Northwest Atlantic Fisheries Organization

Serial No. N5852 **NAFO SCR Doc. 10/61**

NAFO/ICES WG *PANDALUS* ASSESSMENT GROUP – OCTOBER 2010

Shrimp (*Pandalus borealis*) in the Barents Sea – stock assessment and precautionary approach and MSY based management considerations

by

C. 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 implicitly 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 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 and conclusions of this year's assessment are similar to those of 2006 to 2009.

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 references. In 2009 ICES decided also to include a "MSY (Maximal Sustainable Yield) framework" (ACOM. ICES Advice, 2010. Book 1. Section 1.2) for deriving advice. The implementation into the advice should be finalised during 2010-2015. This paper updates the 2009 assessment and further provides some basis for management decisions within the new ICES PA/MSY advisory framework

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:

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

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.

Reference points

There are now one 3 reference points to be considered in relation to ICES type advice: F_{msy}, $B_{trigger}$ and B_{lim}. B_{msy} is now out as “the approach does not use a B_{msy} estimate” (ICES 2010, book 1). This may not be entirely precise as $B_{trigger}$ is directly derived from B_{msy}: “$B_{trigger}$ should be selected as a biomass that is encountered with low probability if F_{msy} is implemented” (WKFRAME). If F_{msy} is implemented, then the stock will vary around B_{msy} (Fig. 6). Thus, an estimate of B_{msy} will provide us with just the probability distribution needed to evaluate what “biomass that is encountered with low probability” under F_{msy} exploitation.

From the B_{msy} estimate one need to choose “a biomass that is encountered with low probability”. It is not specified what is meant by low – I would say that the options lie somewhere between the 5^{th} and 25^{th} lower percentile of the Bmsy estimate. Once that is done we need choose what pressure should be applied to the “trigger” to make it trig – i.e. at what risk of exceeding Btrigger should the F reduction kick inn.

In all this I can’t help thinking that it would have been simpler just calculate the probability of being below B_{msy} (as we have done for shrimp and Greenland Halibut for some years) instead of calculating the probability of being below some percentile of Bmsy – but somehow we have passed that.

Changes from the 2009 assessment

This assessment is an update of the 2009 assessment with the following changes:

- Model: has been revised so that P[i] (relative biomass) is P at the end of the ith year instead of at the beginning.
- Priors: No changes.
- Input data:
    - Survey: the 2010 (as well as the 2009) estimate of fishable biomass is based on the average percentage of the fishable- to total biomass 2004-2008 and the total biomass survey estimate of the year as no demographic information was available.
    - Standardised CPUE: The complete data set for 2009 was added along with partial data for 2010. This made the 2010-estimate of the 2008 and 2009 value slightly higher.
    - Catch: Minor adjustments to most recent years.
- New code added to estimate Btrigger etc

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. 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%.

$B_{trigger}$

From any starting point, fishing at Fmsy will eventually drive the stock to Bmsy and it will stay there unless the environment changes outside the dynamics experienced in the model period (Fig. 7). Btrigger is derived from the probability density distribution of Bmsy i.e. the distribution that tells us what stock sizes are likely to be observed under an extended Fmsy exploitation regime and what not. The lower percentiles of the Bmsy is:

	mean	sd	2.50 %	5.00 %	10%	25%
P_{2170}	1.002	0.499	0.299	0.4015	0.524	0.715

The 10^{th} percentile is at about 0.5Bmsy. That is the biomass that will be encountered in 1 out of 10 years while fishing at Fmsy as a result of random variation. 0.3Bmsy which is equal to Blim will be encountered 1 out of 40. Going lower than 0.5Bmsy will bring the value so close to Blim (0.3Bmsy) that it probably loses whatever meaning it had. If one selects a 50% probability of going below this trigger this will make the corresponding risk of going below Bmsy vary between 90 and 50 % depending on the precision with which the stock biomass can be estimated.

Assessment results

Since 1970, the estimated median biomass-ratio has been above its MSY-level (Fig. 8) 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. 8). Since the late 1990s the stock has varied with an overall increasing trend and reached a level in 2010 estimated to be close to K. The estimated risk of stock biomass being below Bmsy in 2010 was 2.5% (Table 6).

The median fishing mortality ratio (*F-ratio*) has been well below 1 throughout the series (Fig. 9). In 2010 there is a low 1% risk of the *F-ratio* being above 1 (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. 10).

The posterior for *MSY* was positively skewed with a mode at 100 ktons (Fig. 4) and upper and lower quartiles at 114 ktons and 337 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 quota recommendations 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 2011 are given in Table 6.

The risk associated with ten-year projections of stock development assuming annual catch of 30 000 to 90 000 t were investigated (Fig. 11). For all options the risk of the stock falling below Bmsy 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 Btrigger over a 10 year period (Fig. 11). Catch options up to 60 000 t, have a low risk (<5%) of exceeding Fmsy in the short term.

Catch options of up to 60 ktons/yr for 2011 have a low risk (<5%) of exceeding Fmsy and is likely to maintain the stock at its current high level (Table 6.4), however, the stock may likely sustain catches higher than that.

Taking 70 000 t/yr will increase the risk of going below Bmsy to more than 10% during the ten years of projection (Fig. 11). However, the risk of going below Btrigger 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 10% after ten years.

If the catches are increased to 90 000 t/yr, the stock is still not likely to go below Btrigger or even Bmsy in the short term, but whether this catch level will be sustainable in the longer term is uncertain.

Yield predictions can be made for fishing mortalities at F_{msy}, but such estimates will have high uncertainty attached as absolute biomass can only be estimated with relatively high variances (see section on "estimation of parameters") and therefore point estimates should be interpreted with caution. However, the risk of exceeding F_{msy} at different catch options may be read of such prediction tables as the percentiles of the estimated probability distribution of the yield prediction (Table 6.5). At a 5% probality of exceeding F_{msy} the yield would be 68 kt for 2011, at 10% it would be 100 kt etc.

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 2010 is estimated at about 1%, given a projected 2010 catch of 22 200 t.

Biomass. The Stock is estimated to be close to the carrying capacity. The estimated risk of stock biomass being below B_{msy} at end 2010 is 3%, and less than 1% of being below $B_{trigger}$ and B_{lim}.

State of the Stock. The stock biomass estimates have been above B_{msy} throughout the history of the fishery. Biomass at the end of 2010 is estimated to be well above B_{msy} and fishing mortality well below F_{msy}.

Yield. A catch option of up to 68 000 t for 2011 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 4 years.

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

References

Anon., 2005a. Report of the Pandalus assessment working group. *ICES CM 2006/ACFM:10. ref G*. 72 pp.

