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An assessment of the shrimp (*Pandalus borealis*) stock in the Barents Sea

by

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Abstract

An assessment of the Barents Sea stock of *Pandalus borealis* was performed based on the logistic stock-recruitment function and Bayesian inference. Fishery effect was modelled explicitly while other mortality was included implicitly in the parameter for overall realised population growth rate, *r*. Work to include also an explicit predation effect by cod is in progress.

Estimated stock biomass has increased since 2004 following a recruitment pulse. Biomass is well above its maximum sustainable yield level (B_{MSY}) and mortality by fishery is well below the value that maximizes yield (F_{MSY}). The median estimate of the maximum annual production surplus, available to the fishery (*MSY*) was 176 ktons. However, this estimate had wide confidence limits and the right-hand side of the posterior for MSY was sensitive to the prior used for *K* (carrying capacity). Analyses using different K-priors showed that the MSY has a more than 95% chance of being above the recent advised maximum annual catch levels of 40-50 ktons.

Projections showed that catches of up to 90 ktons tons/yr is not likely (risk<11%) to drive the stock below B_{MSY} in the short to medium term (< 5 years).

Introduction

The resource of northern shrimp (*Pandalus borealis*) is distributed throughout most of the Barents Sea. Shrimp within this area is assessed as one stock (Martinez et al. 2006). A multinational fishery exploits the stock and annual landings have ranged from 25-130 ktons.

There is no TAC established for this stock and the fishery is partly regulated by effort control. Licenses are required for the Russian and Norwegian vessels to provide an upper ceiling on the effort. The fishing activity of these license holders are constrained only by bycatch regulations whereas the activity of third country fleets operating in the Svalbard zone is also restricted by the number of effective fishing days and the number of vessels by country.

Until 2006 management advice for this stock has basically been formulated by qualitative assessment of trends in various indices of stock condition in response to the catch history and the predation by cod (Anon. 2005a). Management advice was given as an annual Total Allowable Catch (TAC) and a statement about the sustainability of the applied fishing practice as agreed to by the assessment board (Anon. 2005b). The method of deriving the advice has not been explicitly stated and the uncertainty associated with the process not quantified (Hvingel and Kingsley 2006). Therefore an alternative quantitative assessment framework based on the work of Hvingel and Kingsley (2002, 2006) was introduced in 2006 (Hvingel 2006).

Cod is considered an important predator on shrimp (Hvingel and Kingsley 2006 and references therein) and imperative to any shrimp assessment model for the Barents Sea stock (Anon. 2005a). However, whereas there is little doubt that cod can consume considerable quantities of shrimp, Hvingel (2006) concluded that available consumption data and information on cod stock dynamics do at its current resolution in time and space hold little information on the dynamics of the shrimp stock and the mechanics of the cod-shrimp relation is at current unclear. Therefore a “cod effect” was not included in the assessment as this stage. Investigations for including cod predation in the assessment model are fort going. However, This paper presents an update of the 2006 assessment without a predation effect.

Model

Modelling framework

The model was built in a state-space framework (Hvingel and Kingsley 2006, 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 WinBUGS v.1.4 (www.mrc-bsu.cam.ac.uk/bugs; Spiegelhalter et al. 2003).

State equations

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

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 K=2. The ‘process errors’, v, are normally, independently and identically distributed with mean 0 and variance σ_v^2 .

Observation equations

The model synthesized information from input priors and three independent series of shrimp biomasses and one series of shrimp catches (Table 1). The three series of shrimp biomass indices were: a standardised series of annual commercial-vessel catch rates for 1980–2006, $CPUE_t$, (Hvingel and Aschan 2006); and two trawl-survey biomass index for 1982–2004, $survR_t$, (Anon. 2005a) and 2004-2006, $survE_t$ (Hvingel 2006). These indices were scaled to true biomass by catchability parameters, q_C, q_R and q_E. Lognormal observation errors, ω, κ and ε were applied, giving:

(4)
$$CPUE_t = q_C B_{MSY} P_t \exp(\omega_t)$$
$$survR_t = q_R B_{MSY} P_t \exp(\kappa_t)$$
$$survE_t = q_E B_{MSY} P_t \exp(\varepsilon_t)$$

The error terms, ω, κ and ε are normally, independently and identically distributed with mean 0 and variance σ^2_ω, σ^2_κ and σ^2_ε.

Total reported catch in ICES Div. I and II 1970-2006 was used as yield data (Table 1). The fishery being without major discarding problems or variable misreporting, reported catches were entered into the model as error-free.

Priors
The "initial" stock biomass in 1970, P_1, is considered to have been high as the fishery at that time was confined to inshore areas only. This parameter was given a normal distribution with mean=1.5 and sigma=0.26, i.e. a wide distribution with a mean between K and B_{msy} (Table 2).

A prior for K was constructed based on an estimated posterior for this parameter from the West Greenland shrimp stock (Hvingel and Kingsley 2006). This had a median of 728 ktons and 95% of the distribution between 300 and 2500 ktons. The area of the Barents sea is ca. 3.4 times that of the West Greenland area and thus the Greenland estimate of K was multiplied by 3.4 to give the K-prior for the Barents Sea, i.e. approximated by a lognormal distribution with median of 2500 ktons and 95% confidence limits at 800 and 8000 ktons (Table 2).

The error terms (CV's) for the three input data series were given a gamma distribution with a 95% range of 10-30%, thought to be the typical range for such data.

Reference priors (low-information priors) were given to the other parameters of the model (Table 2) as I had little or no information on what their probability distributions might look like. When truncated distributions were used, upper and lower limits were chosen wide enough not to interfere with the posterior.

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).

Model check
In order to check whether the model was a 'good' fit to the data, different goodness-of-fit statistics were computed. Firstly, we 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:

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

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.

Thirdly, the 'Conditional Predictive Ordinate' (Gelfand and Dey, 1994) was calculated as a harmonic mean of the likelihood:

$$CPO_{\mathrm{i}} = \left[\frac{1}{\mathrm{n}} \sum_{\mathrm{j}=1}^{\mathrm{N}} \frac{1}{p(data_{\mathrm{i}} \mid \theta_{\mathrm{j}})} \right]^{-1}$$

where n is the number of MCMC samples. This statistic indicated by small values if the relevant data points were a poor fit to the model.

