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Shrimp (*Pandalus borealis*) in the Barents Sea – Stock assessment 2011

by

Carsten Hvingel
Institute of Marine Research
Box 6404, N-9294 Tromsø, Norway

Abstract

An assessment of the Barents Sea stock of *Pandalus borealis* was performed based on the logistic stock-production model and Bayesian inference. The fishery effect was modelled explicitly while other mortality was included in the parameter for overall realised population growth rate, r, and habitat carrying capacity, k.

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 60 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 and conclusions of this year's assessment are similar to those of 2006 to 2011.

Introduction

The resource of northern shrimp (*Pandalus borealis*) is distributed throughout most of the Barents Sea and round Svalbard (Fig. 1). 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 22-128 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 allocated fishing 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 assessment modelling framework states stock status and predictions in probabilistic terms relative to the Precautionary Approach (PA) framework– and MSY (Maximal Sustainable Yield) framework reference points.

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 1980–2009, $CPUE_t$, (Hvingel and Thangstad 2008); and two trawl-survey biomass index for 1982–2004, $survR_t$, (Anon. 2005a) and 2004-2009, $survE_t$ (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 1970-2009 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:

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

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.

Reference points

There are 3 reference points to be considered in relation to ICES type advice: F_{msy}, $B_{trigger}$ and B_{lim}, see Hvingel (2010) for some discussion of these in relation to the Barents Sea shrimp stock.

Changes from the 2010 assessment

This assessment is an update of the 2010 assessment with the following changes:

- Model: No changes.
- Priors: No changes.
- Input data: No changes.

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 0.07 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 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. 5). The prior for the "initial" shrimp stock biomass (P_0) was slightly informative giving credit to "virgin 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 (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 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 12%. The process error, σ_p, had a median of 19%.

Assessment results

Since 1970, 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 and the median estimate of biomass-ratio went close to Bmsy (Fig. 7). Since the late 1990s the stock has varied with a slightly increasing trend. The median 2011 level is at K. The estimated risk of stock biomass being below B_{MSY} in 2011 was 2% (Table 6).

The median fishing mortality ratio (*F-ratio*) has been well below 1 throughout the series (Fig. 8). In 2011 there is a low 1% risk of the F being above Fmsy (Table 6). Thus, in a single stock biomass/exploitation context within the PA framework the fishing mortality is low and stock biomass is high, well away from limit references (Fig. 9).

The posterior for *MSY* was positively skewed with a mode at 100 ktons (Fig. 4) and upper and lower quartiles at 112 ktons and 329 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 95% that *MSY* is higher than the recent quota recommendations of 60 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 2012 are given in Table 6.

Assuming a catch of 23 kt for 2011, catch options up to 60 kt for 2012 have a low risk (<5%) of exceeding FMSY (Table 6) and is likely to maintain the stock at its current high level.

The risks associated with ten-year projections of stock development assuming annual catch of 30 000 to 90 000 t were investigated (Fig. 10). For all options the risk of the stock falling below B_{MSY} in the short to medium term (1-5 years) is low (<10%) and all of these catch options result in a probability of less than 5% of going below $B_{trigger}$ over a 10 year period (Fig. 10). Catch options up to 60 000 t, have a low risk (<5%) of exceeding F_{MSY} in the short term (Fig. 10).

Taking 90 000 t/yr will increase the risk of going below B_{MSY} to more than 10% during the ten years of projection (Fig. 10). However, the risk of going below $B_{trigger}$ remains under 5%. The risk that catches of this magnitude will not be sustainable (prob(F >FMSY)) in the longer term increase as compared to the 60 000 t option but is still below 15% after ten years.

Yield predictions can be made for various levels of fishing mortalities (e.g. at target fishing mortality=F_{MSY}) but such estimates have high uncertainties as absolute biomass can only be estimated with relatively high variances (see section on “estimation of parameters”) and therefore such point estimates should be interpreted with caution. Instead we estimate yield at risk level of exceeding the target of FMSY (Table 7) and managers may pick their preferred risk level from this.

Conclusions:

Mortality. The fishing mortality has been below F_{msy} throughout the exploitation history of the stock. The risk that F will exceed F_{msy} in 2011 is estimated to be less than 1%.

Biomass. The stock biomass estimates have been above B_{msy} throughout the history of the fishery. Biomass at the end of 2011 is estimated to be well above $B_{trigger}$.

Recruitment. Recruitment indices have decreased from 2004 to 2007-2008 but were higher in 2009 to 2011

State of the Stock. The Stock is estimated to be close to the carrying capacity. The risk of stock biomass being below $B_{trigger}$ and fishing mortality above F_{msy} at end 2011 is less than 1%.

Yield. A catch option of up to 68 000 t for 2012 would have less than 5% risk of exceeding F_{msy}. Catch options up to 60 000 t/yr, have a low risk (<5%) of exceeding F_{msy} in the coming 3 years. At a higher risk tolerance larger yield may be achieved.

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. 12 *left*). Thus without fishery it would take 3-10 years to rebuild the stock from Blim to Bmsy (Fig. 12 *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 large amounts of shrimp. 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.

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

Temperatures in the Barents Sea have been high during the last eight years, mostly due to the inflow of warm water masses from the Norwegian Sea. The summer temperatures decreased in 2007 and 2008, but the temperatures in late winter 2008 (March) were record-high in the western Barents Sea. However, as the Atlantic inflow in late March and April was well below average, the typical temperature increase in spring did not occur in 2008. In summary the climatic situation in the Barents Sea has been somewhat extraordinary in 2008. The low temperatures in spring may have increased the mortality of young shrimp.

