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Towards a Quantitative Assessment Framework for 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. The inclusion of an explicit predation effect by cod was considered, but even though estimates of shrimp consumption by cod was on average 5 times that of the catches this effect was weakly correlated with dynamics of the shrimp stock. Seemingly, scaling as well as variation originating from an underlying spatial structure of the estimates of shrimp stock size and consumption by cod needs to be resolved before this effect can be included.

Estimated stock biomass has increased since 2004. 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 159 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 current advised catch level of 40 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 30 000-130 000 tons.

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 is 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. Such methods lack predictive rigour, including formal statements of uncertainty, and are therefore not suited for quantitative comparisons between alternative management options (Hvingel and Kingsley, 2006).

This paper presents the construction of a quantitative assessment framework for the Barents Sea stock based on the work of Hvingel and Kingsley (2002, 2006) who derived the model adopted by STACFIS and Scientific Council (NAFO) in 2002 for West Greenland shrimp stock.

Short-term (1-year) and medium-term (five- ten-year) projections of stock development were made for different levels of annual catch and the associated risks of transgressing the reference parameters B_{msy} (maximum sustainable yield level of biomass), F_{msy} (fishing mortality) and B_{lim} (lower stock biomass limit point set at 30% of B_{msy}) were estimated.

Model Development

Information in data

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, the quantitative implementation of this observation in an assessment model might not be straightforward.

The correlation between estimated consumption in a year (Aschan *et al*., 2006) and the change in shrimp stock biomass from that year to the next (survey estimates) are indeed negative however not without considerable residual variation (Fig. 1A). If the change in shrimp stock biomass is measured over 2 or 3 years (Fig. 1B and 1C) the correlation is stronger and somewhat less noisy. This might imply that the cod is eating "smaller" shrimp i.e. the shrimp that doesn’t contribute notably to the stock biomass until they have grown 2-3 years older. Although this is biologically plausible it could not be confirmed by data from the cod stomach samples.

Total cod biomass is not correlated with changes in shrimp biomass (Fig. 1D) – not even when lagged 2-3 year as suggested by the consumption data. A probable reason could be that smaller cod, which is of lesser importance for the bulk cod biomass, is the most important predator. Then of course, large cod biomass should mean lots of smaller cod some years ago but that couldn’t bee seen in the data either. However, comparing small cod abundance (age 3) directly with the shrimp stock biomass changes to the next year showed a significant negative correlation – still negative when lagged 2 years (however not significant), but no correlation when lagged 3 years.

The estimates of annual consumption by cod have a mean of 250 Ktons while that of the catches is 50 Ktons. Thus one might suspect that the effect of the fishery to be swamped by the predation effect. However, that does not seem to be the case. Changes in shrimp stock biomass are negatively correlated with catch (Fig. 1E). The paradox of the "small" catches having an effect while the "large" cod consumption does not might be caused by a spatial effect. A large part of the estimated consumption stems from large areas of low shrimp density i.e. outside the areas where the fishery operates – and where the shrimp survey measures stock size. Thus the effect of a major part of the consumptions might not be measured whereas all the effect of the catches are recorded as the survey and fishery are both focused on the high density areas.

Conclusions

- The fishery does have an effect on the stock in areas covered by the shrimp survey.
- Even though the estimates of consumption by cod is on average 5 times that of the catches and range from 160-450 ktons (in 1994-2004) the correlation with changes in the size of the shrimp stock is weaker than that of the catches.
- The lack of correlation to the between the size of the cod and shrimp stocks can currently not be explained.

Available consumption data and information on cod stock dynamics does 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 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) $$\begin{aligned} CPUE_t &= q_C B_{MSY} P_t \exp(\omega_t) \\ survR_t &= q_R B_{MSY} P_t \exp(\kappa_t) \\ survE_t &= q_E B_{MSY} P_t \exp(\varepsilon_t) \end{aligned}$$

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 2 500 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 2 500 ktons and 95% confidence limits at 800 and 8 000 ktons (Table 2).

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:

$$F\mathrm{ratio}_t = \frac{F_t}{F_{MSY}} = \frac{-\ln\left(\frac{B_t - C_t)}{B_t}\right)}{\frac{MSY}{B_{MSY}}}$$

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. 2). After 50 stored iterations the sampler had converged to the target distribution (Fig. 3) leaving 9950 samples for each parameter for the final analysis.

The model was able to produce a reasonable simulation of the observed data (Fig. 4). The probabilities of getting more extreme observations than the realised ones given in the data series on stock size were in the range of 0.04 to 0.5 i.e. the observations did not lie in the tails of their posterior distributions (Table 4). The CPUE series was generally better estimated than the survey series. In particular the 2004-value for survey 1 – suggested by a low CPO and large residual (Table 4) to be a relatively poor fit to the model – was interpreted as being to pessimistic. 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. 5). 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. 6).

