the analyses. Where possible assumptions should be decided by a group of experts or, preferably, informed by independent data-limited methods, such as cpue or $L_{mean}/L_{(F=M)}$ and L_{mean}/L_{opt}. Such methods were developed simultaneously during WKLIFE V, but were not applied in this analysis. For data-limited stocks caught together in mixed fisheries targeting data-rich stocks, a Robin Hood approach could also be used to inform prior estimates. E.g. it is likely that a lot of the data-limited flatfish bycatch species in the North Sea demersal fisheries would have experience similar trends in fishing pressure over time compared to the plaice and sole stocks (e.g. dab, flounder, witch flounder, etc.).

For plaice, C_{MSY} produced better estimates of current stock status, even with a broad end B/K prior, when the long time-series was truncated to recent period (2000–2014). Shorter time-series will likely have more consistency in the quality of the catch data and may have the benefit of making it easier to make prior assumptions on start and intermediate biomass (more general information on fishing pressure, likely some indications of stock status from independent surveys). However, it is important for the method that there is enough contrast in the catch time-series. In the EU, more reliable discard data are available since the implementation of the DCF in 2002, and many data-limited stocks will only have shorter time-series available since they are often not commercially interesting, so it is a positive result that C_{MSY} seems to handle short time-series fairly well. However, tests on other data-rich stocks with long time-series have shown that C_{MSY} is capable of reproducing these as well, so unless good reasons exist to exclude older catch data, this should probably not be done as a rule.

While the retrospective pattern in relative biomass for plaice was relatively good, the retrospective pattern for sole was particularly problematic. The narrow end biomass prior, and low but recovering biomass of the stock, combined to produce the same median estimate of last year relative biomass in each subsequent year. In such cases, it may be necessary to allow a broader range on the prior otherwise the forced assumption of the stock being low will continue to impact the C_{MSY} output as the stock recovers. Additionally, it is not necessary for data-limited methods to be applied in isolation. Available knowledge and data could be used more efficiently by combining the results of independent methods, for example by using length-based indicators to inform the assumptions for priors in the C_{MSY} method (e.g. the end biomass window). This would reduce the subjectivity of the method, though from an ICES perspective stocks where such additional information is available would likely be moved to Category 3 of the DLS approach rather than remaining in the catch data only Category 4.

The results described here apply to these two stocks, but the broad conclusions should apply to other stocks as well. However, further analyses (e.g. additional retrospective analyses) would need to be applied on different stocks with different trends in recent catch/exploitation/biomass to draw any firm conclusions on the method.

4.3 Application to *Nephrops* in FUs 28–29

Input setting:

Region=Southwest and South Portugal

stock=nep-2829_comcpue

Name=*Nephrops*

EnglishName=*Nephrops*

ScientificName=*Nephrops norvegicus*

MinOfYear=1997

MaxOfYear=2014

StartYear=1997

EndYear=2014

Resilience=Medium

r_low=NA

r_hi=NA

stb_low=0.1

stb_hi=0.5

intyr=2005

intbio_low=0.1

intbio_hi=0.9

endbio_low=0.1

endbio_hi=0.5

Btype=cpue

FutureCrash=Possible

comment=Using commercial cpue; assuming low biomass

Output:

Species: *Nephrops norvegicus*, stock: nep-2829_comcpue

Name and region: *Nephrops*, Southwest and South Portugal

Catch data used from years 1997–2014, biomass = cpue

Prior initial relative biomass = 0.1–0.5

Prior intermediate rel. biomass= 0.1–0.9 in year 2005

Prior final relative biomass = 0.1–0.5

If current catches continue, is the stock likely to crash within three years? Possible

Prior range for r = 0.2–0.8, prior range for k = 0.448–5.37

Prior range of q = 0.00781–0.0313

Results from Bayesian Schaefer model using catch & cpue biomass

r = 0.511, 95% CL = 0.465–0.601, k = 2.31, 95% CL = 1.6–3.55

MSY = 0.299, 95% CL = 0.208–0.449

q = 0.01, lcl = 0.00793, ucl = 0.0125

Biomass in last year from cpue/q = 0.76 or 0.329 k

Results of C_{MSY} analysis

Altogether 5244 viable trajectories for 2314 r-k pairs were found

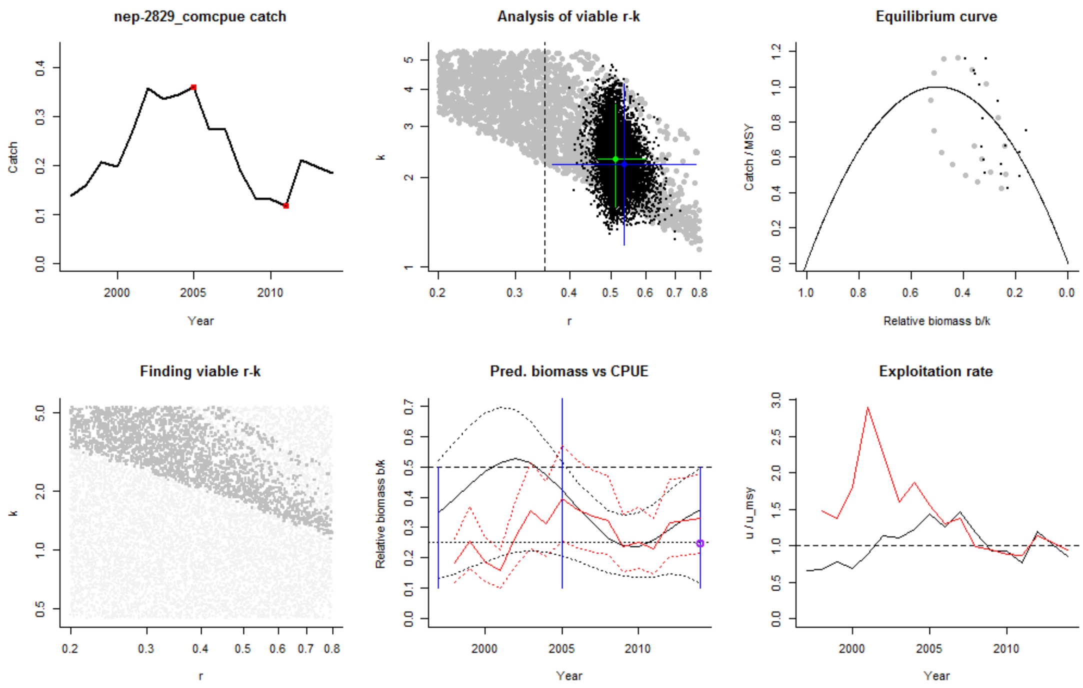
1244 r-k pairs above r = 0.351 and 2050 trajectories within r-k CLs were analyzed r = 0.535, 95% CL = 0.366–0.783, k = 2.23, 95% CL = 1.19–4.17

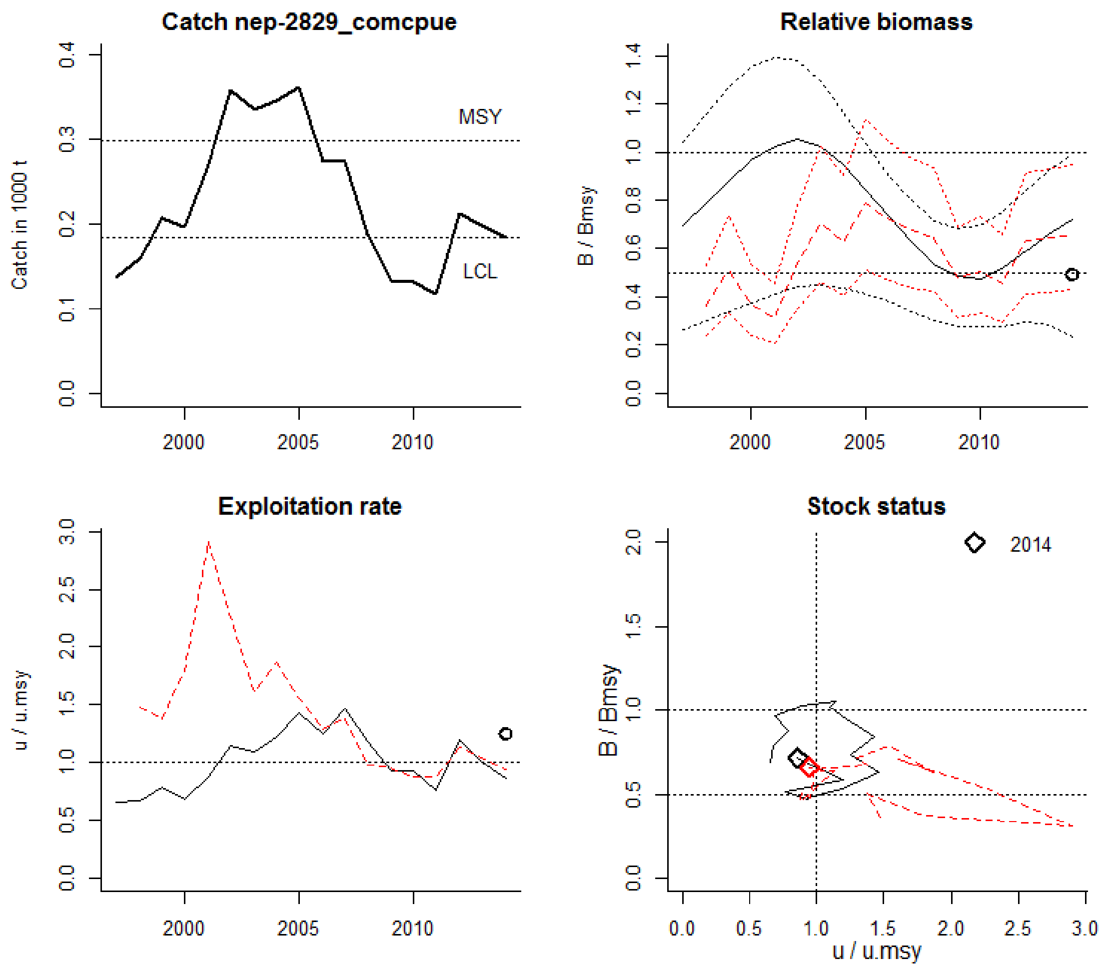
MSY = 0.298, 95% CL = 0.183–0.485

Predicted biomass in last year = 0.359, 2.5th perc = 0.115 25th perc = 0.247 97.5th perc = 0.494

Predicted biomass in next year = 0.381, 2.5th perc = 0.0626 25th perc = 0.24, 97.5th perc = 0.538

Predicted exploitation rate in last year= 0.856, 25th = 1.243





Comment: Good agreement after 2005 between C_{MSY} results and relative biomass and exploitation rate trends from commercial cpue, as scaled by BSM.

4.4 References

Froese, R., Demirel, D., Coro, G., Kleisner, K.M., Winker, H. Estimating fisheries reference points from catch and resilience. Submitted to Fish and Fisheries on 28 February 2015.

Froese, R. 2015. Results of preliminary runs of the CMSY-method against data-limited ICCAT stocks. SCRS 2015/113, ICCAT, Madrid.

ICES. 2014. Report of the Workshop on the Development of Quantitative Assessment Methodologies based on LIFE-history traits, exploitation characteristics, and other relevant parameters for data-limited stocks (WKLIFE IV), 27–31 October 2014, Lisbon, Portugal. ICES CM 2014/ACOM:54. 241 pp.

Martell, S. and R. Froese. 2013. A simple method for estimating MSY from catch and resilience. Fish and Fisheries 14: 504–514.

5 Selection of an appropriate method

5.1 Introduction

Although a number of candidate methods have been presented, discussed and tested during this fifth meeting of WKLIFE, it was concluded that it would be premature to specify a decision tree to guide the choice of appropriate method for category 3 and 4 stocks. The methods considered at this and previous meetings of this workshop series have clearly specified the data requirements and needs of the methods, indicating strengths and weaknesses of each approach. It is important to identify the data sources and assumptions that are pertinent for each stock to be assessed and to select the most appropriate method which best uses all the available information.

WKLIFE V developed operational methods for setting reference point proxies (F/F_{MSY}, B/B_{MSY}) for stocks in categories 3 and 4. These methods will have immediate application to the stocks and fisheries in a subsequent meeting: ICES Workshop to develop MSY and precautionary reference point proxies for selected stocks in ICES categories 3 and 4 in Western Waters [WKProxy] to be held at ICES HQ, Copenhagen, Denmark from 3–6 November 2015. In the next Section 5.2, WKLIFE provides initial guidance on the method appropriate to each stock based on the availability of data.

5.2 Guidance to ICES WKProxy

For the 28 stocks to be considered by ICES WKProxy, a provisional identification of method to be considered was discussed by the WKLIFE chairs, the WKProxy chairs and the WKLIFE reviewer based on the available data for each stock and the expertise at WKProxy (Table 5.2.1). WKLIFE recognizes that more advanced and complex size-based assessment models (e.g. SS3) might be appropriate to the available data, but the time and expertise required to develop such models to the large number of stocks is not realistic, and simpler, more robust models are needed.

Table 5.2.1. Provisional identification of method to be used by ICES WKProxy (SPiCT: Stochastic Production model in Continuous-Time, Mean-length Z: mean-length-based mortality estimator, LB-SPR: length-based spawning potential ratio, C_{MSY}: catch-based method, ICES advice: F_{PROXY} based on catch/survey biomass).

	SPiCT	Mean-length Z	LB-SPR	CMSY	ICES' advice
anb-78ab					
anp-78ab					
ang-ivvi					
arg-123a4					
arg-5b6a					
arg-icel					HR Fproxy
arg-rest					
bss-8ab					
had-iris					
lin-oth					
meg-rock					
mgw-78					
nep-2021					
nep-2324					
nep-25					
nep-2627					
nep-2829					
nep-30					
nep-31					
ple-echw					
ple-7h-k					
ple-celt					
ple-iris					
pol-celt					
sol-7h-k					
usk-oth					
usk-rock					
whg-iris					
total	10	4	11	2	1

6 Other crustaceans and molluscs

6.1 Shellfish assessments

With the exception of *Nephrops*, shellfish fisheries lie outside the EU TAC system, and are subject to relatively few international constraints (Western Waters Effort rules apply to Crab and Scallop fisheries, and there are EU Minimum Landing Sizes). This is not to say that shellfish fisheries are small or low value, but the management of them has largely be devolved to the Member States as the species in question are generally fairly sessile. However, the Marine Strategy Framework Directive, (MSFD) states: "Populations of all commercially exploited fish and shellfish are within safe biological limits, exhibiting a population age and size distribution that is indicative of a healthy stock". Given the international and political requirement of the EU TAC system, the focus of stock assessment has almost exclusively been with quota stocks meaning that the basic data requirements of shellfish stocks have sometimes been overlooked. This is compounded by the often challenging nature of collecting both fishery statistics and basic biological data for shellfish. WKLIFE V explored some of these issues.

6.1.1 Landings

Shellfish fisheries are highly varied in terms of fishing method and scale. A large proportion of fisheries targeting shellfish occur in inshore waters (<6 or 12 nm) and are operated by vessels of between 3 and 13 m length overall (LOA) and operating on a daily basis. There are also large-scale fishing operations targeting species such as brown crab *Cancer pagurus* and scallop *Pecten maximus* with vessels over 13 m making multi-day trips. Fishing practices include active trawling/dredging, passive netting, baited traps and hand-gathering. Although the tonnage of landings is generally low compared to finfish fisheries, the value of harvested shellfish species has a high average value (Marine Institute and Bord Iascaigh Mhara, 2015).

As a consequence of their size distribution, a large majority of the vessels involved in shellfish fisheries are *de facto* excluded from the obligation to be equipped with VMS transmitters (mandatory for vessels >12 m LOA) and to submit logbooks (mandatory for vessels >10 m). A large section of vessels under 10 m do generate sales notes (for sales over 25 kg from any single landing) and bivalve fishers complete registration documents for food traceability purposes, but there has been a lack of consistency over time and between fisheries in the level of information returned to those public institutions in charge of the fishery management (i.e. high variability of actual data entry and reporting). Effort and landings are therefore poorly estimated for a large majority of shellfish fisheries despite the official systems in place for the collection of such data

6.1.2 Effort

The effective effort of some fishing gears used for shellfish is very difficult to measure. The effective effort of active gears such as trawls and dredges could be measured as swept-area and is probably more accurate than for finfish as there will be little or no herding effect (due to the lower mobility of shellfish). The effective effort of passive gears such as fixed nets and particularly baited traps is more complex. For fixed nets the effective effort is predominantly a function of net length and soak time, whereas for pots there is the added effect of attraction to the pots and behaviour around the pots influenced by things like bait type, pot type and inter & intra specific interactions around the pot itself. While many of these factors can only be investigated through scientific monitoring and research, the basic data such as number of dredges or pots fished, or soak time is usually poorly captured by national data collection programmes, partially because such fields are not mandatory in the EU data collection schema.

6.1.3 Abundance indices

On-board observer programmes have been developed for monitoring stock dynamics through the estimation of landings, discards, effort and size compositions on a sample of fishing trips. These programmes, supported by the EU Data Collection Framework (DCF) and the recent Data Collection Multi Annual Programme (DC MAP) have been providing valuable information for a number of fisheries for the last ten years. The level of coverage in both space and time of these programmes is such that the more heterogeneous distribution of shellfish along with seasonal/patchy exploitation patterns and small-scale fisheries means they are often poorly sampled. This scattered pattern, poor precision, and potential bias make it difficult to monitor shellfish fisheries properly, and hence to deliver reliable abundance indices, even at a regional level.

The uncertainties around the statistics of abundance indices are also intensified for some stocks by the lack of knowledge of the relationship between population abundance and catch rates. The use of catch rates as indices of population abundance relies upon the assumption that they are linked in a linear relationship, and this relies upon a statistical assumption that all individuals in a population have an equal probability of being caught by the gear. Deviations from this assumption will lead to non-linearity in the relationship between abundance and index and factors affecting these can be subdivided in two main types of uncertainties:

1) **based on the fishing technique**: catch rates of passive fishing gears mostly rely on the behaviour of targeted species. For example, catch rates in lobster and crab traps are expected to depend on the attractiveness of baits (hence also probably on physiological rates, that can vary seasonally), on individual interactions around and at the trap location, escapement, (Goñi *et al.*, 2003; Barber and Cobb, 2009; Watson and Jury, 2013). But also on the gear saturation (physical or through individual interactions) that could prevent to detect any change in indices until the effort reach a very high level or the stock density decrease substantially (Groeneveld *et al.*, 2003; Barber and Cobb, 2009).

2) **based on spatial distribution of species**: The assumption of random interaction between gear and individuals could result from either the target species or the fishery having a random spatial distribution. For highly mobile species this assumption may be valid, but for sedentary species the random movement can only come from the fishery. As fisheries are economic activities and are aided by positioning technology, their ability to concentrate on the most productive sites is likely to exert considerable influence on the assumption of randomness and cannot be ignored. For instance, sequential exploitation of separate beds might result in hyperstability in catch indices (as shown for finfish aggregations, e.g. Erisman *et al.*, 2011). However, spatially explicit data on fishing effort at an appropriate scale could be used to detect such sequential exploitation.

Such uncertainties in shellfish cpue or lpue indices mean that a great deal of caution should be used when interpreting changes in level as a proxy for changes in stock abundance. Even where the input data are considered reliable, the statistical properties and assumptions being made suggest that the direction of long-term trends might be a more appropriate interpretation of the data rather than a tool for setting of annual quotas in response to interannual stock changes.

6.1.4 Biological data

The varied life-history traits of shellfish have implications for the range of biological data it is possible to collect:

1) Age-size parameters:

  1.1) Crustaceans: because of growth by moult and the subsequent absence of permanent hard parts usable for aging, routine estimations of growth rate cannot be obtained in an easy manner. For a large number of crustaceans growth parameters are therefore not available, although for the major stocks (crab, lobster, *Nephrops*), historic growth rates through tagging studies are available.

  1.2) Molluscs (Bivalves and Gastropods): for a few species such as scallop and cockle, detecting annual growth marks is relatively straightforward but requires training and intercalibration to get consistent results over time and locations. Where the growth parameters exist, they can be highly variable at relatively short distances (10s KM or less), especially for species having a low mobility (where growth depends on local conditions of food availability/temperature, etc.). For some other species, no operational technique for routinely aging individuals already exists.

2) Length–weight parameters: this relationship is generally well defined and easily obtained.

3) Size-at-maturity: available for some stocks, based on surveys, port and/or on-board samplings.

4) Size composition: DCF rules require the collection of some length distributions for major shellfish species, although in reality some of the targets set do not generate sufficient numbers to be of practical use and therefore national programmes are instigated over and above these levels. The highly variable growth rates associated with some shellfish, combined with their relatively sedentary nature means that sampling frequency may have to be considerably higher for reliable and practical determination of length frequencies than for finfish. Size composition data are usually available where surveys and/or on-board observer programmes exist and such size distributions by sex (when relevant) may be considered sufficiently reliable information for stock assessment purposes (accounting for the gear selectivity profile).

6.1.5 Issues for assessment

Owing to the large uncertainties and gaps in the reporting of fisheries statistics, some shellfish stocks cannot be considered as category 4 or 5 stocks, and usual data-poor models cannot be applied for assessment purposes. The scale of this problem however is not well defined and varies locally, regionally and between countries. There are a few exceptions where assessment models have been used, such as for lobster

(*Homarus gammarus*) and brown crab (*Cancer pagurus*) stocks around the UK and Ireland for which a Length Cohort Analysis (LCA) and Egg production per recruit (EPR) was recently implemented, and the current status regarding MSY assessed using the 35% Spawners per Recruit (SPR) proxy (Marine Institute, 2009; Cefas, 2015a; b). In a few other cases, survey-based trends in biomass are effectively used for managing Bivalves (e.g. *Pecten maximus* in the Bay of Seine: Foucher, 2014; Cockle *Cerastoderma edule* in East Ireland). Investigations for applying alternatives such as in-season depletion estimates of F or production models on these species are planned. Also, near real-time data on the depletion of cpue during the fishing season is used to manage cockle and clam fisheries in Ireland using an *ad hoc* but pre-agreed cpue as a limit reference point. Such approaches are adaptive to new signals in observed data and consistent with the ICES approach to data-limited stocks.

