NOT TO BE CITED WITHOUT PRIOR
REFERENCE TO THE AUTHOR(S)

Northwest Atlantic Fisheries Organization

Serial No. N6368 **NAFO SCR Doc. 14/64**

NAFO/ICES WG *PANDALUS* ASSESSMENT GROUP – OCTOBER 2014

Shrimp (*Pandalus borealis*) in the Barents Sea – Stock assessment 2014

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 the populations' intrinsic 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.

Catches of 70 000 tonnes in 2015 and 2016 have a less than 5% risk of transgressing PA limits and MSY references. Catches at this level will maintain the stock at the current high biomass. The results and conclusions of this year's assessment are in line with those of previous years using the same assessment framework (i.e. since 2006).

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 18-128 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 participate in this fishery. 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 (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 OpenBUGS v.3.2.1 (www.openbugs.info; Spiegelhalter et al. 2004).

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 four 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 since 1980, $CPUE_t$, (Hvingel and Thangstad 2008, 2012b); and three trawl-survey biomass index for 1982–2004, $survR_t$, for 1984-2005, $survRu_t$ and 2004-now, $survE_t$ (Hvingel et al 2012a). These indices were scaled to true biomass by catchability parameters, q_C, q_R, q_{Ru} and q_E. Lognormal observation errors, η were applied, giving:

(4) $$\begin{aligned} CPUE_t &= q_C B_{MSY} P_t \exp(\omega_t) \\ survR_t &= q_R B_{MSY} P_t \exp(\kappa_t) \\ survRu_t &= q_{Ru} B_{MSY} P_t \exp(\eta_t) \\ survE_t &= q_E B_{MSY} P_t \exp(\varepsilon_t) \end{aligned}$$

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

Total reported annual catch in ICES Div. I and II since 1970 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 1969, P_0, 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 four 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 there was little or no information on what their probability distributions might look like.

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.

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 equation added for generating posterior distributions of the F-ratio were:

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

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

Four reference points are considered: F_{msy}, $B_{trigger}$, F_{lim} and B_{lim}. In the present assessment, F_{msy} directly as is the probability of exceeding reference points. "buffer" reference points are obsolete due to the available risk analyses. B_{lim} is set at 30% B_{msy} (NIPAG, 2006), $B_{trigger}$ at 50% B_{msy} and F_{lim} at 1.7F_{msy} (NIPAG, 2010).:

	Type	Value	Technical basis
MSY approach	$B_{trigger}$	$0.5B_{MSY}$*	Approx. corresponding to10th percentile of the B_{MSY} estimate
	F_{MSY}	*	Resulting from the production model.
Precautionary approach	B_{lim}	$0.3B_{MSY}$	The B where production is reduced to 50% MSY
	F_{lim}	$1.7F_{MSY}$	the F that drives the stock to B_{lim}

Changes from previous assessment

This assessment is an update of the 2012 assessment with the following changes:

- Model: No changes.
- Priors: No changes.
- Input data: new data added to series

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 (25000 actual 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 generally inside the 90% confidence limits i.e. the observations did not lie in the extreme tails of their posterior distributions ($0.05<pr<0.95$ in Table 4). The CPUE series was generally better estimated than the survey series – survey 2 showed some variation that was poorly captured in particular 1991 and 95. Otherwise no major problems in capturing the variability of the data were detected.

For the parameters K and P_0 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 series with different P_0-priors 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 somewhat 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, q_{Ru} and q_E, indicated that the new joint "Ecosystem survey" (survey 3, q_E) has a higher catchability than the two older separate surveys (survey 2, q_{Ru} and survey 1, q_R) (Table 5). The estimated CVs of survey 1 and 3 had a median at about 17% while the CV of survey 2 was double that at 0.34. The CV of the CPUE series was lowest at 12%. The process error, σ_p, had a median of 19%.

Assessment results

Stock status
Since 1970, the estimated median biomass-ratio has been above its MSY-level (Fig. 7 upper) 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 in the mid-1980s was noted following some years with high catches and the median relative biomass dropped nearly to 1 (Fig. 7, upper). Since the late 1980s, however, the stock has varied with a slightly increasing trend. The median 2013-14 values are above Bmsy. The estimated risk of stock biomass being below $B_{trigger}$ in 2014 was less than 1% (Table 6). The median estimate of fishing mortality has remained below Fmsy throughout the history of the fishery (Fig. 7 lower). In 2014, there is a less than 5% risk of the F being above Fmsy (Table 6)

The posterior for *MSY* was positively skewed with a mode at 100 ktons (Fig. 4) and upper and lower quartiles at 122 ktons and 369 ktons (Table 5). As mentioned above the right tail of the MSY-posterior showed some sensitivity to changes in the prior for *K*.

Projections
Risk associated with six optional catch levels for 2015 and 2015-16 were explored (Table 6).
Assuming a catch of 21 kt for 2014, catches of 70 000 tonnes in 2015 and 2016 have a less than 5% risk of transgressing PA limits and MSY references. Catches at this level will maintain the stock at the current high biomass At 90 kt the risk of exceeding F_{msy} is only 12% but >5% of exceeding F_{lim}.

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 $B_{trigger}$ in the longer term (10 years) is less than 10%. Catch options up to 60 000 t, have a low risk (<5%) of exceeding *Flim* and a less than 10% risk of exceeding F_{msy} after 10 years. Taking up to 90 000 t/yr will increase the risk of going above F_{lim} by the end of the ten-year projection to around 10%.

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. To better capture the uncertainty involved we have estimated the yield associated with different risk levels of exceeding Fmsy (Table 7).

Conclusions:
Mortality. Fishing mortality has remained below F_{msy} throughout the history of the fishery. In 2014 there is a less than 5% risk of the *F* being above F_{msy}.

Biomass. Stock biomass has been above $B_{trigger}$ throughout the history of the fishery. The risk that the biomass at the end of 2014 is below $B_{trigger}$ is less than 1%

Recruitment. Recruitment indices have varied without trend in 2004 – 2013.