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. 6) except for a slight increase in uncertainty (Fig.7). 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 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. 8) and the probability that it had been below the optimum level was small for most years (Fig. 9), i.e. it seemed likely that the stock had been at or above its MSY level since the start of the fishery. This perception still stands when the prior for *K* is changed

(Fig. 7) – even towards low ranges not considered plausible by shrimp experts. The 2006 biomass value is among the highest of the series.

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 2006 estimated to be close to K. The estimated risk of stock biomass being below B_{MSY} in 2006 was 4% (Fig. 9).

The median fishing mortality ratio (*F-ratio*) has been well below 1 throughout the series (Fig. 8). However, as this parameter can only be estimated with relatively large uncertainty (Fig. 10) there is some probability that the stock was fished above F_{msy} (Fig. 9). Since 2003 there has been les than 8% risk of the *F-ratio* being above 1 (Fig. 9).

The posterior for *MSY* was positively skewed with a mode at 95 ktons (Fig. 5) and upper and lower quartiles at 91 ktons and 282 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 2005 TAC of 40 ktons.

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 2007 are as follows:

Catch option (ktons)	30	50	70	90	110	130
Risk of falling below B_{lim}	<1%	<1%	<1%	<1%	<1%	1 %
Risk of falling below B_{MSY}	4 %	4 %	5 %	5 %	5 %	6 %
Risk of exceeding F_{MSY}	2 %	4 %	8 %	12 %	17 %	21 %

The risk profile associated with ten-year projections of stock development assuming annual catch of 50, 70 and 90 ktons 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). However, it is less certain that these catch levels can be sustained in the longer term. 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).

A catch options of 50 ktons – 10 ktons above the advised maximum catch level for 2006 (ACFM, 2005), but at what is estimated to be the realised catches of 2006 – has 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}
- The stock may likely sustain catches considerably higher than the 2005 advice of 40 ktons.
- Catch options of 50-90 ktons are not likely to drive the stock below optimum levels in the short term.

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 (1970-2006), 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.

Changes in temperature, salinity, and large-scale water movements have been observed in the North Atlantic over the past few years (ICES, 2006). 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.The bottom temperatures were between approx. 0.3 and 1.3 higher in autumn 2006 than in autumn 2005 in most of the Barents Sea except in the northern and eastern parts, where waters were colder than in 2005. The water temperature at depths of 100 and 200 m was in general higher in 2006 than in 2005 in most of the survey area.

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	0.767	-	-
1981	44.6	0.890	-	-
1982	62.8	0.845	327	-
1983	104.8	0.963	429	-
1984	128.1	1.006	471	-
1985	124.5	0.799	246	-
1986	65.3	0.482	166	-
1987	43.4	0.365	146	-
1988	48.7	0.400	181	-
1989	62.7	0.522	216	-
1990	81.2	0.522	262	-
1991	74.9	0.551	321	-
1992	68.6	0.634	239	-
1993	56.3	0.678	233	-
1994	28.3	0.536	161	-
1995	25.2	0.472	193	-
1996	34.5	0.606	276	-
1997	35.7	0.594	300	-
1998	55.8	0.716	341	-
1999	75.7	0.731	316	-
2000	83.2	0.656	247	-
2001	57.0	0.659	184	-
2002	60.7	0.650	196	-
2003	39.3	0.645	212	-
2004	43.4	0.577	151	129
2005	41.3	0.841	-	145
2006	0.0	1.000	-	188