For the majority of other stocks, neither the status regarding reference points nor the trends in abundances can be effectively used for management. In this situation where monitoring the stock status is not possible, managing the fisheries by using effort limitation would make little sense. Especially as the fishing effort may be difficult to monitor for some gears (e.g. pots) and then the enforcement of its limitation unlikely to be effective. In this context, the main tool for managing these shellfish fisheries remains regulations regarding minimum/maximum landing size. This tool seems particularly relevant as the survival rates in shellfish discards are known to be generally high. This however is a limited approach that may be suboptimal with respect to the economic viability of the fishery; as fishing effort (and mortality of the exploited proportion of the stock) increases further increases in MLS are required to stabilise the average value of F. Consequently, discard rates increase and the costs per unit landed increases while the value per KG landed may actually decrease as the size of animals attracting the premium prices are sometimes smaller than maximum attainable size. Recent changes to size limits for lobster in Ireland was based on an EPR assessment relative to an assumed 10% limit reference point and an estimate of F from LCA.

In the following, we investigate whether fishery management using only minimum landing size (MLS) could be used to manage a fishery while approximately achieving "MSY". Such an approach might be appropriate in situations where landings and or effort are difficult to monitor or control, or in emerging and very data-limited fisheries. We examine the impact of different fishing mortalities and MLS upon stock metrics such as Spawners per Recruit, yield-per-recruit and the number of spawning events by individuals, using stocks where we have some knowledge of life-history traits. We then look to see if simple proxies based upon maximum size and/or length at maturity can be used to define an MLS likely to be "MSY compliant". This is therefore not the evaluation of a stock assessment approach but more an exploration of a management approach that might be taken where assessment is not possible. It is desirable to have a stock assessment approach that can be used to monitor the performance of the management in place and therefore the best option is to increase the quality and variety of data in order to be able to estimate metrics such as current stock biomass and exploitation status.

6.2 MSY compliant management using MLS

For some species, particularly low-volume high-value shellfish species, there are few data available. Landings might be poorly understood possibly due to multiple small-scale sales which are not captured by official statistics, or through undocumented recreational removals. Fishing effort might also be poorly understood, even when documented as the realised fishing effort of potting operations depends upon complex interplay between numerous factors including deployment, baiting, season and inter/intraspecific interactions. In such situations it might be impractical or undesirable to develop fishery management plans which control inputs or total output, instead control through technical measures is often the tool of choice or necessity. How then, might fishery managers set the rules for technical measures that have some correspondence to MSY principles?

This section explores the potential for minimum landing sizes to be set such that they provide a management scheme which deliver MSY-like results for the stock while being robust to uncertainty in overall fishing effort. While the use of MLS as the only management tool is unsatisfactory for species with high discard mortality and particularly in where it occurs in mixed fisheries, for the majority of crustaceans and most molluscs where discard survival might be expected to be good, MLS could be a viable primary tool for fishery managers.

A simulation framework was constructed in which the fate and spawning success of cohorts of individuals was followed while subject to a fixed fishing pattern. A range of fishing patterns (varying both the MLS and the overall F pattern) were then tested on a number of species, in order to see if some generic rules based upon very simple metrics (maximum observed length and/or length at maturity) could be developed.

6.2.1 Model framework

An Individual Based Model was constructed in C++ allowing rapid computation of the fate of a large number of individuals within a cohort. The model used von Bertanaffy growth parameters to derive the growth of individuals, each individual was given a starting size drawn from a normal distribution around the expected size-at-first age. For each time-step (set to be annual), the expected proportional growth from a deterministic implementation of the growth function was established and the size of all individuals was increased by the expected proportion. Maturity-at-length was controlled by a sigmoid function. Immediately after the growth increment was determined, the probability of immature individuals becoming mature was taken from the maturity-at-length ogive and the individual status then determined by comparing the probability against a random number drawn from a uniform 0–1 distribution. Mature individuals were assumed to spawn annually, and mature individuals remained mature over their lifespan. Individual mortality was determined through the probability of dying in a time-step ($1-e^{-z}$) compared to a random number (uniform 0–1). Each simulation continued until all individuals had died.

Upon death of each individual, the simulation recorded the number of spawning events completed and the total effective spawning biomass of that individual (i.e. the cumulative annual biomass of the individual from the time of the first spawning to the time of its death). Spawning activity took place before the mortality calculation, similar to the assumption that spawning took place on January 1st each year.

The input parameters were as follows: Number of individuals in the cohort, the starting age, a CV for the distribution around the expected size-at-first age (default 10%), von Bertanaffy parameters, weight–length parameters, maturity parameters (in one of two forms) parameters for selection at length and a specified range of F-mulitpliers to explore.

The model formulation for selection at length was as follows:

$$p = \frac{1}{1 + exp\left(\frac{\ln(3) * (L_{50} - l)}{L_{50} - L_{25}}\right)}$$

There was a choice of maturity ogive formulation, either using the same formulation as the selection at length ("B" formulation"), or the more traditional ogive ("A" formulation) as follows:

$$p = 1 - \frac{1}{1 + exp(a) * \exp(b * l)}$$

The C++ model was placed inside an R-script wrapper to both extend the model to explore a range of different minimum landing sizes, and to handle the extensive output. The R-script produced three plots Yield vs. MLS, mean number of spawning events vs. MLS and SSB vs. MLS. For the mean number of spawning events, only those individuals which achieved at least one spawning event were included. Within each simulation there would be a proportion of individuals which would die of natural causes before the fisher had any effect, and the proportion of this section of the population would depend upon the starting age of the simulation.

6.2.2 Application

The model was applied to parameters for the females of two species not assessed by ICES (European lobster, *Homarus gammarus*, and brown crab, *Cancer pagurus*). In addition to these non-quota crustaceans, parameters from several quota stocks were explored as proxies for different life-history traits. These were *Nephrops norwegicus* (FU6), North Sea plaice (males and females), Northern hake and Norway pout. The parameters are given in Table 6.1.

For all species except Norway pout, the F-multiplier range used was 0 to 1.2 in steps of 0.2. For Norway pout a wider range of 0–2.5 in steps of 0.5 was used due to the much higher estimates of natural mortality used for the stock. The range of MLS was selected individually for each species, starting at current MLS and extending such that that F_{MAX} could be determined.

Six different metrics were extracted from the results of the runs:

1) The average number of spawning events expected when fishing at F=M (proxy for MSY) and a MLS at either current levels or $L_{50\%mat}$, whichever was the higher.

2) The average number of spawning events expected when fishing at F_{MAX}.

3) The L_{50} estimated to deliver F_{MAX}.

4) The L_{50} which gives the number of average spawning events defined in (1), but when fishing at a high fishing mortality (F>1) (termed "L_{robust}").

5) The L_{50} which gives 35% of unfished spawning biomass per recruit when fishing at a high fishing mortality.

6) The ratio of spawning biomass per recruit when fishing at F_{MAX} compared to the unfished state.

Metric 1 was selected to represent a MSY-like level of spawning opportunities. Metric 4, L_{robust} could therefore be considered to be a MLS that would deliver a fishery management strategy that had links to MSY and was robust to unconstrained fishing levels. Metrics 5 and 6 (% virgin SpR) were designed to see how the approach performed against the 30–40% SpR ranges used in many situations as proxies for MSY.

Three proxies for an MSY compliant MLS were tested,

a) 66% of L_{inf} (itself a proxy for L_{opt}),

b) $L_{95\%mat}$, and

c) $L_{50\%mat}$ + (L_{inf}–$L_{50\%mat}$)/3, termed "L_{hybrid}"

6.2.3 Results

The graphical outputs for each stock are shown in Figure 6.1 and the summary of metrics are given in Table 6.1.

Maximum yield-per-recruit among MLS options was not well defined at low fishing mortality, is generally well defined at high fishing mortality and in all cases is generated by the highest fishing mortality tested and is produced at a L_{50} in excess of all current MLS (Norway pout has no MLS). All stocks have an average number of spawning opportunities >1 when fished at "MSY" type levels and MLS is above the $L_{50\%maturity}$ level with crab, lobster and plaice having in excess of two or even three spawning opportunities.

The L_{50} required to achieve the same level of spawning opportunity at high F that is expected for MSY conditions appears to be broadly consistent with the L_{50} associated with F_{MAX} across the range of species and life-history traits. The L_{50} required to achieve 35% of virgin SpR at high values of F is generally higher than the L_{50} for F_{MAX}, the SpR obtained at F_{MAX} averaging ~27% across the range of species tested here.

Of the three proxies for an MSY compliant MLS, $L_{95\%mat}$ is, with the exception of Norway pout, lower than the L_{robust} estimate. There is generally little difference between the L_{opt} proxy compared to the L_{hybrid} proxy although for hake the L_{hybrid} proxy is closer to the L_{robust} proxy than L_{opt}.

6.2.4 Discussion

The analyses presented here suggest that the use of L_{opt}, or the L_{hybrid} measure could be justified as being more "MSY compliant" than the more traditional use of $L_{50\%mature}$ as a Minimum Landing Size. In highly data-poor situations, or where other types of fishery management are impractical such high MLS would appear to be a reasonable first approximation.

There are, of course, difficulties with having such high MLS; unless gear selectivity is adjusted accordingly, the fishers will see a lot of catch being returned to the sea (increasing the risk of landing undersize animals) and for baited trap operations the bait cost per individual retained would be higher.

There are a number of issues with the approach taken here that warrant further investigation. The number of species parameters investigated is very low and a more thorough examination is warranted. The relatively simple cohort model does not have the full feedback of a stock–recruit function and therefore density-dependent effects on recruitment, such as might be expected in hake (through cannibalism) and lobster (through competition for habitat) are ignored. In these sort of situations, the expected yield curves might be quite different, with higher MSY fishing rates and smaller L_{50}s, so the forecasts here could be over-optimistic in terms of yield with unrealistically high MLS recommendations. The approach presented here would, however, be expected to work reasonably well in situations where asymptotic recruitment functions exist and there are no effects of density-dependence in growth rates at the population densities estimated under "MSY" like exploitation rates.

6.2.5 References

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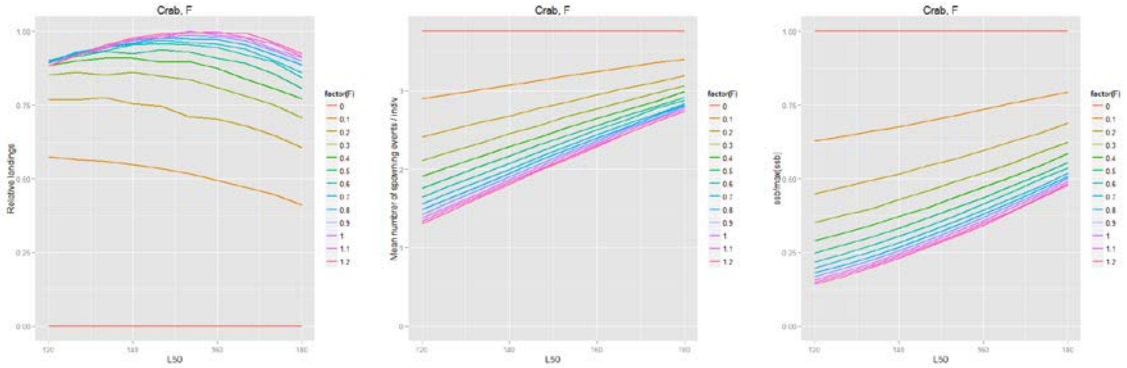
Table 6.1. Input parameters to the Spawning Opportunities model.

Species	Maturity			Weight-Length		Growth			M
	Model	a	b	a	b	k	Linf	t0	
Crab (female)	A	-10.4438	0.093592	0.000189	2.947	0.191	240	0	0.25
Lobster (female)	A	-28.2061	0.33623	0.001086	2.896	0.1088	168.71	0	0.15
Nephrops (FU6, female)	B	27.2	30.5	0.000492	3.056	0.16	58	0	0.2
North Sea Plaice (female)	B	27.44	28	0.098	2.99	0.13	56.1	0	0.1
North Sea Plaice (male)	B	24.5	25	0.098	2.99	0.12	44.6	0	0.15
Northern Hake	B	41.993	42.85	0.00513	3.074	0.17	130	0	0.4
Norway pout	B	18.228	18.6	0.0068	3	0.59	22.6	0	1.54

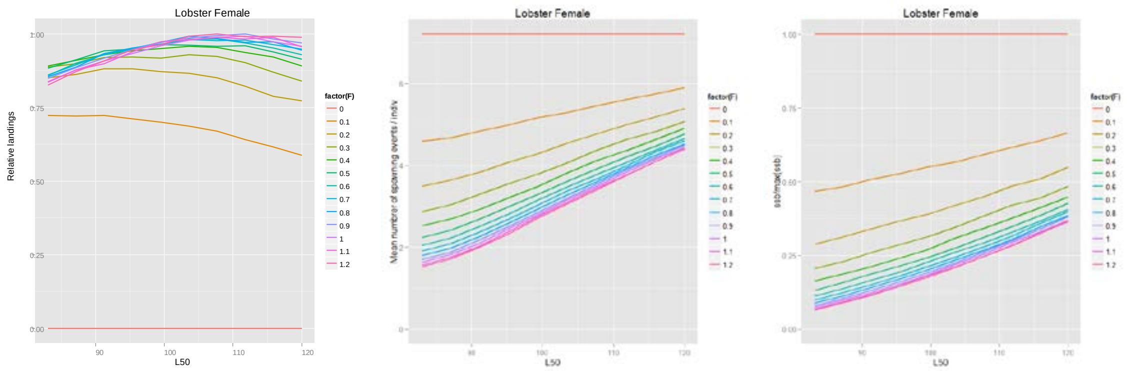
Table 6.2. Output metrics from the Spawning Opportunities model.

Species		Spawning opportunity metrics		L50 metrics			SpR	L50 proxies		
		Nspawn at MSY & $L_{50\ current}$	Nspawn at F_{MAX}	F_{MAX}	Robust	35%SpR	F_{MAX}	66% L_{inf}	$L_{95\%mat}$	L_{hybrid}
Crab		2.4	2.25	155	165	165	35%	158	144	150
Lobster		4	3.5	107	114	120	27%	110	93	109
Nephrops		1.15	1.5	38	35	42	27%	38	31	39
NS Plaice	F	3.5	3	40	43	45	20%	37	29.75	36
	M	4.5	3.5	32	35	33	26%	30	26.5	31
Hake		1.5	1.4	65	68	65	35%	86	45.5	69
Norway Pout		1.1	1	10	18	16	19%	15	19.75	20

Crab



Lobster



Nephrops

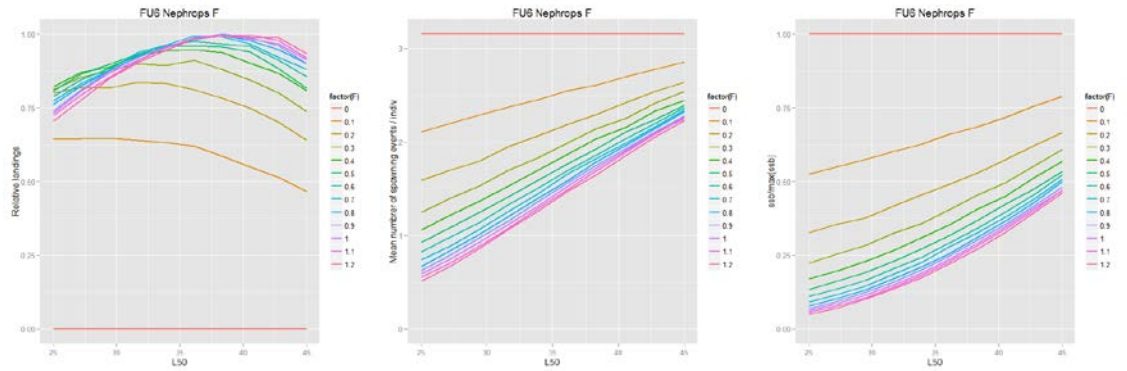
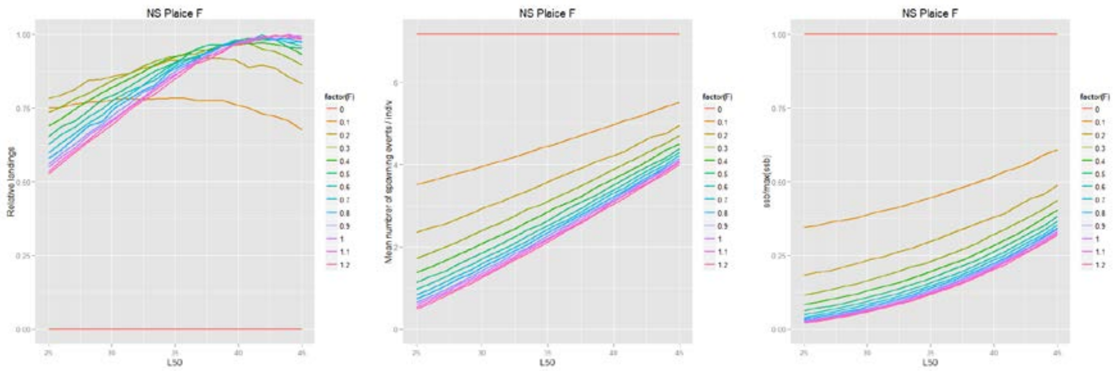
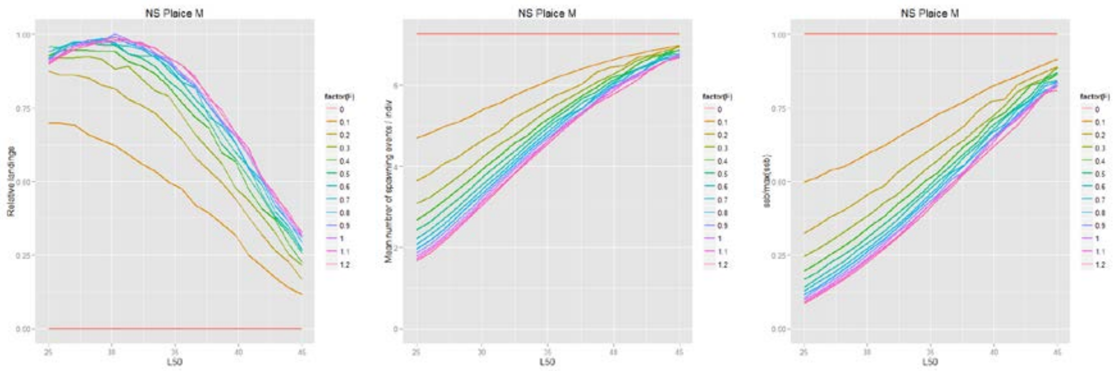


Figure 6.1. Outputs from the spawning opportunities model.

North Sea Plaice (Female)



North Sea Plaice (Male)



Northern Hake

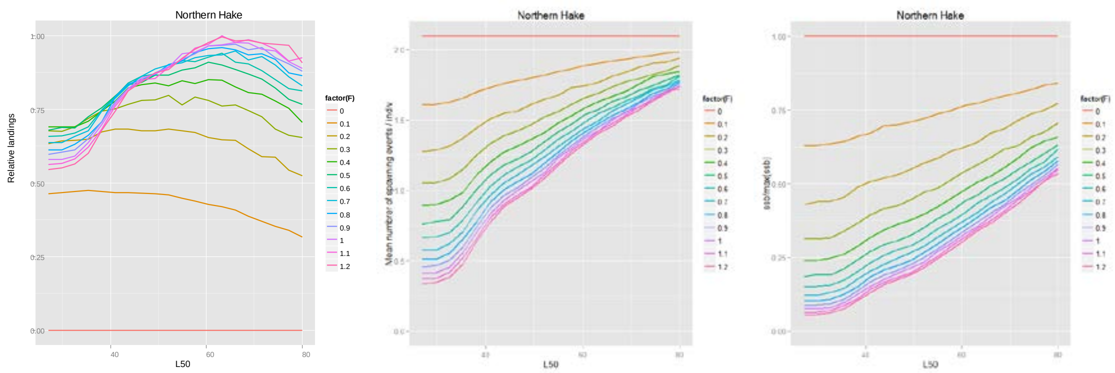


Figure 6.1. Continued. Outputs from the spawning opportunities model.

Norway Pout

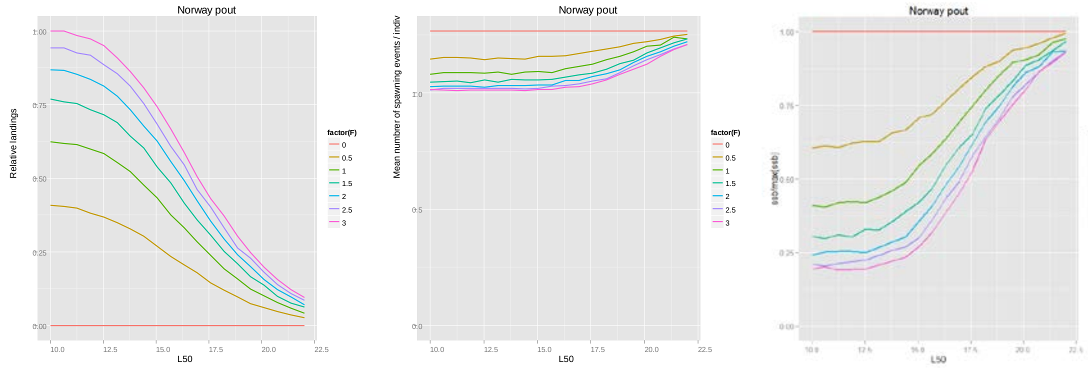


Figure 6.1. Continued. Outputs from the spawning opportunities model.

7 Future work

7.1 Future Terms of Reference (ToRs)

The next WKLIFE should meet in Lisbon, Portugal for five days from the 3–7 October 2016 with the current co-chairs (Carl O'Brien, UK and Manuela Azevedo, Portugal). The ToRs should be decided by ACOM at their December 2015 meeting, once the reports of the ICES WKMSYREF4 and WKProxy meetings have been considered by ACOM.

