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An assessment of the shrimp (*Pandalus borealis*) stock in the Barents Sea 2008

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.

There is a high probability that the stock biomass is above its maximum sustainable yield level (B_{MSY}) and mortality by fishery is well below the value that maximizes yield (F_{MSY}). The mode of the estimated distribution of the maximum annual production surplus, available to the fishery (MSY) was at 100 ktons. However, this estimate had wide confidence limits.

Catch options of up to 50 ktons/yr have a low risk (<5%) of exceeding F_{lim} and is likely to maintain the stock at its current high level. The results of this years assessment are similar to those of the 2006 and 2007.

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). An alternative quantitative assessment framework based on the work of Hvingel and Kingsley (2002, 2006) was introduced in 2006 (Hvingel 2006) and has been used since then.

This paper presents an update of the 2007 assessment with the following changes:

- Model: None
- Priors: None.
- Input data:
    - Survey: The 2004-2008 series (Survey 2 in table 1) has been recalculated. Russian data are now included together with Norwegian data and a new stratification scheme has been applied (Hvingel et al 2008). The trend of this series is similar to the one used earlier.
    - Standardised CPUE: Data has been reanalysed (Hvingel and Thangstad 2008). Individual vessels have been identified and the model (GLM) is now run using individual vessels instead of vessel groupings to represent levels of fishing power. Generally the trend of the resulting standardised CPUE series is similar to the one used previously, however, the increasing trend over the last 10-year period slightly lower.

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:

$$p(\theta \mid data) \propto p(data \mid \theta)\, p(\theta) \tag{1}$$

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):

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

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:

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

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 1980–2008, $CPUE_t$, (Hvingel and Thangstad 2008); and two trawl-survey biomass index for 1982–2004, $survR_t$, (Anon. 2005a) and 2004-2008, $survE_t$ (Hvingel et al 2008). 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)
$$\begin{aligned} CPUE_t &= q_C B_{MSY} P_t \exp(\omega_t) \\ survR_t &= q_R B_{MSY} P_t \exp(\kappa_t) \\ survE_t &= q_E B_{MSY} P_t \exp(\varepsilon_t) \end{aligned}$$

The error terms, ω, κ and ε are normally, independently and identically distributed with mean 0 and variance σ_ω^2, σ_κ^2 and σ_ε^2.

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:

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

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.

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:

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

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.

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 500th 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 in the range of 0.06 to 0.91 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 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 (Hvingel 2006).

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 (Hvingel 2007) 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% higher 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 19%.

Assessment results

Since 1970s, the estimated median biomass-ratio has been above its MSY-level (Fig. 7) and 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 close to the optimum (Fig. 8). Since the late 1990s the stock has varied with an slightly increasing trend. The median 2008 level is about 80% of K. The estimated risk of stock biomass being below B_{MSY} in 2008 was 4%.

The median fishing mortality ratio (*F-ratio*) has been well below 1 throughout the series (Fig. 7). In 2008 there is a low 1% risk of the *F-ratio* being above 1.

The posterior for *MSY* was positively skewed with a mode at 100 ktons (Fig. 4) and upper and lower quartiles at 114 ktons and 349 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 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
Probability of falling below B_{lim}	<1%	<1%	<1%	<1%	<1%	<1%
Probability of falling below B_{MSY}	5.4 %	5.5 %	5.8 %	5.9 %	6.0 %	6.6 %
Probability of exceeding F_{lim}	2.1 %	3.1 %	4.5 %	5.9 %	7.4 %	11.1 %

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 (<5%) 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 above B_{msy}
- Low risk of being below B_{lim}
- Catch options of up to 50 ktons/yr have a low risk (<5%) 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 4-5 times the catches. If predation on shrimp were to increase rapidly outside the range previously experienced by the shrimp stock within the modelled period (1970–2008), the shrimp stock might decrease in size more than the model results have indicated as likely. The cod stock has shown signs of increase recently (Arctic WG, ICES). However, as the total predation depends on the abundance both of cod, shrimp and also of other prey species the likelihood of such large reductions is at present hard to quantify.

Continuing investigations to include cod predation as an explicit effect in the assessment model has not so far been successful as it has not been possible to establish a relationship between shrimp/cod densities.

Potential bias in the input std. CPUE series

In the 2007 assessment it was noted that the recent restructuring of the fleet might have caused bias in the standardized CPUE input data series due to the way it was calculated (Hvingel and Thangstad 2007, 2008; Hvingel 2007). This problem is now believed to be solved (Hvingel and Thangstad 2008).