State of the Stock. The stock has declined since 2010, when it is estimated to have been close to the carrying capacity. Stock biomass is however estimated to be still well above $B_{trigger}$. The risks of stock biomass being below $B_{trigger}$ or of fishing mortality being above F_{msy} at the end of 2014 are both less than 5%.

Yield. Catch options up to 70 000 t/yr, have a risk below 10% of exceeding F_{msy} and below 5% of exceeding F_{lim} in the coming 2 years. At a higher risk larger yields may be achieved. E.g. catches of more than 200 kt can be taken without exceeding the median estimate of F_{msy}.

Special Comment. In recent years the distribution of the stock has changed, and some of the traditional fishing grounds are now less attractive to the fishery. Access to certain other fishing grounds is restricted by closures to prevent bycatch, and by regulations requiring vessels to sail long distances to specified entry and exit points of the Russian EEZ.

Additional considerations

Rebuilding potential

At 30% B_{msy} (B_{lim}) production is reduced to 50% of its maximum. With an 80% confidence interval on *r* (the intrinsic rate of increase) ranging from 0.11 to 0.53 per year, it would take 4-14 years to rebuild the stock from B_{lim} to B_{msy} without a fishery

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 documented as capable of consuming large amounts of shrimp. Continuing investigations to include cod predation as an explicit effect in the assessment model have so far not been successful; it has not been possible to establish a relationship between the density of cod and the stock dynamics of shrimp. The cod stock in the Barents Sea has increased considerably within the last ten years. If predation on shrimp were to increase rapidly beyond the range previously experienced, the shrimp stock might decrease in size more than the model results have indicated as likely.

Recruitment, and reaction time of the assessment model. The model used is best at describing trends in stock development but estimates, and uses, long-term averages of stock dynamic parameters. Large and/or sudden changes in recruitment or mortality may therefore be underestimated in model predictions. However such changes have not been observed in the recent period..

Oceanography

Temperatures in the Barents Sea have been high since 2004, largely due to increased inflow of warm water masses from the Norwegian Sea. An increase from 2011 to 2012 was observed in near-bottom temperatures primarily in the north and northwestern parts of the Barents Sea, but also in the southwest where temperatures at the bottom were the highest on record since 1951 (pers. comm. R. Ingvaldsen/A. Trofimov). In 2012 temperatures in the rest of the water column were largely unchanged, while temperatures near the surface were substantially lower than in 2011, probably due to a marked shift in the large wind and pressure field in the northernmost parts of the Barents Sea/Arctic Ocean (SCR Doc. 12/49).

Shrimps are mainly caught in areas where bottom temperatures are above 0°C. Highest densities are observed between zero and 4°C, while the upper limit of their preferred temperature range appears to lie at about 6-8°C. The eastward shift in shrimp distribution in recent years may be associated with changes in temperature

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.

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., 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. 2010. Shrimp (*Pandalus borealis*) in the Barents Sea – stock assessment and precautionary approach and MSY based management considerations. *NAFO SCR Doc. 10/61*.

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

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

Hvingel, C. and Thangstad, T. 2012a. Research survey information regarding northern shrimp (*Pandalus borealis*) in the Barents Sea and Svalbard area 2004-2012. *NAFO SCR Doc. 12/50.*.

Hvingel, C. and Thangstad, T 2012b. The Norwegian fishery for northern shrimp (Pandalus borealis) in the Barents Sea and round Svalbard 1970-2012. *NAFO SCR Doc. 12/51.*

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 (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 and four indices of fishable biomass – a standardized catch rate index based on fishery data (cpue), a Norwegian research survey index discontinued in 2004 (Survey 1), a Russian survey index discontinued in 2005 (Survey 2) and the current Joint Russian-Norwegian survey started in 2004 (Survey 3).

Year	Catch (ktons)	CPUE (index)	Survey 1 (ktons)	Survey 2 (ktons)	Survey 3 (ktons)
1970	5.5	-	-	-	-
1971	5.1	-	-	-	-
1972	6.8	-	-	-	-
1973	6.9	-	-	-	-
1974	8.0	-	-	-	-
1975	8.2	-	-	-	-
1976	9.8	-	-	-	-
1977	19.6	-	-	-	-
1978	38.9	-	-	-	-
1979	36.3	-	-	-	-
1980	46.3	1.000	-	-	-
1981	43.6	1.195	-	-	-
1982	62.8	1.150	327	-	-
1983	104.8	1.306	429	-	-
1984	128.1	1.382	471	661	-
1985	124.5	1.145	246	468	-
1986	65.3	0.677	166	399	-
1987	43.4	0.533	146	346	-
1988	48.7	0.573	181	233	-
1989	62.7	0.721	216	603	-
1990	81.2	0.736	262	1028	-
1991	75.3	0.778	321	1192	-
1992	68.6	0.903	239	876	-
1993	55.9	0.974	233	892	-
1994	28.3	0.800	161	404	-
1995	25.2	0.669	193	248	-
1996	34.5	0.838	276	441	-
1997	35.7	0.799	300	765	-
1998	55.8	0.969	341	576	-
1999	75.7	1.020	316	966	-
2000	80.7	0.902	247	800	-
2001	57.3	0.909	184	468	-
2002	61.5	0.896	196	980	-
2003	39.2	0.879	212	-	-
2004	42.7	0.751	151	-	261
2005	42.6	1.037	-	656	446
2006	29.6	1.133	-	-	517
2007	29.9	1.019	-	-	426
2008	28.2	1.040	-	-	317
2009	27.3	1.053	-	-	343
2010	25.2	0.986	-	-	482
2011	29.8	1.093	-	-	442
2012	25.5	0.813	-	-	487
2013	18.7	0.635	-	-	413
2014	21.0	0.634	-	-	-

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_{Ru}	reference	$\ln(q_E)$~dunif(-10,1)
Catchability survey 3	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	$1/\sigma_{Ru}^2$	reference	~dgamma(4,0.1125)
Precision survey 3	$1/\sigma_E^2$	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).