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 equations added for generating posterior distributions of the F ratio were:

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

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.

Changes as compared to the 2006-run

Minor corrections of the input catch series. The input 'ecosystem survey' series has grown by another year – biomass estimated were done as before. The 'shrimp survey' series is unchanged. The standardised catch rate series include an additional year of data and the GLM was re-run giving small relative changes to the pre-2006 values, an minor update of the 2006 value and a 2007 estimate. Everything else remained unchanged as compared to last year's run.

Results, model performance

Some of the parameters showed high linear correlations (Table 3). These correlations meant that a large number of iterations were needed to secure a complete representation of the posterior distributions. The sampler was therefore set to do 5 million iterations. Only each 500^{th} 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.

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 – except for one point – in the range of 0.13 to 0.92 i.e. the observations did not lie in the extreme tails of their posterior distributions (Table 4). However, the 2004-value for survey 1 – suggested also by a low CPO and large residual (Table 4) to be a relatively poor fit to the model – was interpreted as being to pessimistic. 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_1 the posterior distributions tended to approximate the input priors (Fig. 4). The prior for the "initial" shrimp stock biomass (P_1) was slightly informative giving credit to "virgin stock conditions" at the start of the series in 1970. Making this prior low-informative by giving P_1 a uniform prior between 0 and 2 had 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 (Fig. 5).

The model was having problems estimating absolute stock size. Therefore, K also could not be well estimated from the data alone and its posterior will depend on the chosen prior. For the estimates of relative stock size relaxing the

K-prior did not have much effect (Fig. 5) except for a slight increase in uncertainty. However, the posterior for *MSY* is sensitive as *K* is correlated with *MSY*: in particular the right-hand side of the posterior distribution is widened while the left-hand side seem pretty well determined by the data.

The retrospective pattern of relative biomass series estimated by consecutively leaving out from 0 to 10 years of data did not reveal any problems with sensitivity of the model to particular years (Fig. 6).

The survey catchabilities, q_R and q_E, indicated that the new "Ecosystem survey" has a 50% lower catchability than the old "Shrimp survey" (Table 5). The estimated CVs of the two surveys series had a median at about 17% and for the CPUE series at 13%. The process error, σ_p, had a median of 20%.

Assessment results

Since 1970s, the estimated median biomass-ratio has been above its MSY-level (Fig. 7) and the probability that it had been below the optimum level was small for most years, i.e. it seemed likely that the stock had been at or above its MSY level since the start of the fishery.

A steep decline in stock biomass was noted in the mid 1980s following some years with high catches (Table 1) and the median estimate of biomass-ratio went below the optimum (Fig. 8). Since the late 1990s the stock has varied with an overall increasing trend and reached a level in 2007 estimated to be close to K. The estimated risk of stock biomass being below B_{MSY} in 2007 was 3%.

The median fishing mortality ratio (*F-ratio*) has been well below 1 throughout the series (Fig. 7). In 2007 there is a low 2% risk of the *F-ratio* being above 1.

The posterior for *MSY* was positively skewed with a mode at 95 ktons (Fig. 4) and upper and lower quartiles at 100 ktons and 309 ktons (Table 5). As mentioned above the right tail of the MSY-posterior showed some sensitivity to changes in the prior for *K*. However, no matter which prior used the model estimated a probability of at least 95% that *MSY* is higher than the recent TACs of 40-50 ktons/yr.

Given the high probabilities of the stock being considerably above B_{MSY}, risk of stock biomass falling below this optimum level within a one-year perspective is low. Risk associated with six optional catch levels for 2008 are as follows:

Catch option (ktons)	30	40	50	60	70	90
Risk of falling below B_{lim}	<1%	<1%	<1%	<1%	<1%	<1%
Risk of falling below B_{MSY}	4 %	4 %	4 %	4 %	4 %	5 %
Risk of exceeding F_{MSY}	2 %	3 %	4 %	6 %	7 %	11 %

The risk profile associated with ten-year projections of stock development assuming annual catch of 30-90ktons were investigated (Fig. 9). For all options the risk of the stock falling below B_{msy} in the short to medium term (1-5 years) is low, (<11%) (Fig. 9). The stock has a less than 1% risk of being below B_{lim} and none of these catch options are likely to increase that risk above 5% over a 10 year period (Fig. 9).

Catch options of up to 50 ktons have a low risk of exceeding F_{lim} and is likely to maintain the stock at its current high level.

Taking 70 ktons/yr will increase risk of going below B_{msy} by about 5% during the ten years of projection. However, they will still be lower than 10% during the next 5 years. The risk of that catches of this magnitude will not be sustainable (p($F>F_{lim}$) see Fig. 9)) in the longer term doubles as compared to the 50 ktons-option but is still below or at 10% after five years .

If the catches are increased to 90 ktons/yr the stock are still not likely to go below its optimum in short term, but whether this catch level will be sustainable in the longer term is uncertain.

Conclusions:

- High probability of being well above B_{msy}
- Low risk of being below B_{lim}
- Catch options of up to 50 ktons/yr have a low risk of exceeding F_{lim} and is likely to maintain the stock at its current high level
- However, the stock may likely sustain catches higher than that.
- Catch options of 50-90 ktons are not likely to drive the stock below optimum levels in the short term.

Additional considerations

Rebuilding potential

At 30%Bmsy (Blim) production is reduced to 50% of its maximum The estimate of the *r* (intrinsic rate of increase) had 95% confidence intervals ranging from 0.05 to 0.33 (Fig. 10 *left*). Thus without fishery it would take 3-10 years to rebuild the stock from Blim to Bmsy (Fig. 10 *right*).

Predation

Both stock development and the rate at which changes might take place can be affected by changes in predation—in particular by cod, which has been estimated to consume on average 5 times the catches. If predation on shrimp were to increase rapidly outside the range previously experienced by the shrimp stock within the modelled period (1970–2007), the shrimp stock might decrease in size more than the model results have indicated as likely. However, as the total predation depends on the abundance both of cod and also of other prey species the likelihood of such large reductions is at present hard to quantify.