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(0.1,0.1)
Precision survey 2	$1/\sigma_E{}^2$	reference	~dgamma(0.1,0.1)
Precision CPUE	$1/\sigma_C{}^2$	reference	~dgamma(0.1,0.1)
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	0.57	1	-0.58	-0.58	-0.20	0.00	0.00	0.00	0.00	0.08
q_R	-0.48	-0.58	1	0.98	0.09	-0.05	-0.04	0.00	0.03	-0.08
q_E	-0.49	-0.62	0.98	1	0.08	-0.05	-0.02	0.00	0.00	-0.08
q_C	0.54	-0.20	0.09	0.08	1	-0.03	-0.02	0.01	0.08	0.07
P_1	-0.01	0.00	-0.05	-0.05	-0.03	1	0.00	0.00	0.00	0.02
σ_R	0.00	0.00	-0.04	-0.02	-0.02	0.00	1	-0.04	-0.18	-0.12
σ_E	0.01	0.00	0.00	0.00	0.01	0.00	-0.04	1	0.00	0.05
σ_C	0.05	0.00	0.03	0.00	0.08	0.00	-0.18	0.00	1	0.11
σ_P	0.12	0.08	-0.08	-0.08	0.07	0.02	-0.12	0.05	0.11	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	3.34	0.44	1.84	-	-	-	-	-	-
1981	-2.65	0.43	1.84	-	-	-	-	-	-
1982	2.51	0.45	2.48	2.33	0.46	0.56	-	-	-
1983	2.24	0.46	2.16	-11.29	0.27	0.32	-	-	-
1984	-0.27	0.48	1.91	-17.72	0.16	0.20	-	-	-
1985	-9.69	0.26	1.36	13.43	0.28	0.55	-	-	-
1986	0.12	0.49	4.45	12.31	0.29	0.86	-	-	-
1987	9.10	0.31	3.79	5.36	0.41	1.20	-	-	-
1988	9.39	0.30	3.73	-6.54	0.36	0.92	-	-	-
1989	1.22	0.48	4.13	-5.47	0.38	0.80	-	-	-
1990	10.59	0.28	2.56	-14.78	0.21	0.42	-	-	-
1991	14.19	0.22	1.50	-24.27	0.09	0.17	-	-	-
1992	-0.67	0.47	3.45	1.87	0.48	0.78	-	-	-
1993	-7.55	0.30	2.12	3.92	0.43	0.77	-	-	-
1994	-4.04	0.39	3.54	23.43	0.16	0.50	-	-	-
1995	8.10	0.32	3.46	2.16	0.47	0.96	-	-	-
1996	3.59	0.42	3.36	-12.04	0.26	0.47	-	-	-
1997	12.05	0.25	1.88	-14.23	0.22	0.38	-	-	-
1998	5.37	0.39	2.61	-14.51	0.21	0.33	-	-	-
1999	2.15	0.46	2.87	-8.71	0.32	0.49	-	-	-
2000	0.42	0.50	3.29	3.15	0.45	0.74	-	-	-
2001	-8.73	0.29	1.82	26.33	0.14	0.37	-	-	-
2002	-7.61	0.30	2.30	18.35	0.21	0.55	-	-	-
2003	-6.47	0.33	2.51	10.04	0.33	0.74	-	-	-
2004	-1.24	0.46	3.69	45.88	0.03	0.16	-8.06	0.33	0.97
2005	-9.01	0.29	1.32	-	-	-	9.71	0.34	0.93
2006	-7.99	0.31	1.13	-	-	-	1.70	0.47	0.87

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	213	171	91	159	282
K	3144	1963	1743	2693	4003
r	0.291	0.160	0.170	0.278	0.394
q_R	0.168	0.139	0.078	0.126	0.211
q_E	0.091	0.077	0.042	0.068	0.114
q_C	0.00044	0.00036	0.00020	0.00033	0.00055
P_1	1.50	0.26	1.33	1.50	1.68
σ_R	0.183	0.031	0.161	0.179	0.201
σ_E	0.173	0.046	0.142	0.165	0.195
σ_C	0.133	0.023	0.116	0.130	0.146
σ_P	0.207	0.036	0.181	0.203	0.228