Pearson Correlation Coefficients, N = 10000
Prob > |r| under H0: Rho=0

	MSY	K	qR	qRu	qE	qC	P0	sdsurvR	sdsurvRu	sdsurvE	sdCPUE	sdP
MSY	1.00000	0.65545 <.0001	-0.56320 <.0001	-0.56175 <.0001	-0.56027 <.0001	-0.56409 <.0001	-0.01168 0.2430	0.01995 0.0461	-0.01820 0.0687	-0.01416 0.1569	0.02422 0.0154	0.08204 <.0001
K	0.65545 <.0001	1.00000	-0.73089 <.0001	-0.72768 <.0001	-0.72651 <.0001	-0.73280 <.0001	-0.00932 0.3515	0.00702 0.4826	-0.00036 0.9714	-0.00699 0.4846	-0.02530 0.0114	0.05607 <.0001
qR	-0.56320 <.0001	-0.73089 <.0001	1.00000	0.98871 <.0001	0.98903 <.0001	0.99673 <.0001	-0.00054 0.9571	-0.01488 0.1368	0.01062 0.2881	0.01825 0.0680	0.02601 0.0093	-0.05430 <.0001
qRu	-0.56175 <.0001	-0.72768 <.0001	0.98871 <.0001	1.00000	0.98215 <.0001	0.98969 <.0001	0.00120 0.9047	-0.01091 0.2753	0.00915 0.3601	0.01848 0.0646	0.02184 0.0290	-0.05531 <.0001
qE	-0.56027 <.0001	-0.72651 <.0001	0.98903 <.0001	0.98215 <.0001	1.00000	0.99173 <.0001	0.00020 0.9842	-0.02336 0.0195	0.01121 0.2624	0.01870 0.0616	0.03238 0.0012	-0.05105 <.0001
qC	-0.56409 <.0001	-0.73280 <.0001	0.99673 <.0001	0.98969 <.0001	0.99173 <.0001	1.00000	-0.00051 0.9596	-0.01460 0.1443	0.00952 0.3409	0.01823 0.0683	0.02633 0.0085	-0.05522 <.0001
P0	-0.01168 0.2430	-0.00932 0.3515	-0.00054 0.9571	0.00120 0.9047	0.00020 0.9842	-0.00051 0.9596	1.00000	-0.00206 0.8369	-0.01350 0.1770	-0.01676 0.0937	0.00419 0.6752	-0.00504 0.6146
sdsurvR	0.01995 0.0461	0.00702 0.4826	-0.01488 0.1368	-0.01091 0.2753	-0.02336 0.0195	-0.01460 0.1443	-0.00206 0.8369	1.00000	0.02534 0.0113	0.05056 <.0001	-0.18688 <.0001	-0.12418 <.0001
sdsurvRu	-0.01820 0.0687	-0.00036 0.9714	0.01062 0.2881	0.00915 0.3601	0.01121 0.2624	0.00952 0.3409	-0.01350 0.1770	0.02534 0.0113	1.00000	0.01850 0.0644	-0.09425 <.0001	-0.04920 <.0001
sdsurvE	-0.01416 0.1569	-0.00699 0.4846	0.01825 0.0680	0.01848 0.0646	0.01870 0.0616	0.01823 0.0683	-0.01676 0.0937	0.05056 <.0001	0.01850 0.0644	1.00000	-0.08917 <.0001	-0.04341 <.0001
sdCPUE	0.02422 0.0154	-0.02530 0.0114	0.02601 0.0093	0.02184 0.0290	0.03238 0.0012	0.02633 0.0085	0.00419 0.6752	-0.18688 <.0001	-0.09425 <.0001	-0.08917 <.0001	1.00000	0.18170 <.0001
sdP	0.08204 <.0001	0.05607 <.0001	-0.05430 <.0001	-0.05531 <.0001	-0.05105 <.0001	-0.05522 <.0001	-0.00504 0.6146	-0.12418 <.0001	-0.04920 <.0001	-0.04341 <.0001	0.18170 <.0001	1.00000

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

	CPUE		Survey 1		Survey 2		Survey 3	
Year	resid (%)	Pr	resid (%)	Pr	resid (%)	Pr	resid (%)	Pr
1980	2.78	0.46	-	-	-	-	-	-
1981	-3.82	0.60	-	-	-	-	-	-
1982	1.92	0.46	0.08	0.50	-	-	-	-
1983	2.35	0.45	-13.01	0.77	-	-	-	-
1984	-2.78	0.58	-20.36	0.88	42.10	0.16	-	-
1985	-14.97	0.85	10.49	0.31	45.43	0.16	-	-
1986	-1.78	0.56	11.84	0.29	16.50	0.34	-	-
1987	4.95	0.39	6.96	0.37	13.02	0.38	-	-
1988	4.27	0.40	-7.84	0.67	79.25	0.05	-	-
1989	3.15	0.43	-3.86	0.59	-13.78	0.67	-	-
1990	15.87	0.19	-9.12	0.69	-42.02	0.94	-	-
1991	20.93	0.13	-18.17	0.84	-44.83	0.95	-	-
1992	1.56	0.47	7.12	0.37	-26.82	0.82	-	-
1993	-6.59	0.67	9.01	0.34	-28.70	0.83	-	-
1994	-9.74	0.74	25.22	0.12	24.94	0.27	-	-
1995	2.15	0.45	-1.14	0.53	92.63	0.04	-	-
1996	1.23	0.49	-14.20	0.79	34.46	0.22	-	-
1997	15.44	0.20	-14.16	0.79	-15.71	0.70	-	-
1998	5.62	0.38	-16.20	0.82	24.21	0.28	-	-
1999	3.73	0.42	-6.52	0.65	-23.45	0.78	-	-
2000	2.21	0.45	4.21	0.44	-19.45	0.74	-	-
2001	-10.10	0.75	24.00	0.14	22.06	0.29	-	-
2002	-5.26	0.64	20.92	0.18	-39.44	0.92	-	-
2003	-7.03	0.67	7.63	0.36	-	-	-	-
2004	-6.00	0.66	30.54	0.09	-	-	18.24	0.22
2005	-5.76	0.65	-	-	4.17	0.46	-4.25	0.60
2006	-2.88	0.58	-	-	-	-	-6.99	0.64
2007	-1.09	0.54	-	-	-	-	3.38	0.44
2008	-9.80	0.75	-	-	-	-	29.29	0.11
2009	-8.99	0.72	-	-	-	-	22.10	0.18
2010	3.23	0.44	-	-	-	-	-7.71	0.66
2011	-5.53	0.65	-	-	-	-	2.10	0.47
2012	11.37	0.27	-	-	-	-	-18.74	0.84
2013	18.98	0.16	-	-	-	-	-20.04	0.86
2014	8.67	0.34	-	-	-	-	-	-