Recruitment/reaction time of the assessment model

The model used is best at describing trends in stock development and will have some inertia in its response to year-to-year changes. Large and sudden changes in recruitment may therefore not be fully captured in model predictions.

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	1.195	-	-
1982	62.8	1.150	327	-
1983	104.8	1.305	429	-
1984	128.1	1.383	471	-
1985	124.5	1.145	246	-
1986	65.3	0.678	166	-
1987	43.4	0.533	146	-
1988	48.7	0.573	181	-
1989	62.7	0.722	216	-
1990	81.2	0.736	262	-
1991	74.9	0.778	321	-
1992	68.6	0.904	239	-
1993	56.3	0.974	233	-
1994	28.3	0.801	161	-
1995	25.2	0.670	193	-
1996	34.5	0.839	276	-
1997	35.7	0.800	300	-
1998	55.8	0.969	341	-
1999	75.7	1.020	316	-
2000	83.2	0.903	247	-
2001	57.5	0.911	184	-
2002	61.5	0.899	196	-
2003	38.0	0.883	212	-
2004	41.3	0.755	151	325
2005	41.4	1.047	-	489
2006	29.6	1.146	-	549
2007	30.4	1.048	-	454
2008	26.0	0.982	-	330

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	0.61	1								
q_R	-0.50	-0.66	1							
q_E	-0.51	-0.65	0.98	1						
q_C	-0.53	-0.64	1.00	0.98	1					
P_1	-0.01	-0.01	-0.02	-0.02	-0.02	1				
σ_R	-0.01	0.01	-0.01	-0.03	-0.02	0.00	1			
σ_E	0.00	0.01	-0.01	-0.01	-0.01	0.00	-0.05	1		
σ_C	0.04	-0.01	0.01	0.03	0.01	-0.01	-0.17	0.02	1	
σ_P	0.11	0.08	-0.10	-0.09	-0.10	-0.01	-0.11	0.07	0.08	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	3.59	0.43	1.51	-	-	-	-	-	-
1981	-3.09	0.59	1.39	-	-	-	-	-	-
1982	2.38	0.45	1.88	0.07	0.51	0.57	-	-	-
1983	2.55	0.45	1.64	-13.30	0.76	0.29	-	-	-
1984	-0.25	0.52	1.49	-18.60	0.85	0.19	-	-	-
1985	-10.83	0.78	0.80	15.35	0.25	0.51	-	-	-
1986	0.55	0.50	3.23	14.13	0.27	0.81	-	-	-
1987	6.76	0.34	3.17	8.32	0.35	1.13	-	-	-
1988	7.82	0.32	2.91	-5.14	0.61	0.97	-	-	-
1989	1.71	0.47	3.00	-5.52	0.62	0.80	-	-	-
1990	9.56	0.29	1.85	-14.47	0.78	0.43	-	-	-
1991	12.91	0.23	1.18	-23.95	0.91	0.18	-	-	-
1992	-1.48	0.55	2.39	3.57	0.44	0.77	-	-	-
1993	-8.16	0.72	1.37	6.71	0.39	0.74	-	-	-
1994	-6.86	0.68	1.87	28.79	0.11	0.37	-	-	-
1995	7.50	0.33	2.46	3.71	0.44	0.94	-	-	-
1996	3.46	0.43	2.49	-12.60	0.75	0.46	-	-	-
1997	13.21	0.23	1.17	-16.10	0.81	0.34	-	-	-
1998	6.08	0.36	1.84	-16.23	0.81	0.30	-	-	-
1999	1.41	0.47	2.13	-9.03	0.68	0.48	-	-	-
2000	0.83	0.49	2.42	2.45	0.46	0.75	-	-	-
2001	-8.13	0.72	1.48	26.42	0.13	0.38	-	-	-
2002	-7.17	0.69	1.72	18.34	0.21	0.56	-	-	-
2003	-6.16	0.67	1.95	8.63	0.35	0.78	-	-	-
2004	-0.81	0.53	3.02	37.86	0.06	0.23	1.56	0.49	0.56
2005	-1.72	0.56	1.93	-	-	-	0.76	0.67	0.31
2006	-0.38	0.52	1.80	-	-	-	-8.04	0.70	0.27
2007	-0.66	0.52	2.02	-	-	-	-9.12	0.51	0.40
2008	-6.13	0.66	1.41	-	-	-	0.22	0.17	0.26