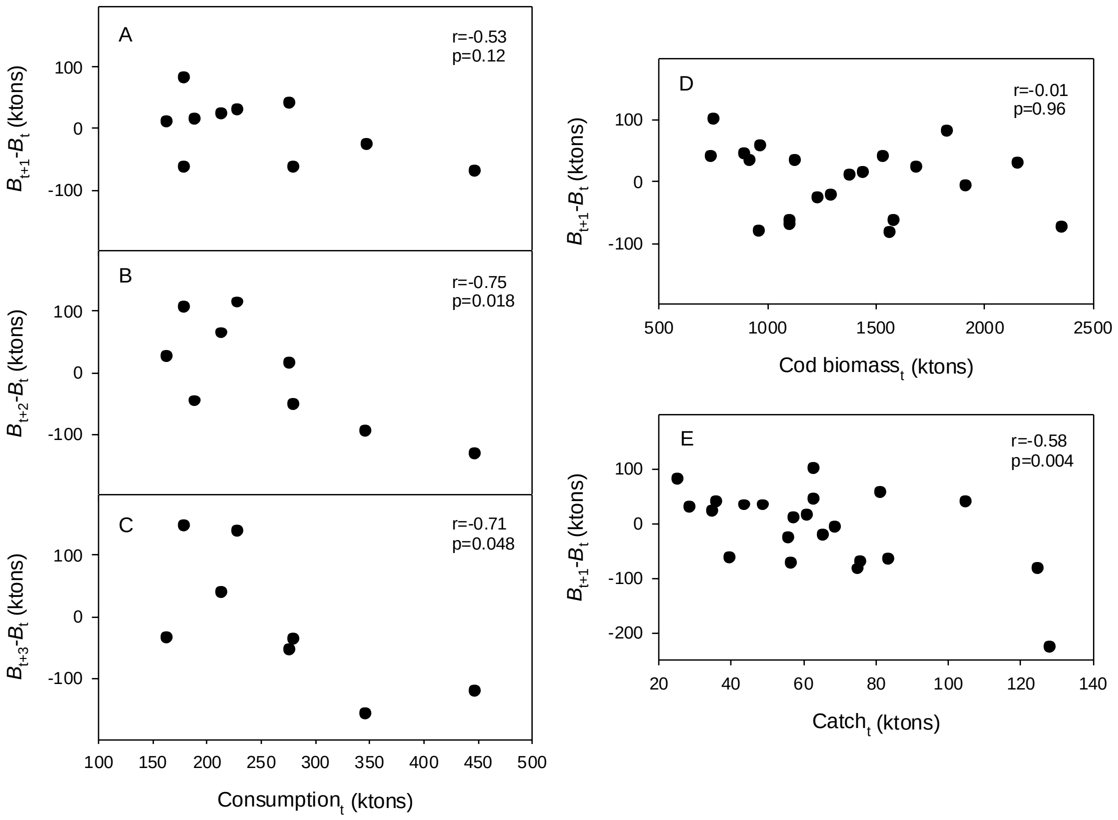

Fig. 1. Estimated consumption of shrimp by cod (A-C), cod biomass (D) and catch (E) *vs.* change in shrimp stock biomass (survey estimates). *r* is the correlation and p is probability of the slope being different from zero.

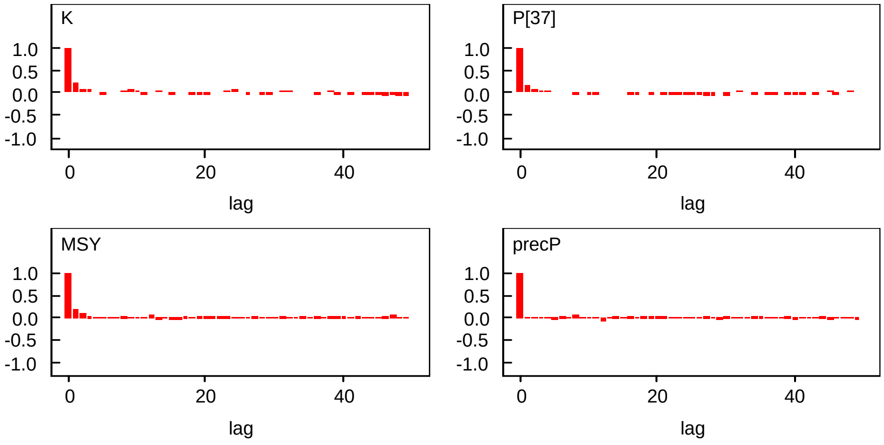

Fig. 2. Autocorrelation function of values sampled for four selected variables out to lag 50. *K* is the carrying capacity, P[37] is the relative biomass in year 2006, MSY is maximum sustainable yield and precP is the process precision (1/ process error).

