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The 2015 assessment of the North Sea/Skagerrak shrimp stock using a Bayesian surplus production model

by

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Abstract

A Bayesian surplus production modelling framework was applied in order to provide a quantitative assessment of the North Sea shrimp stock. There were no major problems in model diagnostics. Results were generally in line with previous years assessment. However, an upward revision of the 2013 values of two input biomass indices in 2014 and again of the of both the 2013 and 2014 indexs values in the 2015 assessment resulted in a slightly more optimistic perception of stock status. The latest revisions upward coincide with a record high recruitment as measured in the survey.

Since the late 1980s the stock has varied with a slightly increasing trend until 2006 when it started to decline. Since 2011 the stock has increased and is now above B_{MSY} with a less than 1% risk of being below the $B_{trigger}$. The 2014 fishing mortality has 5% risk of exceeding F_{MSY}. The posterior for *MSY* had a median at 16.6 ktons and upper and lower quartiles at 14 ktons and 19 ktons.

Background

This stock has been assessed anaully by qualitative non-model based interpretation of various stock indices until 2012. A benchmark for this stock (ICES, 2013) considered a surplus production model (Hvingel 2013) capable of forming the basis for the stock assessment and for deriving advice and it has been used as such since then. An alternative length-based model which the Benchmark deamed as the preferred model, has not been adopted by NIPAG in 2013, 2014 and again this year.

Model

The model was built in a state-space framework (Hvingel and Kingsley 2006, Meyer and Millar 1999, Schnute 1994) with a set of parameters (θ) defining the dynamics of the shrimp stock. The posterior distribution for the parameters of the model, $p(\theta|data)$, given a joint prior distribution, $p(\theta)$, and the likelihood of the data, $p(data|\theta)$, was determined using Bayes' (1763) theorem:

(1) $$p(\theta \mid data) \propto p(data \mid \theta) p(\theta)$$

The posterior was derived by Monte-Carlo-Markov-Chain (MCMC) sampling methods using OpenBUGS v.3.2.2 (www.openbugs.info/w.cgi/FrontPage; Spiegelhalter et al. 2003; Lunn et al 2009).

The equation describing the state transition from time t to t+1 was a discrete form of the logistic model of population growth including fishing mortality (e.g. Schaefer (1954), and parameterised in terms of *MSY* (Maximum Sustainable Yield) rather than *r* (intrinsic growth rate) (cf. Fletcher 1978):

(2)
$$B_{t+1} = B_t - C_t + 4MSY\frac{B_t}{K}\left(1 - \frac{B_t}{K}\right)$$

K is the carrying capacity, or the equilibrium stock size in the absence of fishing. B_t is the stock biomass. C_t is the catch taken by the fishery.

To cancel out the uncertainty of the "catchability" (the parameter that scales biomass indices to real biomass) equation (2) was divided throughout by B_{MSY}, (Hvingel and Kingsley 2006). Finally a term for the process error was applied and the state equation took the form:

(3)
$$P_{t+1} = \left(P_t - \frac{2C_t}{K} + \frac{4MSY\ P_t}{K}\left(1 - \frac{P_t}{2}\right)\right)\cdot \exp(\nu_t)$$

where P_t is the stock biomass relative to biomass at MSY (P_t=B_t/B_{MSY}) in year t. This frames the range of stock biomass (*P*) on a relative scale where P_{MSY}=1 and P_K (carrying capacity)=2. The 'process errors', *v*, are normally, independently and identically distributed with mean 0 and variance σ_v^2 .

The model synthesized information from input priors and four independent series of shrimp biomasses and one series of shrimp catches (Table 1). The four series of shrimp biomass indices were: a standardised series of annual commercial-vessel catch rates for Danish vessels since 1987, $CPUEdk_t$, and Norwegian vessels since 2000 $CPUEnor_t$; and two trawl-survey biomass index for 1984–2002, $surv1_t$, and 2006-2015, $surv2_t$. These indices were scaled to true biomass by catchability parameters, q_{dk}, q_{nor}, q_1 and q_2. Lognormal observation errors, ω,η, κ and ε were applied, giving:

(4)
$$\begin{aligned} CPUEdk_t &= q_{dk} B_{MSY} P_t \exp(\omega_t) \\ CPUEnor_t &= q_{nor} B_{MSY} P_t \exp(\eta_t) \\ surv1_t &= q_1 B_{MSY} P_t \exp(\kappa_t) \\ surv2_t &= q_2 B_{MSY} P_t \exp(\varepsilon_t) \end{aligned}$$

The error terms, ω, η, κ and ε are normally, independently and identically distributed with mean 0 and variance σ_ω^2 , σ_η^2 σ_κ^2 and σ_ε^2 . Total reported catch 1970-2014 and the TAC for 2015 was used as yield data (Table 1) and entered into the model as error-free.