Table 5. **S**ummary 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	257	192	114	203	349
K	3387	1858	1977	2986	4398
r	0.32	0.16	0.20	0.31	0.42
q_R	0.13	0.10	0.06	0.10	0.16
q_E	0.21	0.16	0.10	0.16	0.25
q_C	4.69E-04	3.61E-04	2.32E-04	3.59E-04	5.83E-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	0.17	0.19	0.22

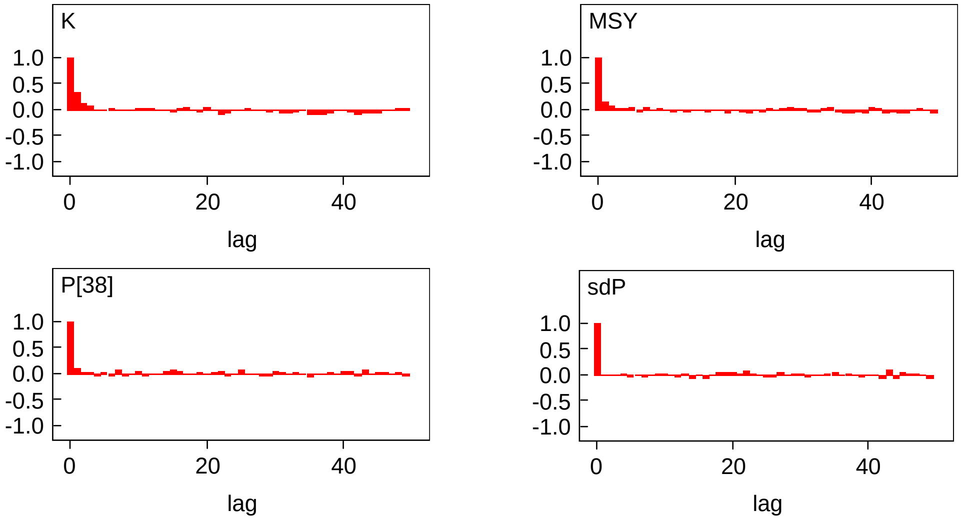

Fig. 1. Autocorrelation function of values sampled for four selected variables out to lag 50. K is the carrying capacity, P[37] is the relative biomass in year 2006, MSY is maximum sustainable yield and precP is the process precision (1/ process error).