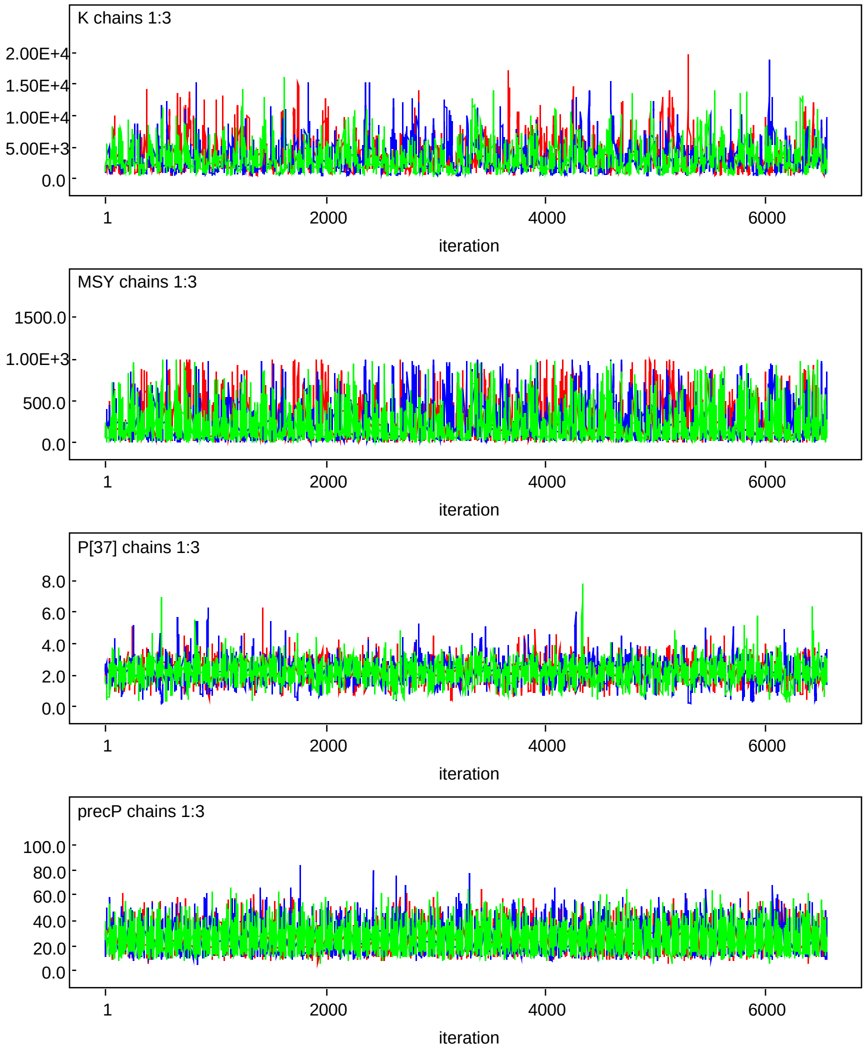

Fig. 3. Three traces (red, green, blue) with different initial values of dour selected variables. *K* is the carrying capacity, P[37] is the relative biomass in year 2006, MSY is maximum sustainable yield and precP is the process precision (1/ process error).

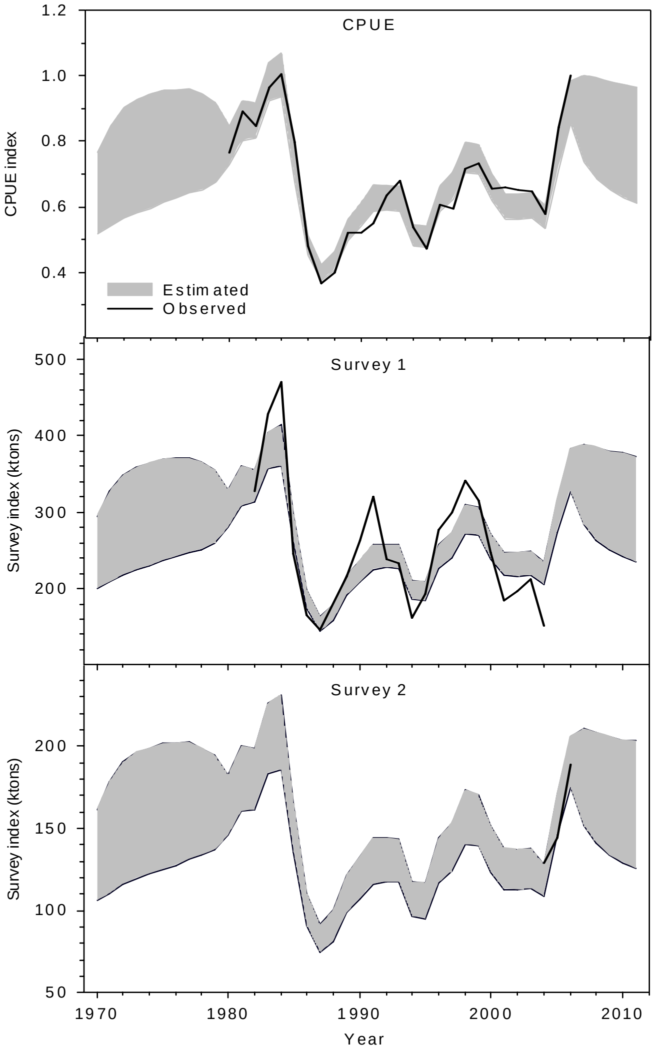

Fig. 4. Observed (solid line) and estimated (shaded) series of the biomass indices derived by standardising commercial vessel catch-per-unit-effort (CPUE), the 1982-2004 shrimp survey and the Ecosystem survey since 2004. Gray shaded areas are inter-quartile range of the posteriors. The projection forward assumes annual catches at 50 ktons.