Table 5. Summary of parameter estimates: mean, standard deviation (sd) and quartiles of the posterior distributions of selected parameters (symbols are as in the text; r = intrinsic growth rate, P_0 = the 'initial" stock biomass in 1969).

	Mean	sd	25 %	Median	75 %
MSY (ktons), maximum sustainable yield	269	193	122	220	369
K (ktons), carying capacity	3426	1809	2050	3031	4394
r, intrinsic growth rate	0.32	0.16	0.20	0.32	0.43
q_R, catchability of survey 2	0.11	0.08	0.06	0.09	0.14
q_{Ru}, catchability of survey 1	0.29	0.20	0.15	0.23	0.36
q_E, catchability of survey 3	0.18	0.12	0.09	0.14	0.23
q_C, catchability of CPUE index	4.1E-04	2.8E-04	2.2E-04	3.3E-04	5.2E-04
P_0, initial relative biomass (1969)	1.51	0.26	1.33	1.50	1.68
P_{2014}, relative biomass in 2014	1.53	0.42	1.25	1.50	1.76
σ_R, coefficient of variation for survey 2	0.17	0.03	0.15	0.17	0.19
σ_{Ru}, coefficient of variation for survey 1	0.34	0.05	0.30	0.33	0.37
σ_E, coefficient of variation for survey 3	0.19	0.04	0.16	0.18	0.21
σ_C, coefficient of variation for CPUE index	0.14	0.02	0.12	0.13	0.15
σ_P, coefficient of variation for process	0.19	0.03	0.17	0.19	0.21

Table 6. Stock status and short term predictions. *Upper*: stock status for 2011-12.*Middle*: Predictions of risk and stock status in 2015 associated with six optional catch levels for 2015. *Lower* Predictions of risk and stock status in 2016 associated with six optional catch levels for 2015-16.

Status	2013	2014*
Risk of falling below B_{lim}	0.0 %	0.0 %
Risk of falling below $B_{trigger}$	0.1 %	0.3 %
Risk of exceeding F_{MSY}	1.1 %	1.3 %
Risk of exceeding F_{lim}	0.6 %	0.7 %
Stock size (B/Bmsy), median	1.38	1.50
Fishing mortality (F/Fmsy),	0.06	0.06
Productivity (% of MSY)	85 %	75 %

*Predicted catch = 21 ktons

	Catch option 2015 (ktons)					
	30	40	50	60	70	90
Risk of falling below B_{lim}	0.0 %	0.0 %	0.1 %	0.1 %	0.0 %	0.1 %
Risk of falling below $B_{trigger}$	0.5 %	0.5 %	0.5 %	0.5 %	0.6 %	0.6 %
Risk of exceeding F_{MSY}	2.3 %	3.6 %	5.1 %	6.3 %	7.9 %	11.5 %
Risk of exceeding F_{lim}	1.1 %	1.6 %	2.5 %	3.1 %	3.9 %	5.5 %
Stock size (B/Bmsy), median	1.58	1.57	1.57	1.55	1.55	1.53
Fishing mortality (F/Fmsy),	0.09	0.11	0.14	0.17	0.20	0.26