Anon. 2005b. ICES Report of the ICES Advisory Commit tee on Fishery Management , Advisory Commit tee on the Marine Environment and Advisory Commit tee on Ecosystems, 2005. *ICES advice. Vol 3*, p. 104-108.

Aschan M, Johannesen E., Bogstad B., Hvingel C. 2006. Why does not the shrimp stock in the Barents Sea respond to predation by cod? *NAFO SCR Doc. 06/71.*

Bayes, T. 1763. An essay towards solving a problem in the doctrine of chances. Philosophical Transactions of the Royal Society, 330–418. Reprinted in Biometrika 1958, 45: 293–315.

Brooks, S. and Gelman, A. 1998. General methods for monitoring convergence of iterative simulations. Journal of Computational and Graphical Statistics 7, 4: 434–455.

Fletcher, R.I. 1978. Time-dependent solutions and efficient parameters for stock-production models. Fisheries Bulletin, 76: 377–388.

Gelman, A. and Rubin, D. B. 1992. Inference from iterative simulation using multiple sequences. Statistical Science, 7: 457–511.

Gelfand, A.E. and Dey, D.K. 1994. Bayesian model choice: asymptotics and exact calculations. Journal of the Royal Statistical Society, B 56: 501–514.

Gelman, A., Meng, X.L., and Stern, H.S. (1996) Posterior predictive assessment of model fitness via realized discrepancies, Statistica Sinica, 6: 733–807

Gelman, A., Carlin, J.C., Stern, H. and Rubin D.B. 1995. Bayesian Data Analysis. Chapman and Hall, New York. 525 pp.

Gelman, A., Meng, X.L. and Stern H.S. 1996. Posterior predictive assessment of model fitness via realized discrepancies. Statistica Sinica, 6: 733-807.Gilks W.R., Richardson, S and Spiegelhalter, D.J. (Editors). 1996. Markov chain Monte Carlo in Practice. Chapman and Hall, London, UK. 512 pp.

Geweke, J. 1992. Evaluating the accuracy of sampling-based approaches to calculating posterior moments. In Bayesian Statistics 4 (ed JM Bernado, JO Berger, AP Dawid and AFM Smith). Clarendon Press, Oxford, UK: 169-194

Heidelberger, P. and Welch, P. 1983. Simulation run length control in the presence of an initial transient. Operations Research, 31: 1109–1144.

Hvingel, C. 2006. Research survey information regarding northern shrimp (*Pandalus borealis*) in the Barents Sea. *NAFO SCR Doc. 06/63.*

Hvingel, C. 2006a. Towards a Quantitative Assessment Framework for the Shrimp (*Pandalus borealis*) Stock in the Barents Sea. *NAFO SCR Doc. 06/64.*

Hvingel, C. 2007. An assessment of the shrimp (*Pandalus borealis*) stock in the Barents Sea. *NAFO SCR Doc. 07/76.*

Hvingel, C., Thangstad, T., Luibin, P. 2008. Research survey information regarding northern shrimp (*Pandalus borealis*) in the Barents Sea and Svalbard area. *NAFO SCR Doc. 08/60.*.

Hvingel, C., Thangstad, T 2008. The Norwegian fishery for northern shrimp (Pandalus borealis) in the Barents Sea and round Svalbard. *NAFO SCR Doc. 08/57.*

Hvingel, C. and M.C.S. Kingsley, 2002. A framework for the development of management advice on a shrimp stock using a Bayesian approach. *NAFO SCR Doc. 02/158 Serial No. N4787.*

Hvingel, C. and M.C.S. Kingsley (2006). A framework to model shrimp (Pandalus borealis) stock dynamics and quantify risk associated with alternative management options, using Bayesian methods. *ICES J. Mar. Sci.* ***63****:68–82.*

ICES. 2006. ICES Report on Ocean Climate 2005. ICES Cooperative Research Report No. 280. 53 pp.

Martinez, I., Aschan, M., Skjerdal, T., and Aljanabi, S. M. 2006. The genetic structure of *Pandalus borealis* in the Northeast Atlantic determined by RAPD analysis. *ICES J. Mar. Sci.* ***63****: 840–850*.

Raftery, A.L. and Lewis, S. 1992. How many iterations in the Gibbs sampler? *In* Bayesian Statistics 4. *Edited by* J.M. Bernardo, J.O. Berger, A.P. Dawid, and A.F.M. Smith. Oxford University Press, Oxford pp. 763–774.

Schaefer, M.B. 1954. Some aspects of the dynamics of populations important to the management of the commercial marine fisheries. Bulletin of the Inter-American Tropical Tuna Commission, 1: 27–56.

Schnute, J. 1994. A general framework for developing sequential fisheries models. Canadian Journal of Fisheries and Aquatic Sciences, 51: 1676–1688.

Spiegelhalter, D.J., Thomas, A., Best, N., Lunn, D. 2004. WinBUGS User Manual version 1.4 January 2003 MRC Biostatistics Unit, Inst. of Public Health, Cambridge, England.

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	1.149	327	-
1983	104.8	1.303	429	-
1984	128.1	1.385	471	-
1985	124.5	1.149	246	-
1986	65.3	0.676	166	-
1987	43.4	0.532	146	-
1988	48.7	0.573	181	-
1989	62.7	0.721	216	-
1990	81.2	0.735	262	-
1991	74.9	0.777	321	-
1992	68.6	0.905	239	-
1993	56.3	0.979	233	-
1994	28.3	0.818	161	-
1995	25.2	0.679	193	-
1996	34.5	0.845	276	-
1997	35.7	0.800	300	-
1998	55.8	0.970	341	-
1999	75.7	1.022	316	-
2000	83.2	0.901	247	-
2001	57.5	0.907	184	-
2002	61.5	0.896	196	-
2003	38.0	0.883	212	-
2004	41.3	0.754	151	261
2005	41.4	1.055	-	446
2006	29.6	1.148	-	517
2007	29.2	1.035	-	426
2008	26.1	1.073	-	317
2009	23.3	1.077	-	*348
2010	22.2	1.048	-	*489

*the 2009-10 estimates of fishable biomass is based on the average percentage of the fishable– to total biomass 2004-2008 and the total biomass survey estimate of the year as no demographic information was available.

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	$_R^2$	reference	~dgamma(4,0.1125)
Precision survey 2	$_E^2$	reference	~dgamma(4,0.1125)
Precision CPUE	$_C^2$	reference	~dgamma(4,0.1125)
Precision model	$_P^2$	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 (p.extr.).