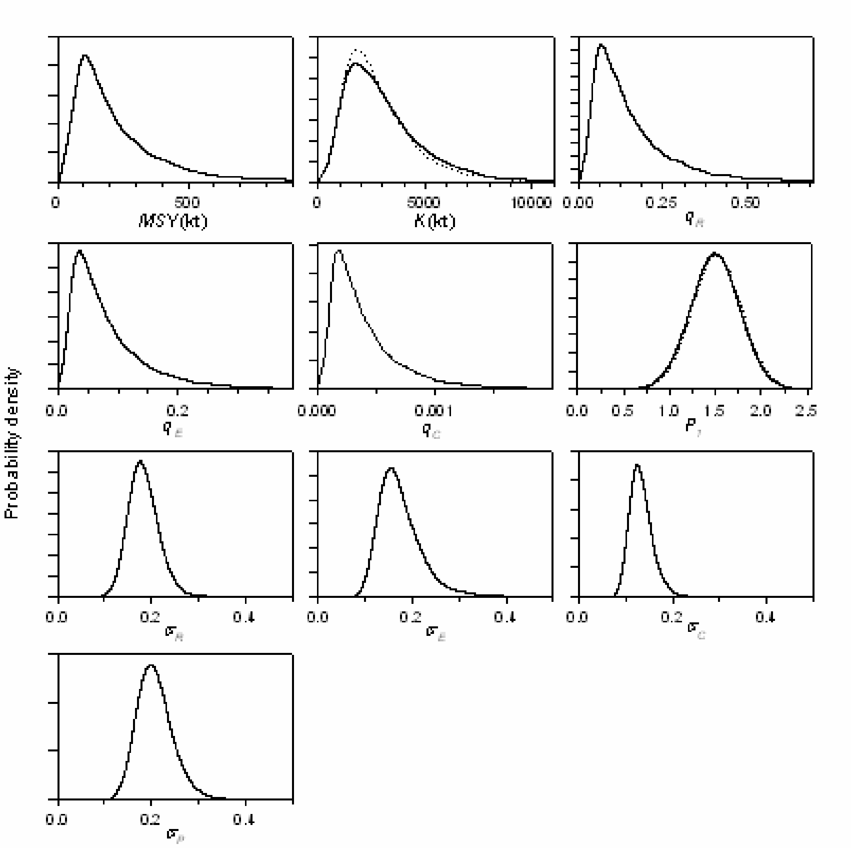

Fig. 5. Probability density distributions of model parameters: estimated: posterior (solid line) and prior (broken line) distributions (only informative priors are shown).

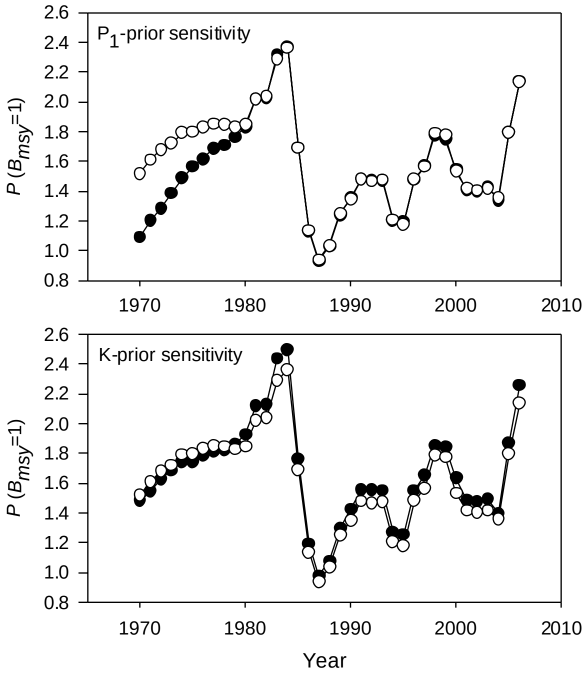

Fig. 6. Median relative biomass, *P*, 1970-2006. Open dotted series as estimated from the model used. Series with closed dots was given low informative priors: upper panel P_1~dunif(0,2), lower panel K~dunif(1,10000).