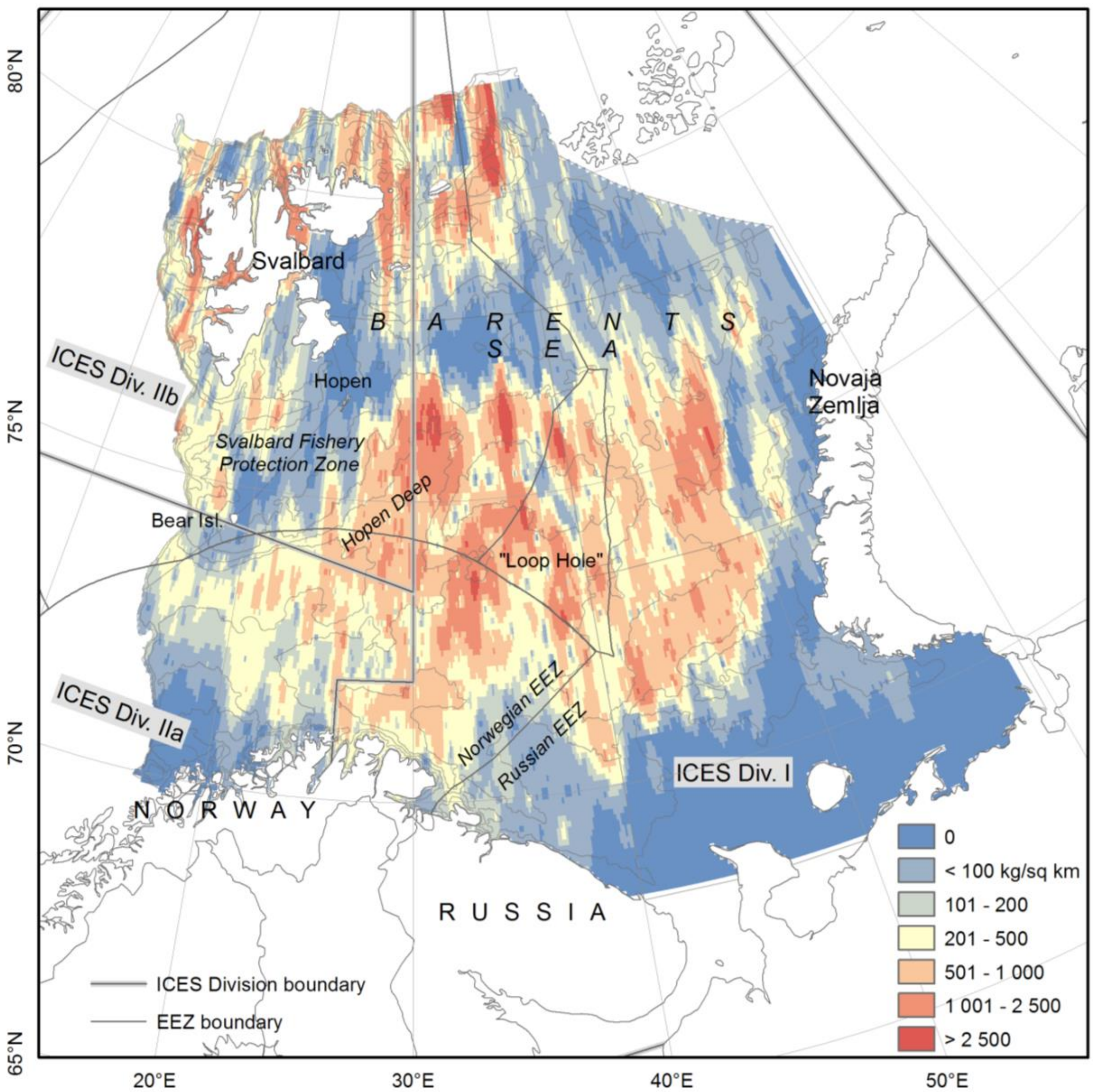
Productivity (% of MSY)	66 %	67 %	68 %	69 %	70 %	72 %

	Catch option 2015-16 (ktons)					
	30	40	50	60	70	90
Risk of falling below B_{lim}	0.0 %	0.1 %	0.1 %	0.1 %	0.2 %	0.2 %
Risk of falling below $B_{trigger}$	0.6 %	0.7 %	0.8 %	0.9 %	0.9 %	1.1 %
Risk of exceeding F_{MSY}	2.5 %	3.6 %	5.2 %	6.4 %	8.3 %	12.0 %
Risk of exceeding F_{lim}	1.2 %	1.7 %	2.6 %	3.4 %	4.0 %	6.2 %
Stock size (B/Bmsy), median	1.65	1.63	1.62	1.61	1.59	1.56
Fishing mortality (F/Fmsy),	0.08	0.11	0.14	0.17	0.20	0.26
Productivity (% of MSY)	58 %	61 %	61 %	63 %	65 %	69 %

Table 7 Yield predictions (kt) at five risk levels of exceeding F_{msy}.

	Risk of exceeding F_{msy}				
Year	5 %	10 %	25 %	35 %	50 %
2015	45	73	151	221	290
2016	45	74	151	219	286
2017	44	73	144	205	266
2018	44	69	137	196	255
2019	42	69	133	189	245

Fig. 1. Stock distribution mean index of density (kg/km^2) based on survey data 2000-2010.



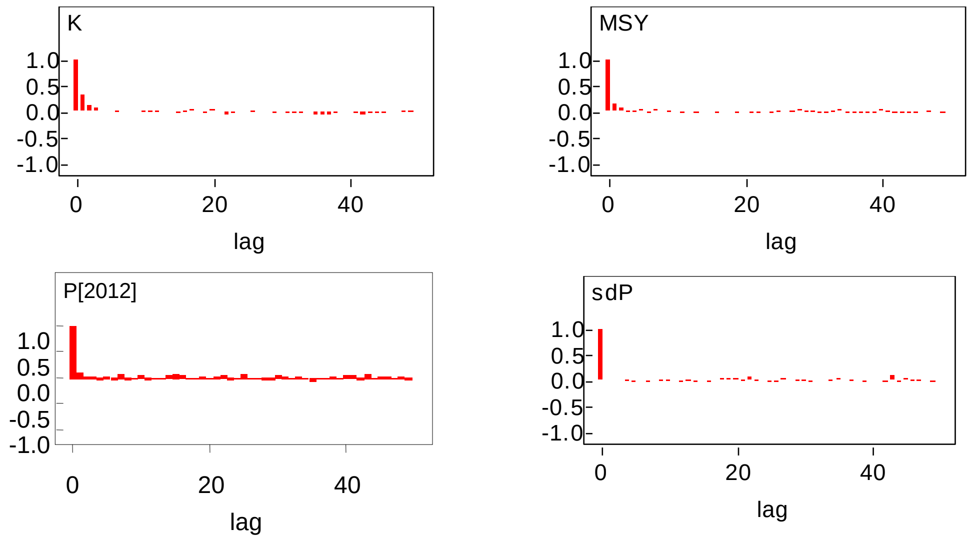


Fig. 2. Autocorrelation function of values sampled for four selected variables out to lag 50. K is the carrying capacity, P[2012] is the relative biomass in year 2012, MSY is maximum sustainable yield and sdP is the process error.