	CPUE		Survey 1		Survey 2	
Year	resid (%)	Pr	resid (%)	Pr	resid (%)	Pr
1980	3.89	0.42	-	-	-	-
1981	-3.01	0.59	-	-	-	-
1982	2.50	0.45	0.05	0.51	-	-
1983	2.62	0.45	-13.42	0.77	-	-
1984	-0.47	0.52	-18.71	0.85	-	-
1985	-11.06	0.78	15.39	0.25	-	-
1986	0.76	0.49	13.98	0.26	-	-
1987	7.17	0.34	8.47	0.35	-	-
1988	8.01	0.32	-5.03	0.61	-	-
1989	1.73	0.47	-5.68	0.62	-	-
1990	9.54	0.29	-14.65	0.79	-	-
1991	12.87	0.23	-24.12	0.92	-	-
1992	-1.52	0.55	3.58	0.44	-	-
1993	-8.25	0.72	7.08	0.38	-	-
1994	-7.56	0.70	30.45	0.10	-	-
1995	7.13	0.34	4.69	0.42	-	-
1996	3.16	0.43	-12.28	0.75	-	-
1997	13.42	0.22	-15.99	0.81	-	-
1998	6.07	0.37	-16.19	0.81	-	-
1999	1.26	0.48	-9.04	0.69	-	-
2000	1.03	0.48	2.37	0.46	-	-
2001	-7.92	0.71	26.08	0.14	-	-
2002	-7.05	0.69	18.03	0.21	-	-
2003	-6.52	0.68	8.16	0.36	-	-
2004	-2.44	0.57	35.35	0.07	9.84	0.32
2005	-1.83	0.56	-	-	-9.59	0.70
2006	1.10	0.48	-	-	-12.56	0.76
2007	2.49	0.44	-	-	-2.87	0.57
2008	-7.37	0.70	-	-	22.20	0.17
2009	-5.31	0.65	-	-	14.58	0.25
2010	4.91	0.39	-	-	-12.08	0.75

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)	250	186	113	197	336
K (ktons)	3275	1836	1894	2860	4245
r	0.32	0.16	0.20	0.31	0.42
q_R	0.14	0.11	0.07	0.11	0.17
q_E	0.20	0.15	0.10	0.15	0.24
q_C	5.0E-04	3.9E-04	2.5E-04	3.9E-04	6.2E-04
P_0	1.50	0.26	1.33	1.50	1.68
P_{2010}	2.00	0.54	1.66	1.96	2.29
$\rightarrow_R$	0.18	0.03	0.16	0.18	0.20
$\rightarrow_E$	0.17	0.04	0.15	0.17	0.19
$\rightarrow_C$	0.13	0.02	0.11	0.12	0.14
$\rightarrow_P$	0.19	0.03	0.17	0.19	0.21

Table 6. Stock status and short term predictions. *Upper*: stock status for 2009 of 2010. *Lower*: predictions for 2011 given catch options ranging from 30 to 90 ktons

Status	2009	2010*
Risk of falling below B_{lim} (0.3B_{MSY})	0.0 %	0.0 %
Risk of falling below B_{MSY}	2.2 %	2.5 %
Risk of exceeding F_{MSY}	0.8 %	0.8 %
Risk of exceeding 1.7F_{MSY}	0.4 %	0.4 %
Stock size (B/Bmsy), median	2.00	2.00
Fishing mortality (F/Fmsy),	0.12	0.11
Productivity (% of MSY)	0 %	1 %

*Predicted catch = 22.2ktons

Catch option 2011 (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 %	0.0 %
Risk of falling below B_{MSY}	3.2 %	3.1 %	3.1 %	3.3 %	3.4 %	3.6 %
Risk of exceeding F_{MSY}	1.4 %	2.1 %	3.1 %	4.3 %	5.7 %	8.9 %
Risk of exceeding 1.7F_{MSY}	0.6 %	1.0 %	1.4 %	1.9 %	2.4 %	3.8 %
Stock size (B/Bmsy), median	1.92	1.91	1.90	1.89	1.88	1.87
Fishing mortality (F/Fmsy),	0.08	0.10	0.13	0.16	0.19	0.24
Productivity (% of MSY)	15 %	17 %	19 %	21 %	22 %	25 %

Table 7. Shrimp in ICES SA I and II: Predictions of yield (kt) at F_{msy}, mean, standard error and percentiles (=risk of exceeding Fmsy).

Year	mean	sd	2.5 %	5 %	10 %	25 %	median	75 %	90 %	95 %	97.5 %
2011	404	307	44	68	100	180	324	544	825	1029	1214
2012	405	307	44	66	99	180	323	547	832	1029	1213
2013	363	274	43	63	93	164	290	486	738	921	1082
2014	336	254	41	60	88	153	269	448	681	848	1005
2015	317	242	39	57	84	145	251	421	645	809	958
2016	304	234	38	55	80	138	240	403	624	776	918
2017	294	228	37	54	78	132	231	388	604	760	898
2018	287	224	36	53	75	128	224	378	583	740	882
2019	281	220	35	51	73	125	219	370	572	727	868
2020	276	218	35	50	72	122	214	363	567	720	864