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GLS

Annex 2: Recommendations

Recommendation	For follow up by:
ToRs for WKLIFE VI be decided once the reports of the ICES WKMSYREF4 and WKProxy meetings have been considered by ACOM at their December 2015 meeting.	ACOM

Annex 3: Report of the breakout group on C_{MSY}

This Annex 3 contains the following issues that were discussed during the breakout group at WKLIFE V:

- General introduction to C_{MSY};
- How to find the most probable estimates of *r* and *k* from among viable *r-k* pairs;
- Testing the sensitivity of C_{MSY} to depletion patterns and resilience of stocks;
- C_{MSY} analysis of catch data of fully assessed stocks;
- Running C_{MSY} on catch data and cpue of data-limited stocks;
- Comparing results with observation error of catch with sigma 0.1 and 0.2;
- References.

General introduction to C_{MSY}

C_{MSY} is a method for estimating maximum sustainable yield (*MSY*) and related fisheries reference points (B_{MSY}, F_{MSY}) from catch data and resilience, developed by R. Froese, G. Coro and H. Winker. It is an advanced implementation of the Catch-MSY method of Martell and Froese (2013). C_{MSY} was tested and found satisfactory at the WKLIVE IV workshop in Lisbon, October 2014 (ICES, 2014) and at an ICCAT workshop on data-limited stocks in Madrid, June 2015 (Froese, 2015). If managers, experts or stakeholders have a perception about the depletion history and the current status of a given stock, then C_{MSY} can test such hypotheses against observed catches and the known resilience of the species. If combinations of productivity and stock size are found that are compatible with catches and resilience, then the stock status and exploitation rate are presented in an MSY-framework. C_{MSY} has been tested against simulated data, where the "true" parameter values were known, and against over one hundred fully assessed stocks, with good agreement between C_{MSY} predictions and "true" or observed data. The full documentation of these tests was available to the participants of WKLIFE V (on SharePoint). A publication describing C_{MSY} (Froese *et al*., submitted) is accepted with revision as of this writing. This report contains several examples of applying C_{MSY} to catch data made available at WKLIFE V. Note that part of the C_{MSY} code is a Bayesian state–space implementation of a full Schaefer model (BSM). If abundance data are made available, e.g. as total biomass, catch per unit of effort, or stock size index, then BSM will analyze these data and show the results in the printout and in the graphical output, so that C_{MSY} results are put in perspective. BSM results can also be used in their own right. Note that time-series of abundance can be shorter than those for catches. If abundance data are available for fewer than e.g. nine years, than they are not analyzed by BSM but shown with a second Y-axis in the C_{MSY} graphical output.

With the C_{MSY} method, prior parameter ranges for the maximum intrinsic range of population increase (*r*) and for unexploited population size or carrying capacity (*k*) are filtered with a Monte Carlo approach to detect 'viable' *r-k* pairs. A parameter pair is 'viable' if the corresponding biomass trajectories calculated with a Schaefer model are compatible with the observed catches, in the sense that predicted biomass does not overshoot carrying capacity nor crash the stock. Also, predicted biomass shall be compatible with prior estimates of relative biomass ranges for the beginning and the end of the respective time-series. Optionally, a third intermediate prior biomass range can be provided to reflect extraordinary year classes or stock depletions. Also optionally, an indication whether the stock is likely to crash within three years if current catches continue can be given. This will improve the estimation of biomass in the final years. Examples of questions to be put to experts to derive the priors required by C_{MSY} are shown in Table 1.

Table 1. Example of questions to be put to experts to establish priors for C_{MSY} analysis.

PRIOR	QUESTION TO EXPERTS
Start year for catch time-series	From what year onward are catch data deemed reliable?
Relative start and end biomass B/B_0	What was the most likely exploitation level at the beginning and end of that time-series: light, full, or overfishing? Given this exploitation level, what was the most likely status of the stock, good or bad?
Relative intermediate biomass B/B_0	Is there an intermediate year where, e.g. exploitation changed from light to full, or where an extraordinary large year class entered the fishery?
$2\ M \approx r$	What is your best guess for the range of values including natural mortality of adults (M)?
$2\ F_{MSY} \approx r$	What is your best guess for the range of values including maximum sustainable fishing mortality (F_{MSY})?
Resilience	What is the classification of resilience for this species: very low, low, medium or high?
$B/B_0 < 0.2$: Possible / No	If current catches continue, is it likely that the stock will be outside safe biological limits within the next three years?

Based on the answers of the experts, the most probable ranges for relative biomass are chosen from Table 2 and the most probable ranges for *r* are chosen from Table 3.

Table 2. Prior relative biomass ranges *B/k* used by C_{MSY} for analyzing the simulated data.

POINT IN TIME-SERIES	STRONG DEPLETION	LOW DEPLETION
Beginning	0.1 – 0.5	0.5 – 0.9
Intermediate	0.01 – 0.4	0.3 – 0.9
End	0.01 – 0.4	0.4 – 0.8

Table 3. Prior ranges for parameter *r*, based on classification of resilience.

RESILIENCE	PRIOR R RANGE
High	0.6 – 1.5
Medium	0.2 – 0.8
Low	0.05 – 0.5
Very low	0.015 – 0.1

A fit-for-use-in-assessments version of the R code for C_{MSY} and BSM was produced and tested at the WKLIVE V meeting, together with a user manual. These were made available at SharePoint of the meeting.

How to find the most probable estimates of *r* and *k* from among viable *r-k* pairs

A question that came up during the meeting was how C_{MSY} determines the most probable *r-k* pair.

A plot of viable *r-k* pairs typically results in a triangular-shaped cloud in log *r-k* space. A special algorithm is applied by C_{MSY} to select the most probable *r-k* pair from the tip-section of the triangle and to establish approximate confidence limits. This algorithm is guided by the following considerations:

1) We are searching for the highest rate of increase that a given population can support. Obviously, this rate should be found among the highest *r*-values identified as "viable" within the prior *r*-range.

2) The uniform prior ranges for *r* as used by C_{MSY} (see Table 3) are derived from expert knowledge, basically saying that a central value with a lognormal distribution of *r* is expected to occur somewhere within these ranges, with a low probability that the central value will fall on the upper or lower bound of the ranges. However, by design, the triangle of "viable" *r-k* pairs found by C_{MSY} always touches the lower bound of the prior *r*-range, because observed catches can always be explained by large stock sizes, such as predicted for low values of *r*. Including these low-*r*-high-*k* pairs in the search for the most probable *r-k* pair creates a bias of underestimating *r* and overestimating *k*, such as documented in Martell and Froese (2013). Figure 1 shows some examples (black dots) of probable *r-k* pairs as identified by a full Schaefer model (BSM). As can be seen, these clouds of probable *r-k* pairs typically occur in the upper have of the range of viable *r*-values.

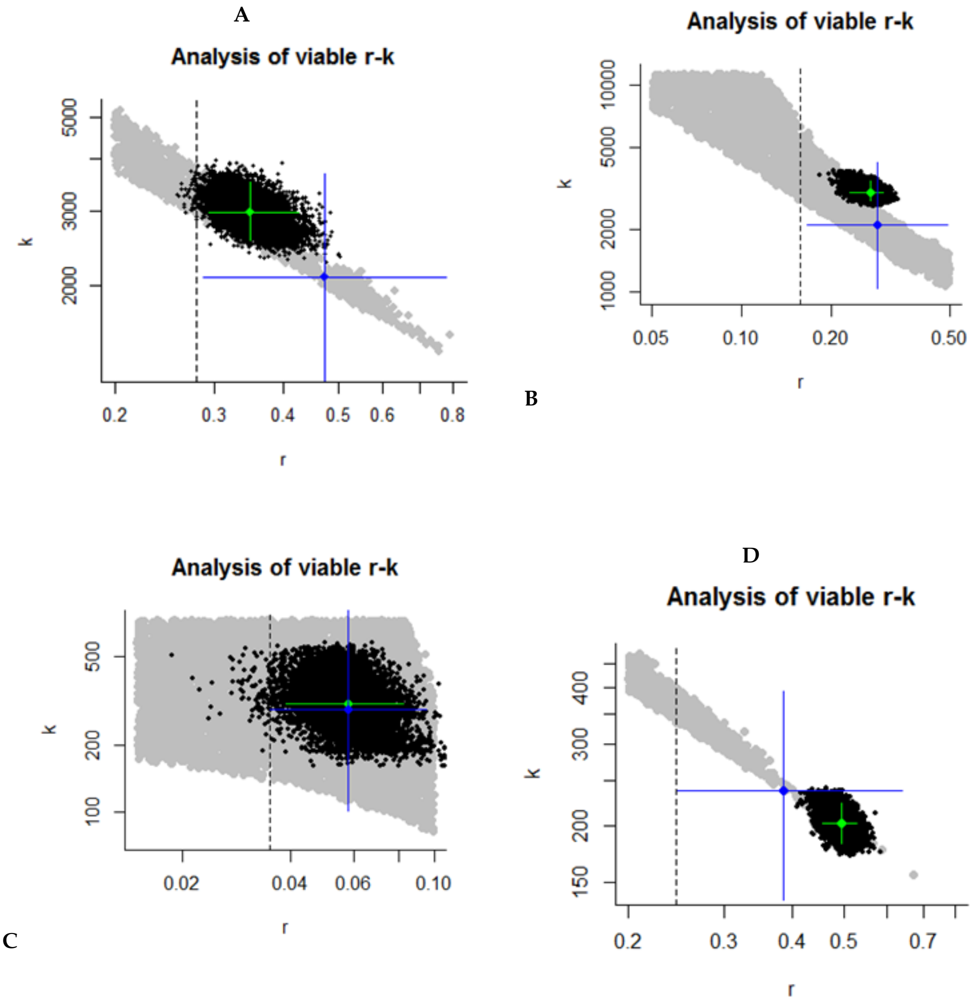


Figure 1. The ellipsoid clouds of black dots shows the distribution of probable *r-k* pairs based on a Bayesian Schaefer model analysis. These clouds typically overlap with the right-hand side of viable *r-k* pairs estimated by CMSY.

CMSY overcomes the bias in Martell and Froese (2013) by a very simple procedure: it estimates the geometric mean of the viable *r*-values and discards values below the geometric mean. The remaining *r*-values are then split into 25 bins of equal width in log-space. The median of the mid-values of occupied bins is taken as the most probable estimate of *r*. This procedure gives equal weight to all occupied bins and reduces the bias caused by the triangular (instead of ellipsoid) shape of the tip section. Taking the median instead of the mean gives less weight to outliers. Approximate 95% confidence limits of *r* are obtained as 2.5th and 97.5th percentiles of the mid-values of occupied bins.

Testing the sensitivity of CMSY to depletion patterns and resilience of stocks

CMSY assessments of 48 simulated stocks were analysed to detect the sensitivity of the CMSY method to different patterns and contrast in stock biomass and to different levels of resilience of the species. Resilience ranges of Very low, Low, Medium and High resilience were analysed (Table 3). The simulations covered a range of biomass scenarios, including strongly as well as lightly depleted stocks, with monotone stable or monotone changing (i.e. steadily decreasing or increasing) or with alternating biomass trajectories: patterns of high-high (HH), high-low (HL), high-low-high (HLH), low-low (LL), low-high (LH), and low-high-low (LHL) biomass trends. Resilience categories were translated into *r*-ranges as shown in Table 3. The detailed analyses of the 48 simulated stocks were available to WKLIFE V participants (on SharePoint). The results of the sensitivity analysis are shown in Table 4 for the intrinsic rate of population increase *r* and in Table 5 for the unexploited stock size *k*.

Table 4. CMSY estimates of *r* relative to the "true" r used in the simulations. Four estimates that diverge 20% or more from the "true" value are shown in bold.

	Very low	Low	Medium	High	Median
HH	1.19	1.18	1.14	**1.20**	1.18
HL	1.13	0.89	0.94	1.08	1.01
HLH	**1.22**	1.18	1.10	1.08	1.14
LL	1.16	0.92	0.94	0.87	0.93
LH	**1.52**	1.09	0.94	**1.26**	1.18
LHL	1.16	1.06	1.02	1.06	1.06
Median	1.17	1.08	0.98	1.08	

With regard to resilience, CMSY estimates exceeded the "true" values of *r* by 17% (median) in simulated stocks with very low resilience and deviated 2–8% (medians) in the low to high resilience categories. With regard to biomass patterns, CMSY overestimated the "true" value of *r* by 14–18% in lightly exploited stocks, where the catches took only a small fraction of the available biomass (HH, HLH, LH). For the other biomass patterns, deviations of CMSY estimates ranged from -7% to +6% (medians). The combination of very low resilience with very light exploitation (LH) led to the largest overestimation of *r* by 52%.

Table 5. CMSY estimates of unexploited biomass *k* relative to the true *k* used in the simulations. Two estimates that diverge 20% or more from the "true" value are shown in bold.

	Very low	Low	Medium	High	Median
HH	0.87	0.85	0.94	0.96	0.90
HL	0.91	1.07	1.03	0.89	0.97
HLH	1.02	0.94	0.91	0.97	0.95
LL	0.86	1.00	0.87	1.00	0.93
LH	**0.36**	1.14	1.11	**0.73**	0.92
LHL	0.90	0.94	0.96	0.92	0.93
Median	0.89	0.97	0.95	0.94	

CMSY underestimated the "true" value of unexploited stock size *k* by 11% (median) in simulated stocks with very low resilience and underestimated the "true" value by 3–5% (medians) in the low to high resilience categories. In lightly exploited stocks, where the catches took only a small fraction of the available biomass (HH, HLH, LH), CMSY underestimated the "true" values of *k* by 5–10% (medians). For the other biomass patterns, "true" unexploited stock size was underestimated by 3–8% (medians).

The combination of very low resilience and very light exploitation (LH-VL) led to the strongest underestimation of "true" *k* by 64%.

In conclusion, C_{MSY} analysis appears to be less well suited for lightly exploited stocks where the catches have very little impact on biomass, and for species with very low resilience, where sustainable levels of exploitation represent a very small fraction of biomass.

C_{MSY} analysis of catch data of fully assessed stocks

Species: *Melanogrammus aeglefinus*, stock: had-faro

Name and region: Haddock, Faroe grounds, ICES Vb

Catch data used from years 1957–2014, biomass = observed

Prior initial relative biomass = 0.2–0.6

Prior intermediate rel. biomass= 0.3–1 in year 2002

Prior final relative biomass = 0.01–0.4

If current catches continue, is the stock likely to crash within three years? Possible

Prior range for r = 0.2–0.8, prior range for k = 33.9–407

Results from Bayesian Schaefer model using catch & observed biomass

r = 0.471, 95% CL = 0.394–0.521, k = 158, 95% CL = 130–202

MSY = 18.5, 95% CL = 15.1–22.9

Biomass in last year = 20.9 or 0.132 k

Results of C_{MSY} analysis

Altogether 386 viable trajectories for 373 r-k pairs were found

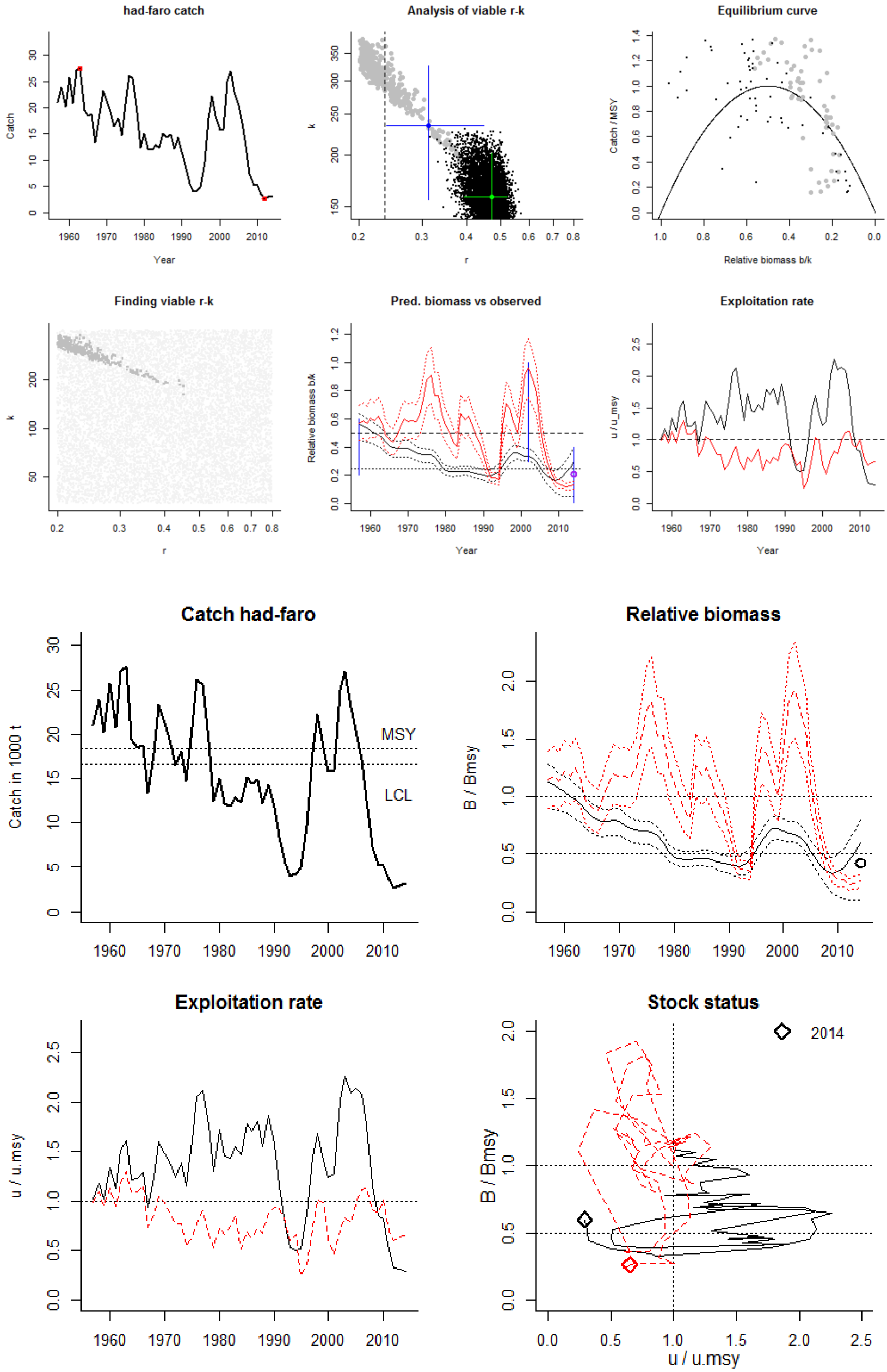
169 r-k pairs above r = 0.236 and 162 trajectories within r-k CLs were analyzed

r = 0.313, 95% CL = 0.238–0.447, k = 235, 95% CL = 156–326

MSY = 18.4, 95% CL = 16.6–20.4

Predicted biomass in last year = 0.298, 2.5th perc = 0.0485 25th perc = 0.212 97.5th perc = 0.397

Predicted biomass in next year = 0.347, 2.5th perc = 0.0534 25th perc = 0.25, 97.5th perc = 0.451


had-faro catch
Catch
Year
Analysis of viable r-k
k
r
Equilibrium curve
Catch / MSY
Relative biomass b/k
Finding viable r-k
k
r
Pred. biomass vs observed
Relative biomass b/k
Year
Exploitation rate
u / u_msy
Year
Catch had-faro
Catch in 1000 t
MSY
LCL
Relative biomass
B / Bmsy
Exploitation rate
u / u.msy
Stock status
2014
B / Bmsy
u / u.msy

Comment: Reasonable agreement between C_{MSY} results and biomass and exploitation rate trends from the full stock analysis. Note that C_{MSY} overestimates stock size and underestimates exploitation in the last years, because C_{MSY} assumes constant productivity, whereas the stock is likely to suffer from reduced recruitment (red curve below half of B_{MSY}, which is a proxy for B_{PA}). Therefore, the black dots derived from the 25th percentile of predicted biomass should be used for management.