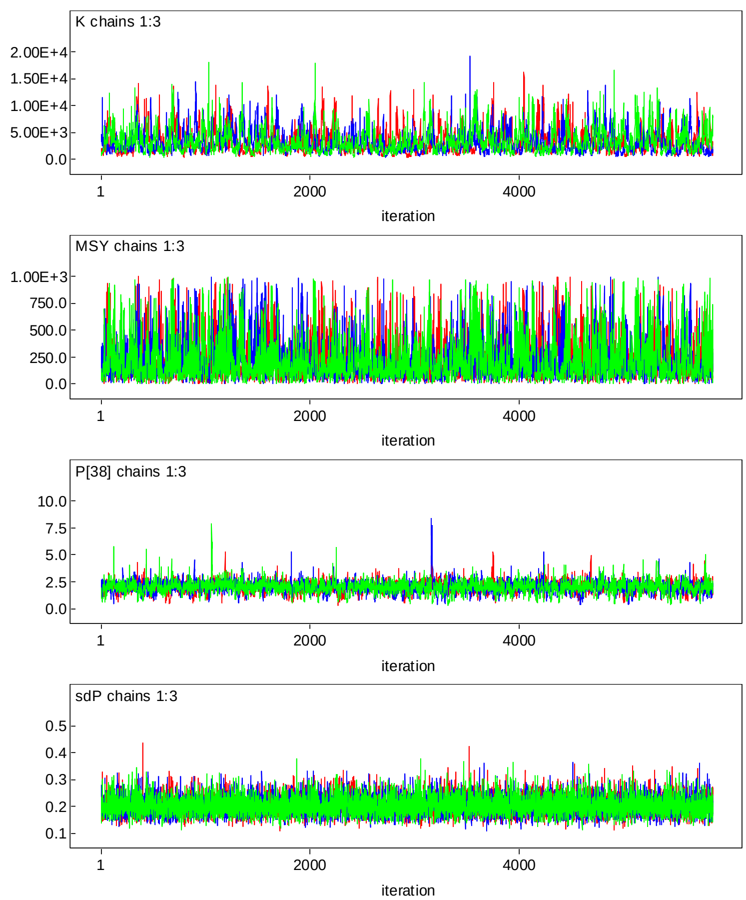


Fig. 3. Three traces (red, green, blue) with different initial values of four selected variables. K is the carrying capacity, MSY is maximum sustainable yield, P[38] is the relative biomass in year 2007, and sdP is the process error.

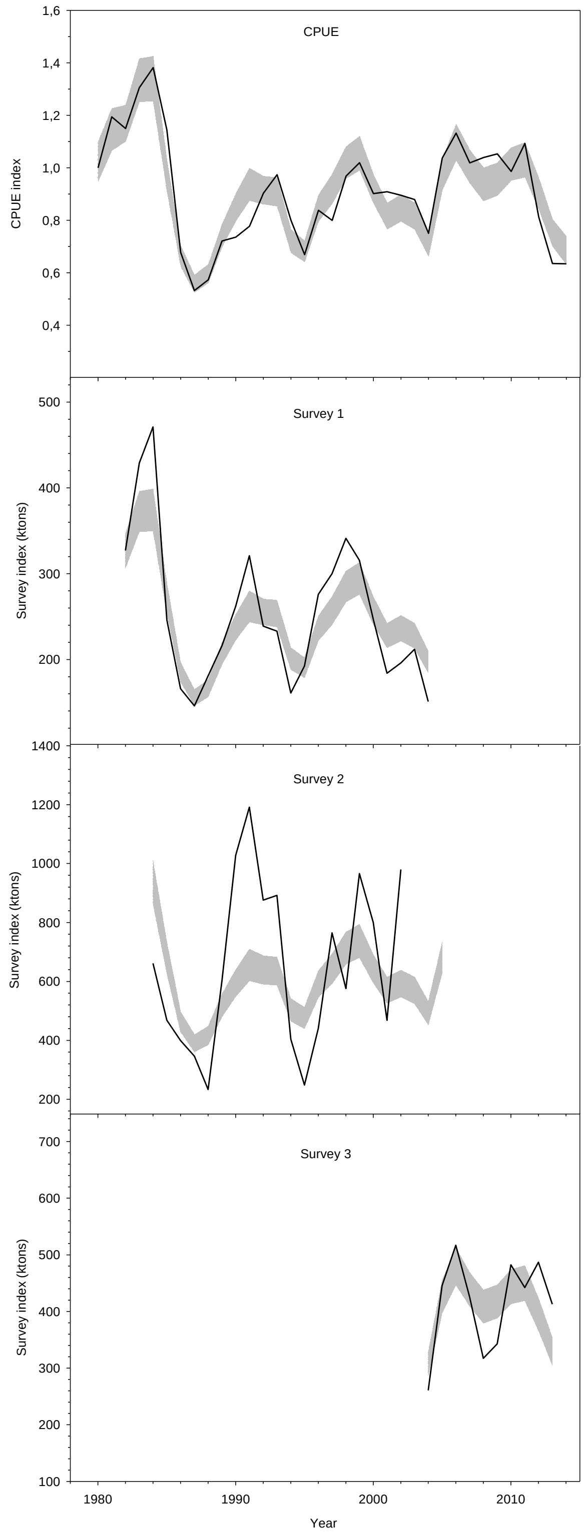


Fig. 4. Observed (solid line) and estimated (shaded) series of the included biomass indices. Gray shaded areas are the inter-quartile ranges of the posteriors.