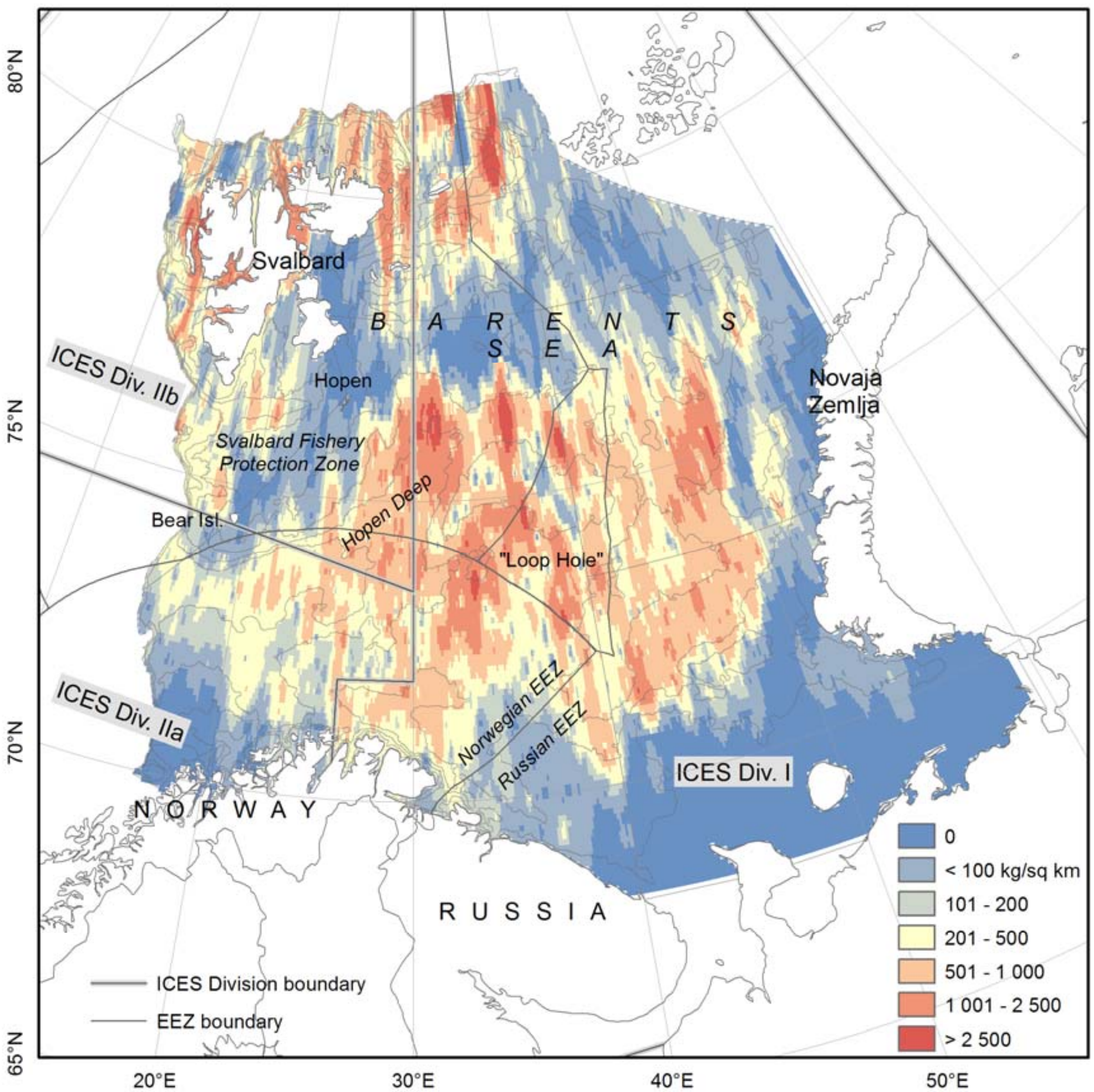

Fig. 1. Shrimp in the Barents Sea: stock distribution mean density (kg/km^2) based on survey data 2000-2010.

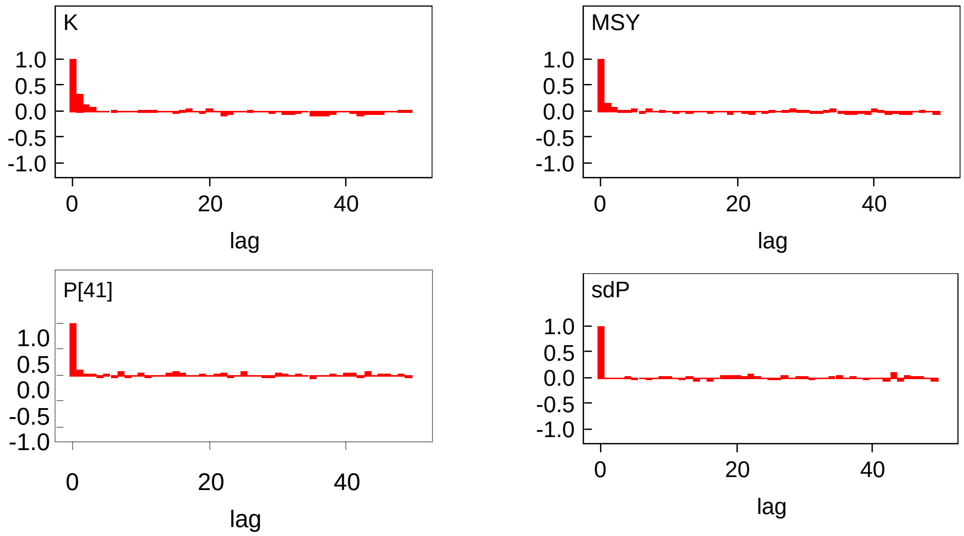

Fig. 2. Autocorrelation function of values sampled for four selected variables out to lag 50. K is the carrying capacity, P[41] is the relative biomass in year 2010, MSY is maximum sustainable yield and precP is the process precision (1/ process error).

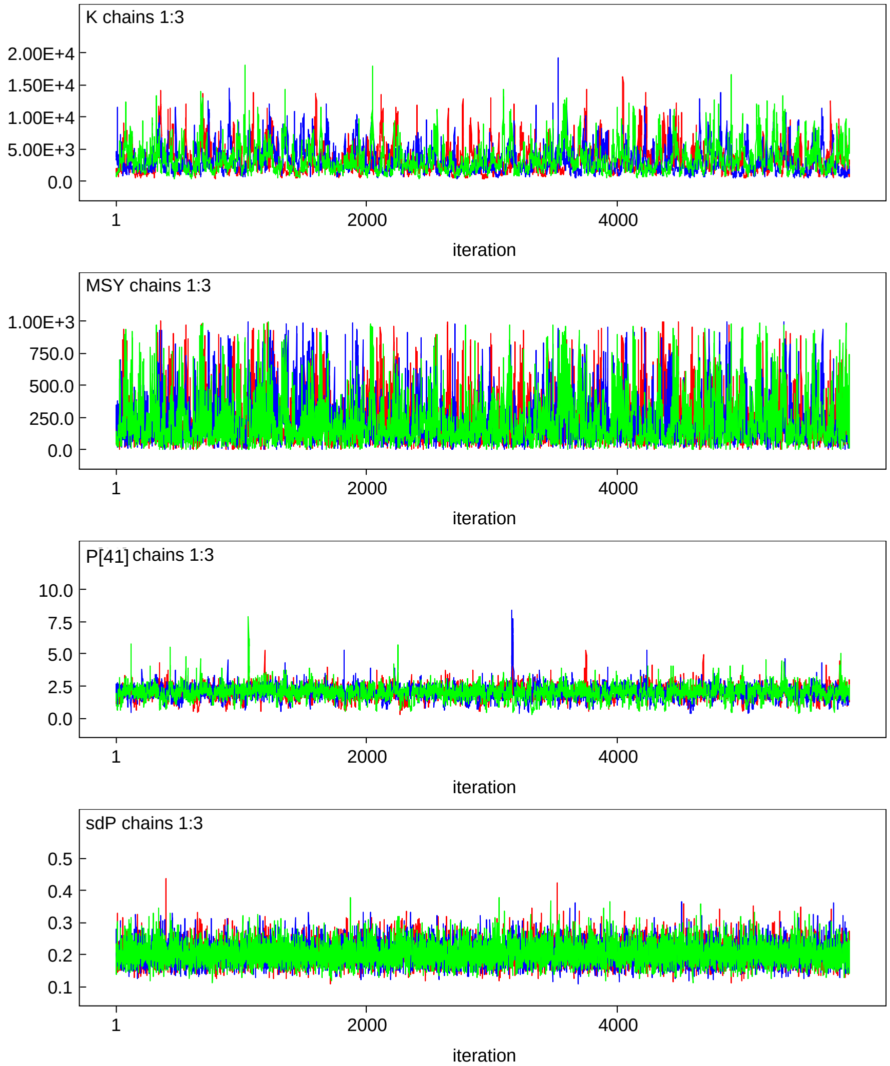

Fig. 3. Three traces (red, green, blue) with different initial values of dour selected variables. K is the carrying capacity, P[41] is the relative biomass in year 2010, MSY is maximum sustainable yield and precP is the process precision (1/ process error).