Low-information priors (reference priors) were given to *MSY*, the process error, σ_v, and the observation error for the two CPUE biomass index series, σ_ω and σ_η, as there was little or no information on what their probability distributions might look like (Table 2). *MSY* was given a generously wide uniform prior between 0 and 100 kt. A prior for *K* was constructed based on the estimated K for the Barents Sea stock (Hvingel 2012) and the relative size of the two survey areas: 57,000 km^2 in the North Sea and 1500,000 km^2 in the Barents Sea. The posterior estimate of K for the Barents Sea was accordingly scaled down by approximately 1/27 and used as the prior for the North Sea (Table 2). The prior for the stock size in the initial year, P_0, was Norm(1.5, 25) a relatively wide distribution indicating a higher probability of the stock being above than below Bmsy as the fishery at and prior to that time was comparatively small; in any case, the model showed little sensitivity to the setting of this prior: only the estimated biomass trajectory of the first ca. 10 years (1970-1980) would differ, after that they would converge.

The prior distributions for the error terms associated with the survey biomass indices were assigned inverse gamma distributions with a mode at 0.2, comparable to the CVs typically found in such surveys. Berenboim et al. (1980) estimated a catchability of 0.173 by calibrating trawl catches to the results of a photo survey. This was chosen as basis for an informative prior by giving *q* a lognormal distribution with a median of 0.173 and a variance of 0.3.

Convergence diagnostics

In order to check whether the sampler had converged to the target distribution a number of parallel chains with different starting points and random number seeds were analysed by the Brooks, Gelman and Rubin convergence diagnostic (Gelman and Rubin 1992; Brooks and Gelman 1998) A stationarity test (Heidelberger and Welch 1983) was applied to individual chains. If evidence of non-stationarity is found iterations were discarded from the beginning of the chain until the remaining chain passed the test. Raftery and Lewis's (1992) tests for convergence to the stationary distribution and estimation of the run-lengths needed to accurately estimate quantiles were used, and finally the Geweke convergence diagnostic was applied (Geweke 1992). A visualisation of the converged chains can be seen in Fig. 1.

Model check

In order to check whether the model was a 'good' fit to the data, different goodness-of-fit statistics were computed. Firstly, I calculated the simple difference between each observed data point and its trial value in each MCMC sampling step. The summary statistics of the distributions of these residuals indicated by their central tendency whether the modelled values were biased with respect to the observations.

Secondly, the overall posterior distribution was investigated for potential effects of model deficiencies by comparing each data point with its posterior predictive distribution (Posterior Predictive Checks; Gelman et al. 1995, 1996). If the model fitted the observed data well, the observed data and the replicate data should look alike. The degree of similarity between the original and the replicate data points was summarised in a vector of *p*-values, calculated as the proportion of n simulations in which a sampling of the posterior distribution for an observed parameter exceeded its input value:

$$p.value = \frac{1}{\mathrm{n}} \sum_{\mathrm{j}=1}^{\mathrm{N}} I((data_{\mathrm{j}}^{rep}, \theta_{\mathrm{j}}) - (data^{obs}, \theta_{\mathrm{j}})) \quad ,$$

where $I(x)$ is 1 if x is true, 0 if x is false. Values close to 0 or 1 in the vector *p-value* would indicate that the observed data point was an unlikely drawing from its posterior distribution.

Derived parameters and risk calculations
The mortality caused by fishery, *F*, is scaled to F_{msy} (fishing mortality that yields MSY) for the same reasons as relative biomass was used instead of absolute. The equation added for generating posterior distributions of the *F*-ratio were:

$$F\mathrm{ratio}_{\mathrm{t}} = \frac{F_{\mathrm{t}}}{F_{msy}} = \frac{\left(\frac{C_{\mathrm{t}}}{B_{\mathrm{t}}}\right)}{\left(\frac{MSY}{B_{msy}}\right)}$$

The risk of a parameter transgressing a reference point is the relative frequency of the MCMC sampled values that are smaller (or larger –depending on type) than the reference points.