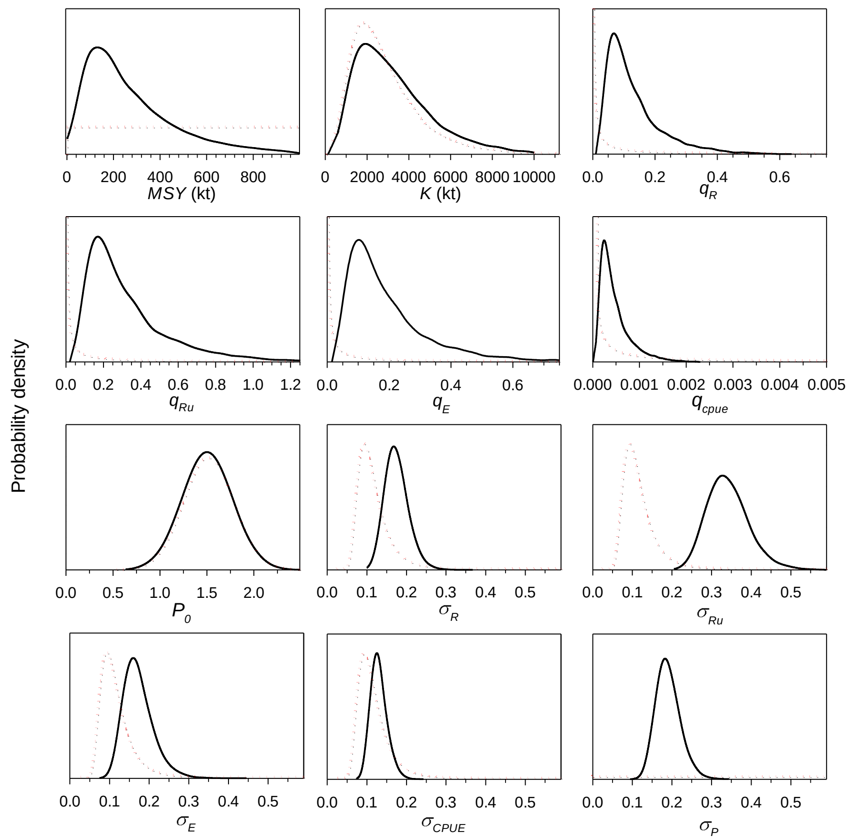


Fig. 5. Probability density distributions of model parameters: estimated posterior (solid line) and prior (broken line) distributions.

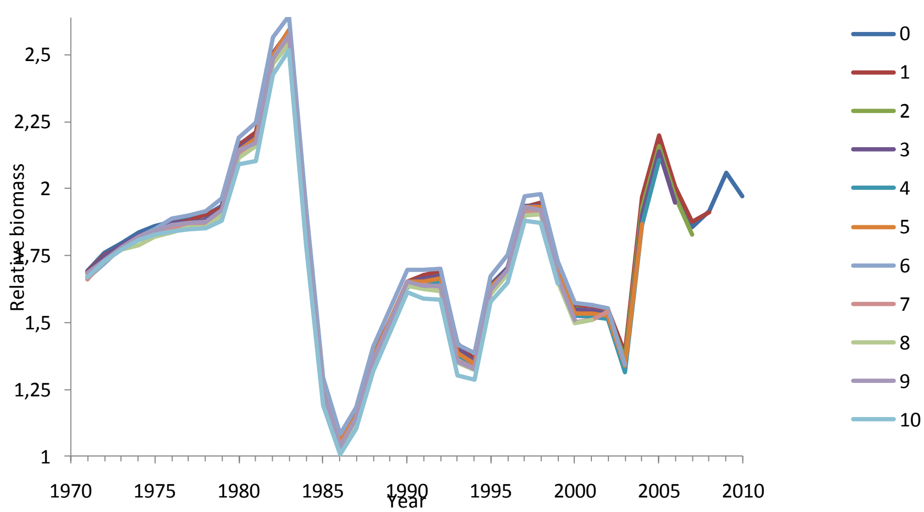


Fig. 6. Retrospective plot of median relative biomass (B/Bmsy). Relative biomass series are estimated by consecutively leaving out from 0 to 10 years of data.

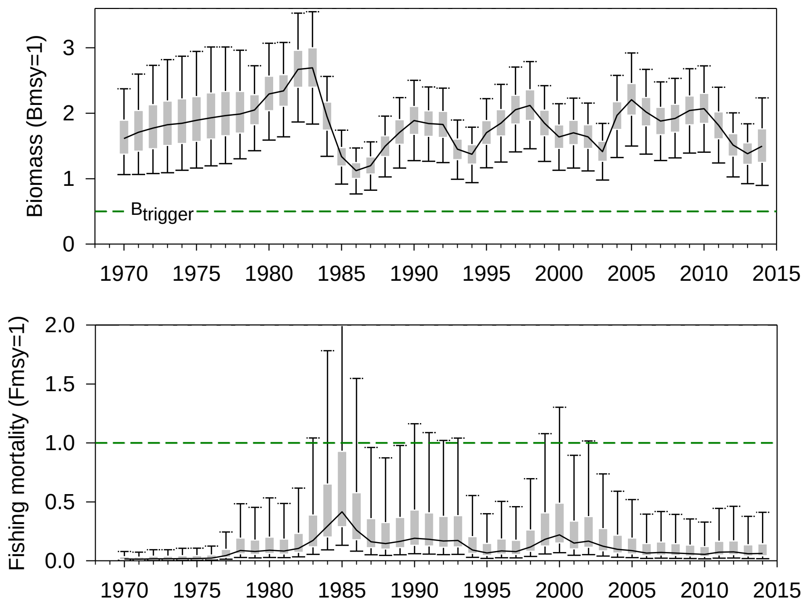


Fig. 7. Estimated relative biomass (B/B_{msy}) and fishing mortality (F/F_{msy}) for 1970–2014. Boxes represent inter-quartile ranges and the solid black line in the (approximate) middle of each box is the median; the arms of each box cover the central 90% of the distribution. The broken lines are the $B_{trigger}$ and F_{msy} references respectively.

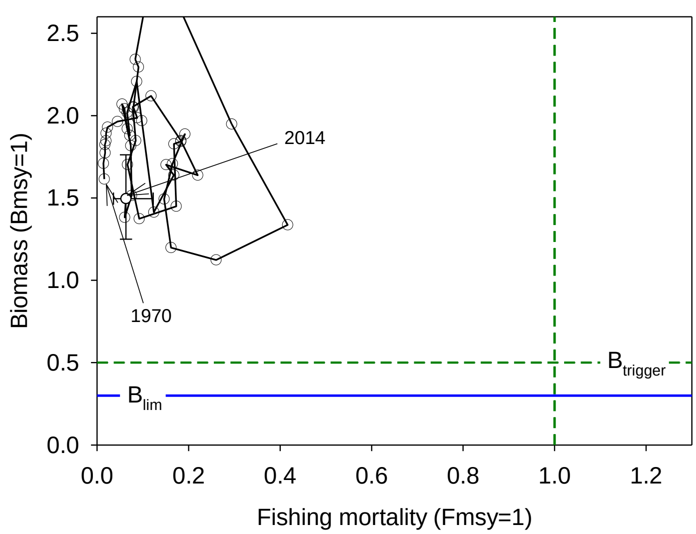


Fig. 9. Estimated annual median biomass-ratio (B/B_{MSY}) and fishing mortality-ratio (F/F_{MSY}) 1970-2014. The MSY reference points for stock biomass, $B_{trigger}$, and fishing mortality, F_{msy}, are indicated by broken lines. The PA reference B_{lim} is the blue line. Error bars on the 2014 value are quartiles.