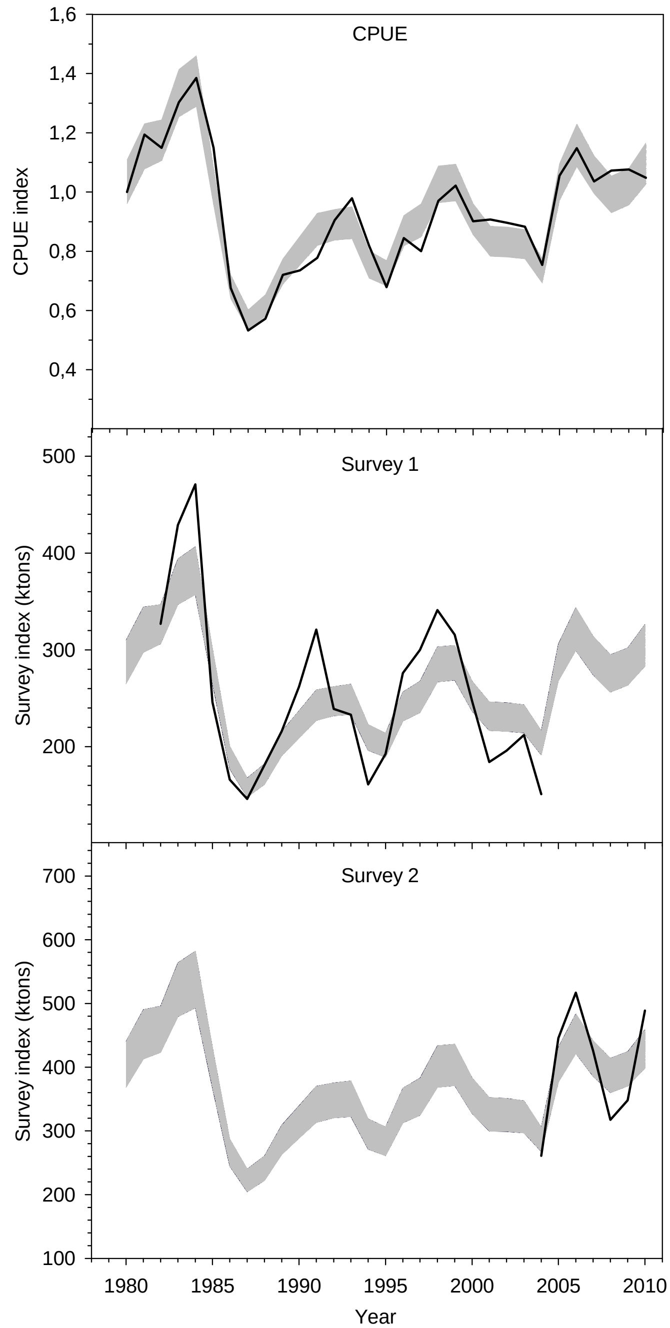

Fig. 4. Observed (solid line) and estimated (shaded) series of the biomass indices derived by standardising commercial vessel catch-per-unit-effort (CPUE), the 1982-2004 shrimp survey (Survey 1) and the Ecosystem survey since 2004 (Survey 2). Gray shaded areas are inter-quartile range of the posteriors.

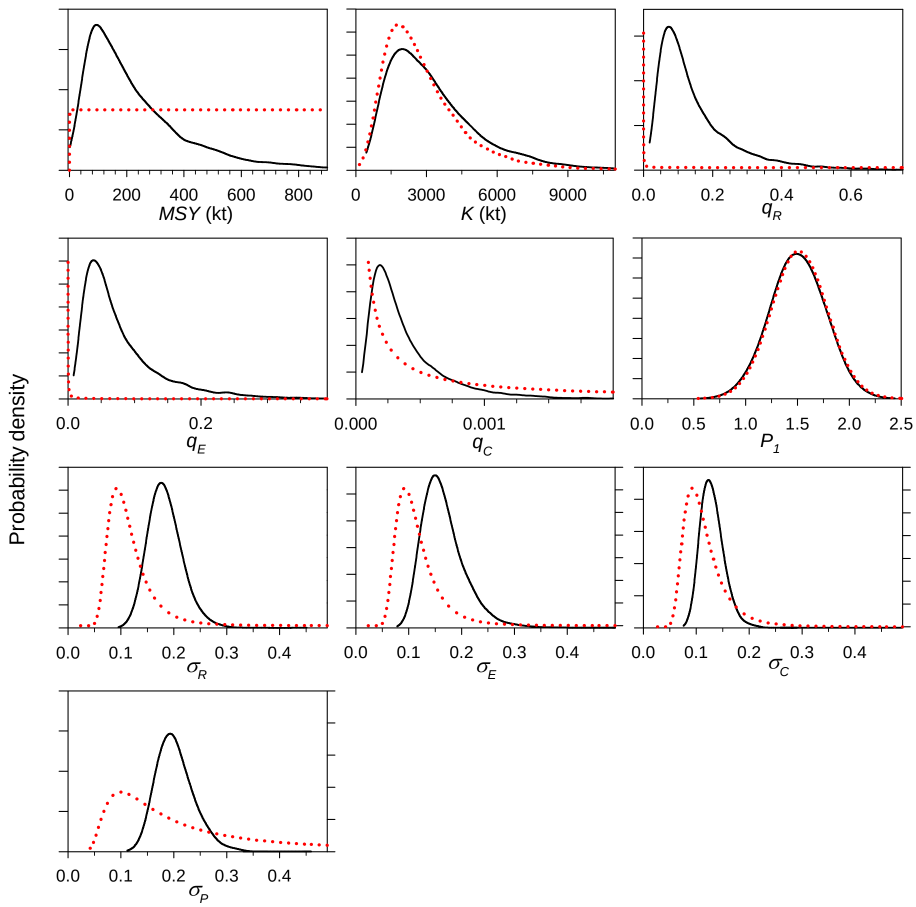

Fig. 5. Probability density distributions of model parameters: estimated: posterior (solid line) and prior (broken line) distributions (only informative priors are shown).