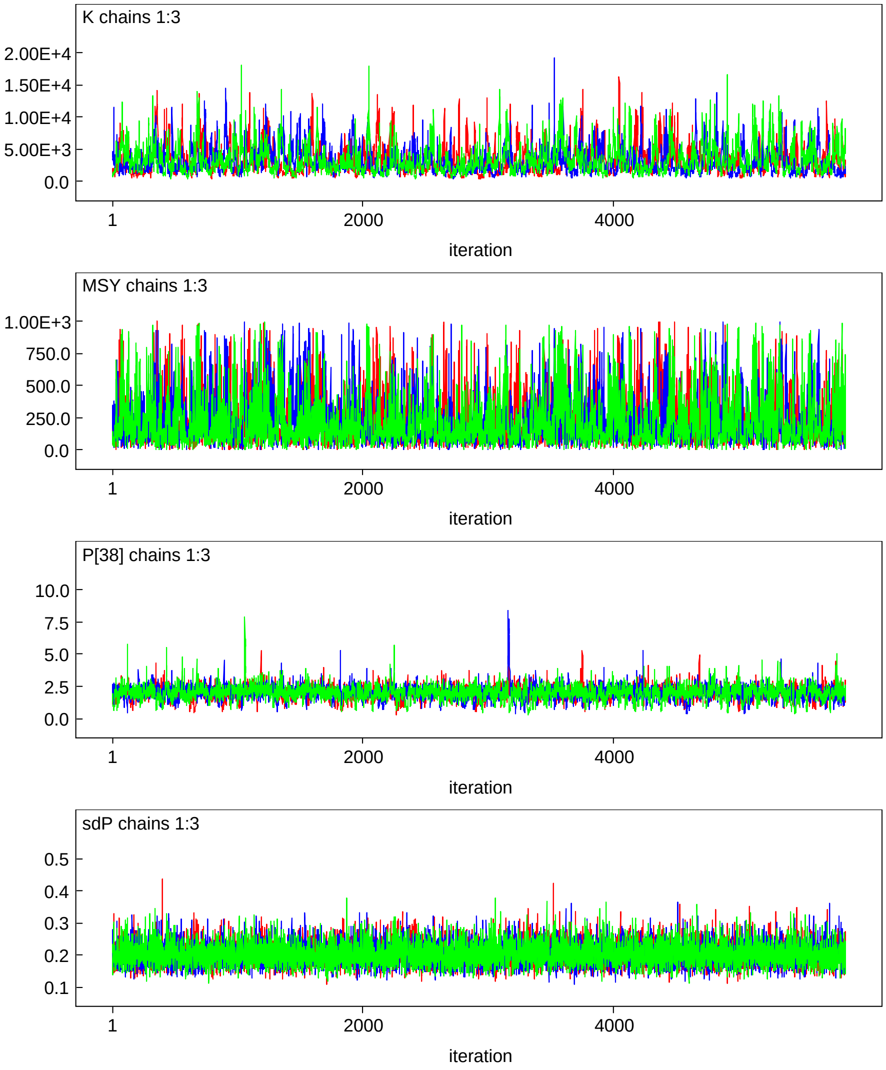

Fig. 2. Three traces (red, green, blue) with different initial values of dour selected variables. K is the carrying capacity, P[37] is the relative biomass in year 2006, MSY is maximum sustainable yield and precP is the process precision (1/ process error).

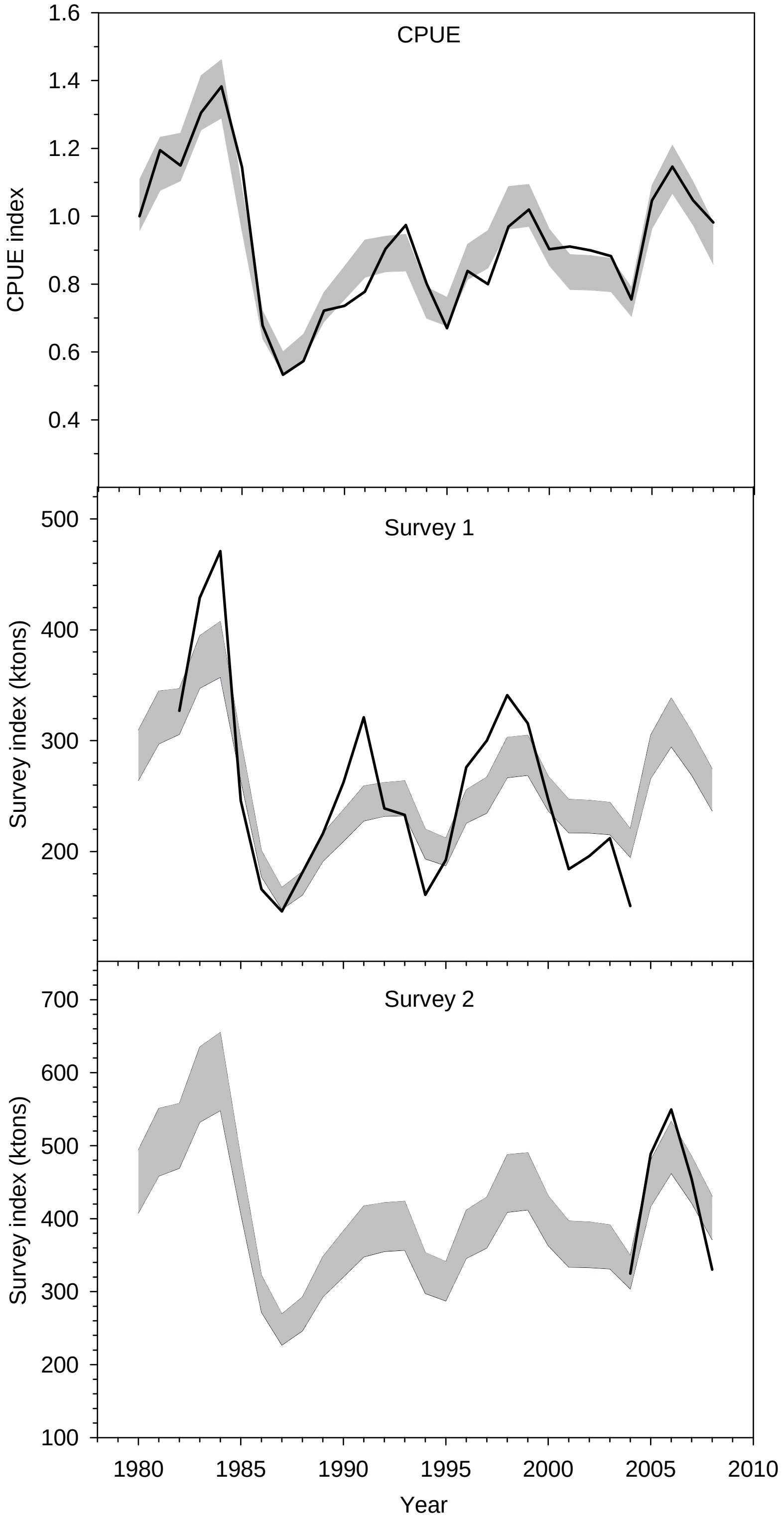

Fig. 3. Observed (solid line) and estimated (shaded) series of the biomass indices derived by standardising commercial vessel catch-per-unit-effort (CPUE), the 1982-2004 shrimp survey and the Ecosystem survey since 2004. Gray shaded areas are inter-quartile range of the posteriors.