In 2010, temperatures close to the bottom were in general slightly lower than in 2009, but still above the long-term mean by 0.1-0.6°C in most of the surveyed area (Anon. 2010). Only small areas with temperatures below 1°C were observed. Shrimps were only caught in areas where bottom temperatures were above 0°C. Highest shrimp densities were found between zero and 4°C, while the limit of upper temperature preference appeared to lie at about 6-8°C. The wedge of cold near-zero degrees water observed in 2009 in the central Barents Sea, which appeared to drive the distribution of shrimps more easterly, has in 2010 shifted/decreased, allowing for increased presence of shrimps in central shelf areas again

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Table 1. Model input data series: Catch by the fishery; three indices of fishable biomass – a standardized catch rate index based on fishery data (CPUE), a research survey index discontinued in 2004 (Survey 1) and the current survey started in 2004 (Survey 2).

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	1.194	-	-
1982	62.8	1.150	327	-
1983	104.8	1.306	429	-
1984	128.1	1.382	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	0.903	239	-
1993	56.3	0.974	233	-
1994	28.3	0.801	161	-
1995	25.2	0.669	193	-
1996	34.5	0.839	276	-
1997	35.7	0.800	300	-
1998	55.8	0.969	341	-
1999	75.7	1.019	316	-
2000	83.2	0.901	247	-
2001	57.5	0.909	184	-
2002	61.5	0.896	196	-
2003	38.0	0.879	212	-
2004	41.3	0.751	151	261
2005	41.4	1.040	-	446
2006	29.5	1.141	-	517
2007	29.3	1.021	-	426
2008	26.5	1.043	-	317
2009	23.6	1.065	-	343
2010	20.9	0.989	-	482
2011	23.0	1.105	-	442

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_0	informative	~dlnorm(0.6,25)
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_0	σ_R	σ_E	σ_C	σ_P
K	0.60	1								
q_R	-0.51	-0.65	1							
q_E	-0.49	-0.63	0.97	1						
q_C	-0.51	-0.66	0.98	0.98	1					
P_0	-0.01	-0.01	-0.02	-0.03	-0.02	1				
σ_R	-0.01	0.01	-0.01	-0.02	-0.02	0.00	1			
σ_E	0.00	0.01	-0.01	-0.01	-0.01	0.00	-0.05	1		
σ_C	0.03	-0.01	0.01	0.03	0.01	-0.01	-0.16	0.02	1	
σ_P	0.11	0.07	-0.10	-0.08	-0.11	-0.01	-0.11	0.07	0.07	1

Table 4. Model diagnostics: residuals (% of observed value) and probability of getting a more extreme observation (Pr).

	CPUE		Survey 1		Survey 2	
Year	resid (%)	Pr	resid (%)	Pr	resid (%)	Pr
1980	3.99	0.42	-	-	-	-
1981	-2.97	0.59	-	-	-	-
1982	2.59	0.45	0.49	0.50	-	-
1983	2.27	0.45	-13.29	0.77	-	-
1984	-0.65	0.53	-18.82	0.85	-	-
1985	-11.02	0.79	15.35	0.25	-	-
1986	0.75	0.49	14.60	0.25	-	-
1987	7.03	0.33	8.82	0.35	-	-
1988	7.96	0.32	-4.82	0.60	-	-
1989	1.71	0.46	-5.32	0.62	-	-
1990	9.35	0.29	-14.45	0.79	-	-
1991	12.70	0.23	-23.93	0.92	-	-
1992	-1.55	0.55	3.59	0.43	-	-
1993	-8.43	0.73	6.62	0.38	-	-
1994	-6.75	0.69	29.21	0.11	-	-
1995	7.80	0.31	4.07	0.43	-	-
1996	3.24	0.44	-12.60	0.76	-	-
1997	13.09	0.22	-16.02	0.81	-	-
1998	5.87	0.37	-16.21	0.82	-	-
1999	1.39	0.47	-8.95	0.68	-	-
2000	0.96	0.48	2.57	0.45	-	-
2001	-7.89	0.71	26.73	0.13	-	-
2002	-7.14	0.70	18.23	0.21	-	-
2003	-6.46	0.68	8.02	0.36	-	-
2004	-3.13	0.59	34.20	0.07	11.89	0.29
2005	-2.28	0.56	-	-	-8.58	0.69
2006	0.21	0.50	-	-	-11.27	0.74
2007	2.10	0.45	-	-	-1.80	0.55
2008	-7.10	0.69	-	-	22.64	0.15
2009	-5.41	0.65	-	-	13.23	0.26
2010	8.69	0.30	-	-	-14.08	0.79
2011	-0.15	0.51	-	-	-2.65	0.57

Table 5. **S**ummary 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)	246	183	112	195	329
K (ktons)	3196	1804	1849	2782	4100
r	0.32	0.16	0.21	0.31	0.42
q_R	0.14	0.11	0.07	0.11	0.18
q_E	0.20	0.15	0.10	0.16	0.25
q_C	5.1E-04	3.8E-04	2.5E-04	4.0E-04	6.3E-04
P_0	1.50	0.26	1.33	1.50	1.68
P_{2011}	2.02	0.54	1.68	1.98	2.31
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	0.12	0.14
σ_P	0.19	0.03	0.17	0.19	0.21

Table 6. Stock status and short term predictions. *Upper*: stock status for 2009 of 2011. *Lower*: predictions for 2012 given catch options ranging from 30 to 90 ktons