Species: *Gadus morhua*, stock: cod-farp

Name and region: ICES Vb1

Catch data used from years 1959–2014, biomass = observed

Prior initial relative biomass = 0.1–0.4

Prior intermediate rel. biomass= 0.3–0.9 in year 1975

Prior final relative biomass = 0.01–0.3

If current catches continue, is the stock likely to crash within three years? Possible

Prior range for r = 0.2–0.8, prior range for k = 49.7–597

Results from Bayesian Schaefer model using catch & observed biomass

r = 0.498, 95% CL = 0.445–0.549, k = 205, 95% CL = 169–267

MSY = 25.6, 95% CL = 21.3–32.3

Biomass in last year = 27.7 or 0.135 k

Results of C_{MSY} analysis

Altogether 393 viable trajectories for 381 r-k pairs were found

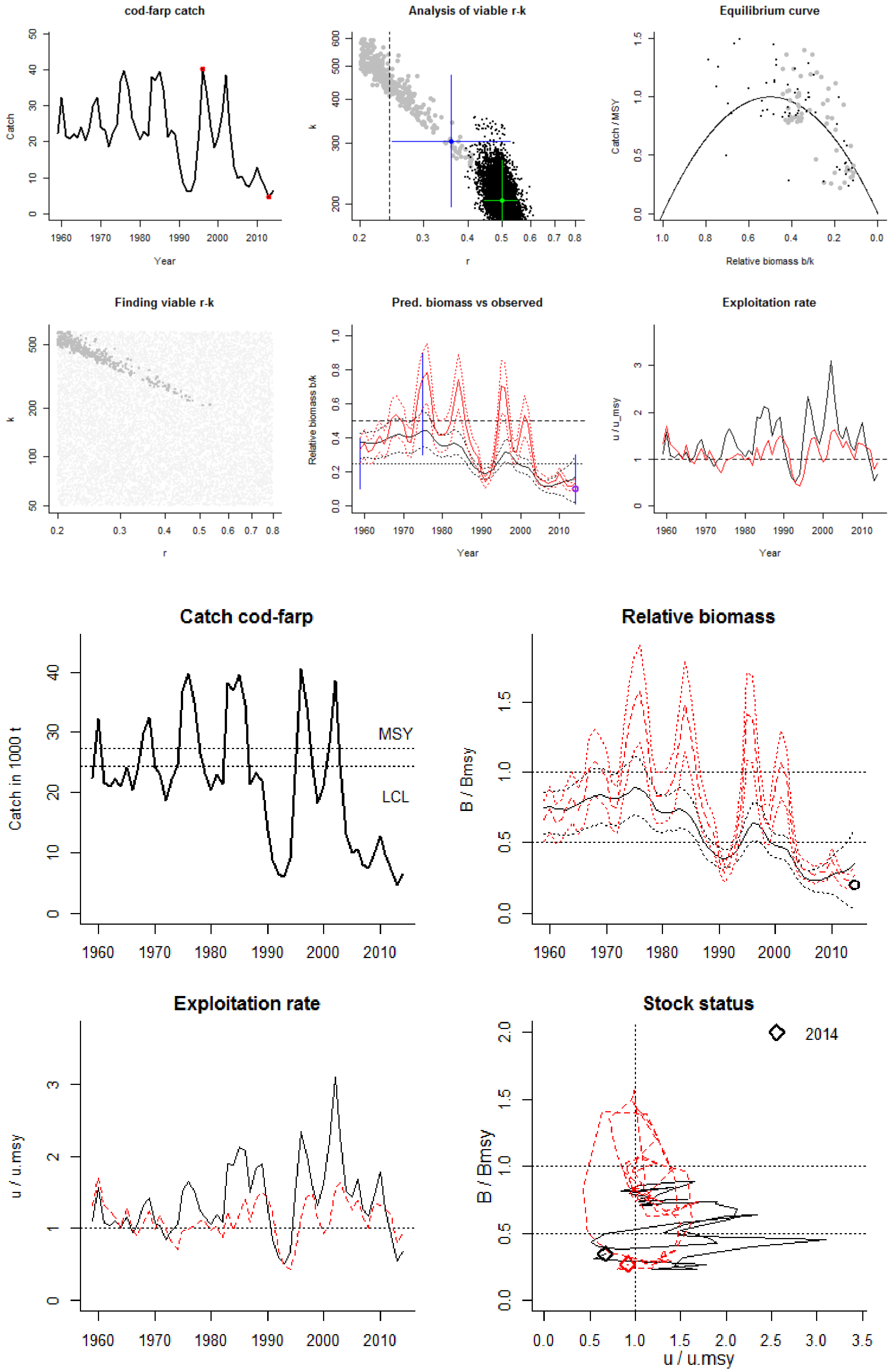
171 r-k pairs above r = 0.242 and 158 trajectories within r-k CLs were analyzed

r = 0.359, 95% CL = 0.245–0.525, k = 304, 95% CL = 196–469

MSY = 27.2, 95% CL = 24.4–30.4

Predicted biomass in last year = 0.174, 2.5th perc = 0.0159 25th perc = 0.101 97.5th perc = 0.298

Predicted biomass in next year = 0.2, 2.5th perc = 0.00296 25th perc = 0.111, 97.5th perc = 0.346


cod-farp catch
Analysis of viable r-k
Equilibrium curve
Finding viable r-k
Pred. biomass vs observed
Exploitation rate
Catch cod-farp
MSY
LCL
Catch in 1000 t
Relative biomass
B / Bmsy
Exploitation rate
u / u.msy
Stock status
2014
u / u.msy

Comment: Reasonable agreement between C_{MSY} results and biomass and exploitation rate trends from the full stock analysis. Note that C_{MSY} slightly overestimates stock size and underestimates exploitation in the last years, because C_{MSY} assumes constant productivity, whereas the stock is likely to suffer from reduced recruitment (red curve below half of B_{MSY}, which is a proxy for B_{PA}). Therefore, the black dots derived from the 25th percentile of predicted biomass should be used for management.

Species: *Pollachius virens*, stock: sai-faro

Name and region: ICES Vb

Catch data used from years 1961–2014, biomass = observed

Prior initial relative biomass = 0.2–0.5

Prior intermediate rel. biomass= 0.4–0.9 in year 2005

Prior final relative biomass = 0.2–0.5

If current catches continue, is the stock likely to crash within three years? No

Prior range for r = 0.2–0.8, prior range for k = 83.6–1004

Results from Bayesian Schaefer model using catch & observed biomass

r = 0.489, 95% CL = 0.428–0.528, k = 353, 95% CL = 317–399

MSY = 42.9, 95% CL = 38.2–47.7

Biomass in last year = 213 or 0.603 k

Results of C_{MSY} analysis

Altogether 6398 viable trajectories for 860 r-k pairs were found

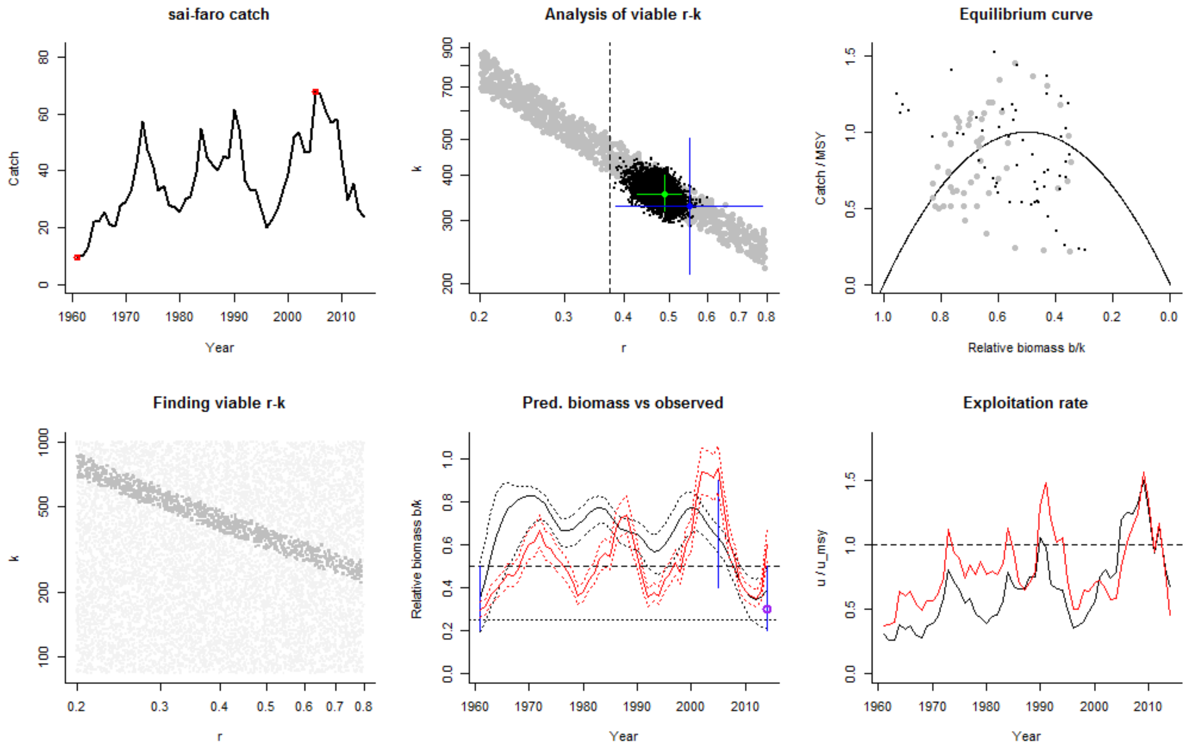
434 r-k pairs above r = 0.375 and 2967 trajectories within r-k CLs were analyzed

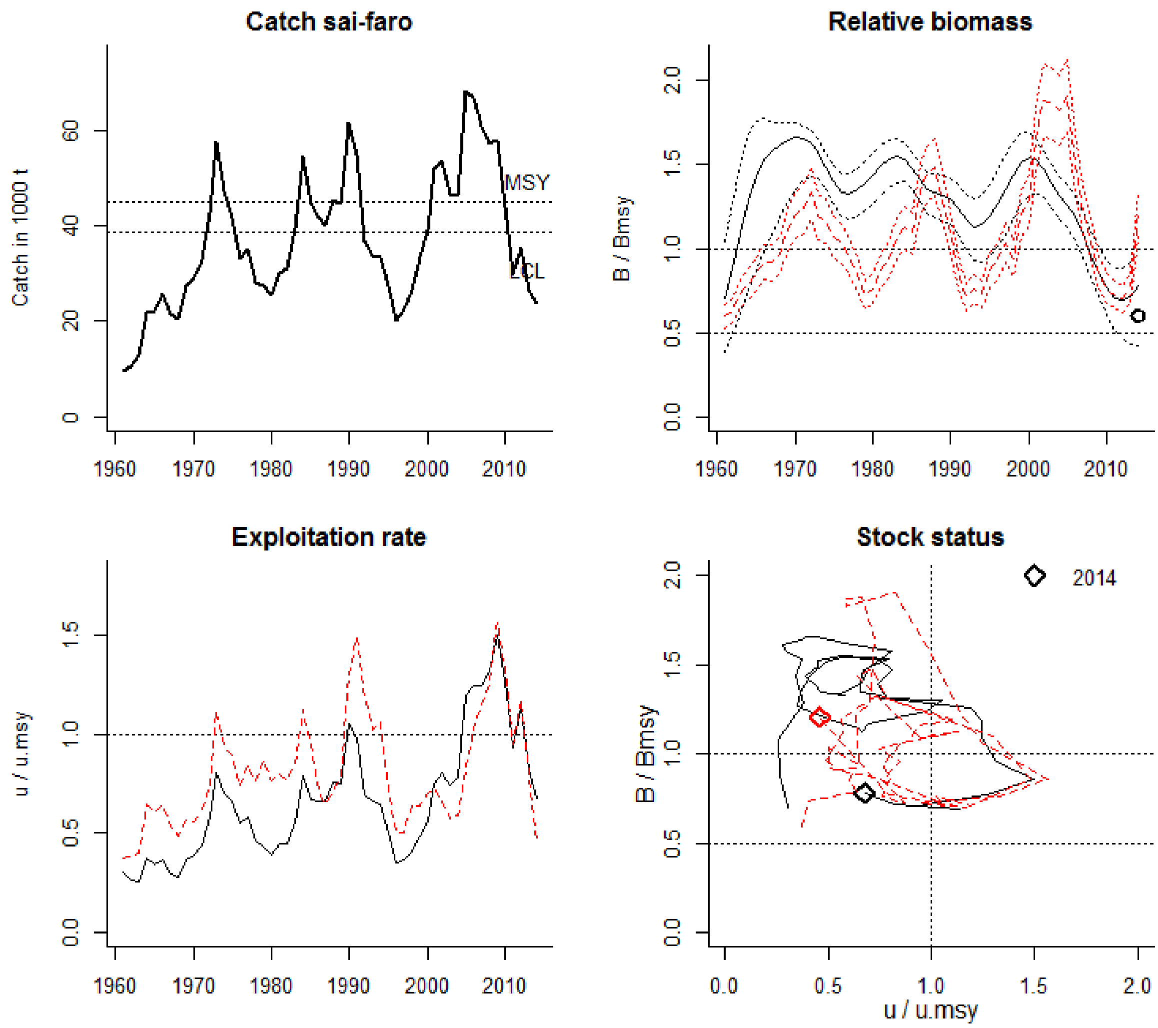
r = 0.549, 95% CL = 0.384–0.784, k = 328, 95% CL = 213–506

MSY = 45, 95% CL = 38.7–52.4

Predicted biomass in last year = 0.391, 2.5th perc = 0.211 25th perc = 0.3 97.5th perc = 0.496

Predicted biomass in next year = 0.432, 2.5th perc = 0.209 25th perc = 0.324, 97.5th perc = 0.561


sai-faro catch
Catch
Year
Analysis of viable r-k
k
r
Equilibrium curve
Catch / MSY
Relative biomass b/k
Finding viable r-k
k
r
Pred. biomass vs observed
Relative biomass b/k
Year
Exploitation rate
u / u_msy
Year


Catch sai-faro
Catch in 1000 t
MSY
LCL
Relative biomass
B / Bmsy
Exploitation rate
u / u.msy
Stock status
2014
B / Bmsy
u / u.msy

Comment: Re-run with new biomass windows

Running C_{MSY} on catch data and cpue of data-limited stocks

Species: *Gadus morhua*, stock: cod-farob

Name and region: ICES Vb2

Catch data used from years 1965–2014, biomass = cpue

Prior initial relative biomass = 0.1–0.5

Prior intermediate rel. biomass= 0.01–0.4 in year 1992

Prior final relative biomass = 0.01–0.3

If current catches continue, is the stock likely to crash within three years? Possible

Prior range for r = 0.2–0.8, prior range for k = 6.38–76.5

Prior range of q = 0.0457–0.183

Results from Bayesian Schaefer model using catch & cpue biomass

r = 0.5, 95% CL = 0.441–0.566, k = 40.1, 95% CL = 27.7–65.5

MSY = 4.99, 95% CL = 3.44–8.33

q = 0.0801, lcl = 0.06, ucl = 0.104

Biomass in last year from cpue/q = 0.322 or 0.00803 k

Results of C_{MSY} analysis

Altogether 487 viable trajectories for 476 r-k pairs were found

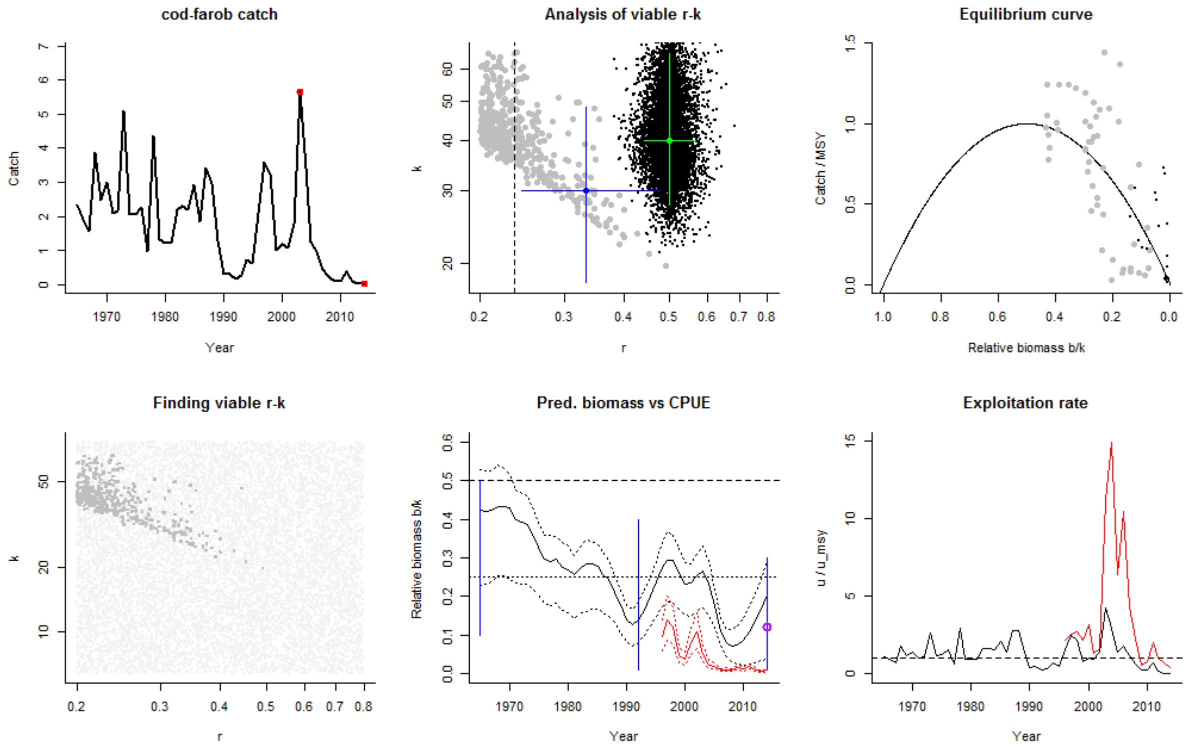
209 r-k pairs above r = 0.235 and 151 trajectories within r-k CLs were analyzed

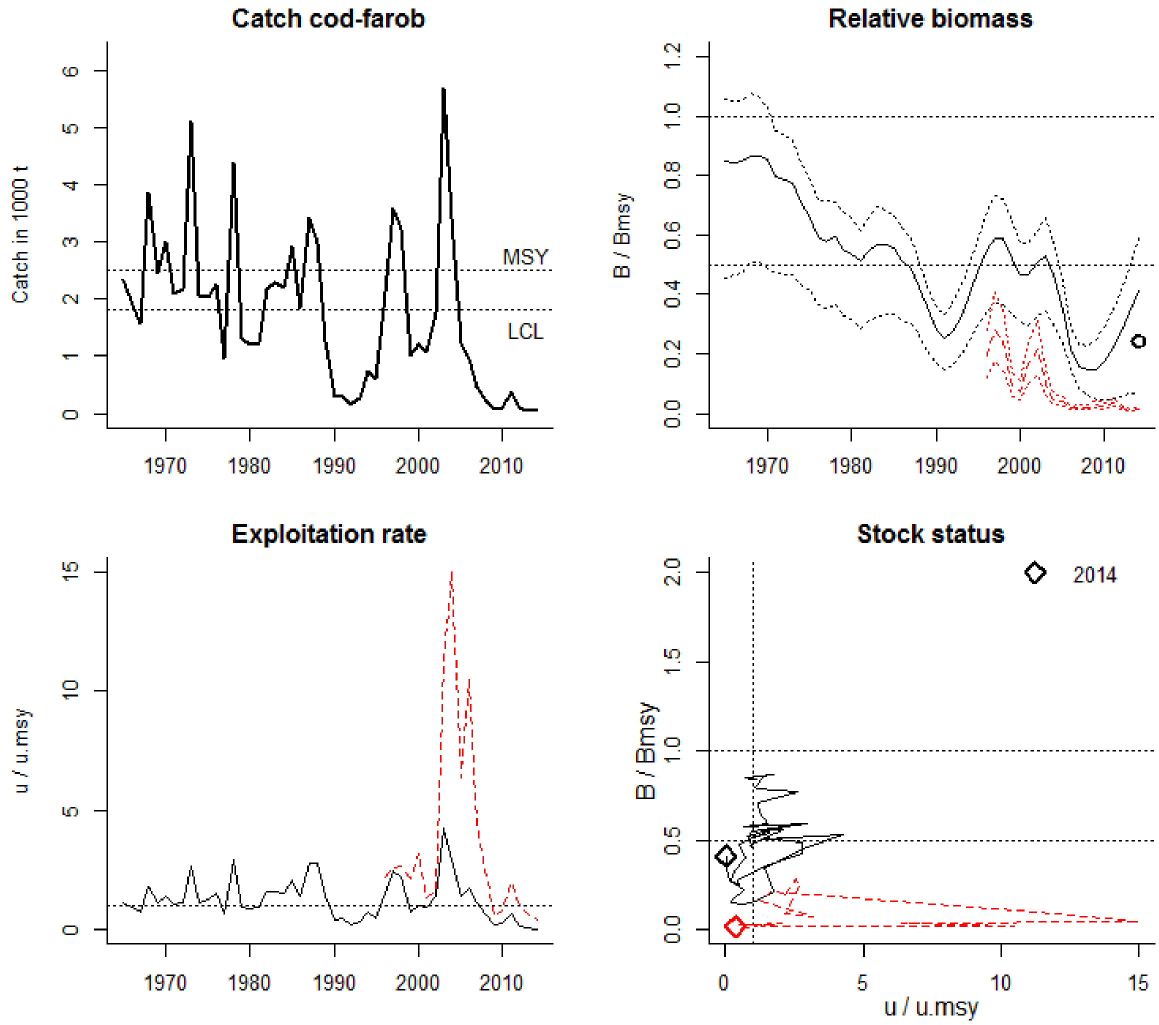
r = 0.333, 95% CL = 0.244–0.477, k = 30.1, 95% CL = 17.9–48.3

MSY = 2.51, 95% CL = 1.82–3.45

Predicted biomass in last year = 0.205, 2.5th perc = 0.0363 25th perc = 0.12 97.5th perc = 0.294

Predicted biomass in next year = 0.257, 2.5th perc = 0.0432 25th perc = 0.151, 97.5th perc = 0.362


cod-farob catch
Catch
Year
Analysis of viable r-k
k
r
Equilibrium curve
Catch / MSY
Relative biomass b/k
Finding viable r-k
k
r
Pred. biomass vs CPUE
Relative biomass b/k
Year
Exploitation rate
u / u_msy
Year


Catch cod-farob
Catch in 1000 t
MSY
LCL
Relative biomass
B / Bmsy
Exploitation rate
u / u.msy
Stock status
B / Bmsy
2014
u / u.msy

Comment: Reasonable agreement between C_{MSY} trends and cpue trends. But note that C_{MSY} overestimates stock size and underestimates exploitation, because C_{MSY} assumes constant productivity, whereas the stock is clearly suffering from reduced recruitment. Even the black dots derived from the 25th percentile of predicted biomass are too optimistic. Here, precautionary management would not follow C_{MSY} but rather the cpue results as scaled by BSM.