Reference points. Four reference points are considered: F_{msy}, $B_{trigger}$, F_{lim} and B_{lim}. In the present assessment, F_{msy} is estimated directly as is the probability of exceeding reference points. "Buffer" reference points are obsolete due to the available risk analyses. B_{lim} is set at 30% B_{msy} (NIPAG, 2006), $B_{trigger}$ at 50% B_{msy} and F_{lim} at $1.7F_{msy}$ (NIPAG, 2010).

	Type	Value	Technical basis
MSY approach	$B_{trigger}$	$0.5B_{MSY}$	Approximately corresponding to10th percentile of the B_{MSY} estimate
	F_{MSY}		Resulting from the production model.
Precautionary approach	B_{lim}	$0.3B_{MSY}$	The B where production is reduced to 50% MSY
	F_{lim}	$1.7F_{MSY}$	the F that drives the stock to B_{lim}

Changes from the 2014 assessment

This assessment is an update of the 2014 assessment with the following changes:

- Model: input catch-rate series and the historic syrvey series are now aligned to correspond to biomass in the middle of the year instead of end of the year. The present survey series with surveys conducted in January still aligns with the beginning of the year. These change had only cosmetic influence on the results.
- Priors: No changes.
- Input data: the update of the standardised CPUE series with new data resulted in an upward revision of the 2014 values for both series. This resulted in a slightly more positive stock status also for 2014 (the same happened in the 2014 assessment with respect to the 2013 index values).

Results, model performance

The sampler was therefore set to do 10 million iterations. Only each 1000th value of the sampled chains for the model parameters was stored and used for further analyses in order to remove within chain autocorrelation (Fig. 1). After 50 stored iterations the sampler had converged to the target distribution (Fig. 2) leaving 9950 samples for each parameter for the final analysis.

Model process error standardised to the estimated relative biomass (P_i) was variable with maximum values around 25% (Fig. 4) and a serial correlation of 0.33. This indicated that there are factors other than those included in the model that affects the dynamics of the stock. These effect are, however, relatively small with a low correlation and are expected to have a minor incluence on the estimated variance of of model predictions.

In the Bayesian framework fundamental absence of information in the data will yield posteriors as a copy of the input priors. For the data to carry information on all the parameters of any such model the biomass should vary widely both above and below B_{MSY} (Hvingel and Kingsley 2006). If the available data does not span these conditions, problems in fitting stock-production models by any method can be expected (Hilborn and Walters 1992). The available time series of indexed stock biomass does not span the range from 0 to *K* (Fig. 5). Even though the conditions for estimation of some parameters are not optimal it may still be possible to get good estimates of parameters relevant for management. Fortunately *MSY* is the easiest single parameter to estimate. If the range of biomass includes B_{MSY}, good estimates of *MSY* can be obtained independently of other parameters. K is notoriously difficult to estimate from data alone.

The model was able to produce a reasonable simulation of the observed data (Fig. 3). The probabilities of getting more extreme observations than the realised ones given in the data series on stock size were investigated (Table 3) – only two observations was found to lie in the extreme tails of their posterior distributions (<5% or >95%): the 1988 Survey1 data point and the 2007 point for Survey2. The CPUE series was generally better estimated than the survey series. Otherwise no major problems in capturing the variability of the data were detected.

For the parameters *K* and P_0 the posterior distributions tended to approximate the input priors. The prior for the "initial" shrimp stock biomass (P_0) was slightly informative giving credit to "low-exploited stock conditions" at the start of the series in 1969. Making this prior low-informative by giving P_0 a uniform prior between 0 and 2 have previously been shown to have little or no effects on the posterior of other parameters in the model – except for the first 9-10 years of P (relative biomass). After this period the series converge.

Assessment results

Since the late 1980s the stock has varied with a slightly increasing trend until 2006 when it started to decline (Fig 5+7). Median biomass in 2014 and 2015 is above B_{MSY} (Table 6). The estimated risk of stock biomass being below $B_{trigger}$ in 2014 and 2015 was less than 1% (Table 6).

The estimated median Fishing mortality has remained below F_{MSY} in recent years (Fig. 6). In 2014 there is 5% risk of the F being above Fmsy (Table 6).

The posterior for *MSY* had a median at 16.6 ktons and upper and lower quartiles at 14 ktons and 19 ktons.(Table 5).

