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Shrimp (*Pandalus borealis*) in the Barents Sea – Stock assessment 2019

by

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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 maximum sustainable yield, *MSY*, and habitat carrying capacity, *K*.

The Stock is estimated to be in a healthy state and exploited sustainably. Stock biomass has been above Btrigger throughout the history of the fishery. The probability that the biomass at the end of 2019 is below Btrigger is less than 1%. Fishing mortality is likely to have remained below F_{msy}. In 2019 there is a less than 2% risk of fishing mortality exceeding F_{lim}.

The mode of the estimated distribution of the maximum annual production surplus, available to the fishery (*MSY*) was at 110,000 tonnes. Catch options up to 150 kt (Fmsy mode) for 2020 have low risks of exceeding F_{msy} (<16%), Flim (<5%), and of going below Btrigger (<1%) by the end of 2020.

The results and conclusions of this year's assessment are consistent with those of previous years when the same assessment framework was used (i.e. since 2006), however, slightly more optimistic than the 2018 assessment. A benchmark assessment workshop is planned for 2020/21.

Introduction

Northern shrimp (*Pandalus borealis*) in the Barents Sea and in the Svalbard fishery protection zone (ICES Subareas 1 and 2) is considered as one stock (Fig. 1) (Martinez et al. 2006). Norwegian and Russian vessels exploit the stock in the entire area, while vessels from other nations are restricted to the Svalbard fishery zone and the "Loop Hole". Norwegian vessels initiated the fishery in 1970. As the fishery developed, vessels from several nations joined and the annual catch reached 128 000 t in 1984. In the recent 10-year period catches have varied between 20 000 and 78 000 t/yr, 30–90% taken by Norwegian vessels and the rest by vessels from Russia, Iceland, Greenland, Faeroes and the EU (Table 1).

There is no TAC established for this stock. The fishery is partly regulated by effort control, and a partial TAC (Russian zone only). Licenses are required for the Russian and Norwegian vessels. The fishing activity of these license holders is 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. The minimum stretched mesh size is 35 mm. Bycatch is limited by mandatory sorting grids and by the temporary closing of areas where excessive bycatch of juvenile cod, haddock, Greenland halibut, redfish or shrimp <15 mm CL is registered.

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. 2005). 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.3.2.3 (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, 2016b); and three trawl-survey biomass index for 1982–2004, $survR_t$, for 1984-2005, $survRu_t$ and 2004-now, $survE_t$ (Hvingel et al 2016a). 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:

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

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:

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

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 (buffer reference points are obsolete as probability of transgressing the PA limit reference points can be calculated directly):

	Type	Value	Technical basis
MSY approach	$B_{trigger}$	$0.5B_{MSY}$	Approximately corresponding to 10th percentile of the B_{msy} estimate (NIPAG 2010)
	F_{MSY}		Resulting from the assessment model.
Precautionary approach	B_{lim}	$0.3B_{MSY}$	The *B* where production is reduced to 50% *MSY* (NIPAG 2006)
	F_{lim}	$1.7F_{MSY}$	The *F* that drives the stock to B_{lim}

Changes from the 2019 assessment
This assessment is an update of the 2018 assessment with the following changes:

- Model: No changes.
- Priors: No changes.
- Input data: addition of two years of survey data to input series (survey 3), no changes back in time. Update of the standardized CPUE series with remaining logbook data for 2018 and partial data for 2019 and addition of these two data points to the input set (the 2018 value was not used in the 2018 assessment, se SCR Doc 18/65)

Results, model performance

The model did have a tendency to be too optimistic regarding the final years during the stock decline 2010 to 2014 (Fig. 6), but all of these were well inside the updated estimated probability distributions the following year. The model did however underestimate the 2018 and 2019 increases. Otherwise, the results of this year's final model run are largely consistent with those of the previous years (model introduced in 2006). 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 mostly better estimated than the survey series except for the two most recent years. Survey 2 showed some variation that was poorly captured in particular in the early-1990s. 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 near "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 median survey catchabilities, q_R, q_{Ru} and q_E, were in the range of 12-31% (Table 5). The estimated CVs of survey 2 and 3 had a median at about 17% while the CV of survey 1 was double that at 0.33. The CV of the CPUE series was lowest at 14%. The process error, σ_p, had a median of 20%.