Potential bias in the input std. CPUE series

Investigative model runs replacing the original long 1970-2007 CPUE series based on vessel grouped by engine size with an alternative 2000-2007 series based on individual vessel fishing power were done. The results showed little change in estimates of stock production potential (MSY) i.e. the median values were the same but the uncertainty of the estimate increased by 20%. Some changes in the series of estimated median stock biomass were noted (Fig. 11). Using the alternative short series provided larger estimates for the ‘peaks in early 1980s, early and late 1990s, but it was less optimistic regarding the development in the most recent years. However, the conclusions about stock status and exploitation i.e. that the stock is well above Bmsy and fishing mortality well below Fmsy still stands. Further, as similar estimates of production potential was obtained from the different runs the perceived future effects of different catch options also remained largely unchanged.

Oceanography

Changes in temperature, salinity, and large-scale water movements have been observed in the North Atlantic over the past few years. The trend in the last decade (1995-2005) has been of warming and increasing salinity in the upper ocean. In the Barents Sea, the period 2001-2005 is the warmest five-year period observed since 1900. 2006 was even warmer than the previous five years. In 2007 the temperatures are still high, but lower than in 2006 especially in the western Barents Sea. Large areas had bottom temperatures of 1-1.5°C above average, and some smaller areas even around 2°C above average.

Volume transport of warm Atlantic water into the Barents Sea increases primary production, which in turn might improve conditions for shrimp growth. On the other hand increased primary production could also lead to increase in the abundance of important shrimp predators, e.g. Atlantic cod.

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Table 1. Model input data series: Catch by the fishery; three indices of shrimp stock biomass – a standardized catch rate index based on fishery data (CPUE), a research survey index (the “shrimp survey”) discontinued in 2004 and the current “Ecosystem survey” started in 2004.

Year	Catch (ktons)	CPUE (index)	Survey 1 (ktons)	Survey 2 (ktons)
1970	5.5	-	-	-
1971	5.1	-	-	-
1972	6.8	-	-	-
1973	6.9	-	-	-
1974	9.0	-	-	-
1975	8.2	-	-	-
1976	10.3	-	-	-
1977	24.4	-	-	-
1978	36.3	-	-	-
1979	36.7	-	-	-
1980	46.3	1.000	-	-
1981	44.6	1.161	-	-
1982	62.8	1.102	327	-
1983	104.8	1.257	429	-
1984	128.1	1.312	471	-
1985	124.5	1.043	246	-
1986	65.3	0.629	166	-
1987	43.4	0.476	146	-
1988	48.7	0.522	181	-
1989	62.7	0.681	216	-
1990	81.2	0.682	262	-
1991	74.9	0.719	321	-
1992	68.6	0.828	239	-
1993	56.3	0.884	233	-
1994	28.3	0.699	161	-
1995	25.2	0.615	193	-
1996	34.5	0.791	276	-
1997	35.7	0.775	300	-
1998	55.8	0.934	341	-
1999	75.7	0.953	316	-
2000	83.2	0.856	247	-
2001	57.5	0.859	184	-
2002	61.5	0.847	196	-
2003	39.2	0.841	212	-
2004	40.7	0.752	151	129
2005	40.7	1.096	-	145
2006	29.7	1.254	-	188
2007	28.0	1.033	-	159

Table 2. Priors used in the model. ~ 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(1,1000)
Carrying capacity	K	informative	~dlnorm(7.82,3)
Catchability survey 1	q_R	reference	$\ln(q_R)$~dunif(-10,1)
Catchability survey 2	q_E	reference	$\ln(q_E)$~dunif(-10,1)
Catchability CPUE	q_C	reference	$\ln(q_C)$~dunif(-10,1)
Initial biomass ratio	P_1	informative	~dnorm(1.5,15)
Precision survey 1	$1/\sigma_R^2$	reference	~dgamma(4,0.1125)
Precision survey 2	$1/\sigma_E^2$	reference	~dgamma(4,0.1125)
Precision CPUE	$1/\sigma_C^2$	reference	~dgamma(4,0.1125)
Precision model	$1/\sigma_P^2$	reference	~dgamma(0.1,0.1)

Table 3. Correlations among selected model parameters (for explanation of symbols, see text).

	MSY	K	q_R	q_E	q_C	P_1	σ_R	σ_E	σ_C	σ_P
K	0.62	1	-0.64	-0.64	-0.64	-0.01	0.01	0.01	-0.01	0.09
q_R	-0.51	-0.64	1	0.98	1.00	-0.02	-0.01	-0.01	0.01	-0.10
q_E	-0.51	-0.64	0.98	1	0.99	-0.02	-0.03	-0.01	0.03	-0.09
q_C	-0.51	-0.64	1.00	0.99	1	-0.02	-0.02	-0.01	0.01	-0.10
P_1	-0.01	-0.01	-0.02	-0.02	-0.02	1	0.00	0.00	-0.01	-0.01
σ_R	-0.01	0.01	-0.01	-0.03	-0.02	0.00	1	-0.04	-0.18	-0.11
σ_E	0.00	0.01	-0.01	-0.01	-0.01	0.00	-0.04	1	0.02	0.07
σ_C	0.04	-0.01	0.01	0.03	0.01	-0.01	-0.18	0.02	1	0.09
σ_P	0.12	0.09	-0.10	-0.09	-0.10	-0.01	-0.11	0.07	0.09	1

Table 4. Model diagnostics: residuals (% of observed value), probability of getting a more extreme observation (p.extr.), conditional predictive ordinate (CPO).