Species: *Nephrops norvegicus*, stock: nep-2829_comcpue

Name and region: *Nephrops*, Southwest and South Portugal

Catch data used from years 1997–2014, biomass = cpue

Prior initial relative biomass = 0.1–0.5

Prior intermediate rel. biomass= 0.1–0.9 in year 2005

Prior final relative biomass = 0.1–0.5

If current catches continue, is the stock likely to crash within three years? Possible

Prior range for r = 0.2–0.8, prior range for k = 0.448–5.37

Prior range of q = 0.00781–0.0313

Results from Bayesian Schaefer model using catch & cpue biomass

r = 0.51, 95% CL = 0.466–0.597, k = 2.38, 95% CL = 1.61–3.57

MSY = 0.307, 95% CL = 0.21–0.45

q = 0.0101, lcl = 0.00795, ucl = 0.0125

Biomass in last year from cpue/q = 0.758 or 0.318 k

Results of C_{MSY} analysis

Altogether 5134 viable trajectories for 2243 r-k pairs were found

1228 r-k pairs above r = 0.346 and 2225 trajectories within r-k CLs were analyzed

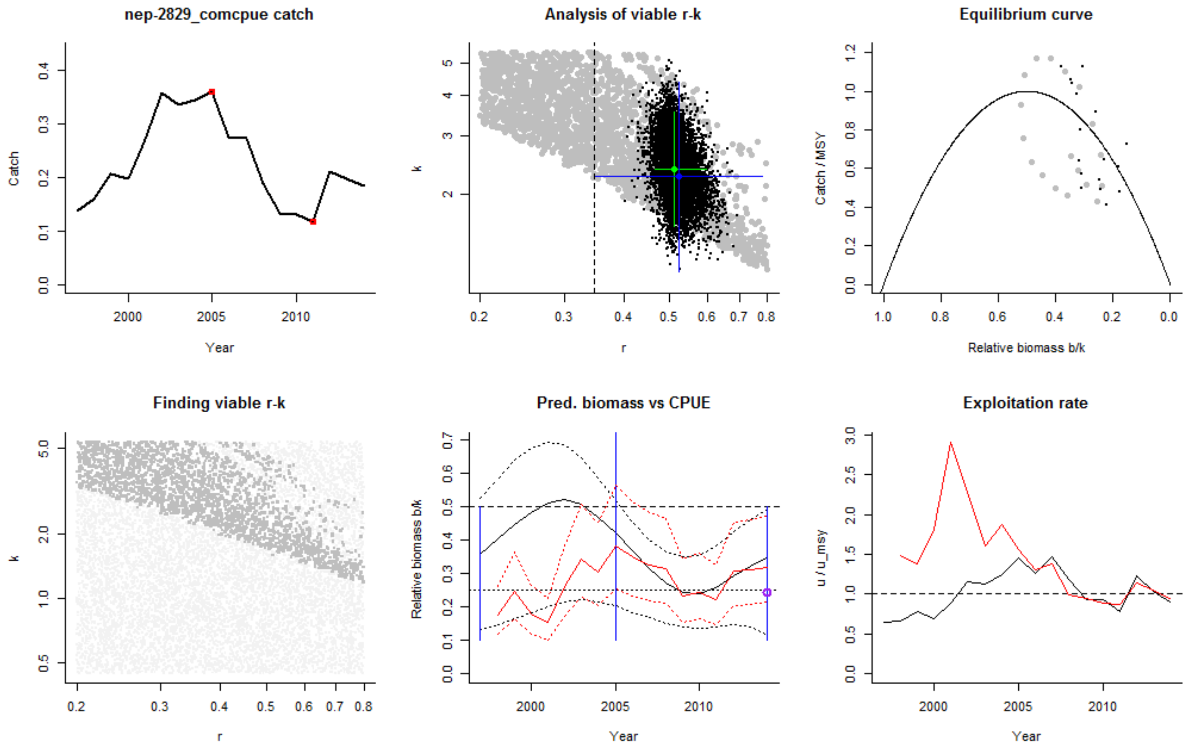
r = 0.522, 95% CL = 0.349–0.782, k = 2.27, 95% CL = 1.17–4.38

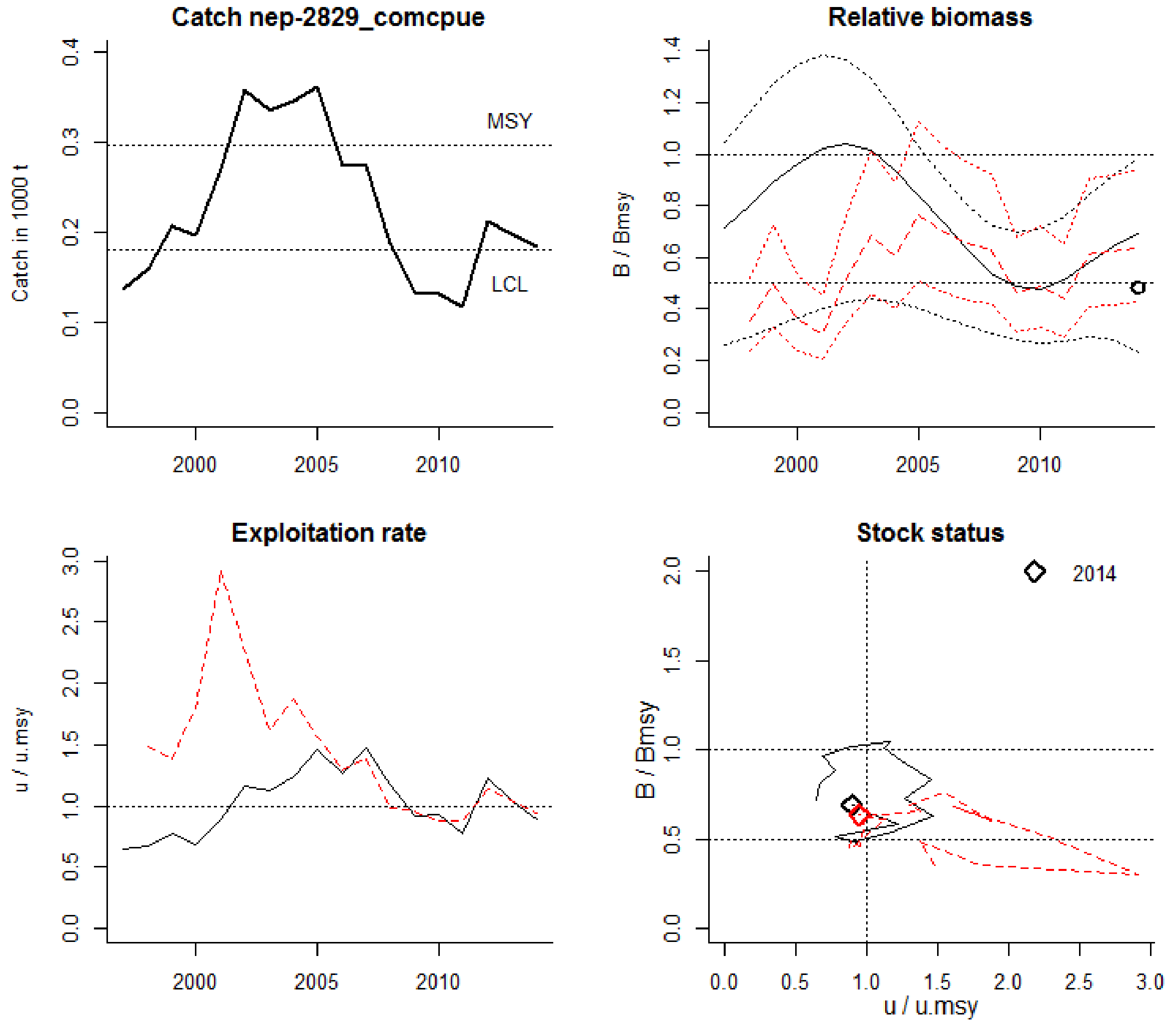
MSY = 0.296, 95% CL = 0.18–0.487

Predicted biomass in last year = 0.346, 2.5th perc = 0.115 25th perc = 0.242 97.5th perc = 0.493

Predicted biomass in next year = 0.365, 2.5th perc = 0.065 25th perc = 0.238, 97.5th perc = 0.536

Comment: Using commercial cpue; assuming low biomass


nep-2829_comcpue catch
Catch
Year
Analysis of viable r-k
k
r
Equilibrium curve
Catch / MSY
Relative biomass b/k
Finding viable r-k
k
r
Pred. biomass vs CPUE
Relative biomass b/k
Year
Exploitation rate
u / u_msy
Year


Catch nep-2829_comcpue
Catch in 1000 t
MSY
LCL
Relative biomass
B / Bmsy
Exploitation rate
u / u.msy
Stock status
2014
B / Bmsy
u / u.msy

Comment: Good agreement after 2005 between C_{MSY} results and biomass and exploitation rate trends from commercial cpue, as scaled by BSM.

Species: *Argentina silus*, stock: arg-5b6a

Name and region: Northeast Atlantic

Catch data used from years 1996–2014, biomass = cpue

Prior initial relative biomass = 0.2–0.8

Prior intermediate rel. biomass= 0.1–0.9 in year 2005

Prior final relative biomass = 0.01–0.5

If current catches continue, is the stock likely to crash within three years? Possible

Prior range for r = 0.2–0.8, prior range for k = 28.9–347

Prior range of q = 0.000349–0.00139

Results from Bayesian Schaefer model using catch & cpue biomass

r = 0.501, 95% CL = 0.448–0.569, k = 132, 95% CL = 109–167

MSY = 16.6, 95% CL = 14.3–20.4

q = 0.000588, lcl = 0.000459, ucl = 0.000734

Biomass in last year from cpue/q = 33.4 or 0.252 k

Results of C_{MSY} analysis

Altogether 9088 viable trajectories for 2431 r-k pairs were found

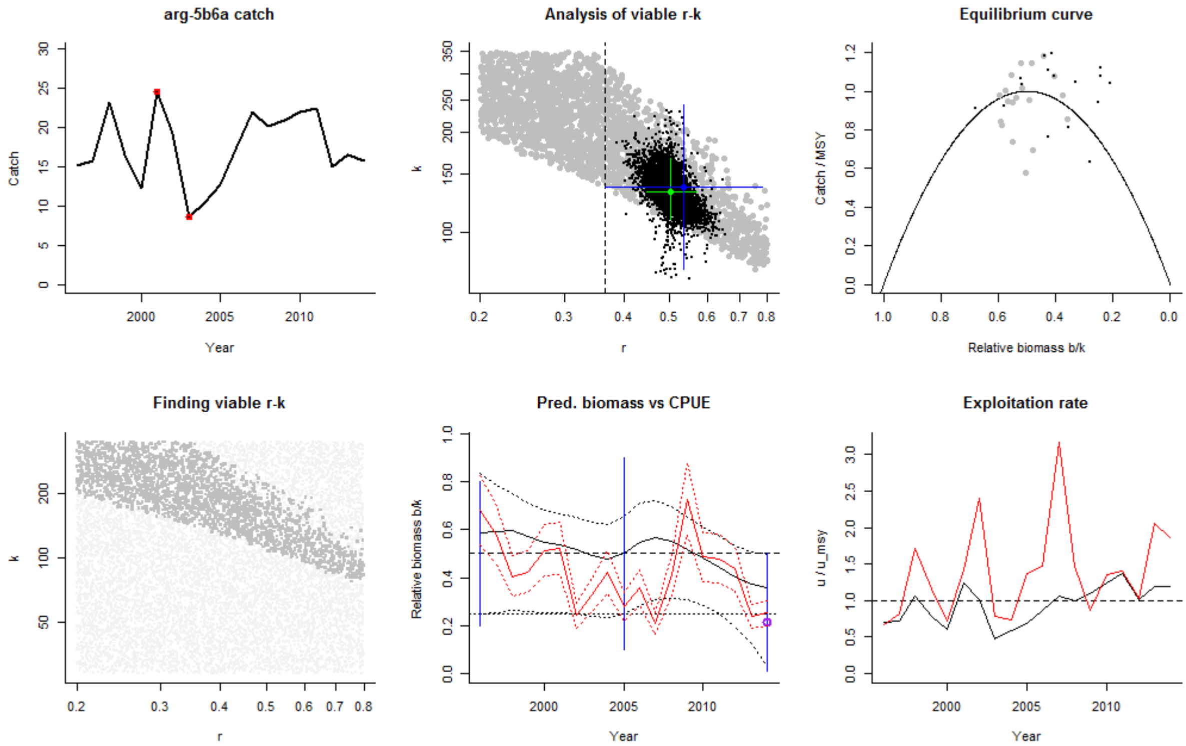
1185 r-k pairs above r = 0.366 and 4004 trajectories within r-k CLs were analyzed

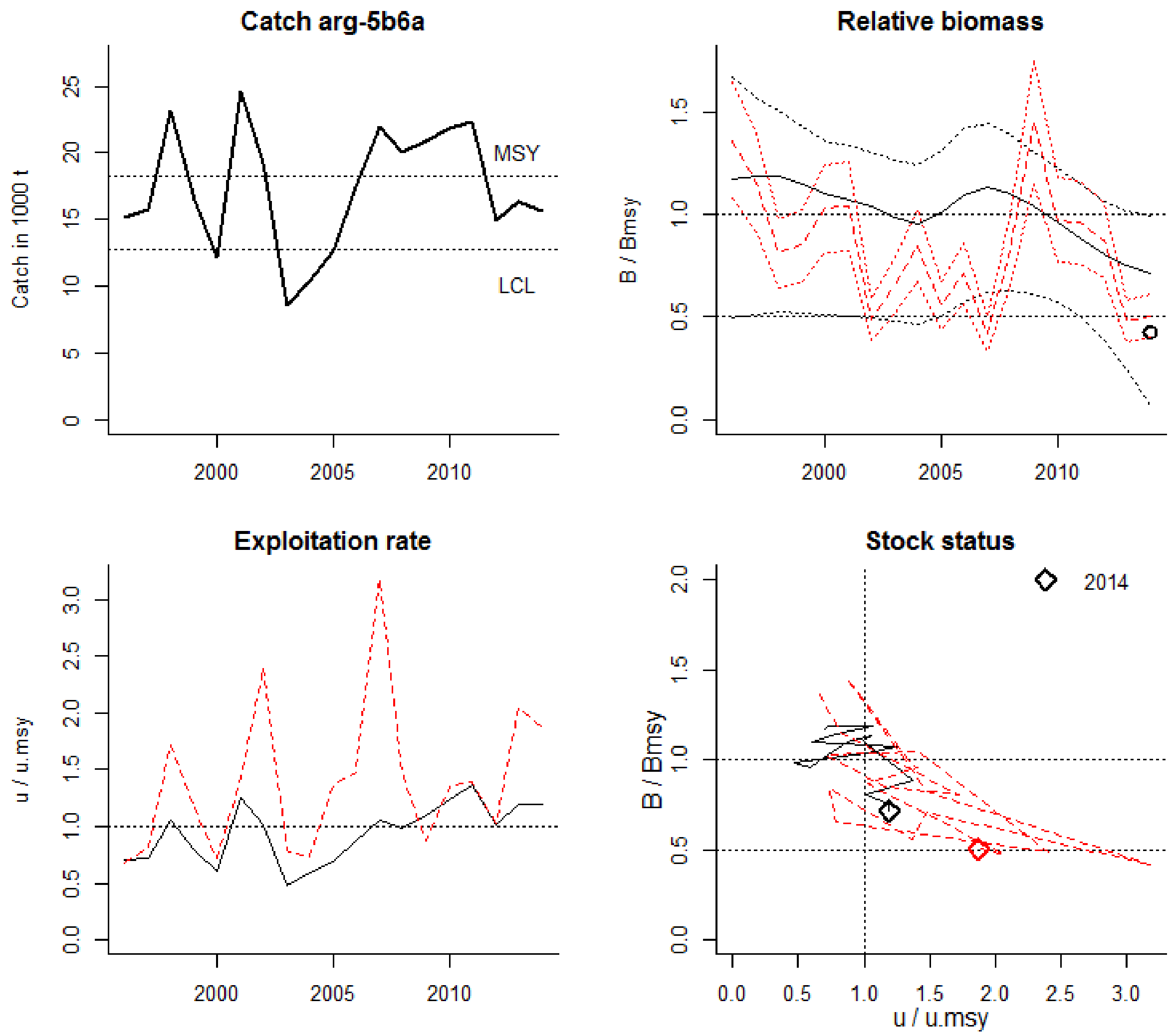
r = 0.535, 95% CL = 0.366–0.783, k = 137, 95% CL = 77.7–241

MSY = 18.3, 95% CL = 12.7–26.4

Predicted biomass in last year = 0.358, 2.5th perc = 0.0326 25th perc = 0.213 97.5th perc = 0.497

Predicted biomass in next year = 0.357, 2.5th perc = -0.0801 25th perc = 0.174, 97.5th perc = 0.523


arg-5b6a catch
Catch
Year
Analysis of viable r-k
k
r
Equilibrium curve
Catch / MSY
Relative biomass b/k
Finding viable r-k
k
r
Pred. biomass vs CPUE
Relative biomass b/k
Year
Exploitation rate
u / u_msy
Year


Catch arg-5b6a
Catch in 1000 t
MSY
LCL
Relative biomass
B / Bmsy
Exploitation rate
u / u.msy
Stock status
2014
B / Bmsy
u / u.msy

Comment: Reasonable agreement between C_{MSY} results and biomass and exploitation rate trends from cpue data, as scaled by BSM. Note that C_{MSY} overestimates stock size and underestimates exploitation in the last years, because C_{MSY} assumes constant productivity, whereas the stock may suffer from reduced recruitment (red curve at half of B_{MSY}, which is a proxy for B_{PA}). Therefore, the black dots derived from the 25th percentile of predicted biomass should be used for management.

Species: *Limanda limanda*, stock: dab-2232

Name and region: Western Baltic

Catch data used from years 1970–2014, biomass = cpue

Prior initial relative biomass = 0.2–0.8

Prior intermediate rel. biomass= 0.1–0.9 in year 2005

Prior final relative biomass = 0.2–0.8

If current catches continue, is the stock likely to crash within three years? No

Prior range for r = 0.2–0.8, prior range for k = 3.68–44.1

Prior range of q = 0.00809–0.0324

Results from Bayesian Schaefer model using catch & cpue biomass

r = 0.509, 95% CL = 0.462–0.597, k = 13.9, 95% CL = 9.71–19.3

MSY = 1.8, 95% CL = 1.23–2.46

q = 0.0119, lcl = 0.00902, ucl = 0.0156

Biomass in last year from cpue/q = 12.1 or 0.871 k

Results of C_{MSY} analysis

Altogether 9268 viable trajectories for 1312 r-k pairs were found

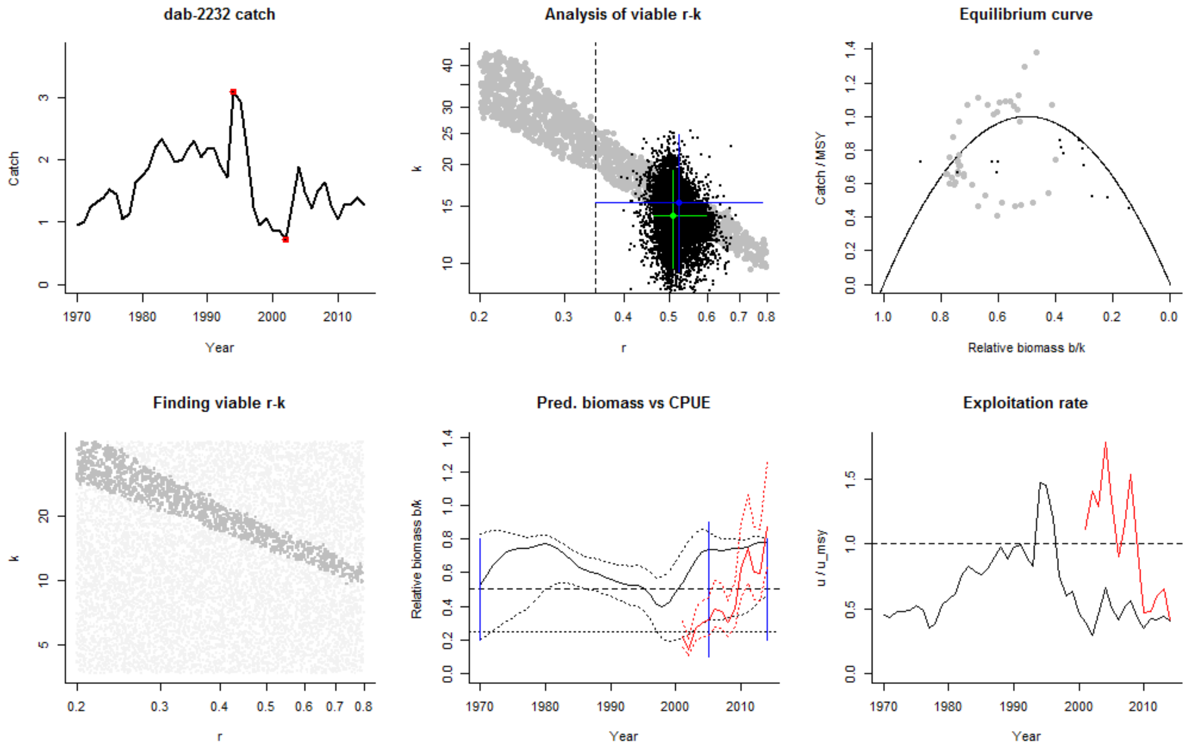
619 r-k pairs above r = 0.348 and 4140 trajectories within r-k CLs were analyzed