Assessment results

Stock status

Since 1970, stock biomass has been above $B_{trigger}$ (Fig. 7 upper). A steep decline in stock biomass in the mid-1980s was noted following some years with high catches and the median relative biomass almost dropped to the Bmsy-level. Since the late 1980s, however, the stock has varied with a slightly increasing trend including a noticeable increase in the most recent years, 2018 and 2019. The estimated risk of stock biomass being below Btrigger by the end of 2019 is less than 1% (Table 6). The median estimate of fishing mortality has remained below F_{msy} throughout the history of the fishery (Fig. 7 lower). In 2019, there is a less than 5% risk of the F being above F_{msy} (Table 6).

The posterior for *MSY* was positively skewed with a mode at 110 ktons (Fig. 5) and upper and lower quartiles at 96 ktons and 255 ktons (Table 5). As mentioned above the right tail of the MSY-posterior showed some sensitivity to changes in the prior for K. Summaries of the estimated posterior probability distributions of selected parameters are shown in Table 5.

Projections.

A catch projection for 2020 at the median of Fmsy (ICES MSY approach) would imply catches of no more than 306 ktons – way outside the catch history of the fishery. Given that the right-hand side of the probability distributions of the yield at the Fmsy is less well estimated, it is considered more appropriate to apply the mode as a point estimate of yield at Fmsy. This mode is at 150 kt. Assuming a catch of 78 kt for 2019, catch options up to 150 kt for 2020 have low risks of exceeding Fmsy (<17%), Flim (<5%), and of going below Btrigger (<1%) by the end of 2020 (Table 7) and all these options are likely to maintain the stock at a high level.

Conclusions:

Biomass. Stock biomass has been above $B_{trigger}$ throughout the history of the fishery. The probability that the biomass at the end of 2019 is below $B_{trigger}$ is less than 1%.

Mortality. Fishing mortality is likely to have remained below F_{msy} throughout the history of the fishery. In 2019 there is a less than 2% risk of fishing mortality exceeding F_{lim}.

Recruitment. No explicit information has been available since 2013.

State of the Stock. The Stock is estimated to be in a healthy state and exploited sustainably.

Additional considerations

Rebuilding potential
At B_{lim} stock production is reduced to 50% of its maximum. The estimate of the *r* (intrinsic rate of increase) had 80% confidence interval ranging from 0.11 to 0.52 (Fig. 8 *left*). With *r* in this interval, it would take between 1.5 and 6 years to rebuild the stock from B_{lim} to $B_{trigger}$ and 4-15 years to rebuild the stock to B_{msy} under moratorium (Fig. 8 *right*).

Environmental conditions
Since the 1980s, the Barents Sea has gone from a situation with high fishing pressure, cold conditions and low demersal fish stock levels, to the current situation with high levels of demersal fish stocks, reduced fishing pressure and warm conditions. Cod biomass have decreased in recent years following a peak around 2013 but is still at a relatively high level. With the reduction in cod abundance, predation pressure on shrimp may be less intense. The levels of environmental and organic pollution in the Barents Sea are generally low and do not exceed threshold limits or global background levels. More detailed information can be found in ICES (2018b).

Temperature. In the ecosystem survey, shrimps were only caught in areas where bottom temperatures were above 0°C. Highest shrimp densities were observed between zero and 4°C, while the limit of their upper temperature preference appears to lie at about 6-8°C. The warming of the western Barents Sea coincides with the shift in shrimp distribution eastwards, thus temperature is probably a factor in explaining the observed changes in spatial distribution.

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 decreased but remained at a relatively high level during the recent ten years. If predation on shrimp was 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 projecting 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 which seems to be exemplified by the 2018-19 abrupt increase in stock biomass.