A recruitment index A recruitment index from the Norwegian survey showed (abundance of 1-year-old shrimp expected to fully enter the fishery in 2015) (SCR. Doc. 15/xx) was high in 2014 following a series of moderate to low values. The 2015 value is low.

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Table 1. Model input data series: Catch by the fishery (Catch 2015=TAC); four indices of fishable biomass – two standardized catch rate index series based on fishery data (CPUE) from Denmark (dk) and Norway (nor) respectively, a research survey index discontinued in 2002 (Survey 1) and the current survey started in 2006 (Survey 2).

Year	Catch (ktons)	CPUEdk (index)	CPUEnor (index)	Survey 1 (ktons)	Survey 2 (ktons)
1970	5.573	-	-	-	-
1971	6.582	-	-	-	-
1972	6.018	-	-	-	-
1973	5.218	-	-	-	-
1974	4.342	-	-	-	-
1975	5.159	-	-	-	-
1976	7.081	-	-	-	-
1977	6.143	-	-	-	-
1978	5.508	-	-	-	-
1979	5.889	-	-	-	-
1980	8.399	-	-	-	-
1981	10.021	-	-	-	-
1982	10.638	-	-	-	-
1983	8.310	-	-	-	-
1984	7.592	-	-	17.60	-
1985	12.619	-	-	25.18	-
1986	12.821	-	-	11.55	-
1987	14.153	1.00	-	18.83	-
1988	12.177	0.81	-	6.83	-
1989	11.249	0.83	-	10.64	-
1990	10.239	1.05	-	12.70	-
1991	11.595	1.16	-	18.40	-
1992	13.081	1.14	-	21.34	-
1993	12.753	1.04	-	17.77	-
1994	11.549	1.15	-	18.50	-
1995	13.361	1.29	-	17.59	-
1996	14.149	1.38	-	24.15	-
1997	15.074	1.68	-	32.02	-
1998	15.504	1.65	-	20.19	-
1999	11.254	1.22	-	17.79	-
2000	11.038	1.15	1.00	17.40	-
2001	11.328	1.18	1.06	24.56	-
2002	12.474	1.44	1.32	24.81	-
2003	13.836	1.50	1.36	-	-
2004	15.952	1.90	1.57	-	-
2005	14.207	1.26	1.47	-	-
2006	14.268	1.71	1.44	-	19.54
2007	13.552	1.88	1.74	-	37.47
2008	13.554	1.42	1.69	-	19.50
2009	11.527	1.09	1.23	-	14.86
2010	8.310	0.82	0.92	-	10.10
2011	9.030	0.83	0.97	-	8.62
2012	8.782	0.67	0.82	-	6.16
2013	9.279	0.91	0.89	-	7.00
2014	12.340	1.23	1.15	-	8.86
2015	10.900	1.31	1.39	-	13.0

Table 2. Priors used in the model run 2. ~ means "distributed as..", dunif = uniform-, dlnorm = lognormal-, dnorm= normal- and dgamma = gammadistributed. Symbols as in text.

Parameter		Prior	
Name	Symbol	Type	Distribution
Maximal Suatainable Yield	*MSY*	reference	~dunif(1,100)
Carrying capacity	*K*	informative	~dlnorm(4.65,3.16)
Catchability survey 1	q_1	informative	~dlnorm(-1.75,11)
Catchability survey 2	q_2	informative	~dlnorm(-1.75,11)
Catchability CPUEdk	$\ln(q_{dk})$	reference	~dunif(-10,1)
Catchability CPUEnor	$\ln(q_{nor})$	reference	~dunif(-10,1)
Initial biomass ratio	P_0	informative	~dnorm(1.5,25)
Precision survey 1	$1/\sigma_\kappa^2$	low-informative	~dgamma(4,0.1125)
Precision survey 2	$1/\sigma_\varepsilon^2$	low-informative	~dgamma(4,0.1125)
Precision CPUEdk	$1/\sigma_\omega^2$	reference	~dgamma(0.1,0.1)
Precision CPUEnor	$1/\sigma_\eta^2$	reference	~dgamma(0.1,0.1)
Precision model process	$1/\sigma_v^2$	reference	~dgamma(0.1,0.1)

Table 3. Model diagnostics: residuals (% of observed value) and probability of getting a more extreme observation (Pr).