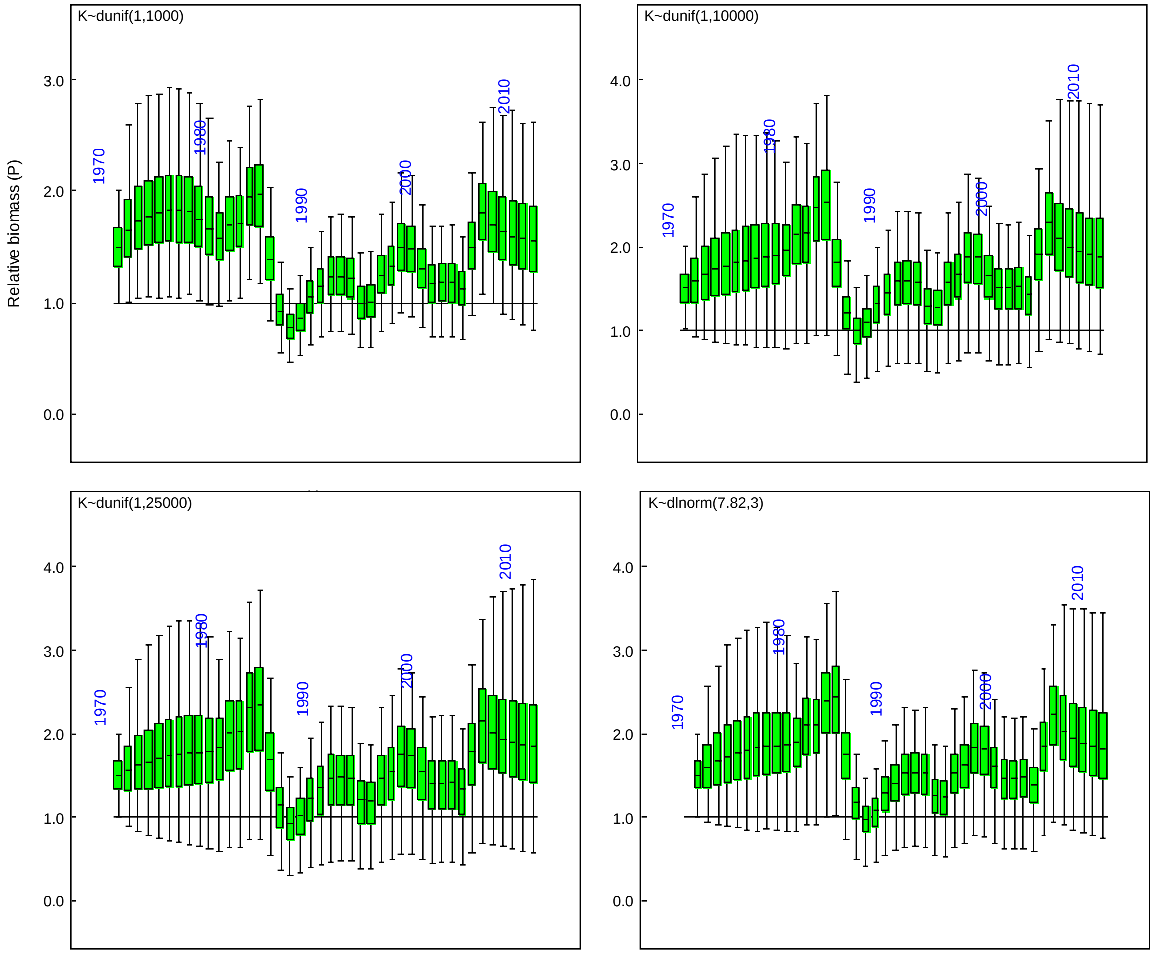

Fig. 7. Shrimp in the Barents Sea: Sensitivity of estimated stock sizes to changes in the prior for *K* (carrying capacity). $P_t=B_t/B_{msy}$ i.e. relative biomass. K~dunif(1,1000) means that the prior for *K* was uniform distributed between 1 and 1 000 ktons; K~dlnorm(7.82,3) means lognormal distributed with median exp(7.82) and precision 3 and *vise versa*. The 2006-2011 catches are assumed at 50 ktons. 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.

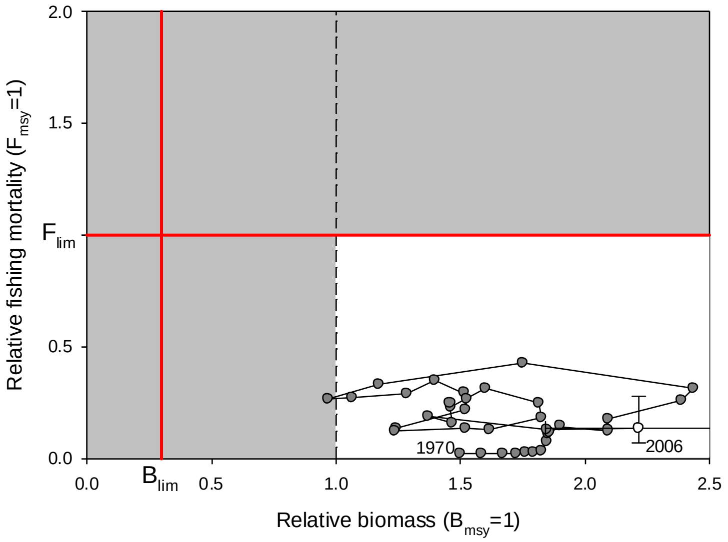

Fig. 8. Shrimp in the Barents Sea: estimated annual median biomass-ratio (B/B_{MSY}) and fishing mortality-ratio (F/F_{MSY}) 1970-2006. The reference points for stock biomass, B_{lim}, and fishing mortality, F_{lim}, are indicated by red lines.