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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	1.378	471	661	-
1985	124.5	1.139	246	468	-
1986	65.3	0.676	166	399	-
1987	43.4	0.532	146	346	-
1988	48.7	0.574	181	233	-
1989	62.7	0.723	216	603	-
1990	81.2	0.737	262	1028	-
1991	75.3	0.779	321	1192	-
1992	68.6	0.905	239	876	-
1993	55.9	0.976	233	892	-
1994	28.3	0.801	161	404	-
1995	25.2	0.670	193	248	-
1996	34.5	0.840	276	441	-
1997	35.7	0.804	300	765	-
1998	55.8	0.975	341	576	-
1999	75.7	1.027	316	966	-
2000	80.7	0.912	247	800	-
2001	57.3	0.924	184	468	-
2002	61.5	0.910	196	980	-
2003	39.2	0.895	212	-	-
2004	42.7	0.765	151	-	261
2005	42.6	1.061	-	656	446
2006	29.6	1.158	-	-	517
2007	29.9	1.048	-	-	426
2008	28.2	1.088	-	-	317
2009	27.3	1.118	-	-	343
2010	25.2	1.040	-	-	482
2011	30.2	1.171	-	-	442
2012	24.8	0.837	-	-	487
2013	19.2	0.707	-	-	413
2014	21.0	0.680	-	-	307
2015	34.0	0.764	-	-	324
2016	30.7	0.696	-	-	257
2017	30.4	0.888	-	-	428
2018	55.9	1.627	-	-	501
2019	78.0	2.044	-	-	632

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(1,500)
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	$1/\sigma_R^2$	informative	~dgamma(4,0.1125)
Precision survey 2	$1/\sigma_{Ru}^2$	informative	~dgamma(4,0.1125)
Precision survey 3	$1/\sigma_E^2$	informative	~dgamma(4,0.1125)
Precision CPUE	$1/\sigma_C^2$	informative	~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 getting a more extreme observation (Pr).

	CPUE		Survey 1		Survey 2		Survey 3	
Year	resid (%)	Pr	resid (%)	Pr	resid (%)	Pr	resid (%)	Pr
1980	4.90	0.41	-	-	-	-	-	-
1981	-2.49	0.57	-	-	-	-	-	-
1982	3.30	0.44	0.73	0.49	-	-	-	-
1983	3.94	0.42	-12.27	0.75	-	-	-	-
1984	-1.71	0.56	-20.28	0.88	42.16	0.16	-	-
1985	-14.25	0.83	10.07	0.32	44.80	0.16	-	-
1986	-1.85	0.56	10.81	0.31	15.37	0.35	-	-
1987	4.77	0.40	5.83	0.39	11.74	0.39	-	-
1988	4.08	0.42	-8.49	0.69	77.87	0.06	-	-
1989	3.51	0.42	-3.94	0.59	-13.91	0.67	-	-
1990	16.55	0.18	-9.11	0.69	-42.03	0.94	-	-
1991	21.66	0.13	-18.16	0.85	-44.85	0.95	-	-
1992	1.94	0.47	7.01	0.37	-26.93	0.82	-	-
1993	-6.47	0.67	8.62	0.34	-29.00	0.84	-	-
1994	-9.90	0.74	24.28	0.13	23.93	0.28	-	-
1995	2.08	0.46	-1.75	0.55	91.33	0.04	-	-
1996	1.61	0.47	-14.27	0.79	34.26	0.21	-	-
1997	15.79	0.20	-13.98	0.79	-15.59	0.69	-	-
1998	6.27	0.36	-15.76	0.81	24.77	0.27	-	-
1999	4.07	0.42	-6.23	0.64	-23.24	0.78	-	-
2000	2.13	0.45	4.53	0.42	-19.24	0.73	-	-
2001	-10.61	0.76	24.46	0.14	22.44	0.28	-	-
2002	-5.70	0.65	21.39	0.17	-39.25	0.93	-	-
2003	-7.60	0.69	8.15	0.36	-	-	-	-
2004	-5.90	0.65	32.20	0.08	-	-	11.90	0.28
2005	-3.67	0.59	-	-	8.12	0.42	-7.04	0.65
2006	-0.07	0.51	-	-	-	-	-9.21	0.70
2007	0.74	0.49	-	-	-	-	0.52	0.50
2008	-10.39	0.75	-	-	-	-	24.73	0.13
2009	-9.79	0.74	-	-	-	-	19.26	0.18
2010	4.80	0.40	-	-	-	-	-8.28	0.68
2011	-5.38	0.65	-	-	-	-	1.68	0.48
2012	16.18	0.20	-	-	-	-	-19.01	0.87
2013	18.24	0.17	-	-	-	-	-17.90	0.85
2014	9.13	0.31	-	-	-	-	-1.95	0.55
2015	0.98	0.49	-	-	-	-	-3.41	0.58
2016	4.66	0.40	-	-	-	-	14.97	0.24
2017	9.37	0.30	-	-	-	-	-7.96	0.68
2018	-14.31	0.83	-	-	-	-	12.87	0.27
2019	-16.75	0.86	-	-	-	-	9.20	0.33