Status	2010	2011*
Risk of falling below B_{lim} ($0.3B_{MSY}$)	0.0 %	0.0 %
Risk of falling below *Btrig* ($0.5B_{MSY}$)	0.1 %	0.1 %
Risk of falling below B_{MSY}	1.7 %	2.1 %
Risk of exceeding F_{MSY}	0.7 %	0.8 %
Risk of exceeding $1.7F_{MSY}$	0.4 %	0.4 %
Stock size (B/Bmsy), median	2.07	1.98
Fishing mortality (F/Fmsy), median	0.05	0.06
Productivity (% of MSY)	-15 %	3 %

*Predicted catch = 23ktons

Catch option 2012 (ktons)	30	40	50	60	70	90
Risk of falling below B_{lim} ($0.3B_{MSY}$)	0.0 %	0.0 %	0.0 %	0.0 %	0.0 %	0.1 %
Risk of falling below *Btrig* ($0.5B_{MSY}$)	0.2 %	0.2 %	0.2 %	0.2 %	0.2 %	0.2 %
Risk of falling below B_{MSY}	2.5 %	2.6 %	2.7 %	3.0 %	2.9 %	3.1 %
Risk of exceeding F_{MSY}	1.3 %	2.1 %	3.1 %	4.4 %	5.5 %	8.7 %
Risk of exceeding $1.7F_{MSY}$	0.6 %	0.9 %	1.4 %	1.8 %	2.5 %	3.7 %
Stock size (B/Bmsy), median	1.93	1.92	1.92	1.91	1.89	1.89
Fishing mortality (F/Fmsy),	0.08	0.11	0.13	0.16	0.19	0.24
Productivity (% of MSY)	13 %	15 %	16 %	18 %	21 %	21 %

Table 7 Northern shrimp (*Pandalus borealis*) in Subareas I and II (Barents Sea). Predictions of yield ('000 t) at different levels of risk of exceeding F_{MSY}.

	Risk of exceeding F_{msy}				
Year	2.5 %	5 %	10 %	25 %	50 %
2012	43	68	98	181	321
2013	44	65	97	180	318
2014	42	62	91	165	286
2015	41	60	88	152	264
2016	39	58	84	142	247
2017	38	55	80	136	235
2018	38	53	76	130	229
2019	36	53	73	125	223
2020	36	51	71	121	216
2021	36	51	72	120	213

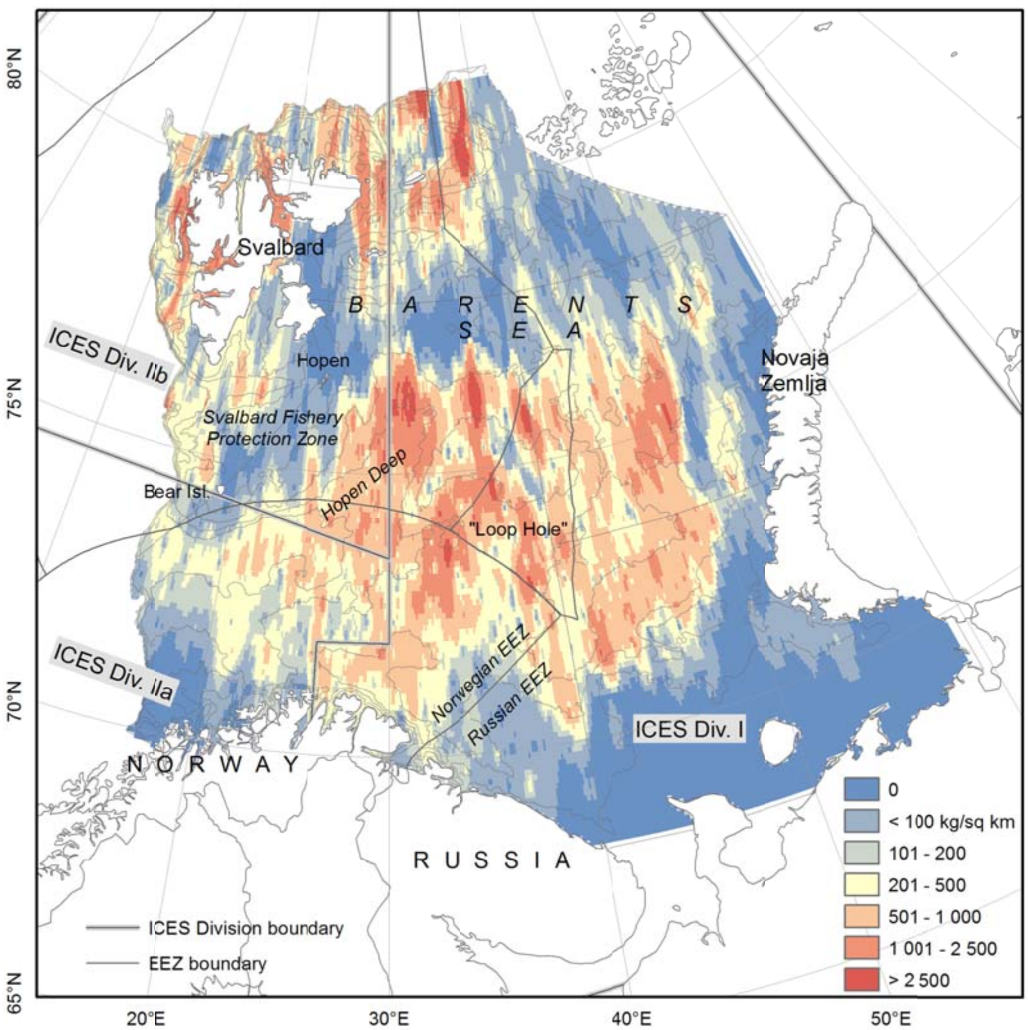

Fig. 1. Shrimp in the Barents Sea: stock distribution mean density (kg/km^2) based on survey data 2000-2010.