	CPUE			Survey 1			Survey 2		
Year	resid.(%)	p.extr.	CPO	resid.(%)	p.extr.	CPO	resid.(%)	p.extr.	CPO
1980	3.15	0.44	2.00	-	-	-	-	-	-
1981	-2.82	0.58	1.77	-	-	-	-	-	-
1982	2.50	0.46	2.53	2.27	0.45	0.56	-	-	-
1983	2.17	0.45	2.17	-11.39	0.73	0.32	-	-	-
1984	-0.34	0.52	2.05	-17.82	0.84	0.20	-	-	-
1985	-9.37	0.75	1.49	13.77	0.27	0.55	-	-	-
1986	0.60	0.49	4.54	12.78	0.29	0.85	-	-	-
1987	9.24	0.30	3.77	5.43	0.41	1.21	-	-	-
1988	9.20	0.30	3.75	-6.74	0.65	0.91	-	-	-
1989	0.99	0.49	4.22	-5.74	0.62	0.79	-	-	-
1990	10.28	0.28	2.46	-15.07	0.79	0.41	-	-	-
1991	13.55	0.23	1.45	-24.74	0.92	0.17	-	-	-
1992	-0.78	0.53	3.49	1.71	0.47	0.78	-	-	-
1993	-7.59	0.71	2.14	3.80	0.43	0.77	-	-	-
1994	-3.82	0.60	3.53	23.65	0.16	0.50	-	-	-
1995	8.20	0.31	3.30	2.19	0.46	0.96	-	-	-
1996	3.36	0.43	3.33	-12.29	0.75	0.47	-	-	-
1997	11.71	0.26	2.00	-14.55	0.78	0.38	-	-	-
1998	5.12	0.39	2.67	-14.75	0.79	0.33	-	-	-
1999	2.13	0.46	2.95	-8.78	0.67	0.49	-	-	-
2000	0.49	0.49	3.26	3.16	0.45	0.74	-	-	-
2001	-8.35	0.71	2.09	26.79	0.13	0.37	-	-	-
2002	-7.21	0.70	2.32	18.79	0.20	0.55	-	-	-
2003	-6.11	0.66	2.65	10.40	0.32	0.73	-	-	-
2004	-0.46	0.52	3.70	46.97	0.03	0.16	-9.11	0.70	1.01
2005	-8.49	0.72	1.45	-	-	-	8.30	0.35	1.05
2006	-8.30	0.71	1.15	-	-	-	-0.52	0.53	0.94
2007	-0.60	0.52	2.40	-	-	-	4.80	0.42	1.04

Table 5. Summary of parameter estimates: mean, standard deviation (s) 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	231	180	100	176	309
K	3328	1949	1889	2893	4288
r	0.29	0.16	0.17	0.28	0.39
q_R	0.15	0.12	0.07	0.11	0.18
q_E	0.08	0.06	0.04	0.06	0.10
q_C	3.83E-04	3.06E-04	1.82E-04	2.88E-04	4.79E-04
P_1	1.50	0.26	1.33	1.50	1.68
σ_R	0.18	0.03	0.16	0.18	0.20
σ_E	0.17	0.04	0.14	0.16	0.19
σ_C	0.13	0.02	0.11	0.13	0.14
σ_P	0.20	0.03	0.18	0.20	0.22

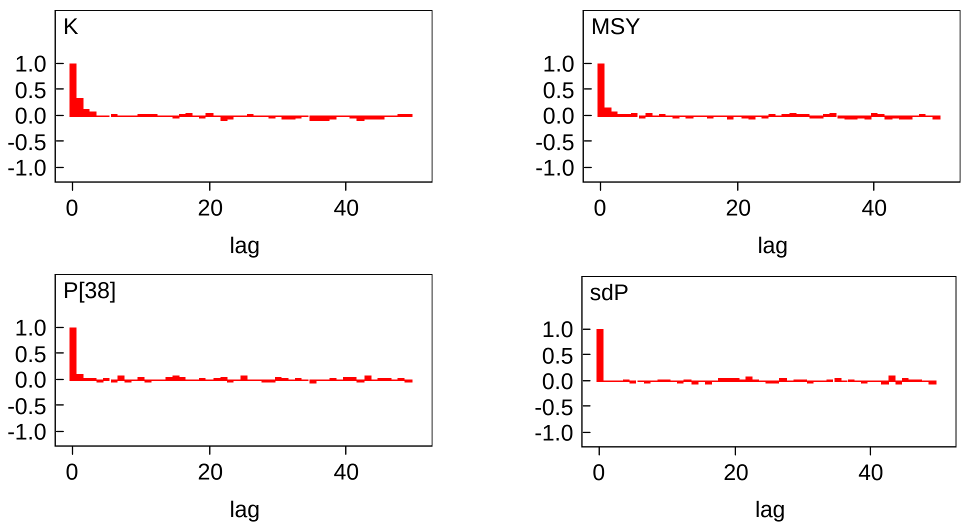

Fig. 1. Autocorrelation function of values sampled for four selected variables out to lag 50. K is the carrying capacity, P[37] is the relative biomass in year 2006, MSY is maximum sustainable yield and precP is the process precision (1/ process error).