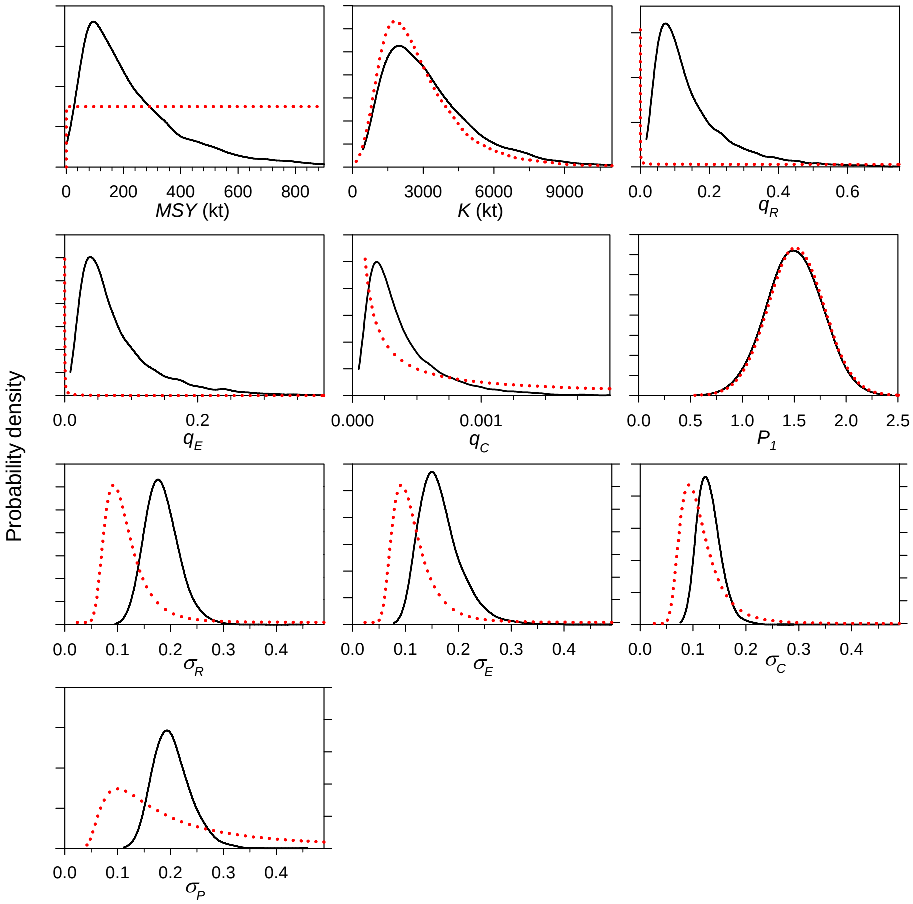

Fig. 4. Probability density distributions of model parameters: estimated: posterior (solid line) and prior (broken line) distributions (only informative priors are shown).