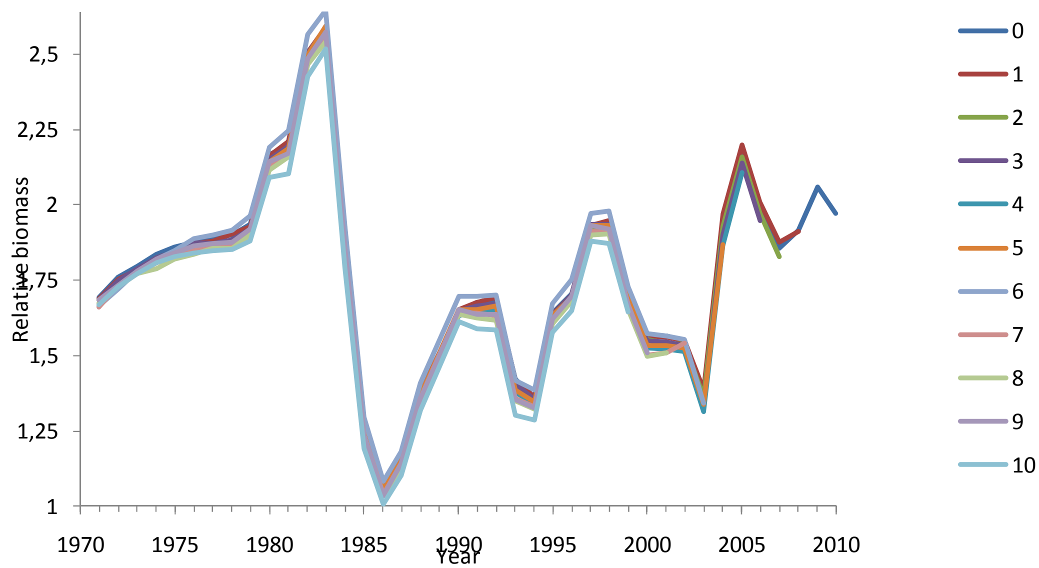

Fig. 6. Retrospective plot of median relative biomass (B/Bmsy). Relative biomass series are estimated by consecutively leaving out from 0 to 10 years of data.

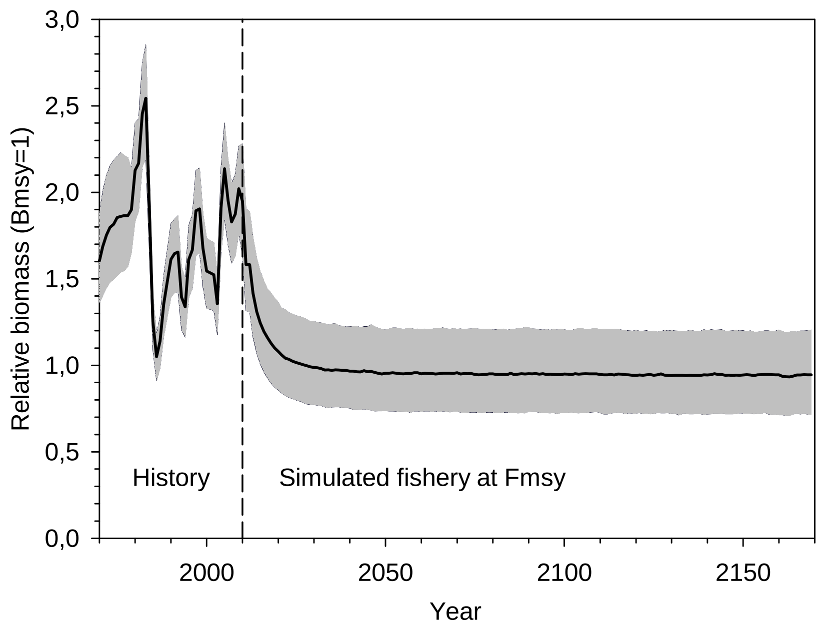

Fig. 7. Dynamics of stock biomass1970-2010 and projected 2011 to 2170 assuming exploitation at Fmsy and environmental fluctuations within those seen 1970-2010.