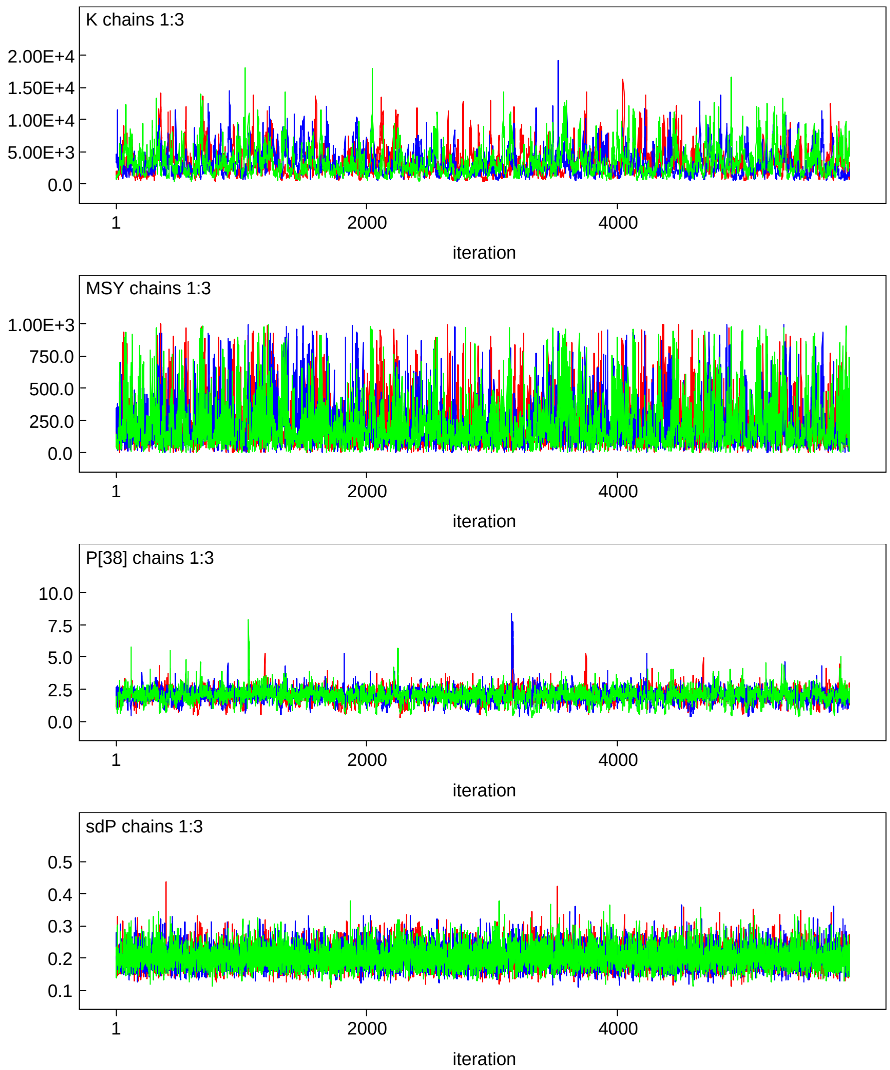

Fig. 2. Three traces (red, green, blue) with different initial values of dour selected variables. K is the carrying capacity, P[37] is the relative biomass in year 2006, MSY is maximum sustainable yield and precP is the process precision (1/ process error).

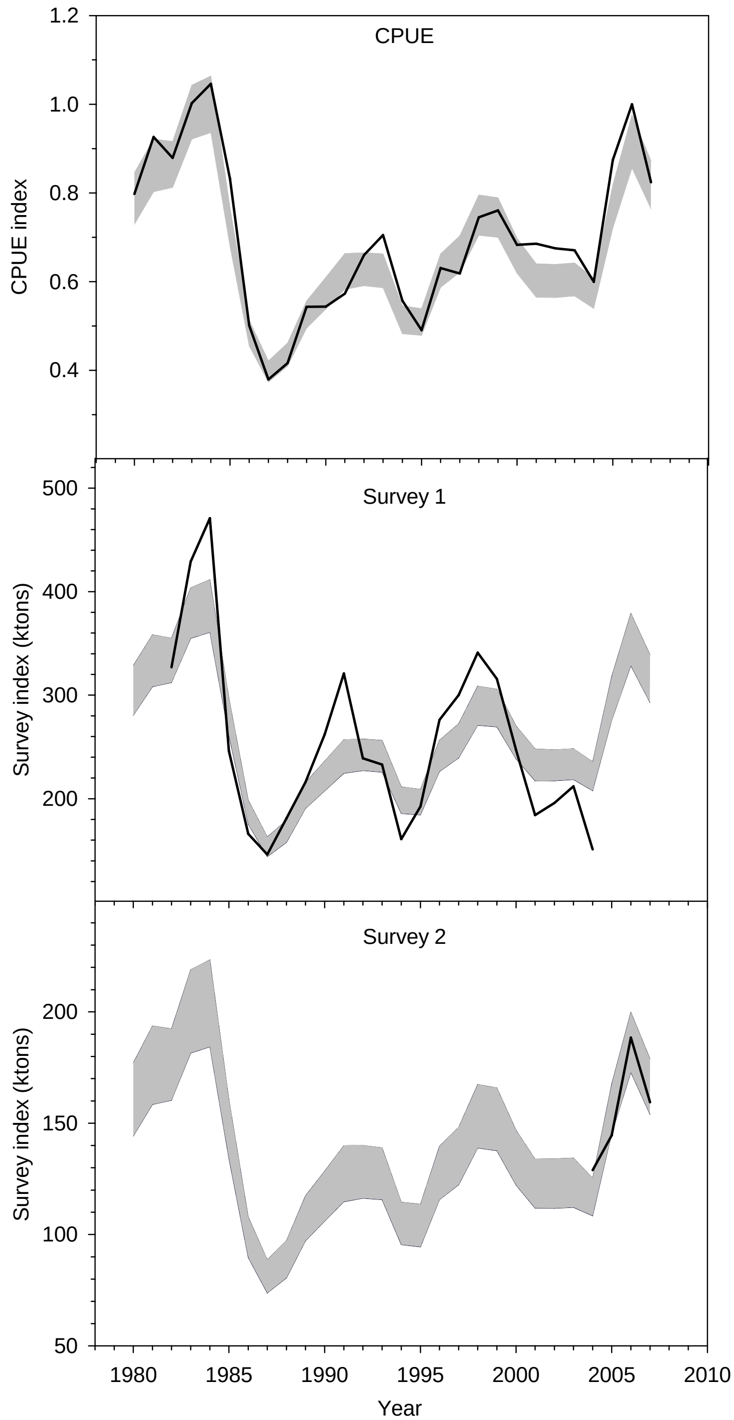

Fig. 3. Observed (solid line) and estimated (shaded) series of the biomass indices derived by standardising commercial vessel catch-per-unit-effort (CPUE), the 1982-2004 shrimp survey and the Ecosystem survey since 2004. Gray shaded areas are inter-quartile range of the posteriors.