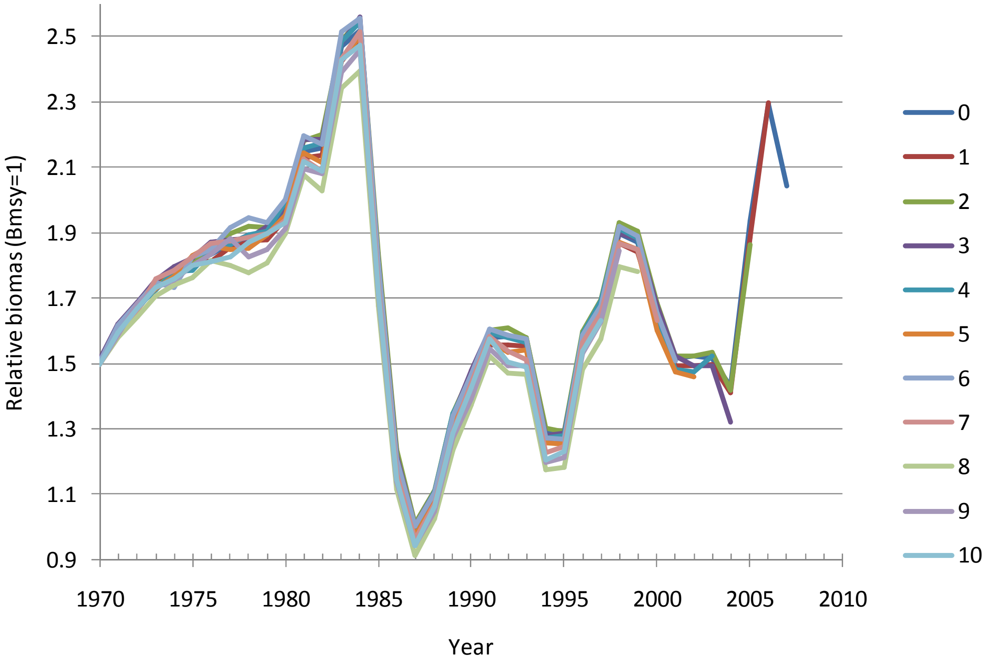

Fig. 6. Retrospective plot of median relative biomass (B/Bmsy). Relative biomass series are estimated by consecutively leaving out from 0 to 10 years of data.

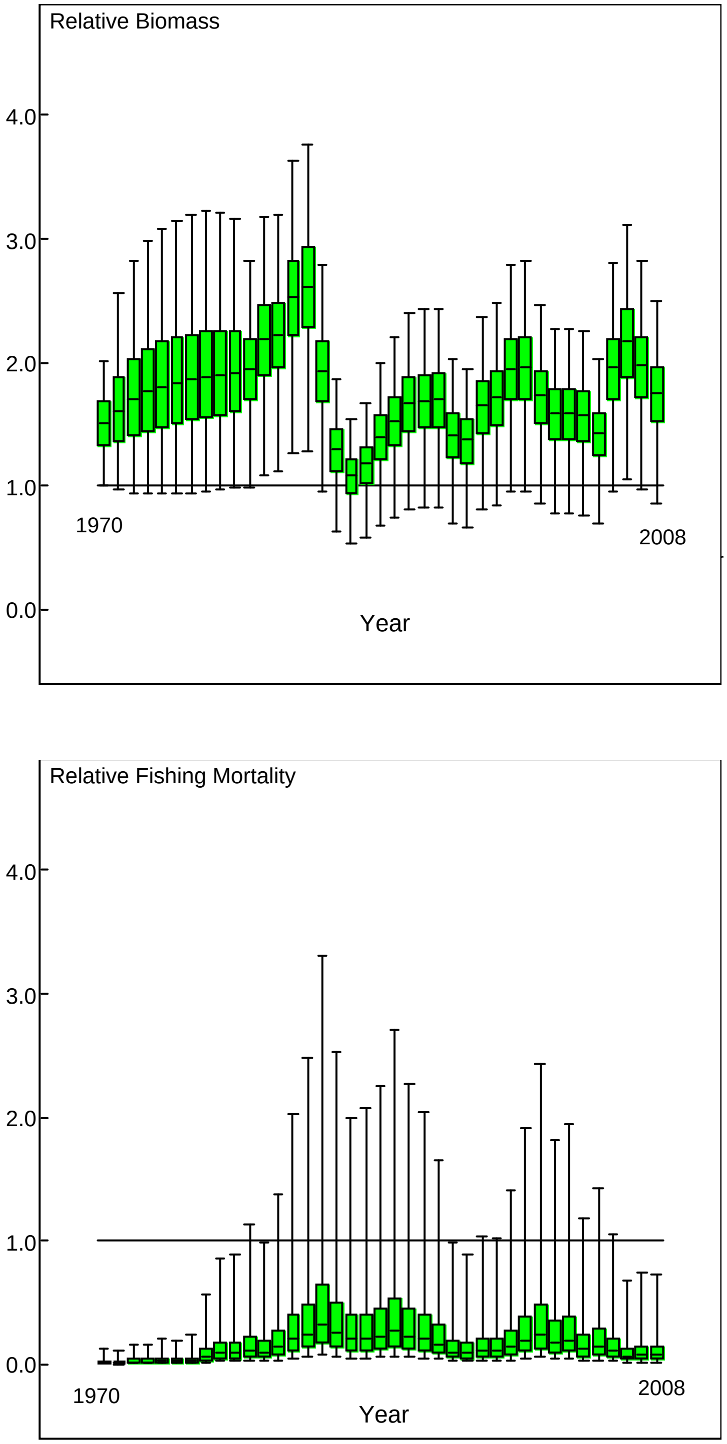

Fig. 7. Shrimp in the Barents Sea: Estimated relative biomass ($P=B_t/B_{msy}$) and fishing mortality (F_t/F_{msy}) 1970-2008. Boxes represent inter-quartile ranges and the solid black line at the (approximate) centre of each box is the median; the arms of each box extend to cover the central 95 per cent of the distribution.