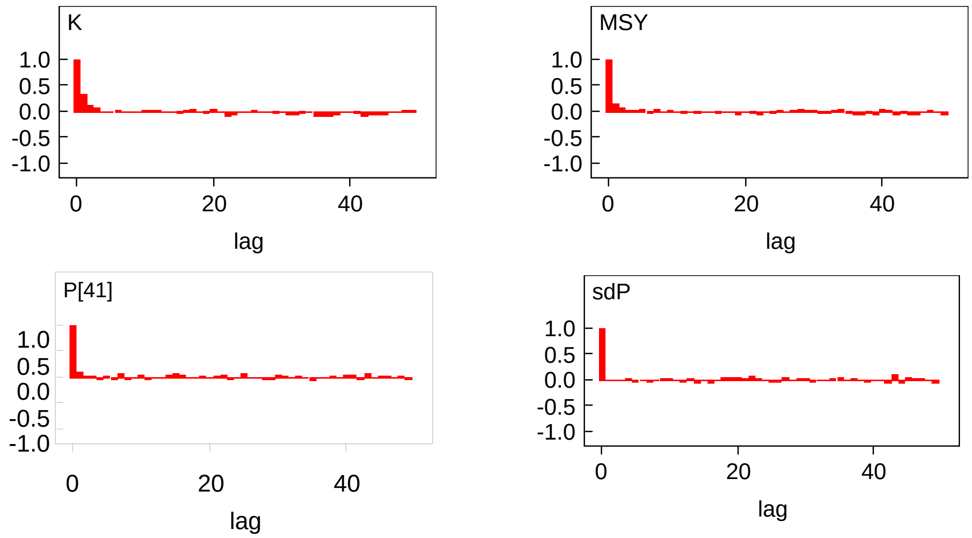

Fig. 2. Autocorrelation function of values sampled for four selected variables out to lag 50. K is the carrying capacity, P[41] is the relative biomass in year 2011, MSY is maximum sustainable yield and precP is the process precision (1/ process error).

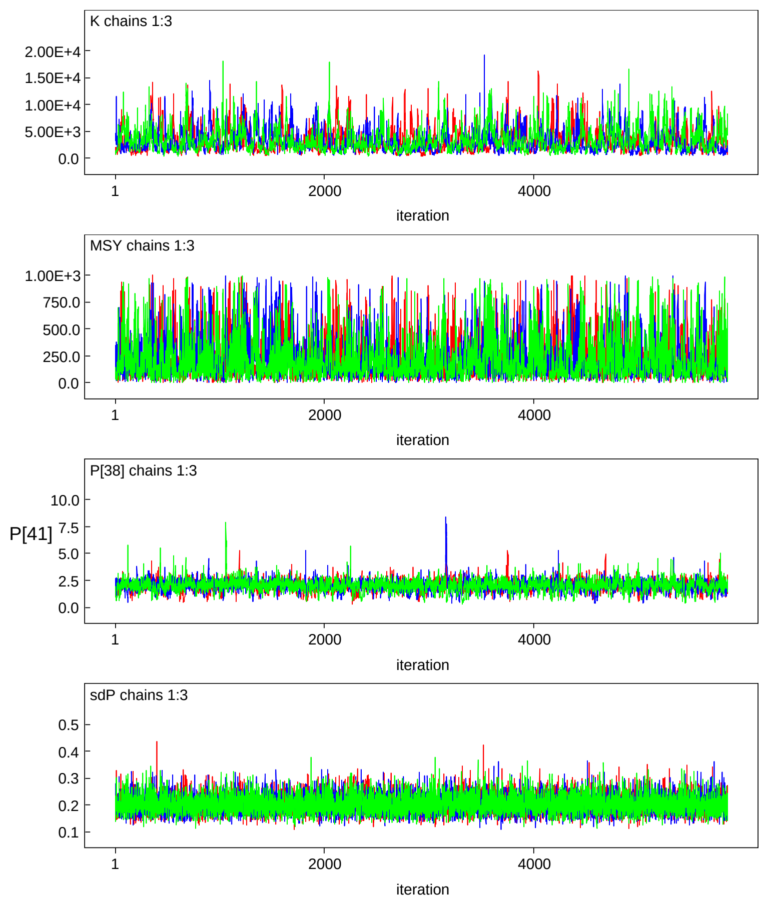

Fig. 3. Three traces (red, green, blue) with different initial values of dour selected variables. K is the carrying capacity, P[41] is the relative biomass in year 2011, MSY is maximum sustainable yield and precP is the process precision (1/ process error).