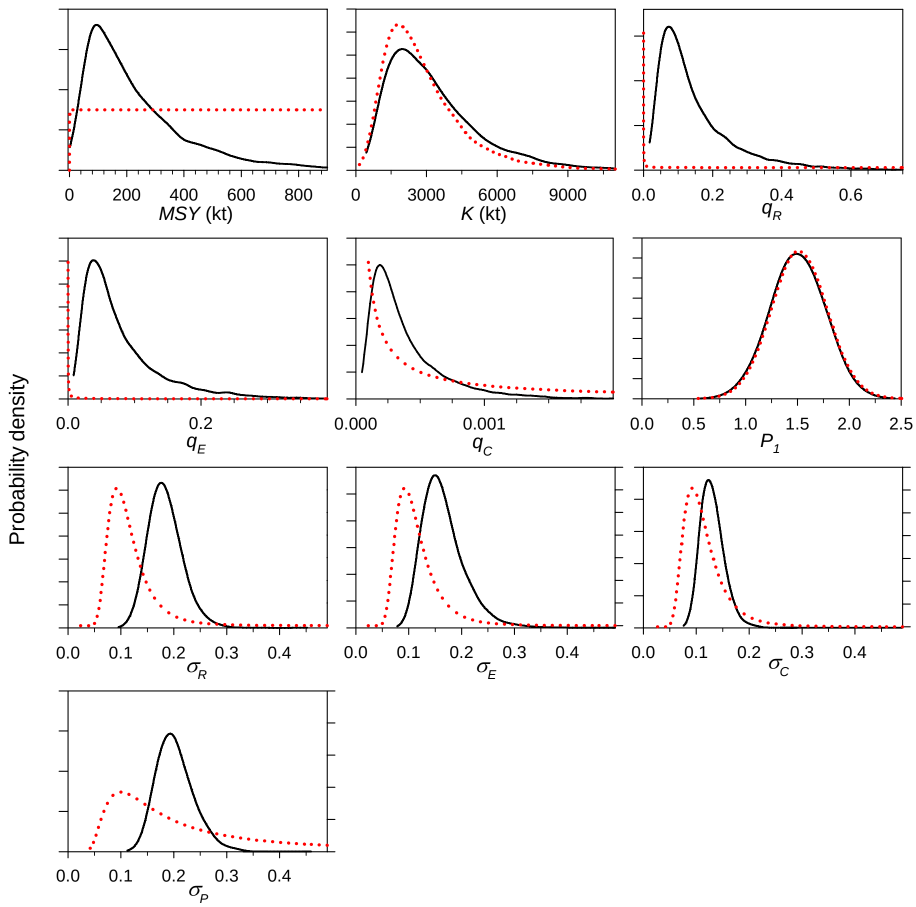

Fig. 4. Probability density distributions of model parameters: estimated: posterior (solid line) and prior (broken line) distributions (only informative priors are shown).

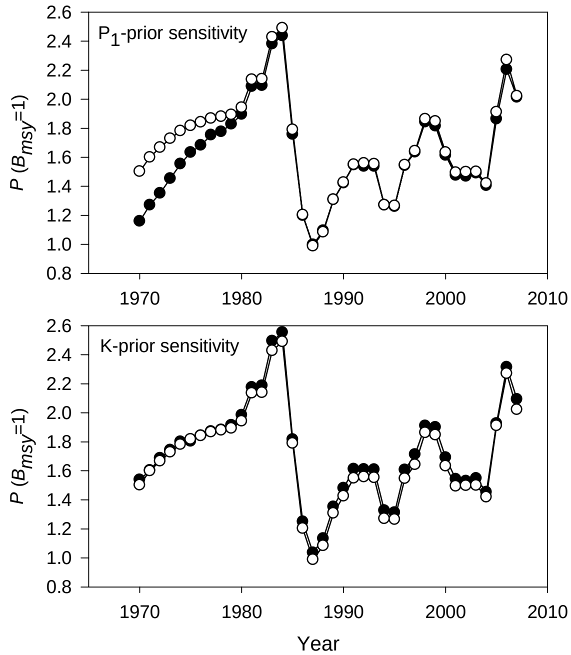

Fig. 5. Median relative biomass, *P*, 1970-2007. Open dotted series as estimated from the model used. Series with closed dots was given low informative priors: upper panel P_1~dunif(0,2), lower panel K~dunif(1,10000).

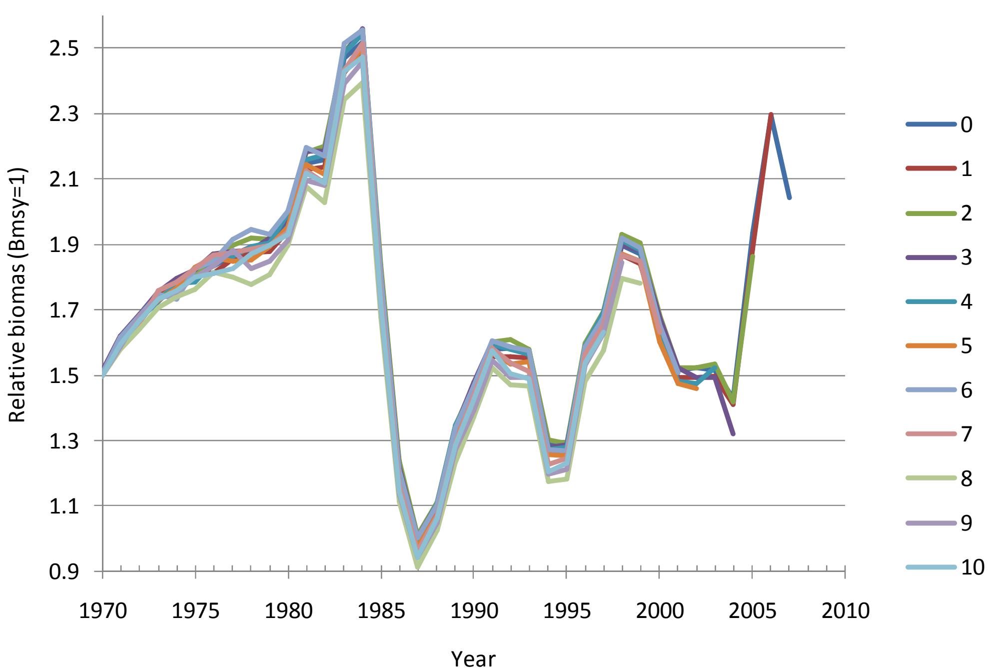

Fig. 6. Retrospective plot of median relative biomass (B/B_{msy}). Relative biomass series are estimated by consecutively leaving out from 0 to 10 years of data.