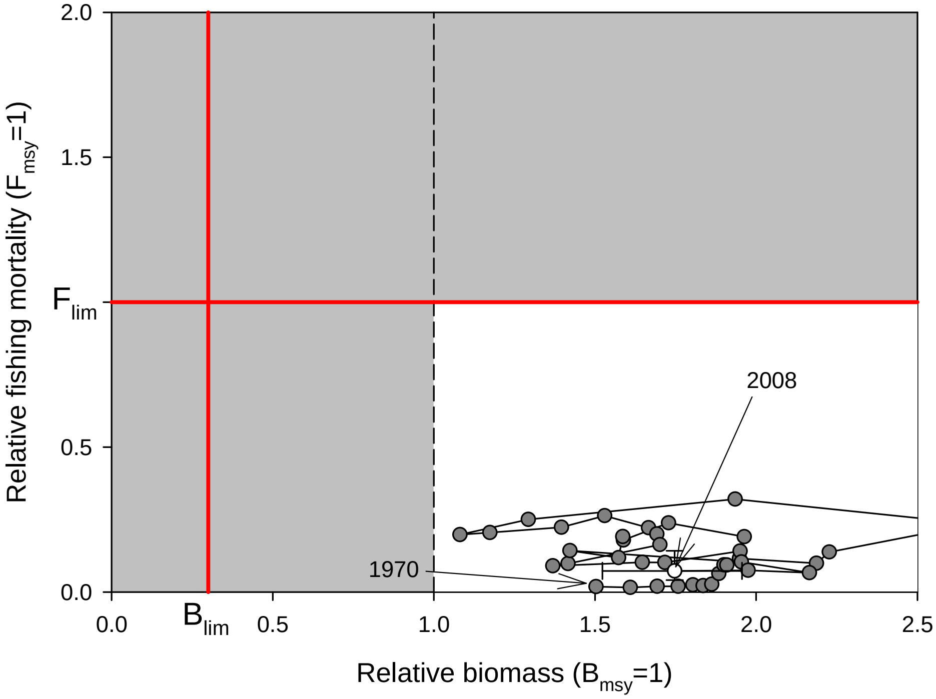

Fig. 8. Shrimp in the Barents Sea: estimated annual median biomass-ratio (B/B_{MSY}) and fishing mortality-ratio (F/F_{MSY}) 1970-2007. The reference points for stock biomas, B_{lim}, and fishing mortality, F_{lim}, are indicated by red lines. Error bars on the 2007 value are inter-quartile range