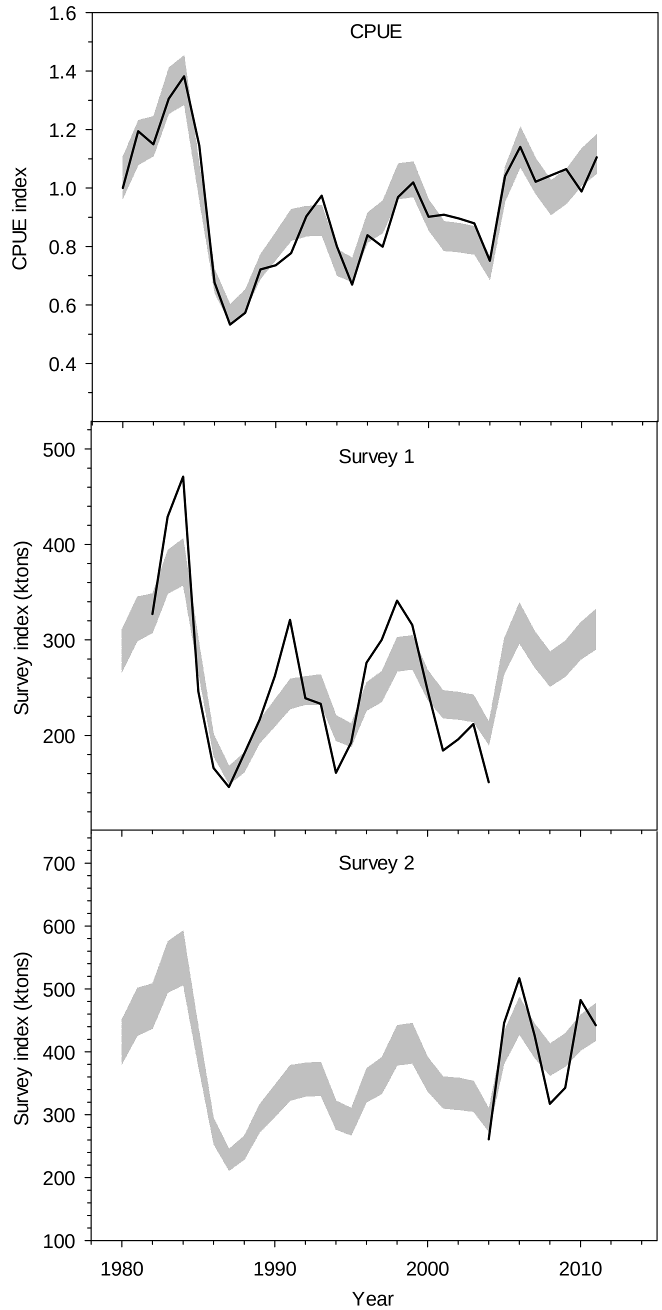

Fig. 4. Observed (solid line) and estimated (shaded) series of the biomass indices derived by standardising commercial vessel catch-per-unit-effort (CPUE), the 1982-2004 shrimp survey (Survey 1) and the Ecosystem survey since 2004 (Survey 2). Gray shaded areas are inter-quartile range of the posteriors.

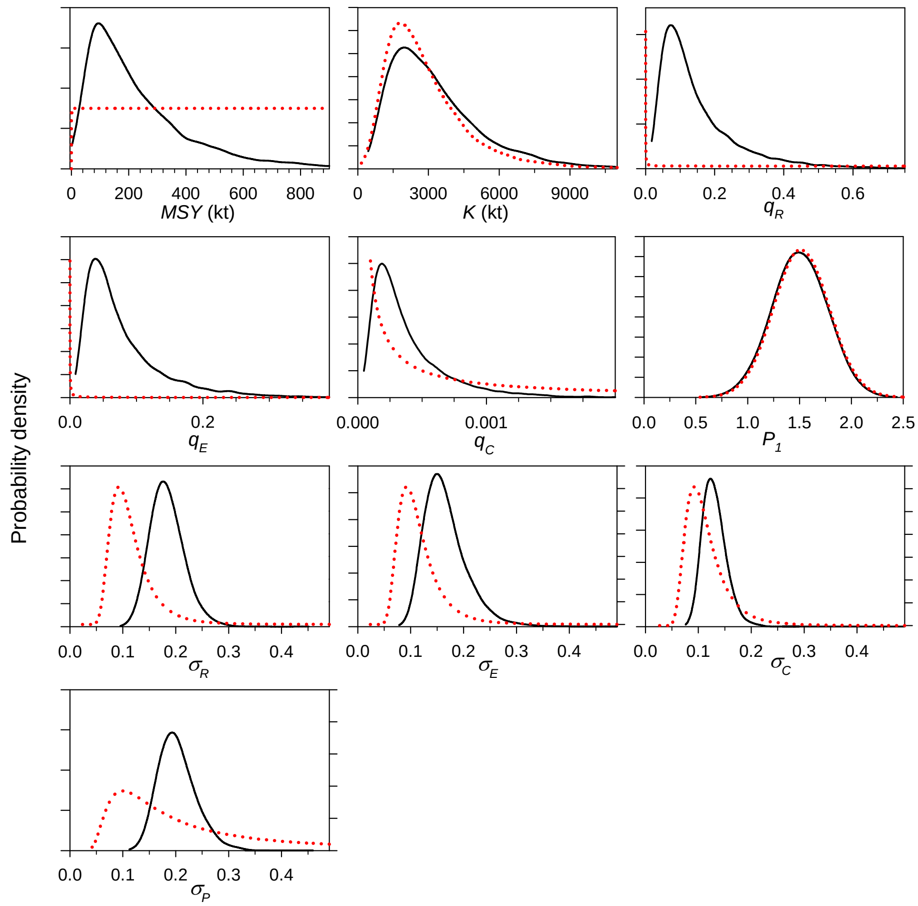

Fig. 5. Probability density distributions of model parameters: estimated: posterior (solid line) and prior (broken line) distributions (only informative priors are shown).