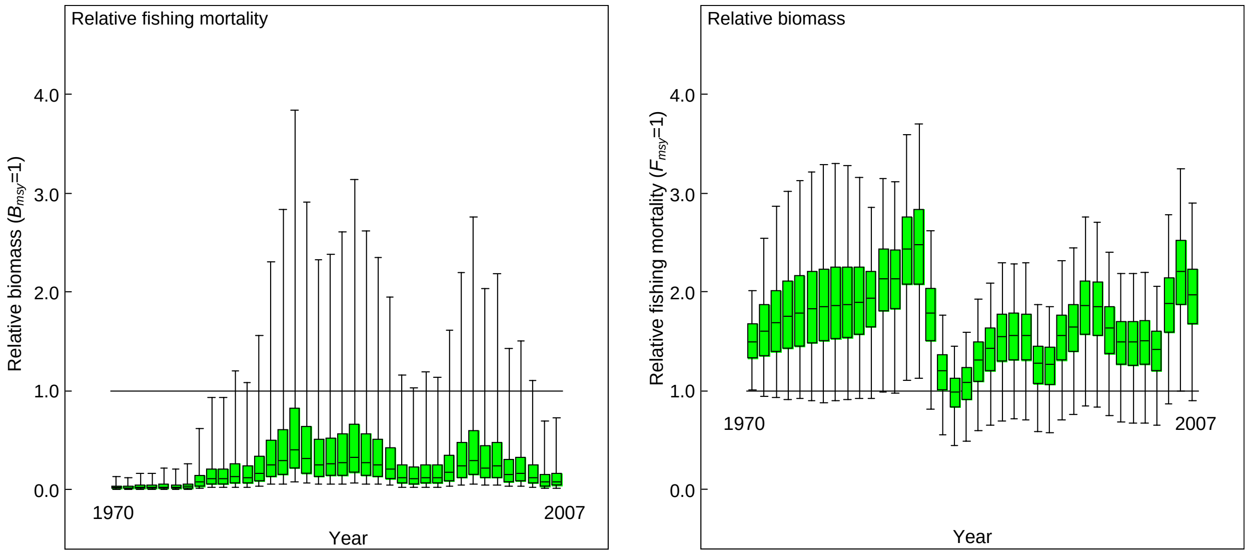

Fig. 7. Shrimp in the Barents Sea: Estimated relative biomass (P=B_t/B_{msy}) and fishing mortality (F_t/F_{msy}) 1970-2007. Boxes represent inter-quartile ranges and the solid black line at the (approximate) centre of each box is the median; the arms of each box extend to cover the central 95 per cent of the distribution.

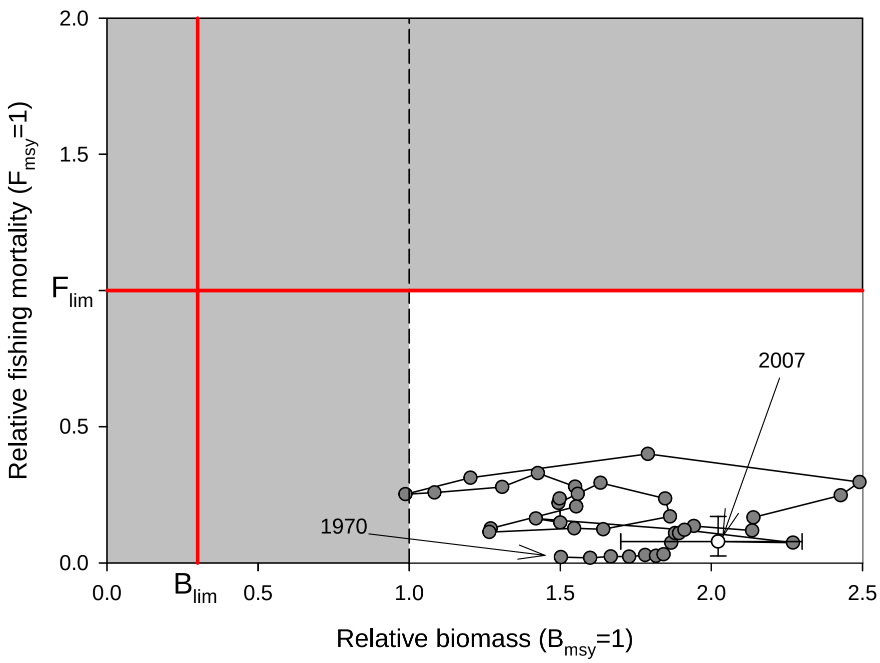

Fig. 8. Shrimp in the Barents Sea: estimated annual median biomass-ratio (B/B_{MSY}) and fishing mortality-ratio (F/F_{MSY}) 1970-2007. The reference points for stock biomas, B_{lim}, and fishing mortality, F_{lim}, are indicated by red lines. Error bars on the 2007 value are inter-quartile range