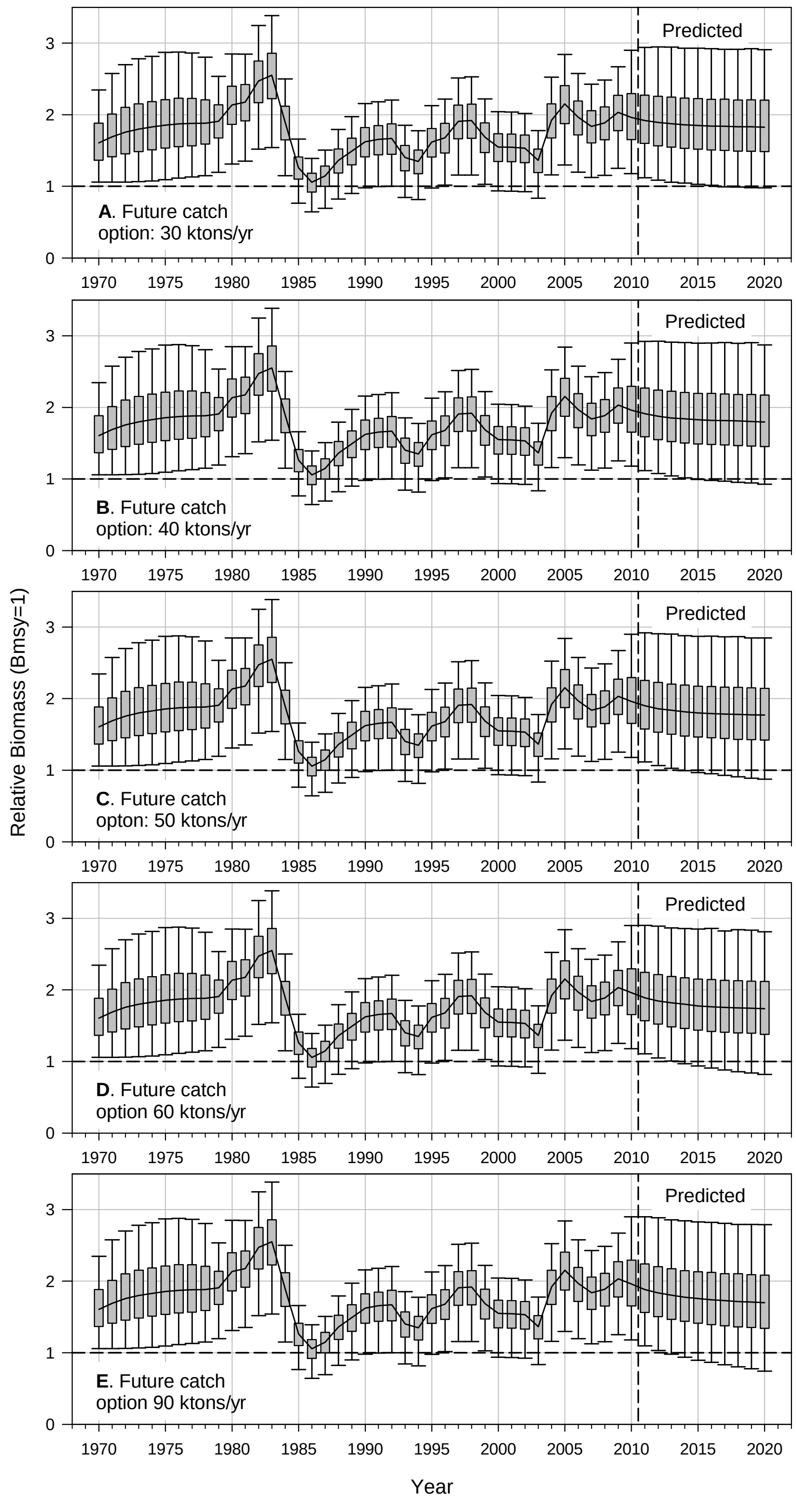

Fig. 8. Shrimp in the Barents Sea: Estimated time series of relative biomass (B_t/B_{msy}) 1970-2020. Future development is estimated at five different levels of annual catch (panel A-E). Boxes represent inter-quartile ranges and the solid black line running through the (approximate) centre of each box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

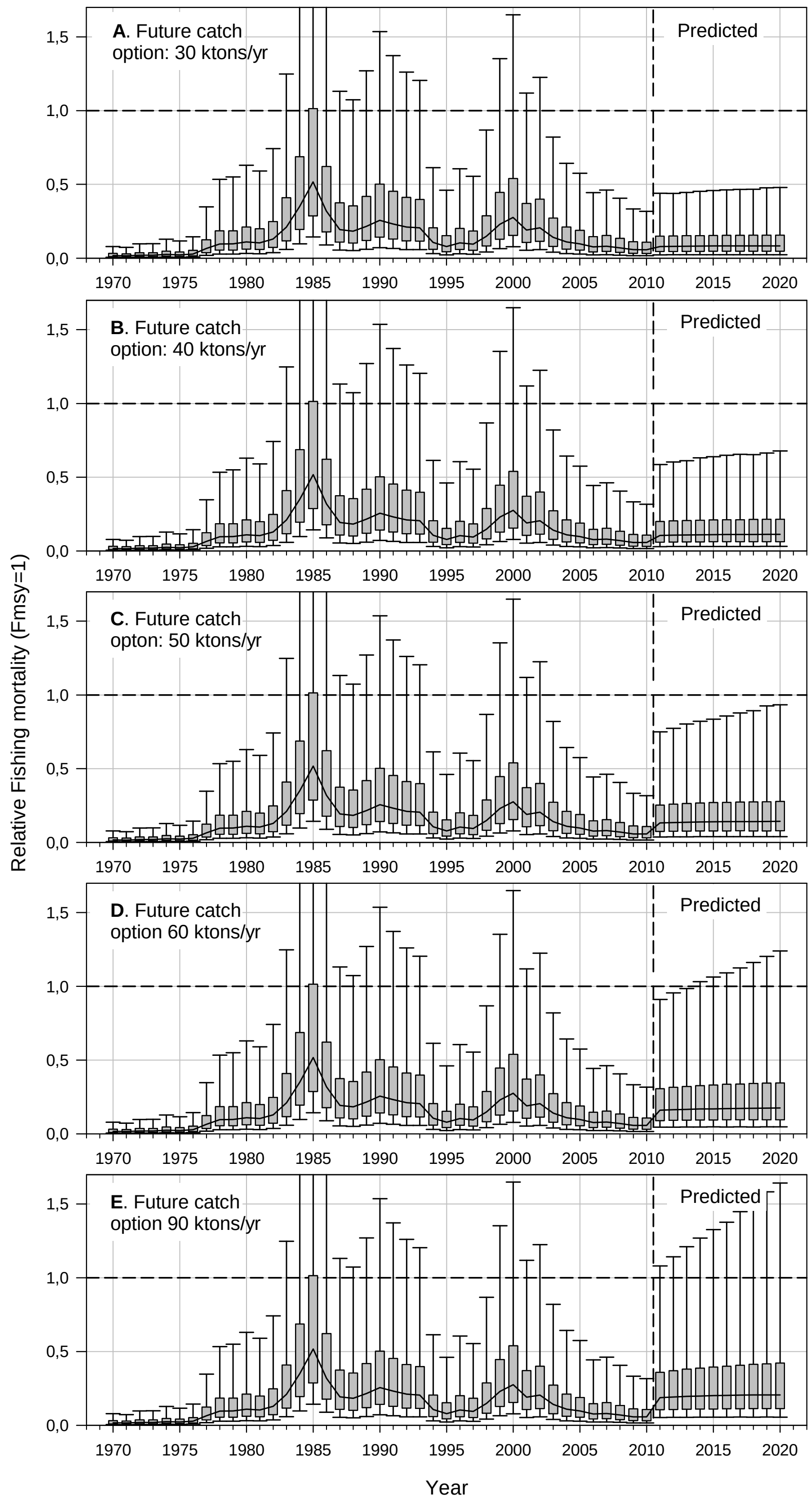

Fig. 9. Shrimp in the Barents Sea: Estimated time series of relative fishing mortality (F_t/F_{msy}) 1970-2020. Future development is estimated at five different levels of annual catch (panel A-E). Boxes represent inter-quartile ranges and the solid black line running through the (approximate) centre of each box is the median; the arms of each box extend to cover the central 90 % of the distribution.