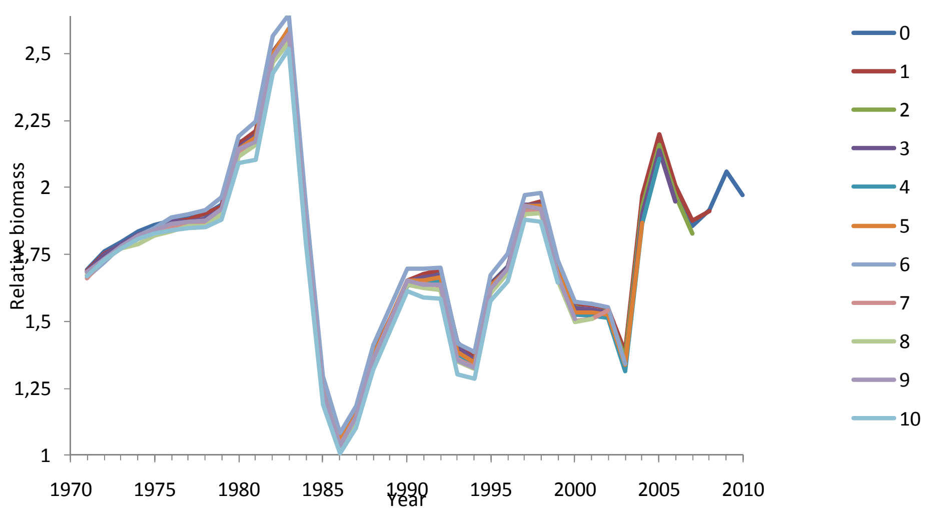

Fig. 6. Retrospective plot of median relative biomass (B/Bmsy). Relative biomass series are estimated by consecutively leaving out from 0 to 10 years of data.

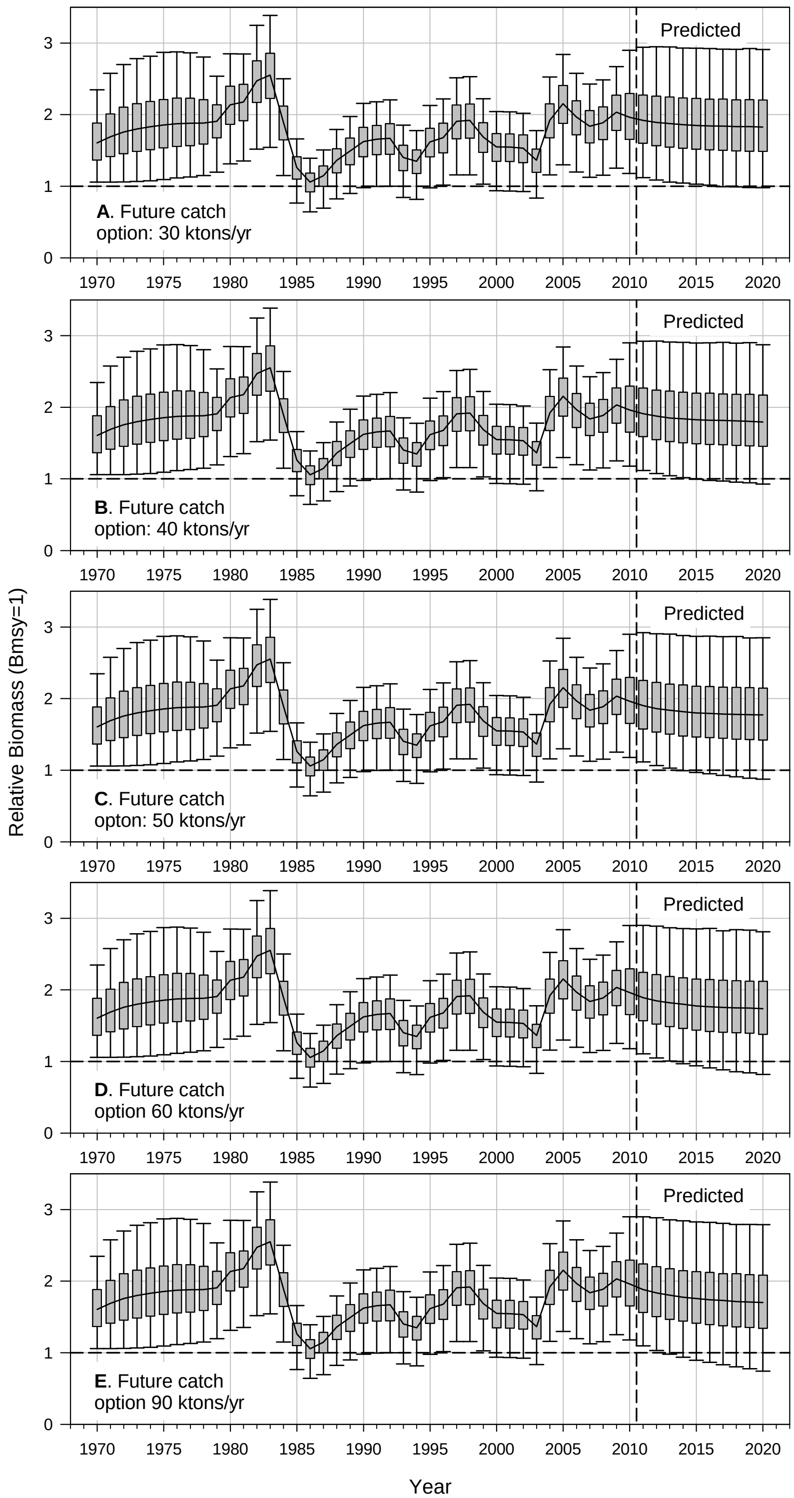

Fig. 7. Shrimp in the Barents Sea: Estimated time series of relative biomass (B_t/B_{msy}) 1970-2020. Future development is estimated at five different levels of annual catch (panel A-E). Boxes represent inter-quartile ranges and the solid black line running through the (approximate) centre of each box is the median; the arms of each box extend to cover the central 90 % of the distribution.