	$CPUE_{dk}$		$CPUE_{nor}$		Survey 1		Survey 2	
Year	resid (%)	Pr	resid (%)	Pr	resid (%)	Pr	resid (%)	Pr
1984	-	-	-	-	13.17	0.34	-	-
1985	-	-	-	-	-24.54	0.86	-	-
1986	-	-	-	-	44.11	0.08	-	-
1987	-5.51	0.64	-	-	-24.19	0.87	-	-
1988	-2.39	0.56	-	-	74.97	0.01	-	-
1989	-2.22	0.56	-	-	15.28	0.29	-	-
1990	-6.22	0.66	-	-	17.18	0.26	-	-
1991	-0.74	0.52	-	-	-5.42	0.59	-	-
1992	3.53	0.43	-	-	-16.40	0.77	-	-
1993	8.93	0.31	-	-	-3.63	0.56	-	-
1994	2.04	0.46	-	-	-4.13	0.57	-	-
1995	-0.70	0.52	-	-	10.08	0.35	-	-
1996	6.39	0.36	-	-	-8.11	0.64	-	-
1997	-2.15	0.57	-	-	-22.39	0.85	-	-
1998	-8.23	0.71	-	-	13.37	0.31	-	-
1999	1.71	0.47	-	-	5.44	0.42	-	-
2000	-0.70	0.53	13.52	0.26	-0.78	0.52	-	-
2001	5.10	0.38	16.29	0.23	-23.66	0.87	-	-
2002	-3.31	0.59	4.84	0.41	-15.14	0.76	-	-
2003	2.46	0.45	12.32	0.28	-	-	-	-
2004	-17.19	0.89	-0.41	0.52	-	-	-	-
2005	19.01	0.14	1.38	0.48	-	-	-	-
2006	-0.43	0.52	17.51	0.20	-	-	-16.05	0.76
2007	-4.01	0.61	3.08	0.44	-	-	-42.96	0.98
2008	5.82	0.36	-11.64	0.75	-	-	-4.22	0.58
2009	4.46	0.40	-8.01	0.68	-	-	-1.28	0.53
2010	11.08	0.26	-1.61	0.54	-	-	4.91	0.44
2011	-2.71	0.58	-17.27	0.84	-	-	11.56	0.35
2012	13.16	0.23	-8.12	0.67	-	-	32.84	0.15
2013	-2.93	0.58	-1.37	0.53	-	-	21.73	0.23
2014	-7.80	0.70	-2.00	0.55	-	-	25.09	0.20
2015	0.66	0.49	-5.72	0.62	-	-	8.35	0.39

Table 4. Summary of parameter estimates: mean, standard deviation (sd) and 25, 50, and 75 percentiles of the posterior distribution of selected parameters (symbols are as in the text).

	Mean	sd	25 %	Median	75 %
MSY (ktons)	17	4	14.2	16.6	19.5
K (ktons)	136	44	110	127	150
r	0.53	0.17	0.41	0.53	0.65
q_{dk}	0.01	0.00	0.01	0.01	0.02
q_{nor}	0.01	0.00	0.01	0.01	0.02
q_1	0.22	0.04	0.19	0.21	0.24
q_2	0.16	0.03	0.14	0.16	0.18
P_0	1.49	0.20	1.35	1.49	1.62
P_{2015}	1.50	0.32	1.30	1.50	1.71
σ_{dk}	0.14	0.02	0.12	0.14	0.15
σ_{nor}	0.18	0.04	0.15	0.17	0.20
σ_1	0.23	0.04	0.20	0.22	0.25
σ_2	0.23	0.05	0.20	0.23	0.26
σ_P	0.24	0.04	0.21	0.24	0.26

Table 5. Stock status and short term predictions: *Upper*: stock status for 2012-13. *Lower*: predictions for 2015 given catch options ranging from 6 to 16 ktons.

Status	2014	2015*
Risk of falling below Blim (0.3BMSY)	0 %	0 %
Risk of falling below Btrig	0 %	0 %
Risk of exceeding FMSY	5 %	2 %
Risk of exceeding Flim (1.7FMSY)	1 %	0 %
Stock size (B/Bmsy), median	1.41	1.50
Fishing mortality (F/Fmsy), median	0.54	0.44
Surplus production (% of MSY)	84 %	75 %