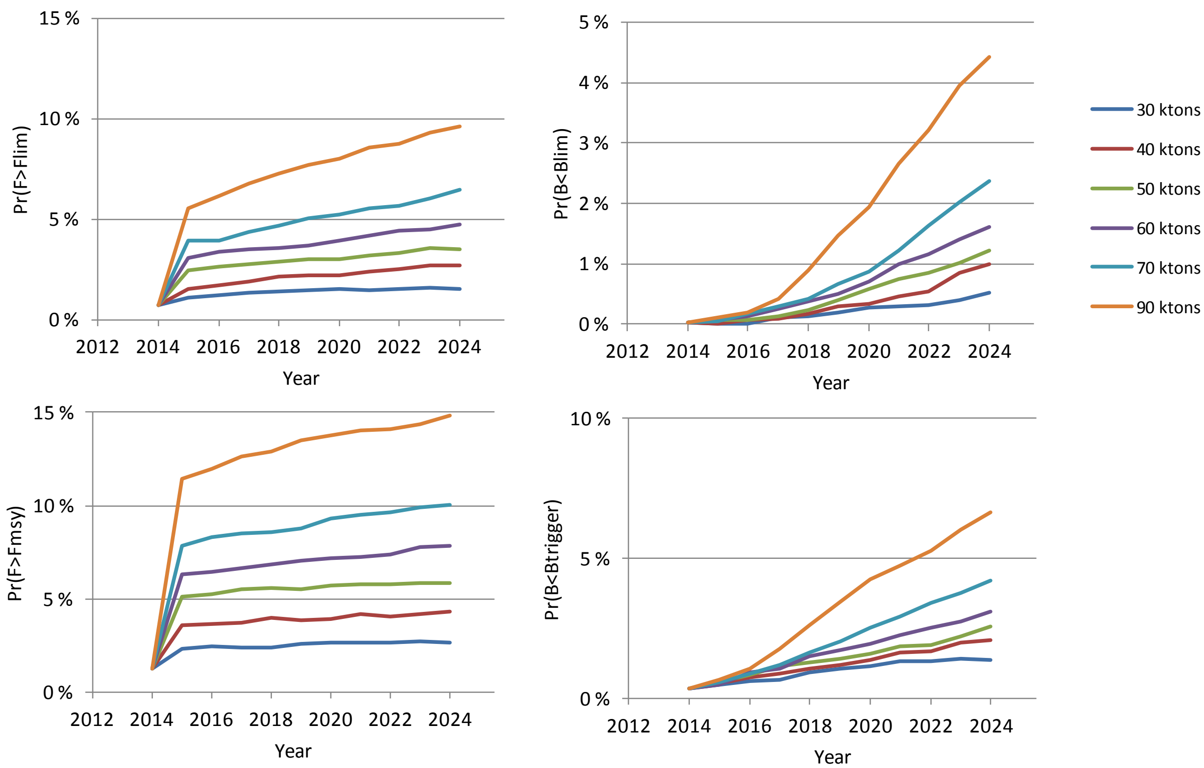


Fig. 10. Risk projections: Projections of estimated risk of going below $B_{trigger}$ and B_{lim}, and of exceeding F_{msy} and F_{lim}, given different catch options.

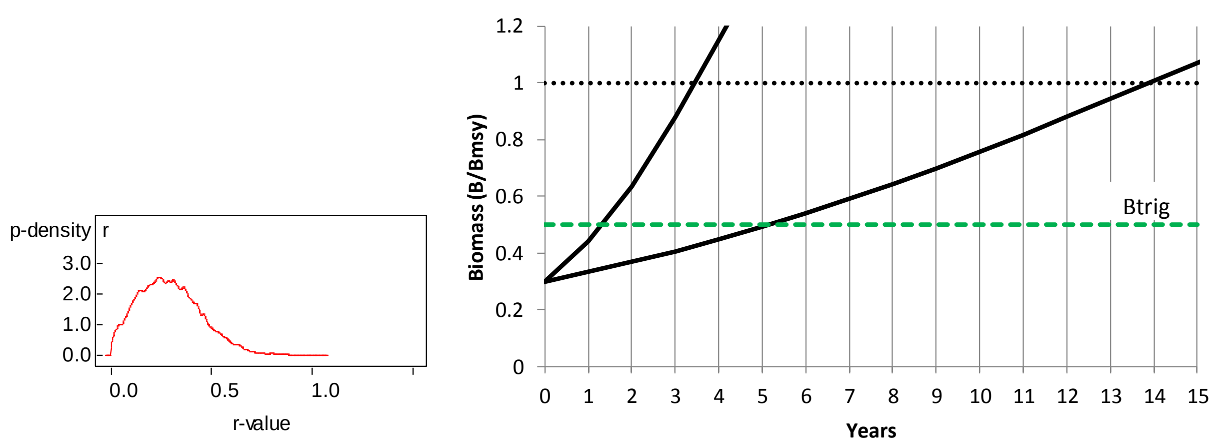


Fig. 11. *Left*:The posterior probability density distribution of r, the intrinsic rate of growth. Right: estimated recovery time from Blim (0.3Bmsy) to Bmsy (relative biomass = 1) given r values ranging within the 80% conf. lim. of the posterior (left figure) and no fishing mortality.