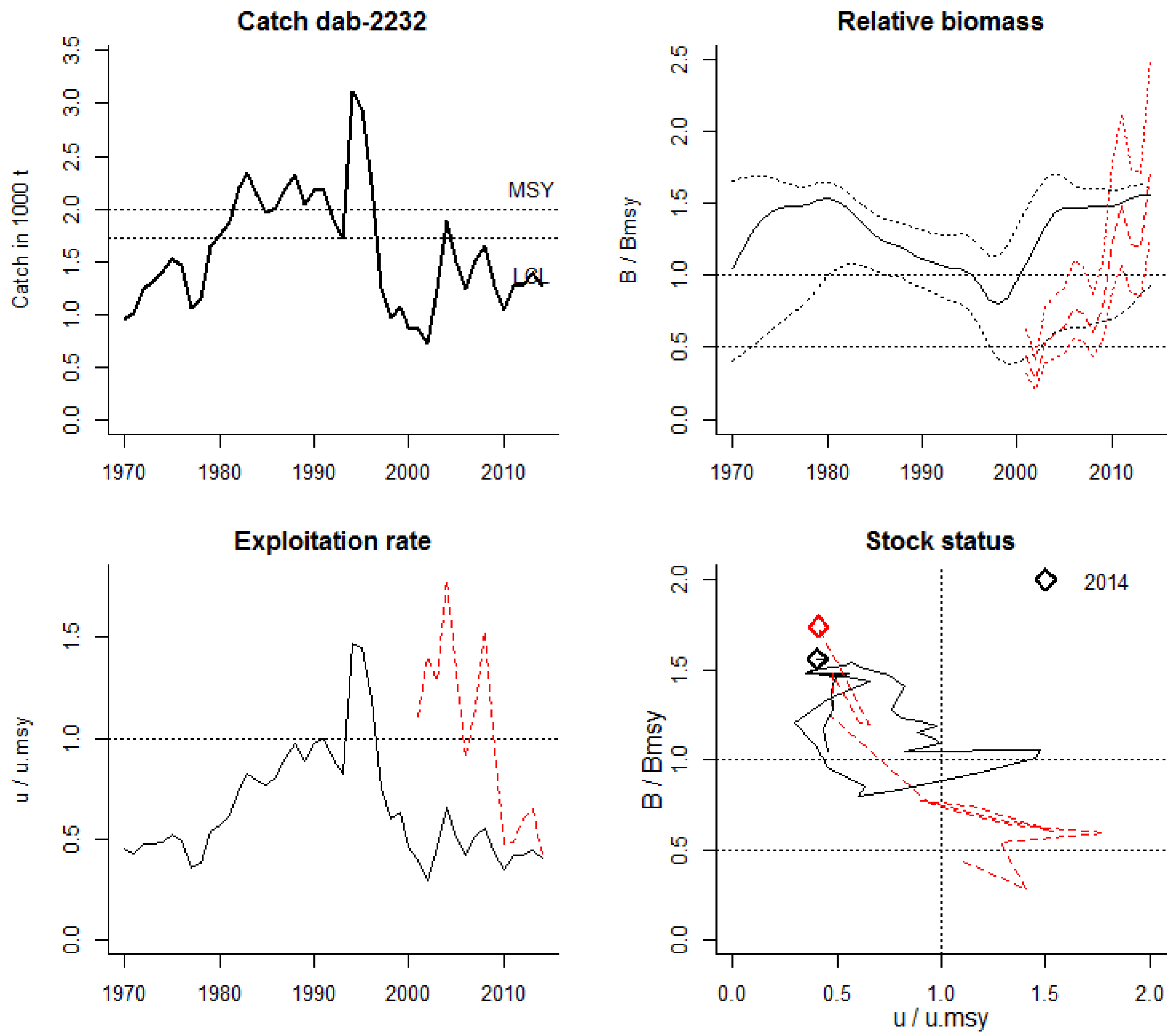
r = 0.522, 95% CL = 0.349–0.782, k = 15.3, 95% CL = 9.46–24.8

MSY = 2, 95% CL = 1.72–2.33

Predicted biomass in last year = 0.781, 2.5th perc = 0.462 25th perc = 0.751 97.5th perc = 0.799

Predicted biomass in next year = 0.782, 2.5th perc = 0.497 25th perc = 0.754, 97.5th perc = 0.813


dab-2232 catch
Catch
Year
Analysis of viable r-k
k
r
Equilibrium curve
Catch / MSY
Relative biomass b/k
Finding viable r-k
k
r
Pred. biomass vs CPUE
Relative biomass b/k
Year
Exploitation rate
u / u_msy
Year


Catch dab-2232
Catch in 1000 t
MSY
LCI
Relative biomass
B / Bmsy
Exploitation rate
u / u.msy
Stock status
2014
B / Bmsy
u / u.msy

Comment: Landings data used; discards may be substantial. No good idea of stock size, so very wide prior biomass windows (0.2–0.8) used. No good agreement between C_{MSY} and cpue as scaled by BSM, although trends are similar and estimates converge in the last years.

Species: *Gadus morhua*, stock: cod-2532

Name and region: Eastern Baltic, Areas 25–32

Catch data used from years 2003–2014, biomass = cpue

Prior initial relative biomass = 0.1–0.5

Prior intermediate rel. biomass= 0.1–0.9 in year 2007

Prior final relative biomass = 0.01–0.4

If current catches continue, is the stock likely to crash within three years? Possible

Prior range for r = 0.2–0.8, prior range for k = 95.6–1147

Prior range of q = 0.000733–0.00293

Results from Bayesian Schaefer model using catch & cpue biomass

r = 0.511, 95% CL = 0.463–0.609, k = 637, 95% CL = 391–1114

MSY = 82.7, 95% CL = 50–144

q = 0.000844, lcl = 0.000664, ucl = 0.00115

Biomass in last year from cpue/q = 149 or 0.235 k

Results of C_{MSY} analysis

Altogether 5681 viable trajectories for 2618 r-k pairs were found

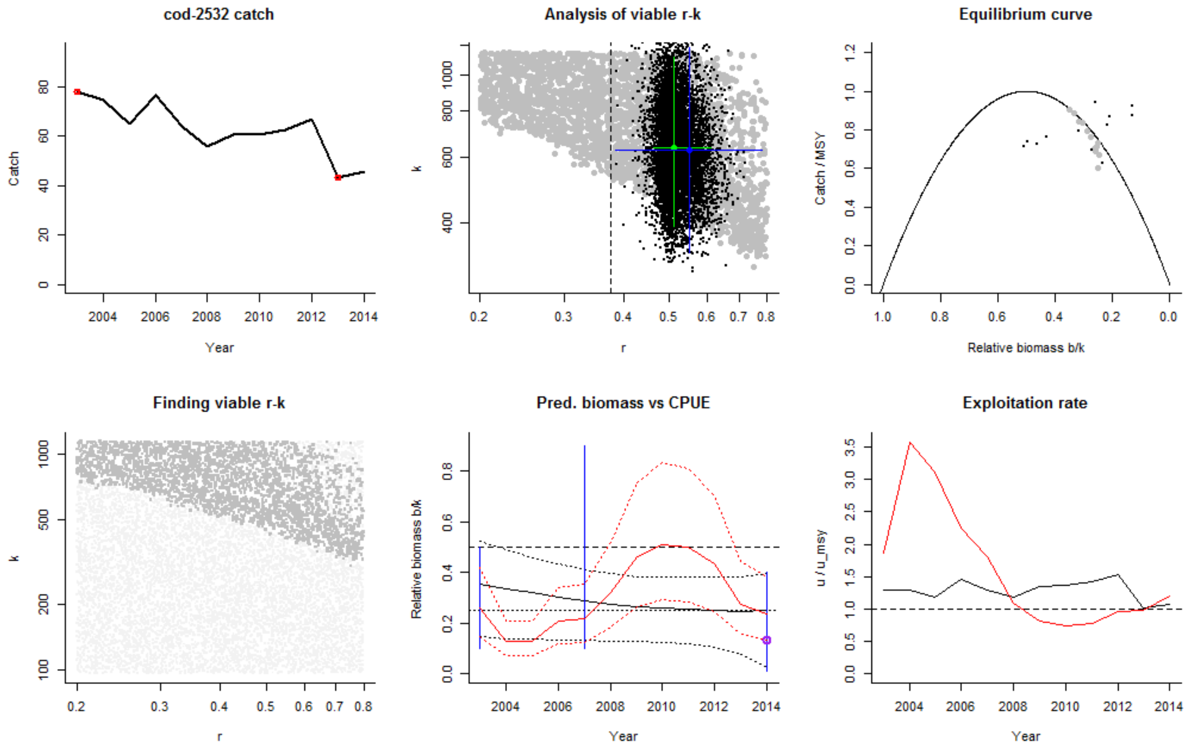
1603 r-k pairs above r = 0.377 and 2561 trajectories within r-k CLs were analyzed

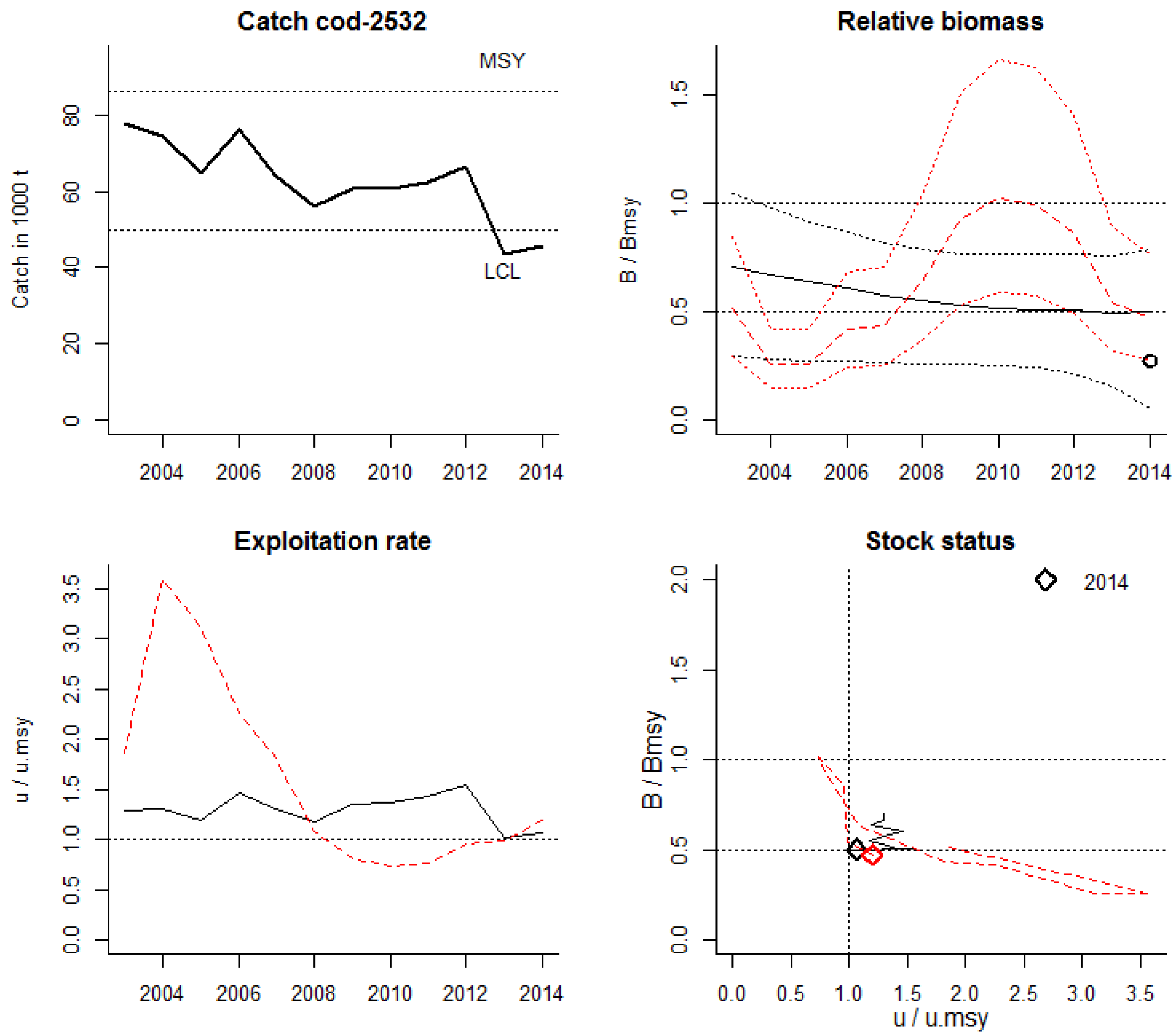
r = 0.549, 95% CL = 0.384–0.784, k = 628, 95% CL = 332–1187

MSY = 86.1, 95% CL = 49.6–149

Predicted biomass in last year = 0.249, 2.5th perc = 0.0225 25th perc = 0.133 97.5th perc = 0.394

Predicted biomass in next year = 0.26, 2.5th perc = -0.0616 25th perc = 0.106, 97.5th perc = 0.453


cod-2532 catch
Catch
Year
Analysis of viable r-k
k
r
Equilibrium curve
Catch / MSY
Relative biomass b/k
Finding viable r-k
k
r
Pred. biomass vs CPUE
Relative biomass b/k
Year
Exploitation rate
u / u_msy
Year


Catch cod-2532
MSY
LCL
Catch in 1000 t
Relative biomass
B / Bmsy
Exploitation rate
u / u.msy
Stock status
2014
B / Bmsy
u / u.msy

Comment: Short time-series. CMSY does not capture the variability of stock index data as scaled by BSM, but gives similar mean results for final biomass and exploitation rate.

Comparing results with observation error of catch with sigma 0.1 and 0.2

CMSY analysis with sigma 0.1 on catch

Species: *Merluccius merluccius*, stock: hke-nrtn

Name and region: Northern hake, Subareas IV, VI, and VII and Divisions IIIa, VIIIa,b,d

Catch data used from years 1978–2014, biomass = observed

Prior initial relative biomass = 0.2–0.6

Prior intermediate rel. biomass= 0.1–0.4 in year 2005

Prior final relative biomass = 0.5–0.9

If current catches continue, is the stock likely to crash within three years? No

Prior range for r = 0.2–0.8, prior range for k = 245–1961

Results from Bayesian Schaefer model using catch & observed biomass

r = 0.807, 95% CL = 0.715–0.892, k = 520, 95% CL = 385–735

MSY = 104, 95% CL = 81.3–140

Biomass in last year = 275 or 0.528 k

Results of CMSY analysis

Altogether 244 viable trajectories for 244 r-k pairs were found

111 r-k pairs above r = 0.286 and 103 trajectories within r-k CLs were analyzed

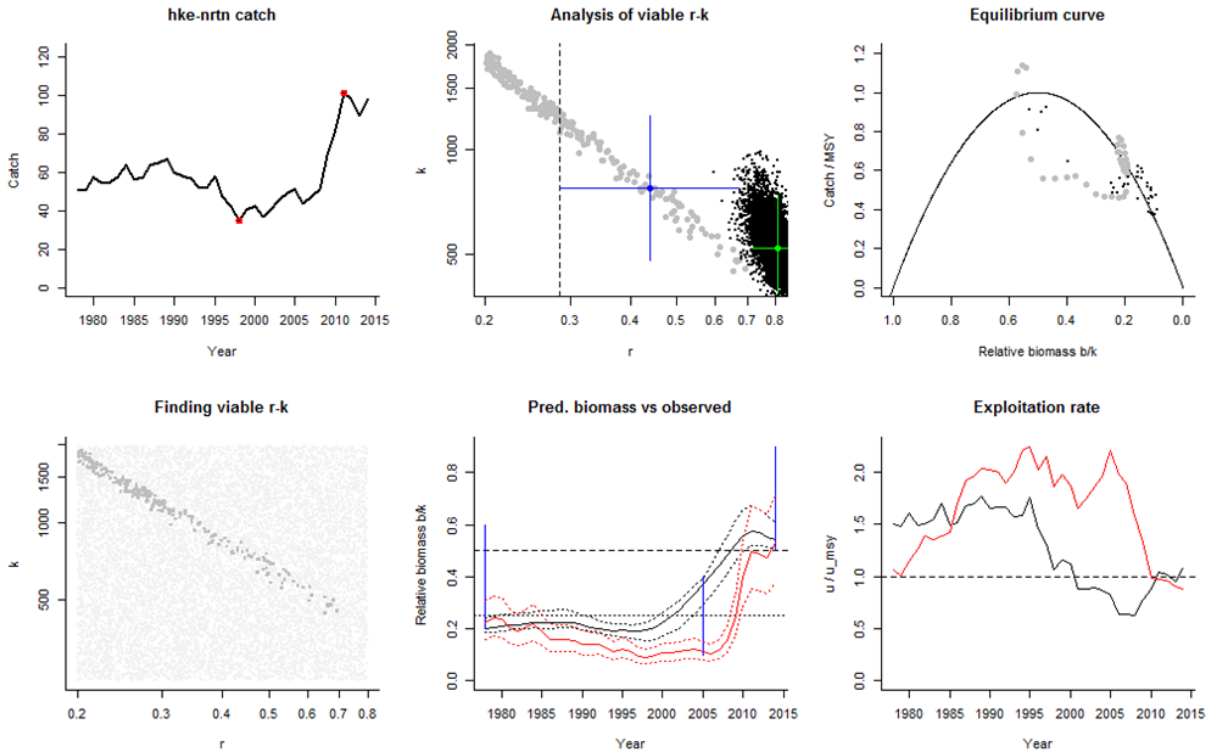
r = 0.438, 95% CL = 0.286–0.672, k = 772, 95% CL = 477–1247

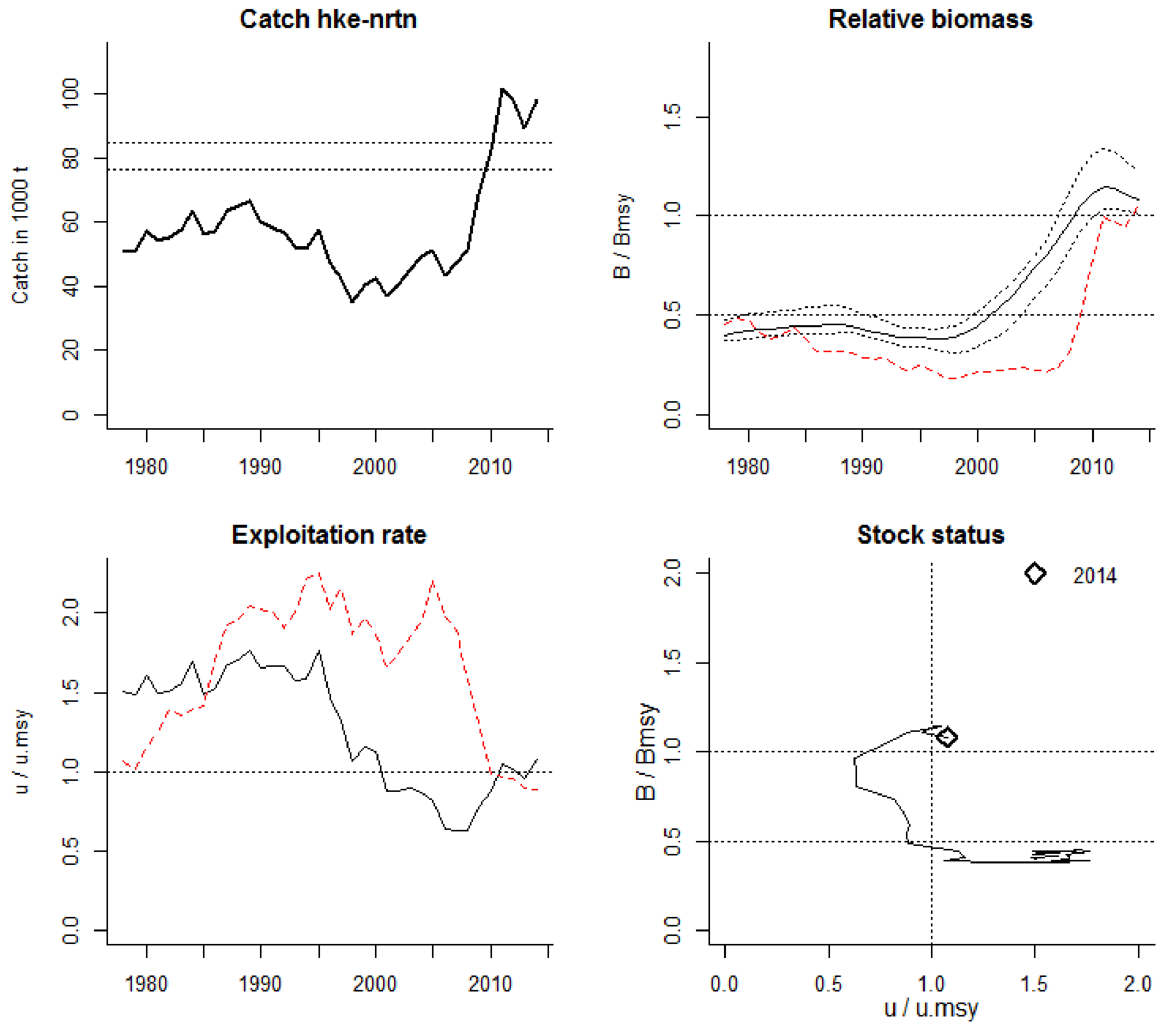
MSY = 84.5, 95% CL = 76.3–93.7

Predicted biomass in last year = 0.54, 2.5th perc = 0.505 25th perc = 0.521 97.5th perc = 0.608

Predicted biomass in next year = 0.528, 2.5th perc = 0.475 25th perc = 0.507, 97.5th perc = 0.596

Comment: Strange recent increase in biomass after 2008


hke-nrtn catch
Catch
Year
Analysis of viable r-k
k
r
Equilibrium curve
Catch / MSY
Relative biomass b/k
Finding viable r-k
k
r
Pred. biomass vs observed
Relative biomass b/k
Year
Exploitation rate
u / u_msy
Year


Catch hke-nrtn
Catch in 1000 t
Relative biomass
B / Bmsy
Exploitation rate
u / u.msy
Stock status
2014
B / Bmsy
u / u.msy

Comment: Northern Hake had a modest biomass at the beginning of the time-series and a very strong increase in biomass in 2007, which lasted until the end of the time-series. Accordingly, prior biomass windows were set 0.2–0.6 for the beginning and 0.5–0.9 for the end. CMSY assumes average productivity of the stock and thus has difficulties to reproduce extraordinary biomass increase in 2007. CMSY modelling was improved by setting a low (10–40% of unexploited biomass) intermediate biomass window to 2005, before the increase, effectively informing the system of the common knowledge that the stock had low biomass throughout most of the time-series until it multiplied in 2007.