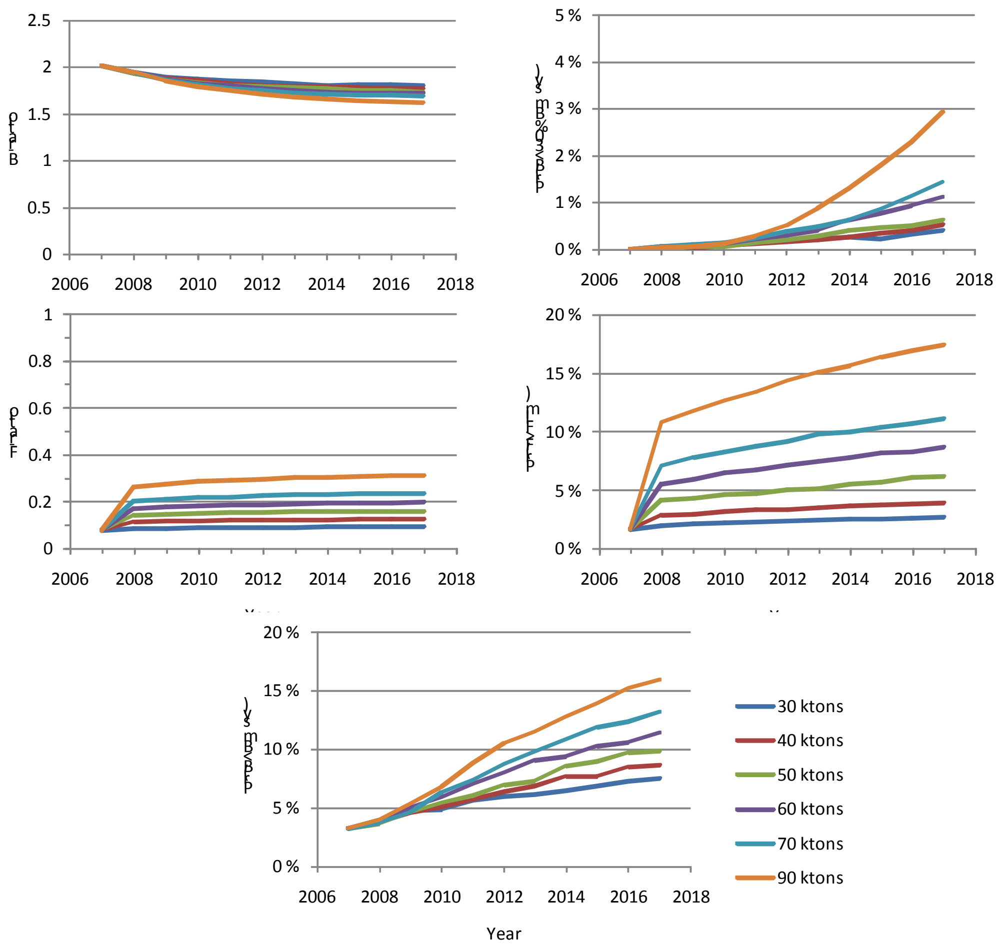

Fig. 9. Projections (*left*): Medians of estimated posterior biomass ratios and fishing mortality ratios; estimated risk (*right and below*) of exceeding F_{msy} and F_{lim} ($1.7F_{msy}$) or going below and B_{lim} given different catch options

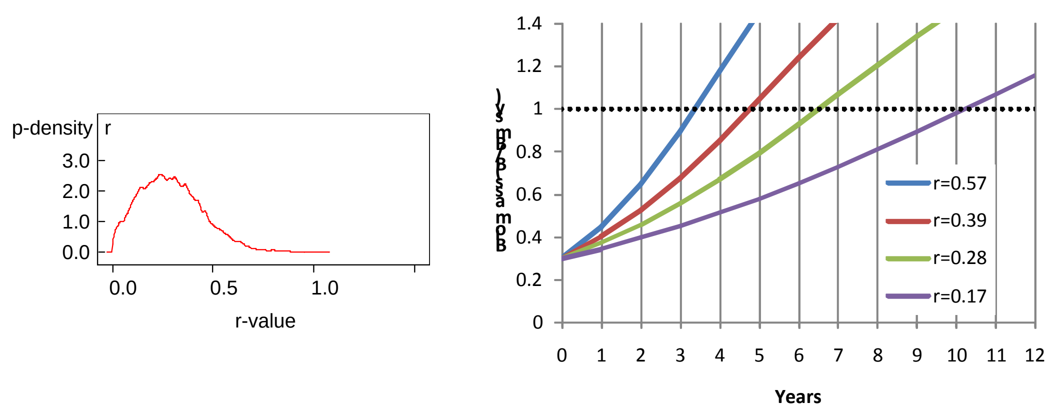

Fig. 10. *Left*:The posterior probability density distribution of r, the intrinsic rate of growth. Right: estimated recovery time from Blim (0.3Bmsy) to Bmsy (relative biomass = 1) given r values ranging within the 95% conf. lim. of the posterior (left figure) and no fishing mortality.

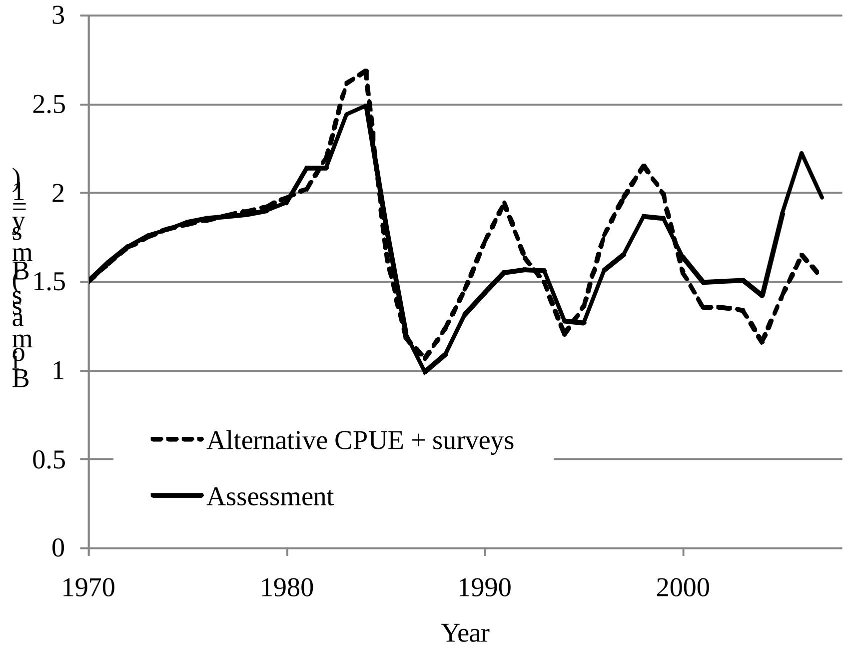

Fig. 11. Shrimp in the Barents Sea: Estimated median biomass trajectories 1970-2007 from 1. an exploratory model run using an alternative short CPUE series (see text) and 2. the results from the original assessment run.