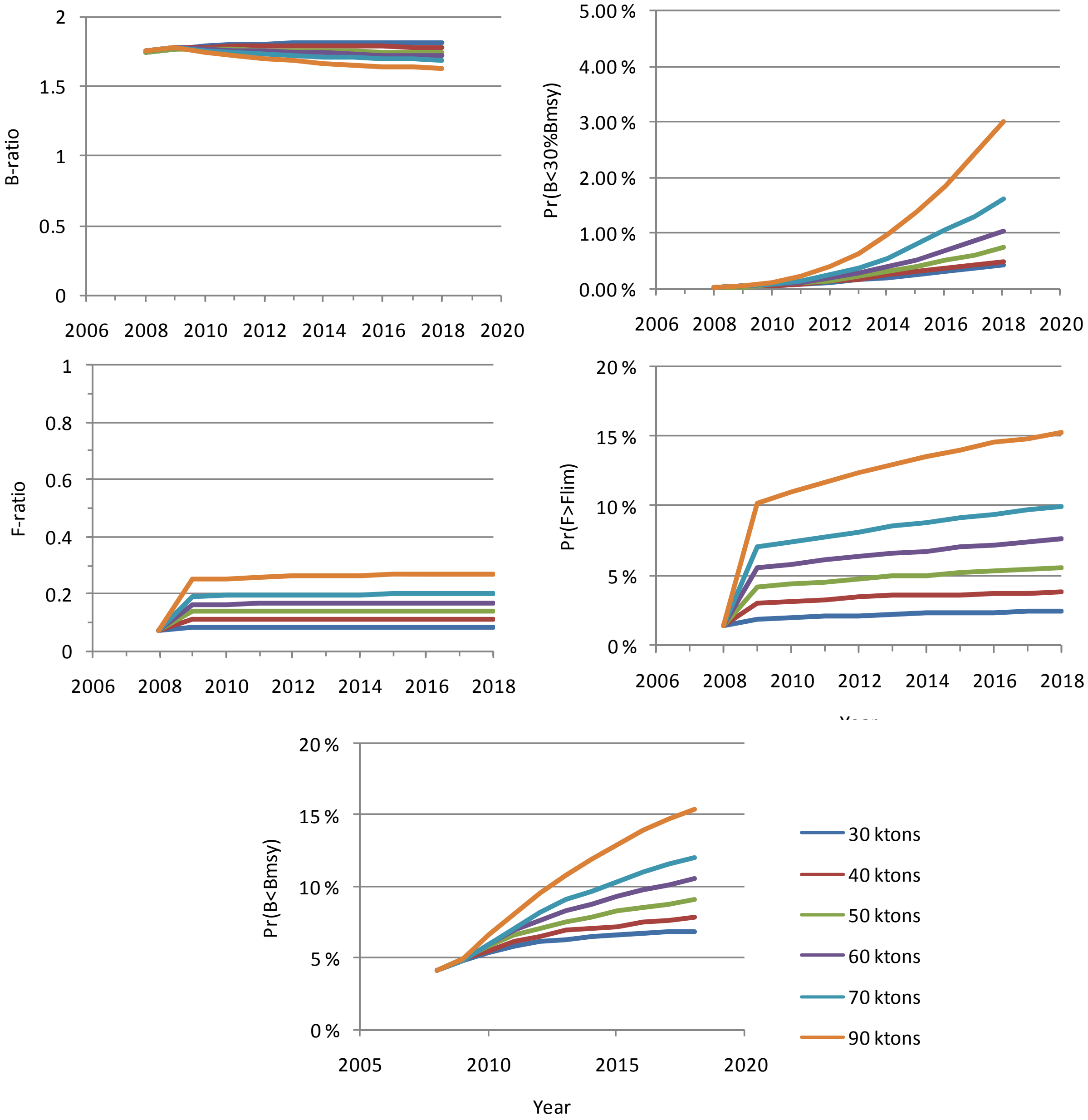

Fig. 9. Projections (*left*): Medians of estimated posterior biomass ratios and fishing mortality ratios; estimated risk (*right and below*) of exceeding F_{msy} and F_{lim} ($1.7F_{msy}$) or going below and B_{lim} given a range of 30 to 90 ktons catch options

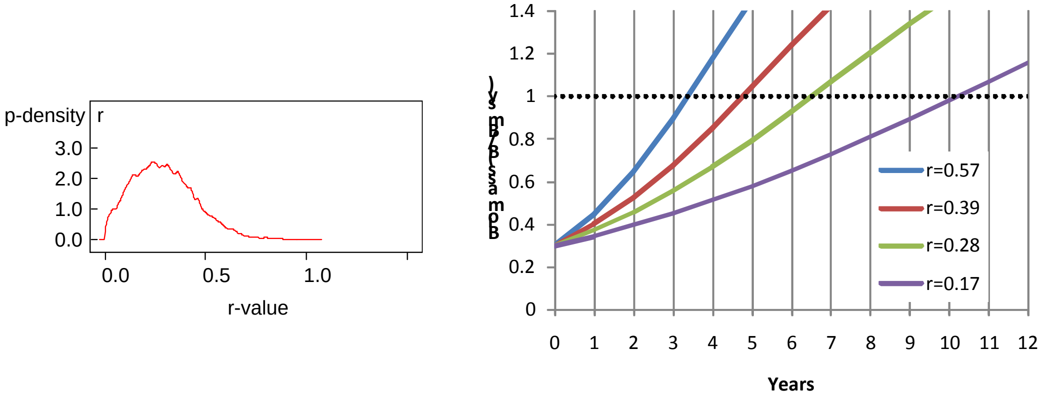

Fig. 10. *Left*:The posterior probability density distribution of r, the intrinsic rate of growth. Right: estimated recovery time from Blim (0.3Bmsy) to Bmsy (relative biomass = 1) given r values ranging within the 95% conf. lim. of the posterior (left figure) and no fishing mortality.