*Predicted catch = TAC

Catch option 2016 (ktons)	14	16	18.5	20	21.5	24
Risk of falling below Blim (0.3BMSY)	0 %	0 %	0 %	0 %	0 %	0 %
Risk of falling below Btrig	0 %	0 %	0 %	0 %	0 %	0 %
Risk of exceeding FMSY	12 %	19 %	28 %	41 %	50 %	63 %
Risk of exceeding Flim (1.7FMSY)	1 %	2 %	5 %	7 %	12 %	17 %
Stock size (B/Bmsy), median	1.42	1.40	1.38	1.33	1.31	1.28
Fishing mortality (F/Fmsy),	0.60	0.69	0.79	0.91	1.00	1.14
Surplus production (% of MSY)	82 %	84 %	85 %	89 %	90 %	92 %

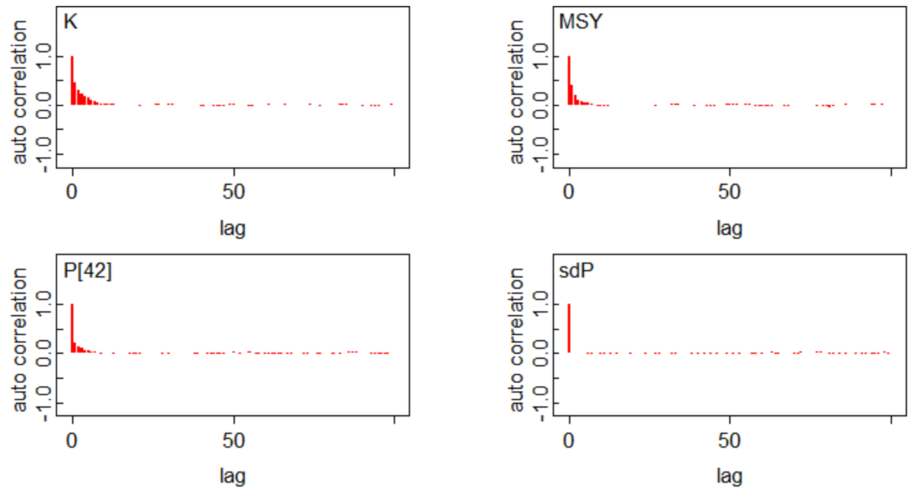

Fig. 1. Autocorrelation function of values sampled for MSY and K and two abitraily selected variables out to lag 50. K is the carrying capacity, MSY is maximum sustainable yield, P[42] is the relative biomass in year 2011and sdP is standard error of P i.e. the process error.