Repetition of previous analysis with sigma=0.2 uncertainty on catch

Species: *Merluccius merluccius*, stock: hke-nrtn

Name and region: Northern hake, Subareas IV, VI, and VII and Divisions IIIa, VIIIa,b,d

Catch data used from years 1978–2014, biomass = observed

Prior initial relative biomass = 0.2–0.6

Prior intermediate rel. biomass= 0.1–0.4 in year 2005

Prior final relative biomass = 0.5–0.9

If current catches continue, is the stock likely to crash within three years? No

Prior range for r = 0.2–0.8, prior range for k = 245–1961

Results from Bayesian Schaefer model using catch & observed biomass

r = 0.799, 95% CL = 0.701–0.89, k = 542, 95% CL = 392–850

MSY = 108, 95% CL = 83.2–157

Biomass in last year = 275 or 0.507 k

Results of CMSY analysis

Altogether 385 viable trajectories for 384 r-k pairs were found

189 r-k pairs above r = 0.29 and 163 trajectories within r-k CLs were analyzed

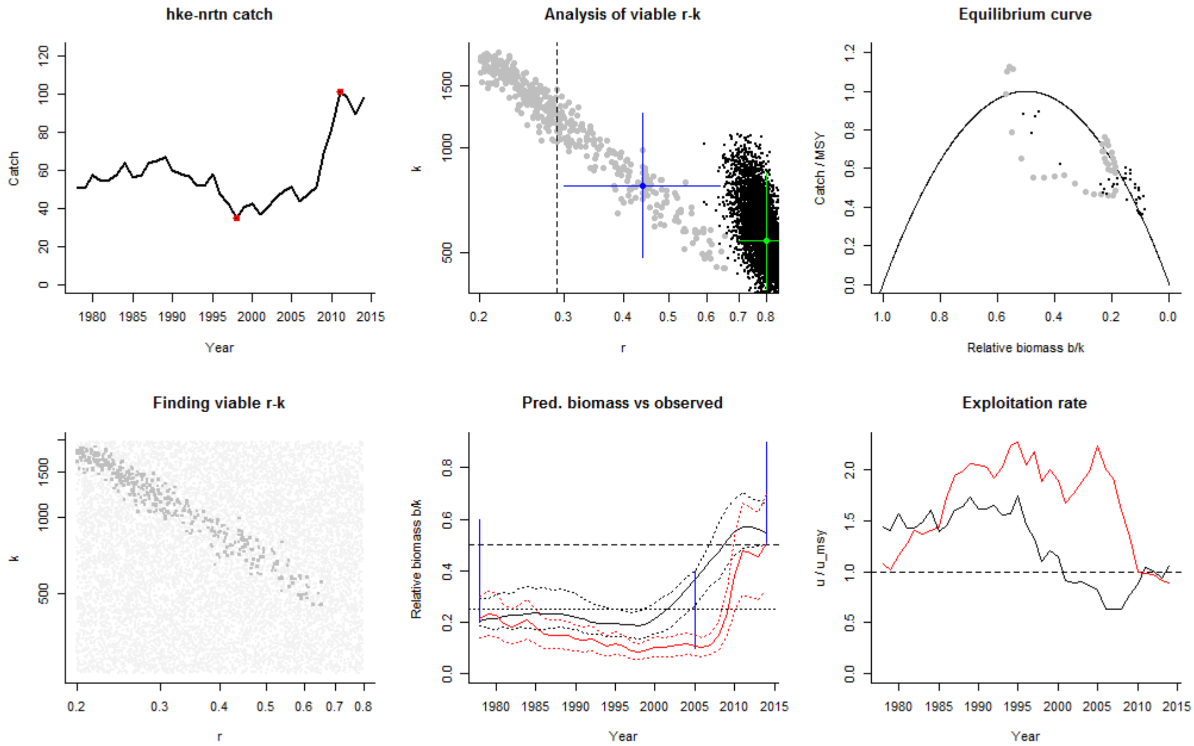
r = 0.438, 95% CL = 0.3–0.641, k = 779, 95% CL = 483–1255

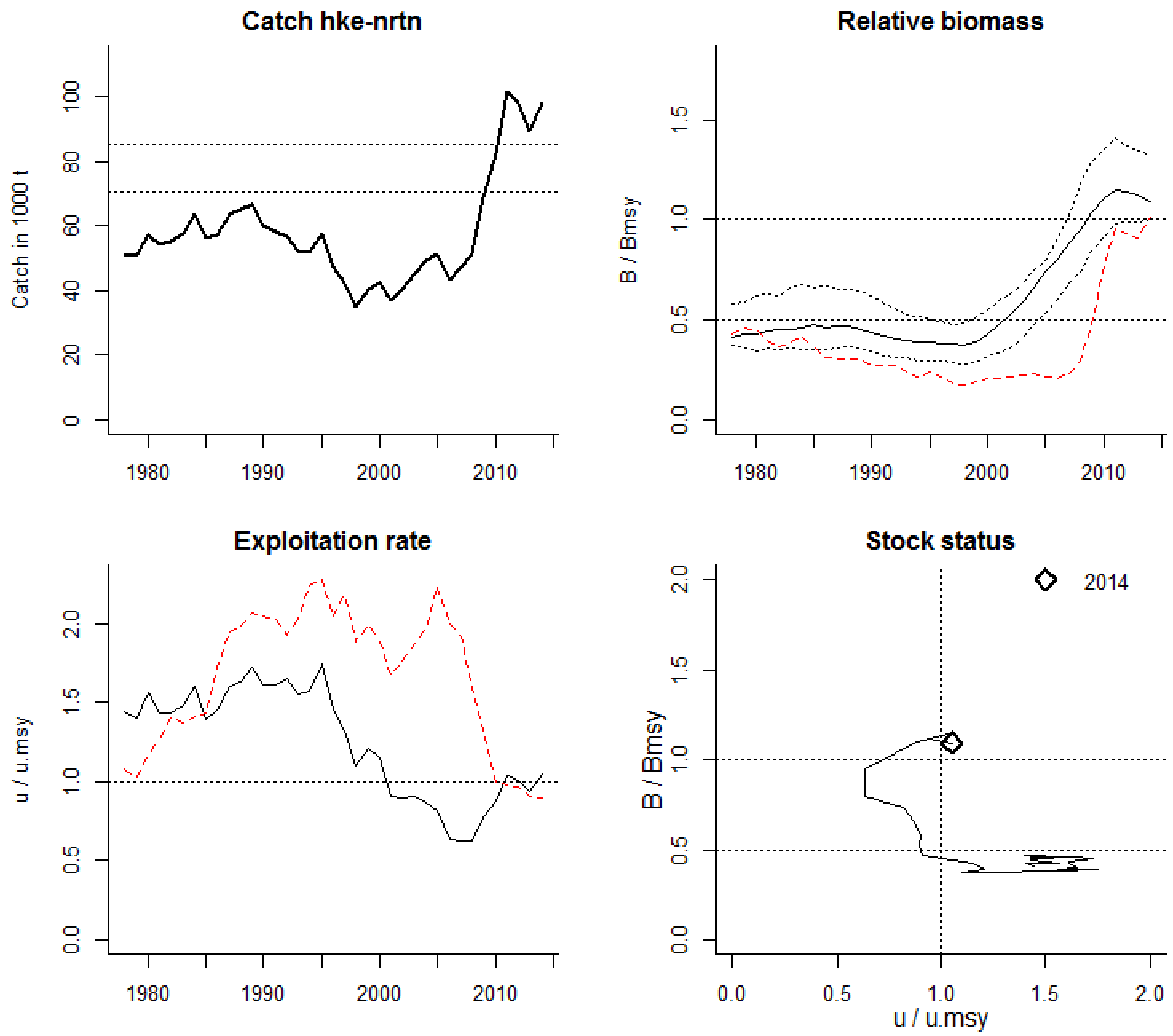
MSY = 85.3, 95% CL = 70.5–103

Predicted biomass in last year = 0.547, 2.5th perc = 0.501 25th perc = 0.519 97.5th perc = 0.66

Predicted biomass in next year = 0.533, 2.5th perc = 0.444 25th perc = 0.499, 97.5th perc = 0.637

Comment: Strange recent increase in biomass after 2008


hke-nrtn catch
Catch
Year
Analysis of viable r-k
k
r
Equilibrium curve
Catch / MSY
Relative biomass b/k
Finding viable r-k
k
r
Pred. biomass vs observed
Relative biomass b/k
Year
Exploitation rate
u / u_msy
Year


Catch hke-nrtn
Catch in 1000 t
Relative biomass
B / Bmsy
Exploitation rate
u / u.msy
Stock status
2014
B / Bmsy
u / u.msy

Comment: CMSY assumes as default a process error of sigma=0.05 and an observation error on catch of sigma=0.1. In the latest version of CMSY _WKLIFEV_7.r, observation error and process error can be set independently. Above analysis of northern hake used an observation error of 0.2 instead of 0.1. This doubling of uncertainty in the catch increased the variability of viable *r-k* pairs found by CMSY (compare lower left graphs in the CMSY output between the two runs), but the increased uncertainty did not affect the estimates of the fisheries reference points in any significant way.

References

Froese, R., Demirel, D., Coro, G., Kleisner, K.M., Winker, H. Estimating fisheries reference points from catch and resilience. Submitted to Fish and Fisheries on 28 February 2015.

Froese, R. 2015. Results of preliminary runs of the CMSY-method against data-limited ICCAT stocks. SCRS 2015/113, ICCAT, Madrid. Available from www.fishbase/rfroese/ under "Other publications."

ICES. 2014. Report of the Workshop on the Development of Quantitative Assessment Methodologies based on LIFE-history traits, exploitation characteristics, and other relevant parameters for data-limited stocks (WKLIFE IV), 27–31 October 2014, Lisbon, Portugal. ICES CM 2014/ACOM:54. 241 pp.

Martell, S. and R. Froese. 2013. A simple method for estimating MSY from catch and resilience. Fish and Fisheries 14: 504–514.

Annex 4: Trials on pollack in Subareas VI–VII (Celtic Seas and the English Channel)

DCAC

The Depletion-Corrected Average Catch method (DCAC) gives an estimate of a yield likely to be sustainable (MacCall, 2009). It is based on the assumption that data adequately capture the entire range of a population, and that a production function with compensation exists for the stock (Dorn *et al*., 2011). It requires a relative long time-series of cumulative removals (generally more than ten years, to approximate generation time). Total catch should be used rather than just landings. Prior distributions are also required for mortality rate (M), ratio of fishing mortality at MSY on mortality rate (F_{MSY}/M), ratio of biomass at MSY on pristine biomass (B_{MSY}/B_0), and depletion delta (Δ). Δ is the change in biomass relative to B_0 during the period over which removals occurred. The DCAC is calculated as the sum of catches divided by the sum of the number of years in the catch series and a windfall ratio, given by:

$$\Delta / \left\{ \left(\frac{B_{MSY}}{B_0} \right) * \left(\frac{F_{MSY}}{M} \right) * M \right\}$$

DCAC uses Monte Carlo simulation to propagate uncertainty in life-history parameters and stock status, resulting in a distribution of yield that is likely to be sustainable. It gives information on precision and bias, and allows estimation of approximate confidence intervals. This method should be used when $M < 0.2\ y^{-1}$. It is still valid for stocks for which M is larger than $0.2\ y^{-1}$, but the depletion correction becomes small and it is therefore not recommended (MacCall, 2009). The main weaknesses of DCAC is its sensitivity to assumptions about depletion delta. This method is usually adapted for category 4 stocks because only reliable catch data are available.

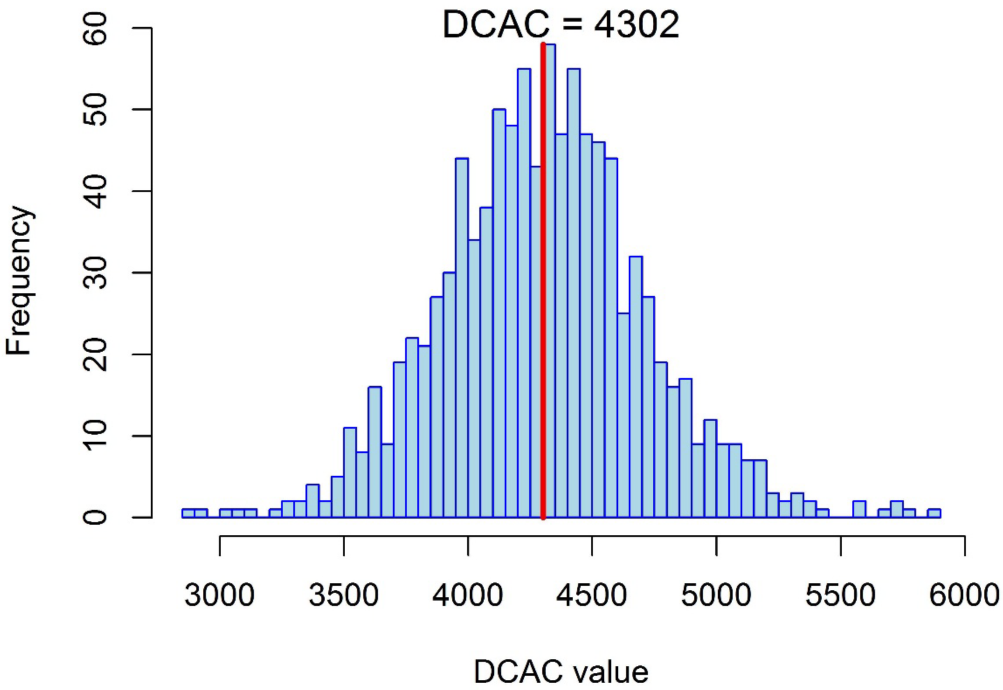


Figure 1. Implementation of DCAC on pollack for Subarea VII in years 1986–2014, with a value of 0.6 for both F_{MSY}/M and Δ.

The weakness of DCAC used for pollack (Figure 1) is the lack of data on recreational fisheries. The amount of fish removed by recreational anglers might be of a similar order of magnitude to commercial landings, which leads to high uncertainties in the results obtained. In order to better manage the stock, more information is needed, as prescribed in WGCSE and WGNEW reports.

CMSY

CMSY is an advanced implementation of the Catch-MSY method of Martell and Froese (2013). It requires prior knowledge of the depletion history, the current status, and the resilience of the stock to be assessed. The model uses the Schaefer production model to calculate annual biomasses for a given set of resilience (*r*) and carrying capacity (*k*). A Monte Carlo approach is used to detect *r-k* pairs compatible with observed catches. If an *r-k* pair results in a crash of the stock, or in an overshot of the carrying capacity, it will be eliminated from the range of plausible pairs. The model assumes that the parameters of the Schaefer model are constant over time. It also assumes that the knowledge of the stock status is accurate. The main advantage of the CMSY model is that few data are required. But the drawback is the sensitivity of the model to prior settings.

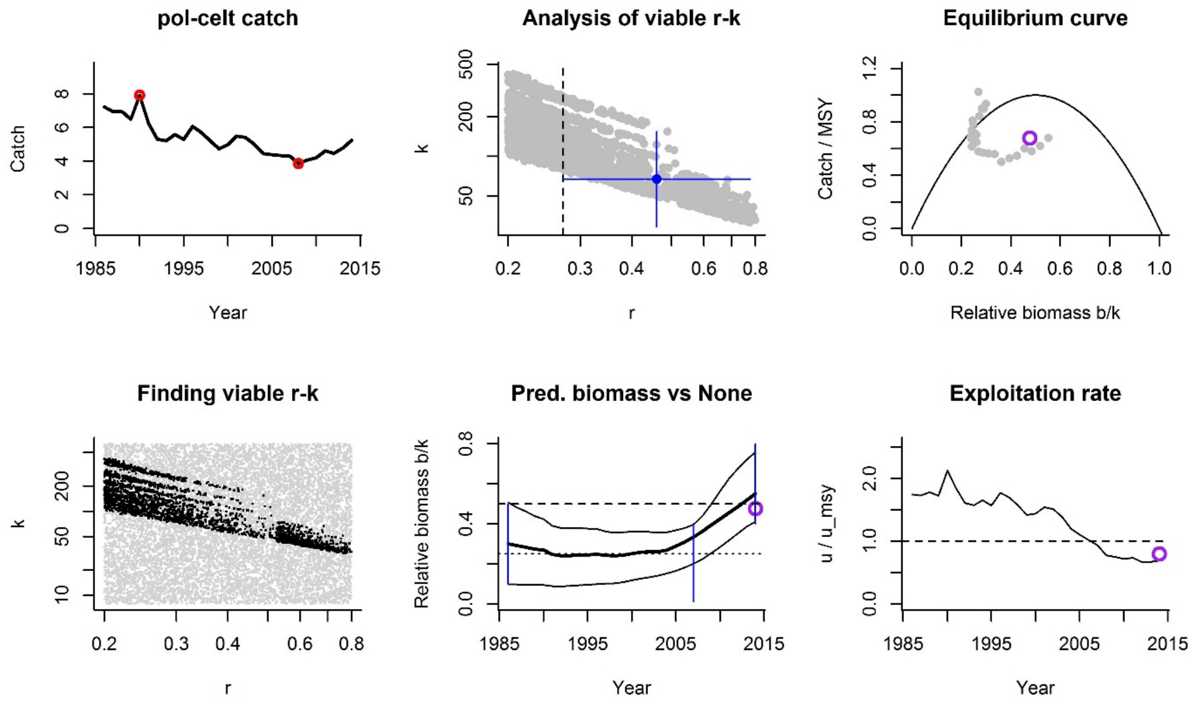


Figure 2. Graphical output of CMSY applied to pollack for Subarea VII in years 1986–2014.

The MSY calculated by CMSY is 7710 tons, with a value of 0.461 for *r* and 67 for *k*. Results of Figure 2 show an increase of predicted biomass during the last ten years. This seems rather coherent, as pollack is not a strong targeted species, and as catches remained stable for the last ten years. Grey dots of the graph "Analysis of viable r-k" are the viable r-k pairs, and the blue dot is the predicted most probable r-k pair, with 95% confidence limits. The "Equilibrium curve" graph shows that under equilibrium assumption, catches could increase in order to reach the maximum sustainable yield. On the graph "Pred. biomass vs. None", the bold line shows the evolution of median relative biomass predicted by the CMSY, with 2.5th and 97.5th percentiles. The purple point indicates the 25th percentile of predicted biomass. According to these results, the stock is underexploited.

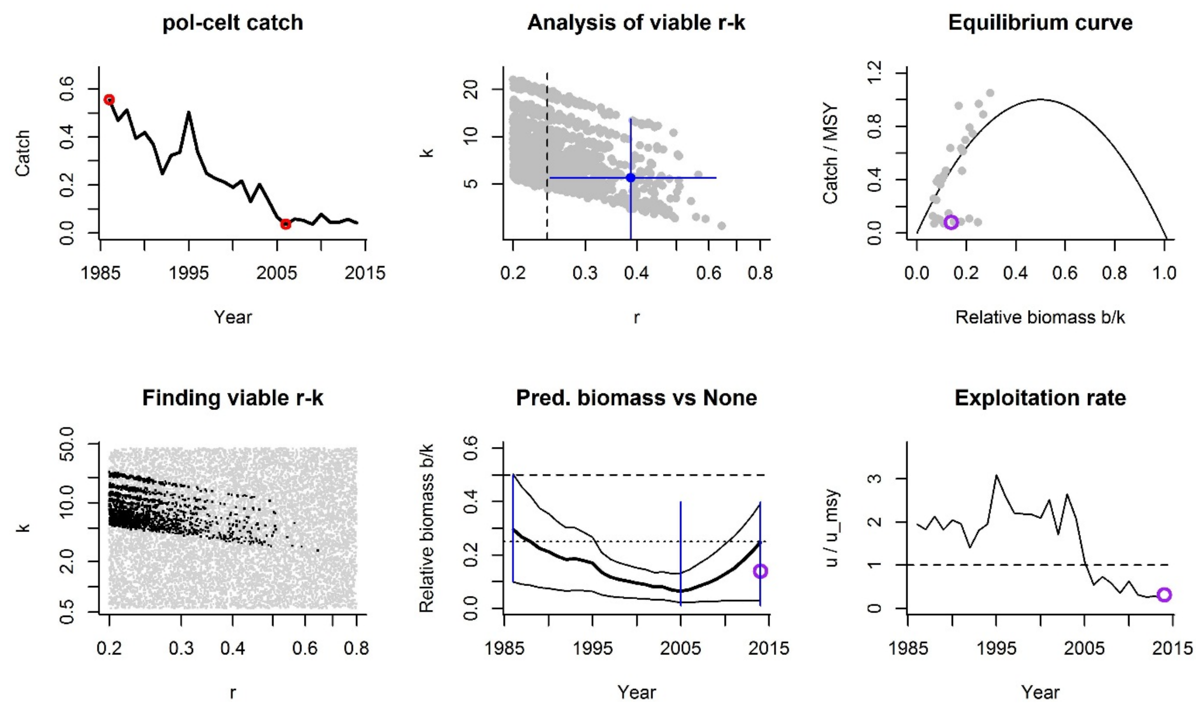


Figure 3. Graphical output of CMSY applied to pollack for Subarea VI in years 1986–2014.

The estimated MSY is 529 tons, with a value of 0.387 for *r* and 5.47 for *k*. An important decrease of exploitation rate is observed between 2003 and 2014, leading to an increase in predicted biomass. According to these results, the stock is slowly recovering after being overexploited, but the biomass is still at a low level. These results suggest that catches should remain low in future.

Length-based reference points

When length composition data are available, length-based reference points can give an idea of the stock status. These indicators of exploitation can even be used as proxies for stocks with unknown fishing mortality and biomass. This method assumes that length–frequency data are representative of the catch. It was used in WKLIFE IV, and we applied it on pollack using data from the French National on-board observer programme (Obsmer). As no sufficient data were available for Subarea VI, we applied this method on Subarea VII only.

Two estimates of mean length were calculated: one using the full length distribution (MuL_all) and one only length classes above the length at first capture (Lc), the length at first capture (MuL). The median of the distribution (LMed) was estimated, as well as the 25th, 75th and 95th percentiles, the maximum observed length in the distribution (LMax) and two estimates for length at first capture. Both estimates of length at first capture were based on using a mode in the distribution to indicate the size at full selection and then estimated the length class where a frequency of 50% of the modal frequency occurred. One approach used the 'raw' frequencies by length class (Lc), while another used predictions of a smoother (Lc_s). One further central metric was calculated; the length class contributing the most to the catch in weight (biomass) to the length distribution (LMaxY).