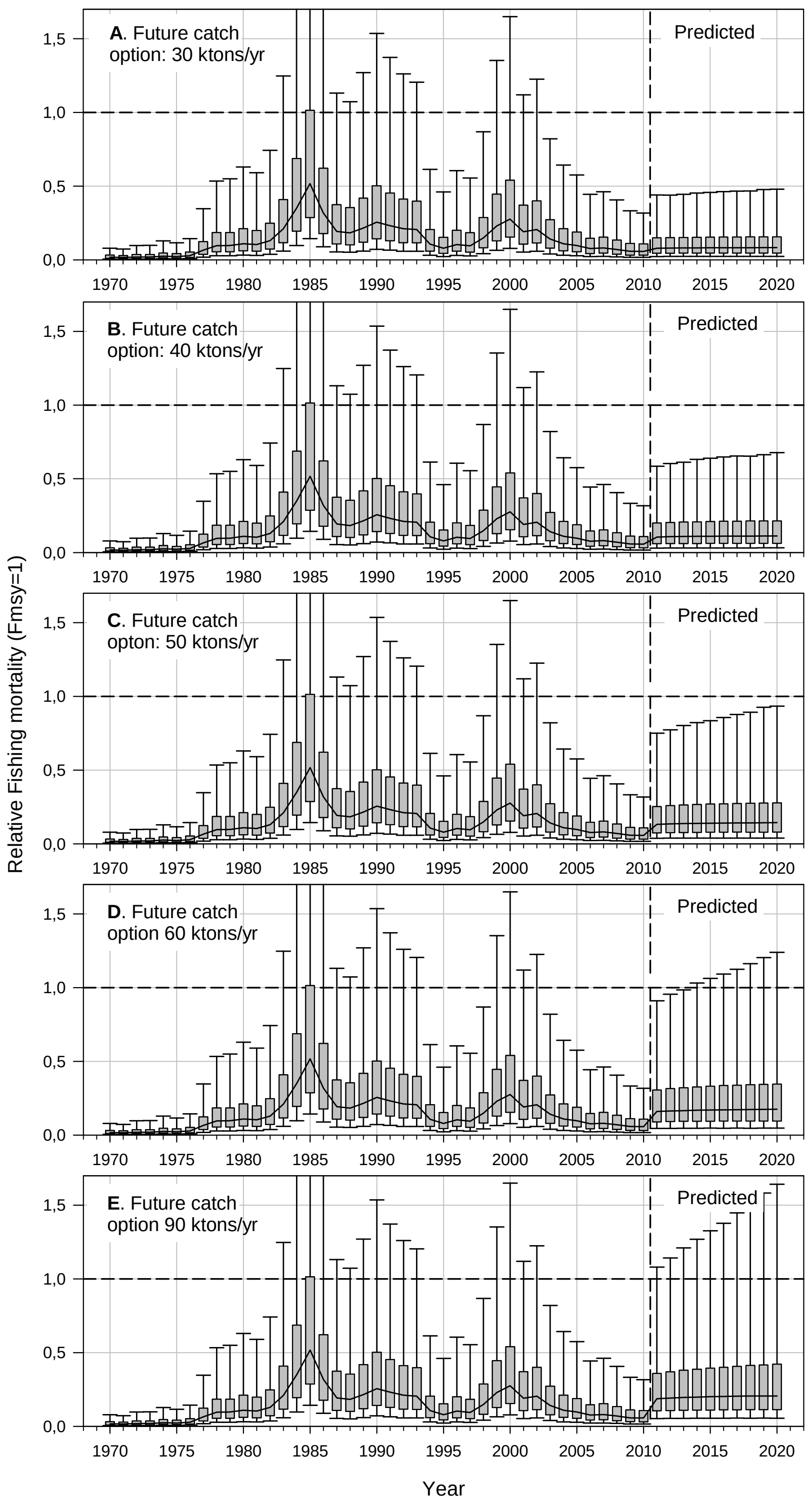

Fig. 8. Shrimp in the Barents Sea: Estimated time series of relative fishing mortality (F_t/F_{msy}) 1970-2020. Future development is estimated at five different levels of annual catch (panel A-E). Boxes represent inter-quartile ranges and the solid black line running through the (approximate) centre of each box is the median; the arms of each box extend to cover the central 90 % of the distribution.