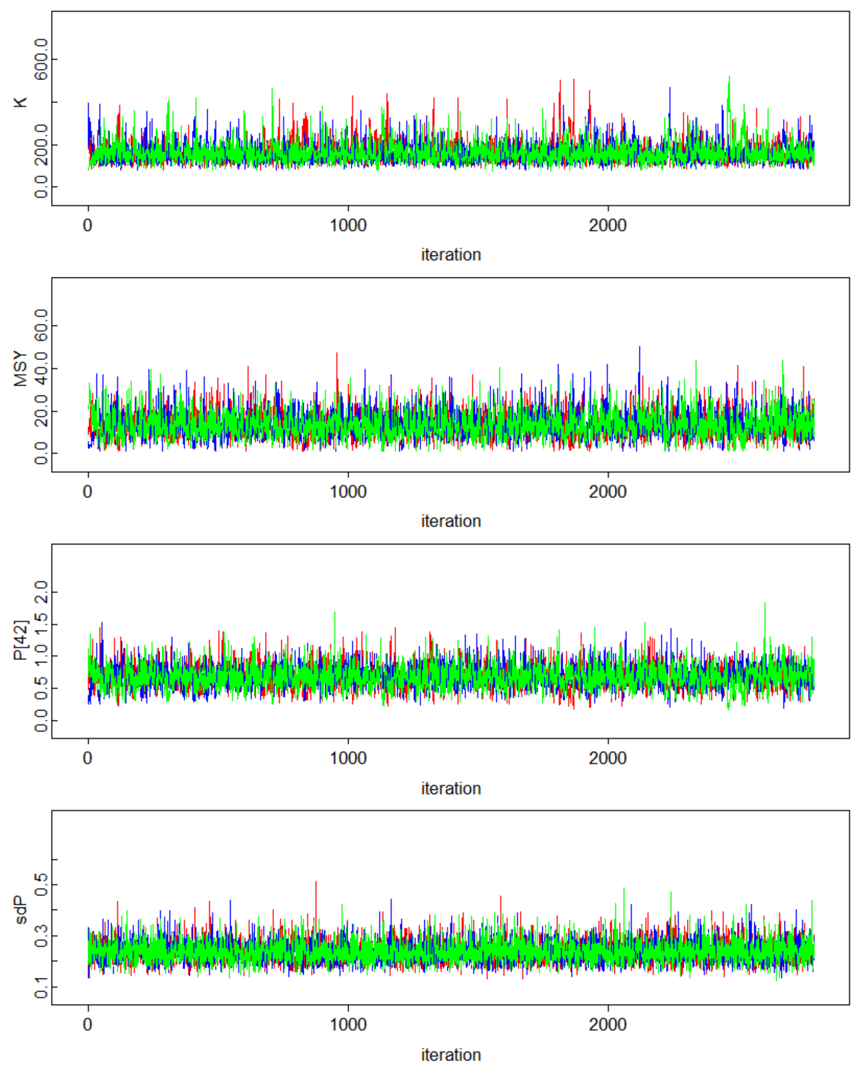

Fig. 2. Three traces (red, green, blue) with different initial values of four selected variables. K is the carrying capacity, P[42] is the relative biomass in year 2011, MSY is maximum sustainable yield and sdP is the process error.

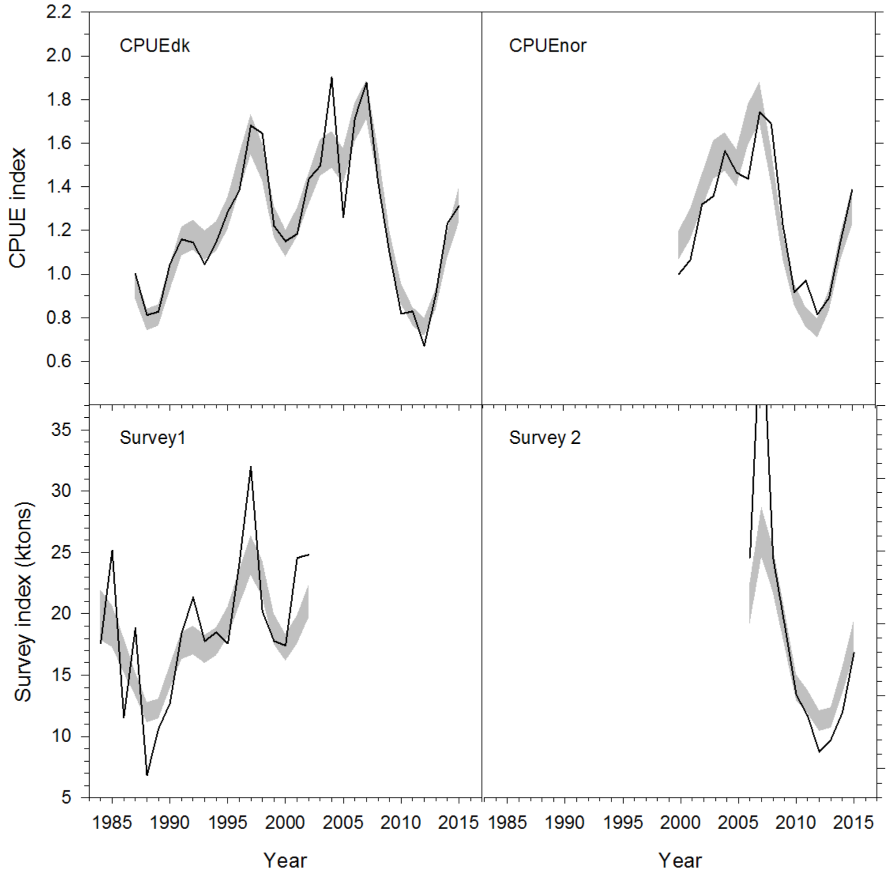

Fig. 3. Observed (solid line) and estimated (shaded) series of the biomass indices. Gray shaded areas are inter-quartile range of the posteriors.