The length where growth rate is maximum (L_{opt}), was considered a good reference point as it represents the point where cohort biomass and egg production are maximal in an unexploited state and where catch is maximal for a given F, or F minimal for a given catch(i.e. the optimum harvest length) (Cope and Punt, 2009; ICES, 2012c). It is empirically defined as:

$$\mathrm{Lopt} = 2 * \mathrm{Linf}/3$$

In addition to the empirical formulation for L_{opt}, an analytical calculation using the von Bertalanffy growth and length–weight relationship parameters was made where L_{opt} was the length class where the increase in growth in weight per unit time was maximal. As an F_{MSY} proxy the empirical formula for length at F equals M ($L_{F=M}$) was used.

Rearranging and simplifying the Beverton and Holt (1956) equation for mean length in the catch as a function of the von Bertalanffy growth parameters, length at first capture and natural and fishing mortality gives an equation for the mean length in the catch that would result from fishing at F=M in the long term:

$$L_{F=M} = (3\mathrm{Lc} + \mathrm{Linf})/4$$

F=M is a proxy for MSY, hence $L_{F=M}$ is a length-based MSY proxy reference point that can be used to compare against current exploitation levels expressed by mean length in the catch (MuL_all).

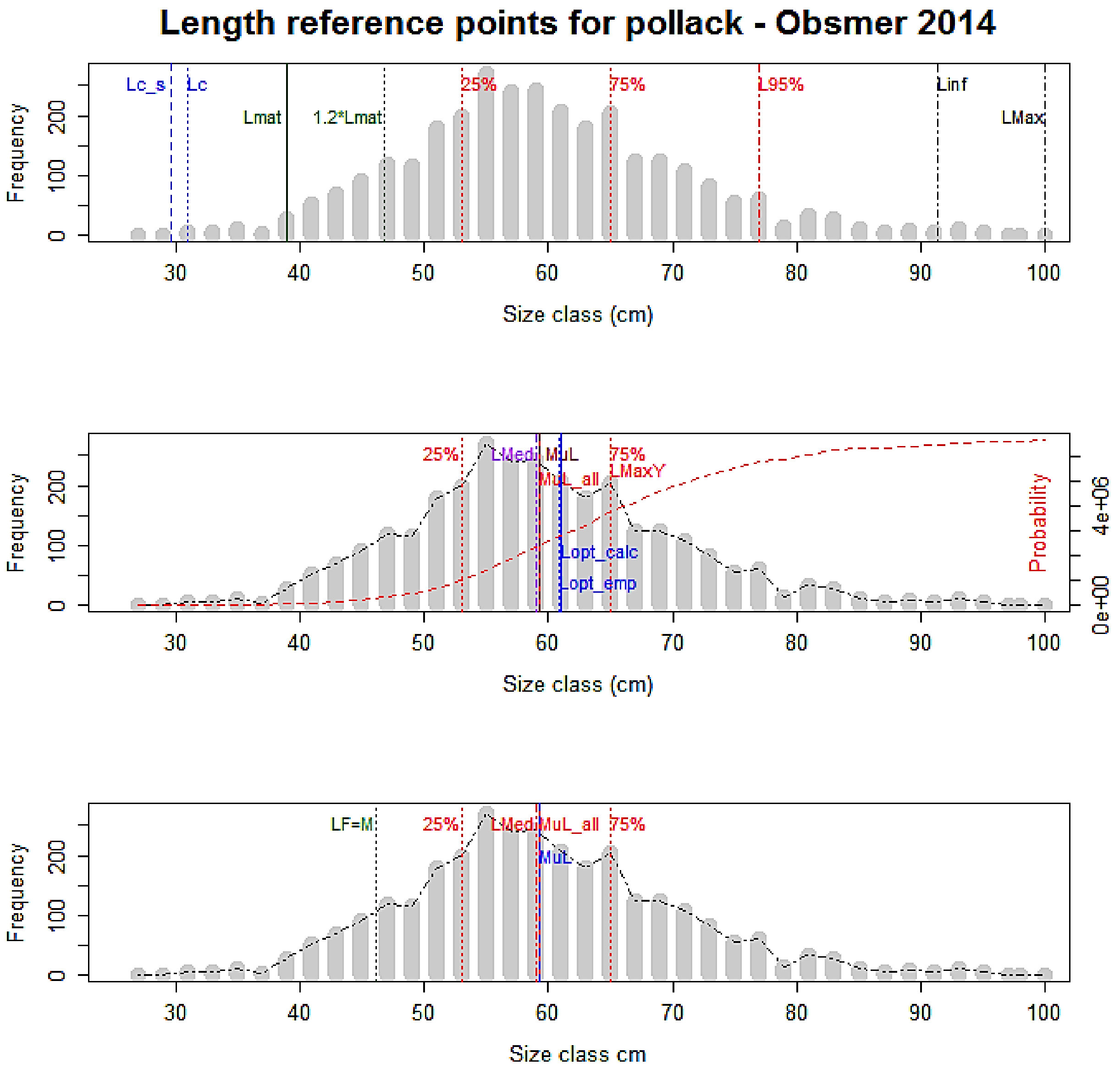


Figure 8. Plot of the length reference points for pollack in Subarea VII for year 2014.

Table 1. Outputs of the length reference points method for pollack in Subarea VII for year 2014.

Lc	Lc_s	MuL_All	MuL
31	29.7	59.29	59.33

Q25%	MedSize	Q75%	LMax	Q95%	LCMaxY	Lmat	Lopt_emp	LoptCalc	LF=M
53	59	65	100	77	65	39	60.87	61	46.08

Three graphs are plotted on Figure 8. The upper graph focuses on conservation and sustainability by comparing the reference points length at first maturity (L_{mat} and L_{mat} *1.2) and L_{inf} with indicators from the lower (L_c and $L_{25\%}$) and upper ($L_{95\%}$ and L_{MAX}) portions of the length distribution, respectively. The central graph focuses on optimal yield and presenting estimates of the reference point L_{opt} compared with central metrics from the length distribution (MuL_all, MuL, LMaxY and the upper and lower quartiles). Cumulative yield was also presented on the right axis of this plot to provide an indication of where (and how rapidly) most yield was taken. The lower graph focuses on MSY and presents central metrics (MuL_all, Lmed and the upper and lower quartiles) compared with the F_{MSY} proxy, the empirical $L_{F=M}$.

Figure 8 shows that central metrics of the length distribution are above the empirical estimate for the MSY proxy ($L_{F=M}$). Fishing mortality is therefore likely sustainable, at levels below F_{MSY}. Central metrics are close below L_{opt}, which is indicative of maximum yield potential. This suggests exploitation is a bit lower than optimal, and there might be a potential to increase yields without exceeding MSY.

Estimates of length at first capture are below L_{mat}, indicating that a part of the catch is harvested before having the opportunity to breed. But as 1.2*L_{mat} is below the 25th percentile of the distribution, it is not a significant proportion. The maximum sampled length (L_{MAX}) is above L_{inf}, indicating that large individuals are present in the population. But as the 95 percentile of length is below L_{inf}, large animals are scarce.

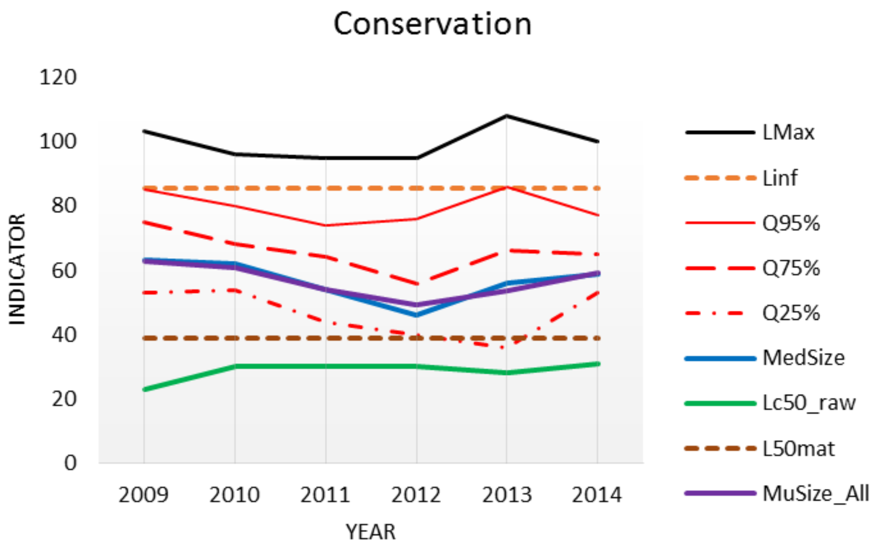


Figure 9. Evolution of length reference points for pollack in Subarea VII from 2009 to 2014.

Table 2. Summary of status for pollack in Subarea VII as suggested by length-based reference points approach.

YEAR	LMAT/LC	LOPT/MUL_ALL	LF=M/MUL_ALL	LINF/LMAX	LMAT/LC_S	LOPT/MUL	LOPT/LCMAXY	LF=M/LMED	LINF/Q95%
2009	1.70	0.97	0.64	0.83	1.97	0.97	0.77	0.64	1.01
2010	1.30	1.00	0.75	0.89	1.33	1.00	0.85	0.73	1.07
2011	1.30	1.13	0.84	0.90	1.36	1.12	0.95	0.84	1.16
2012	1.30	1.24	0.92	0.90	1.39	1.24	1.45	0.99	1.13
2013	1.39	1.13	0.81	0.79	1.46	1.11	0.90	0.78	1.00
2014	1.26	1.03	0.78	0.86	1.31	1.03	0.94	0.78	1.11

We used the length-based reference points approach on years 2009 to 2014 to explore trends of indicators of exploitation over time (Figure 9 and Table 2). Figure 9 shows that the maximum sampled length reached the highest value in 2013. Central metrics decreased from 2009 to 2012 and increased in the last two years.

According to the value of L_{mat}/L_c and L_{mat}/Lc_s (>1) in Table 2, harvest took place before maturation. Values of Linf/LMax are below 1, indicating that large individuals were present in the population, but values of Linf/Q95% are above 1 in all years except in 2013, meaning that large individuals were not well represented in the population. Values of $L_{F=M}$/MuL_all and $L_{F=M}$/Lmed are below 1 for all years, indicating that fishing mortality was below F_{MSY} for all years. Values of L_{opt}/MuL_all and L_{opt}/MuL were above 1.1 from 2011 to 2013, indicating that exploitation was lower than optimal. But the ratio takes the value 1.03 in 2014, showing that exploitation moved closer to the optimal level.

LB–SPR

The length-based spawning potential ratio (LB-SPR) is a length-based model allowing estimation of spawning potential ratio (SPR). It was developed by Hordyk *et al.* (2015a). They demonstrate the link between an exploited stock's expected length composition, and its SPR by using Beverton–Holt life-history invariants. The ratios of natural mortality to growth rate (M/k), of length-at-maturity to asymptotic size (L_m/L_∞), and also the ratio of fishing to natural mortality (F/M) are related to the SPR.

Approximation of the numbers per recruit surviving to age x is obtained with the formula $(1-\tilde{L})^{M/k}$ where $\tilde{L}$ is the length relative to L_∞ and M/k is a ratio which can be considered as constant for similar stocks. Length-at-maturity is estimated from M/k and b, the exponent from length–weight relationship. Yield is calculated as a function of F, using numbers per recruit and length-at-maturity to find an optimum. Inter-individual growth variation can be computed using a normal distribution for L_∞. In case of variable selectivity-at-length, numerical methods or simulation are required.

According to the value of SPR, the status of the stock ranges from unfished (SPR=1) to fully or heavily exploited (SPR<0.2). The length-at-age is modelled with the von Bertalanffy growth curve with increasing variability at longer lengths. The maturity-at-age follows a logistic pattern and is converted to maturity-at-length. The selectivity-at-age, also converted to length, can be asymptotic or dome shaped.

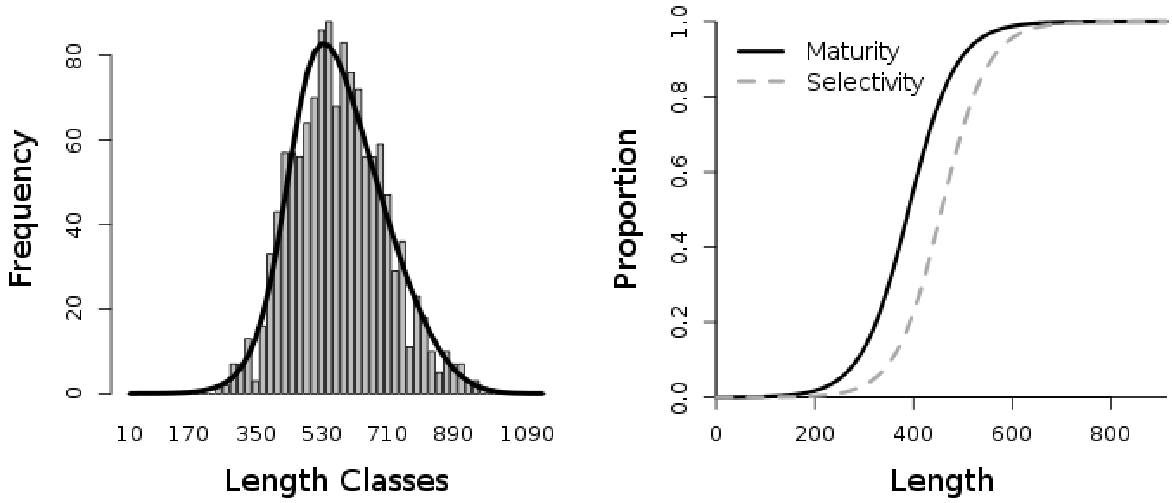


Figure 10. Plot of the LB-SPR method for pollack in Subarea VII.

Table 3. Outputs of the LB-SPR method for pollack in Subarea VII.

F/M	SPR	SL50	SL95
0.47 (0.072)	0.56 (0.034)	456.7 (9.976)	592.9 (18.648)

According to the results, the stock is under-fished and the SPR value shows that there is currently no risk for the stock to collapse. SPR is indeed above 0.4 and F/M is below 1 (Table 3). The caveat of this method is the high sensitivity of F/M to L_{inf} value. SPR is also sensitive to L_{50} and L_{95} value.

FLa4a

The stock assessment model framework FLa4a (Jardim *et al*., 2014a; 2014b) is a non-linear catch-at-age model that can be applied rapidly to a wide range of situations with low parameterization requirements. The main objective of the a4a framework is to help fishery scientists conduct a stock assessment and give management advice. It is based on five sub-models for fishing mortality-at-age, abundance indices catchability-at-age, initial age structure, recruitment, and models for the observation variance of catch-at-age and abundance indices. Catch-at-ages can be obtained by converting catch-at-length data using a growth model.

Each sub-model can be adapted according to the specificity of the stock. The equations used are linear models and splines. Uncertainty in the sub-models can be introduced through the inclusion of parameter uncertainty. This is done by making use of the parameter variance-covariance matrix, which is a correlation matrix scaled by a chosen value of CV. There are two basic types of assessments available: the management procedure fit and the full assessment fit. In the first case, no estimates of covariance are computed. In the second case, parameter estimates and their covariance are returned, taking longer time for the computation.

The statistical catch-at-age model is based on the Baranov catch equation (Baranov, 1918), assuming that the fish population is in a steady state over time, and that instantaneous rates of fishing and natural mortalities of fish are constant over time and age:

$$e^{E[logC_{ay}]} = \frac{F_{ay}}{F_{ay} + M_{ay}}\left(1 - e^{-(F_{ay} + M_{ay})}\right) R_{a=0,y} e^{-\sum(F_{ay}+M_{ay})}$$

and the survey index I:

$$e^{E[logI_{ay}]} = Q_{ay} * R_{a=0,y} e^{-\sum(F_{ay}+M_{ay})}$$

Where

$$C_{ay} \sim LogNormal(E[logC_{ay}], \sigma^2_{ay}) \qquad I_{ay} \sim LogNormal(E[logI_{ay}], \tau^2_{ay})$$

Where C is the catch, M natural mortality, F fishing mortality, R recruitment and Q survey catchability. All these variables are defined by age groups. Recruitment is modelled as a fixed variance random effect, using the hard coded models Ricker, Beverton–Holt, smooth hockeystick or geometric mean. As an alternative the log(R) submodel can use a linear model like the other submodels.

The variance model allows the user to set up the shape of the observation variances. It's quite common to have more precision on the most represented ages and less precision on the less frequent ages. This is due to the fact that the last ages do not appear as often at the auction markets, in the fishing operations or on survey samples. By default the model assumes constant variance over time and ages (~ 1 model) but it can use other models specified by the user.

In linear model one can use covariates to explain part of the variance observed on the data that the 'core' model does not explain. The same can be done in the initiative a4a framework. It’s for example possible to use the North Atlantic Oscillation (NAO) index to model recruitment. There's a set of methods that allow the user to have more flexibility on applying the models referred before. To merge results from several fits, using distinct models or datasets, the initiative a4a follows Millar *et al*. (2014). For now only the AIC model averaging is implemented.

In order to use a4a framework to try a stock assessment on Pollack, we used Obsmer data and total catch in Subarea VII. The length–weight relationship to convert catch in weight into catch in number. We computed cpue with Obsmer database. Lengths were converted into ages with the inverse von Bertalanffy growth equation:

$$t(L) = t_0 - \frac{1}{K} * ln(1 - \frac{L}{L_\infty})$$

Where t(L) is the age-at-length L, t0 is the theoretical time at which fish length is zero, K is the growth coefficient and L_∞ is the asymptotic length.

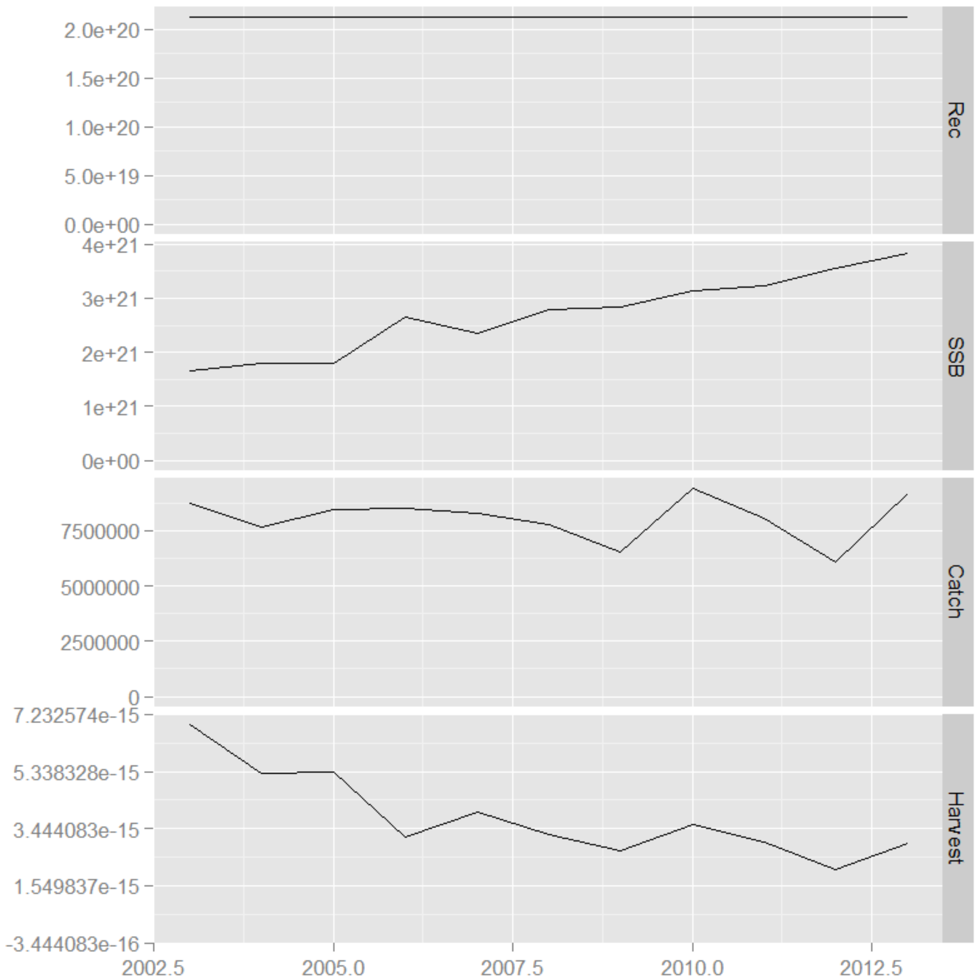


Figure 11. Outputs of FLa4a applied on pollack.

Figure 11 shows a decrease of harvest rate and an increase of spawning–stock biomass.

Annex 5: External Reviewer Report

The form of external review was integrated, rather than terminal. The external reviewer participated in workshop discussions, critiqued each method and application, and contributed to each decision, conclusion and recommendation. The reviewer critiqued the draft report in detail and supports the conclusions in the report.

In general, the reviewer endorsed the general approach and results of the workshop. The terms of reference were effectively addressed. An appropriate range of data-limited stock assessment methods were applied to representative case studies, including data-poor, data-limited and data-rich conditions. Experts on each model participated in the workshop, either in person, remotely or by correspondence with modelling experts at the workshop. The case study analyses complement supplementary simulation testing and broader method applications to data-limited stocks to demonstrate the properties and tendencies of each method. The example case studies provide worked examples for implementing the ICES DLS advisory framework.

Suitable methods were identified for the broader application of data-limited stock assessment methods and the ICES DLS advisory framework to western shelf stocks. Methods were identified based on the information and expertise available. In some cases, multiple data-limited methods may be suitable to consider all information available. For example, both production models and length-based methods may be applicable in situations for which catch, cpue and size composition are available.

Given unlimited time and human resources, complex length-based models (e.g. SS3) could integrate all information available (e.g. catch, size composition, cpue or survey trends) for more informative assessment of some data-limited stocks. However, such investment is not realistic at this stage of implementation, because time and resources are not sufficient to support the necessary expertise. Stocks that are economically valuable or ecologically important may be candidates for further exploration of more advanced methods in subsequent stages of implementing the ICES DLS advisory framework.