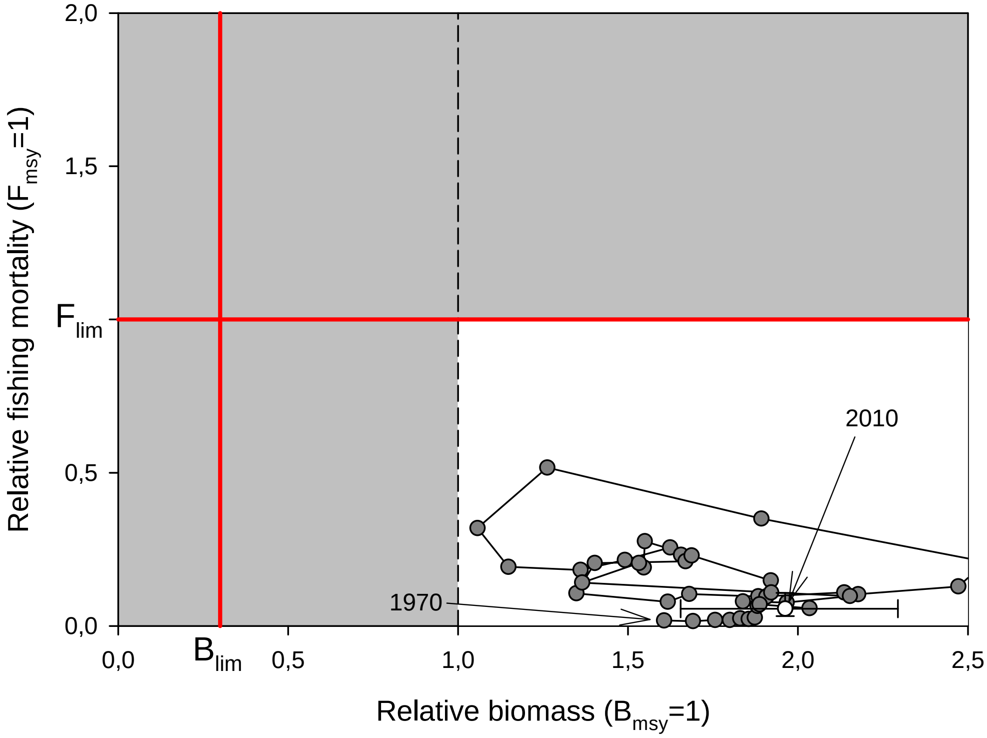

Fig. 10. Shrimp in the Barents Sea: estimated annual median biomass-ratio (B/B_{MSY}) and fishing mortality-ratio (F/F_{MSY}) 1970-2010. The reference points for stock biomas, B_{lim}, and fishing mortality, F_{lim}, are indicated by red lines. Error bars on the 2010 value are inter-quartile range

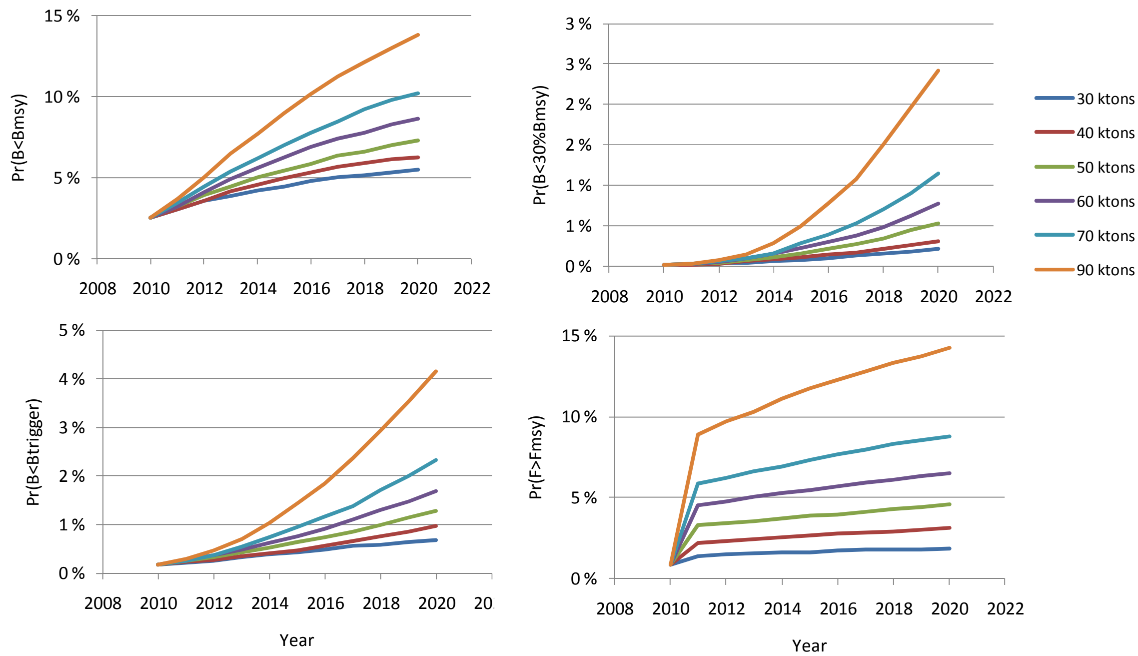

Fig. 11. Shrimp in ICES SA I and II: Projections of estimated risk of going below B_{msy} and B_{lim} (*top*) and of going below $B_{trigger}$ and of exceeding F_{msy} (*bottom*) given different catch options (see legend).

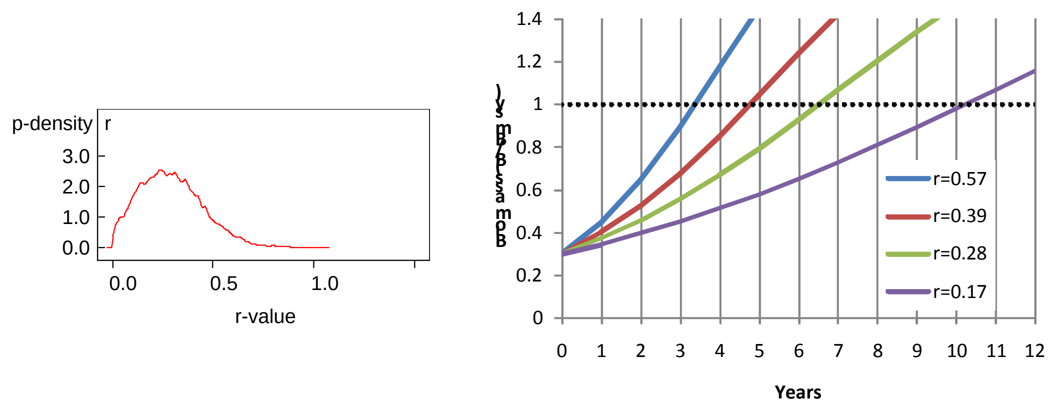

Fig. 12. *Left*:The posterior probability density distribution of r, the intrinsic rate of growth. Right: estimated recovery time from Blim (0.3Bmsy) to Bmsy (relative biomass = 1) given r values ranging within the 95% conf. lim. of the posterior (left figure) and no fishing mortality.