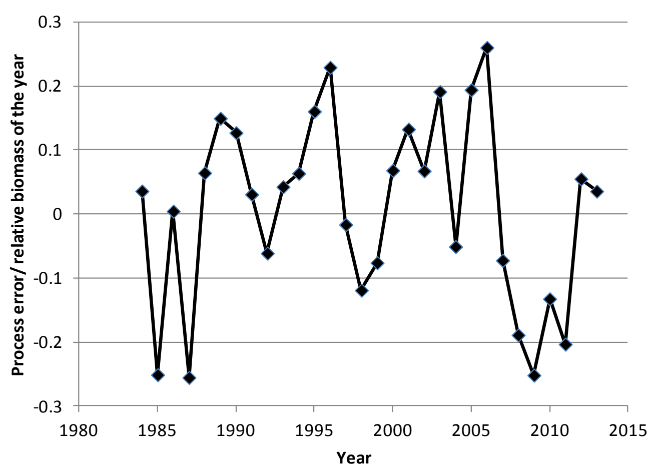

Fig. 4. Model process error. Autocorrelation=0.33.

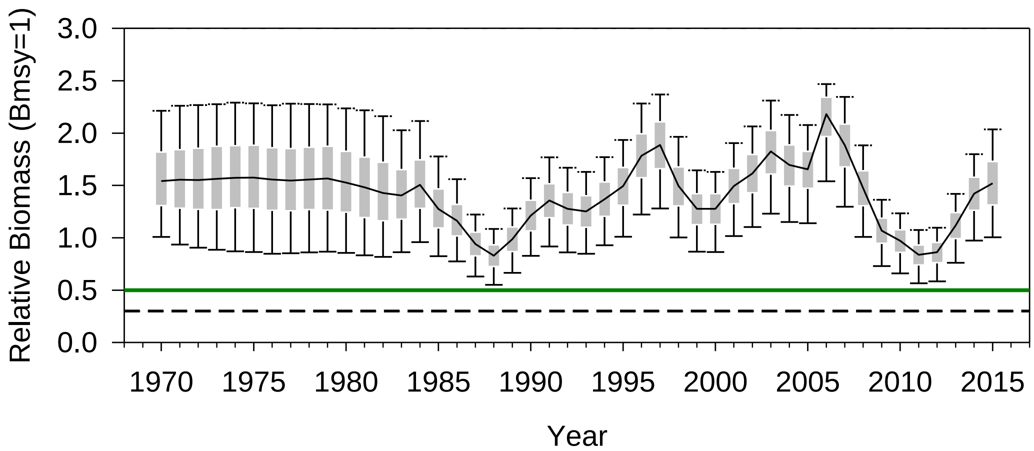

Fig. 5. Estimated time series of relative biomass (B_t/B_{msy}) 1970-2015. The solid black line is the median; boxes represent quartiles; the whiskers cover the central 90 % of the distribution. Dashed black line represents B_{lim}.

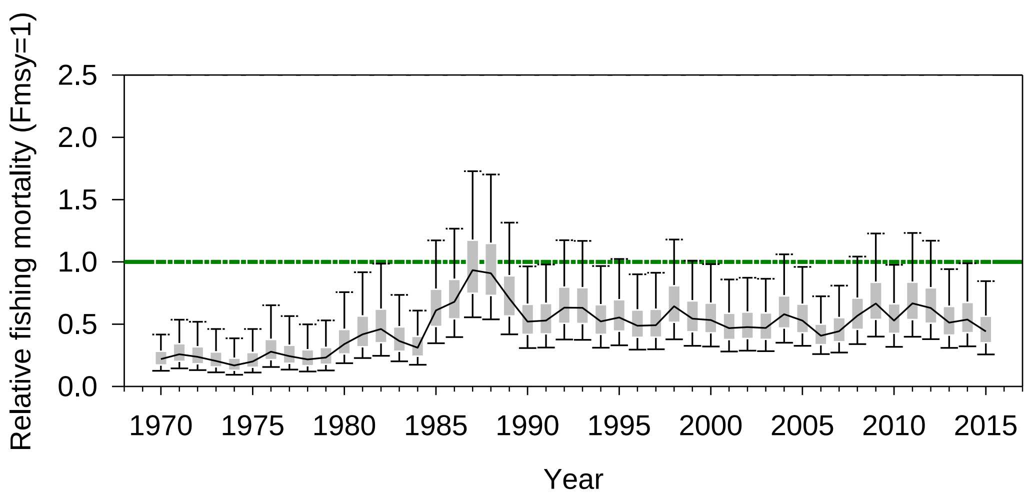

Fig. 6. Estimated time series of relative fishing mortality (Ft/Fmsy) 1970-2015. The solid black line is the median; boxes represent quartiles; the whiskers cover the central 90 % of the distribution. Green line marks F_{msy}