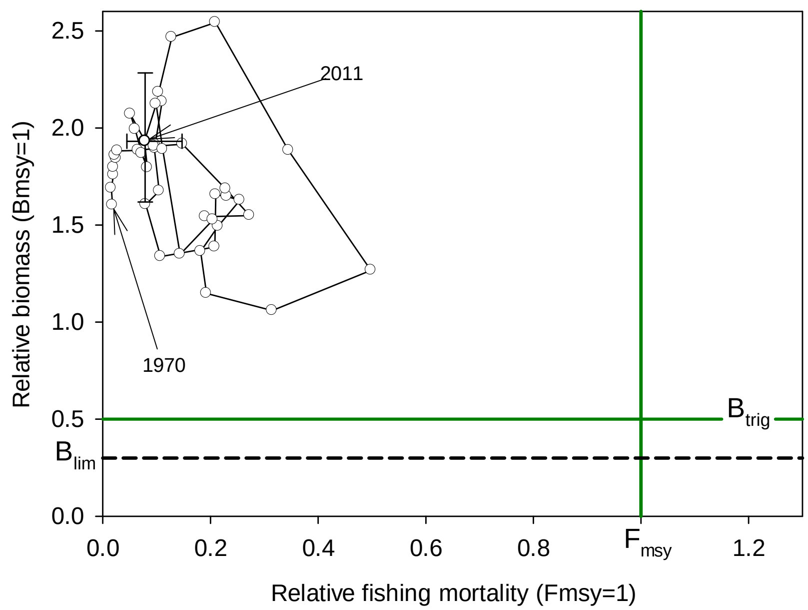

Fig. 9. Shrimp in the Barents Sea: estimated annual median biomass-ratio (B/B_{MSY}) and fishing mortality-ratio (F/F_{MSY}) 1970-2011. The reference points for stock biomas, B_{lim}, and fishing mortality, F_{lim}, are indicated by red lines. Error bars on the 2011 value are inter-quartile range

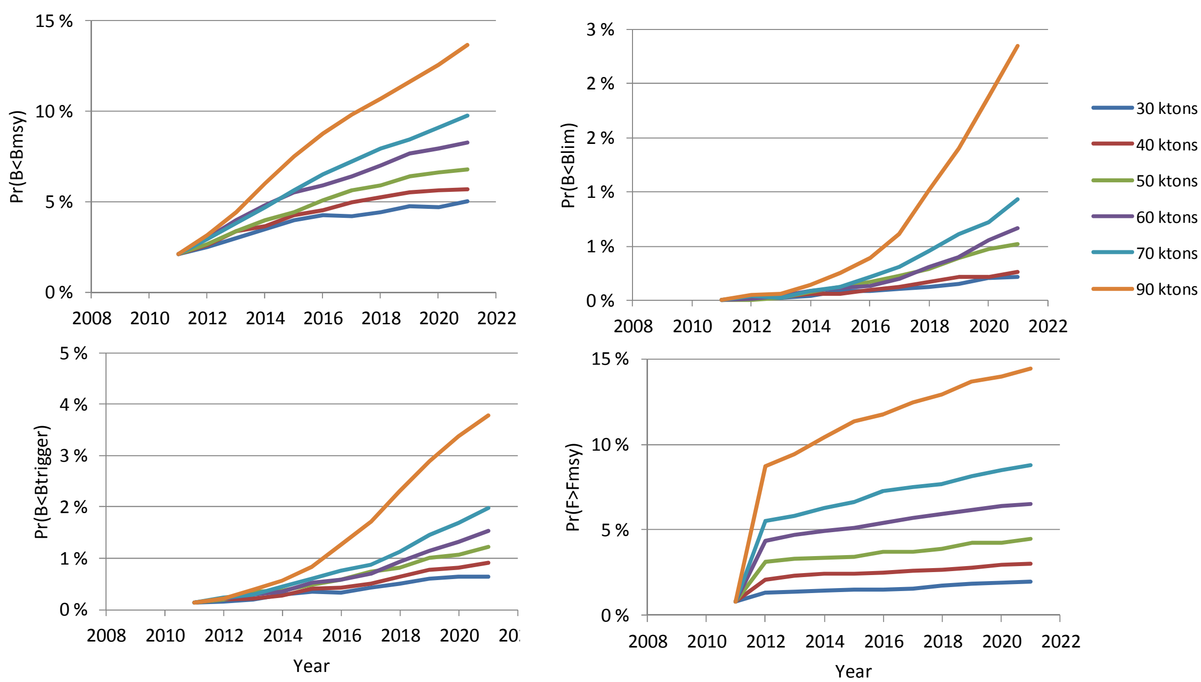

Fig. 10. Risk projections: estimated risk of going below and B_{msy}, $B_{trigger}$, B_{lim} or transgressing F_{msy} given a range of 30 to 90 ktons catch options.

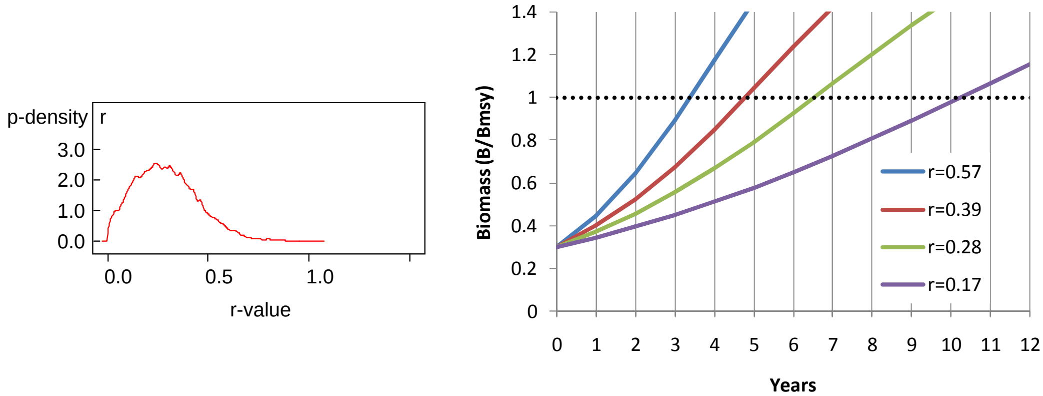

Fig. 11. *Left*:The posterior probability density distribution of r, the intrinsic rate of growth. Right: estimated recovery time from Blim (0.3Bmsy) to Bmsy (relative biomass = 1) given r values ranging within the 95% conf. lim. of the posterior (left figure) and no fishing mortality.