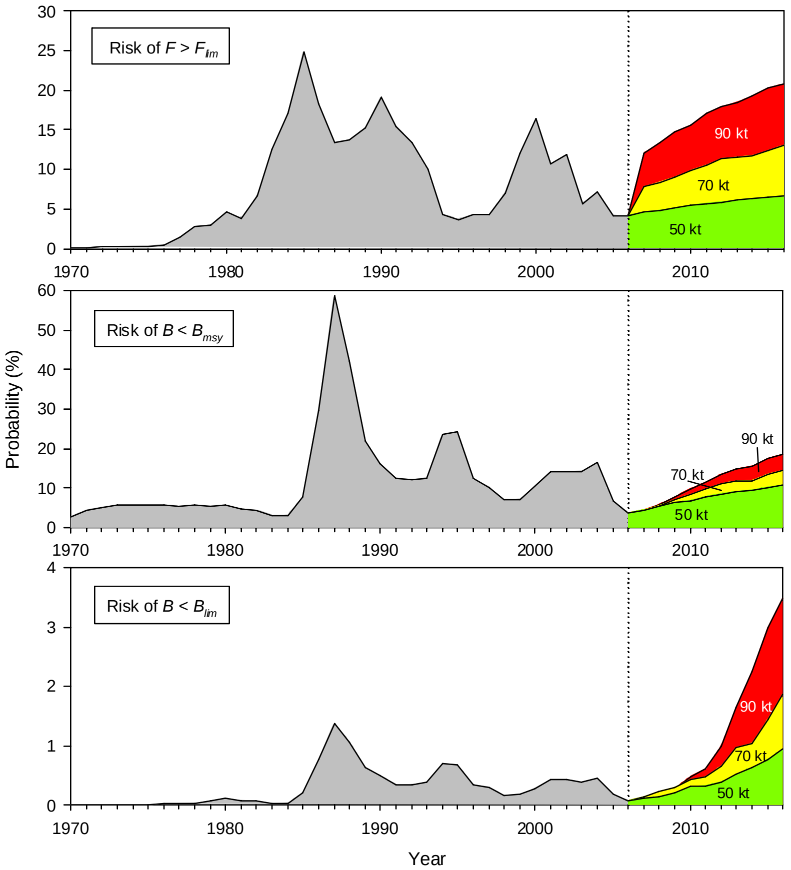

Fig. 9. Risk profiles: Estimated risk of exceeding F_{lim} (upper panel) or going below B_{msy} (middle panel) and B_{lim} (lower panel) for the historic period 1970-2005 (greyed area) and future (coloured area) until 2016. Projections are shown for 3 optional catches 50 (green), 70 (yellow) and 90 ktons/yr (red).

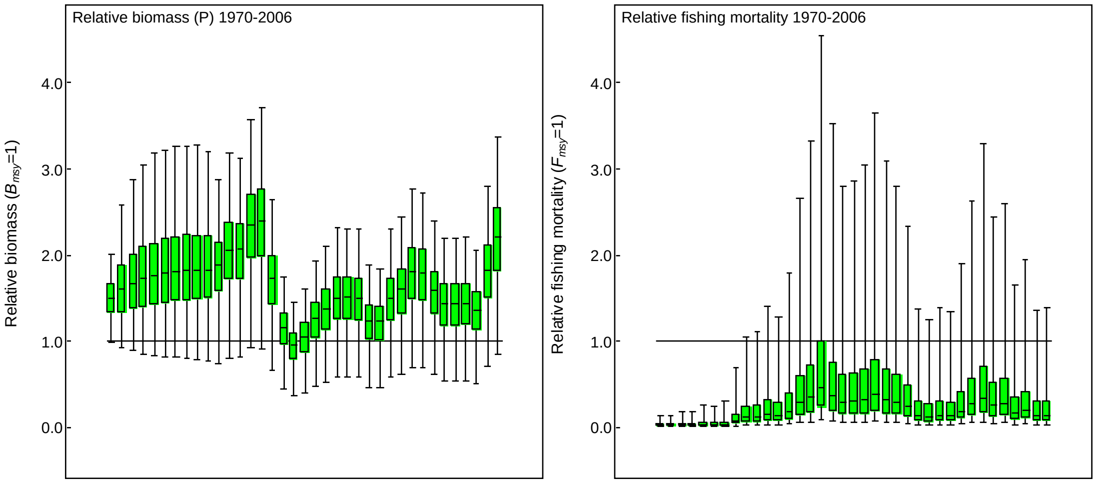

Fig. 10. Shrimp in the Barents Sea: Estimated relative biomass ($P=B_t/B_{msy}$) and fishing mortality (F_t/F_{msy}) 1970-2006. Boxes represent inter-quartile ranges and the solid black line at the (approximate) centre of each box is the median; the arms of each box extend to cover the central 95 per cent of the distribution.