Table 5. Summary 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 %	Median (2018)
MSY (ktons), maximum sustainable yield	185	112	96	160	255	202
K (ktons), carying capacity	2973	1563	1816	2664	3803	2775
r, intrinsic growth rate	0.27	0.14	0.17	0.26	0.36	0.30
q_R, catchability of survey 2	0.15	0.10	0.08	0.12	0.19	0.10
q_{Ru}, catchability of survey 1	0.38	0.25	0.20	0.31	0.48	0.26
q_E, catchability of survey 3	0.22	0.15	0.12	0.18	0.28	0.16
q_C, catchability of CPUE index	5.5E-04	3.6E-04	3.0E-04	4.5E-04	6.9E-04	3.67E-04
P_0, initial relative biomass (1969)	1.50	0.26	1.33	1.50	1.67	1.51
P_{2019}, relative biomass in 2019	2.47	0.73	1.99	2.37	2.83	1.78
σ_R, coefficient of variation for survey 2	0.17	0.03	0.15	0.17	0.19	0.17
σ_{Ru}, coefficient of variation for survey 1	0.34	0.05	0.30	0.33	0.37	0.34
σ_E, coefficient of variation for survey 3	0.17	0.03	0.14	0.16	0.18	0.17
σ_C, coefficient of variation for CPUE index	0.14	0.02	0.12	0.14	0.15	0.13
σ_P, coefficient of variation for process	0.21	0.03	0.19	0.20	0.22	0.18

Table 6. Shrimp in ICES SA 1 and 2: Stock status for 2018 and predicted to the end of 2019.

Status	2018	2019*
Risk of falling below B_{lim}	0.0 %	0.0 %
Risk of falling below $B_{trigger}$	0.0 %	0.0 %
Risk of exceeding F_{MSY}	1.9 %	3.8 %
Risk of exceeding F_{lim}	0.8 %	1.6 %
Stock size (B/Bmsy), median	2.93	2.37
Fishing mortality (F/Fmsy),	0.12	0.20
Productivity (% of MSY)	-272 %	-88 %

*Predicted catch = 78 ktons

Table 7. Shrimp in ICES SA 1 and 2: Predictions of risk and stock status associated with optional catch levels for 2020.

	Catch option 2020 (ktons)						Yield at Fmsy (mode)	Yield at Fmsy (median)
	60	70	80	90	100	110	150	306
Risk of falling below B_{lim}	0.0 %	0.0 %	0.0 %	0.0 %	0.0 %	0.0 %	0.3 %	0.6 %
Risk of falling below $B_{trigger}$	0.0 %	0.0 %	0.1 %	0.1 %	0.1 %	0.0 %	0.9 %	1.7 %
Risk of exceeding F_{MSY}	2.8 %	3.7 %	4.8 %	5.8 %	7.2 %	9.1 %	16.2 %	50 %
Risk of exceeding F_{lim}	1.2 %	1.5 %	1.8 %	2.3 %	2.7 %	3.4 %	4.8 %	25 %
Stock size (B/Bmsy), median	2.17	2.17	2.16	2.15	2.14	2.13	1.95	1.67
Fishing mortality (F/Fmsy),	0.17	0.20	0.23	0.26	0.29	0.32	0.41	1.00
Productivity (% of MSY)	-36 %	-36 %	-35 %	-31 %	-29 %	-28 %	10 %	55 %

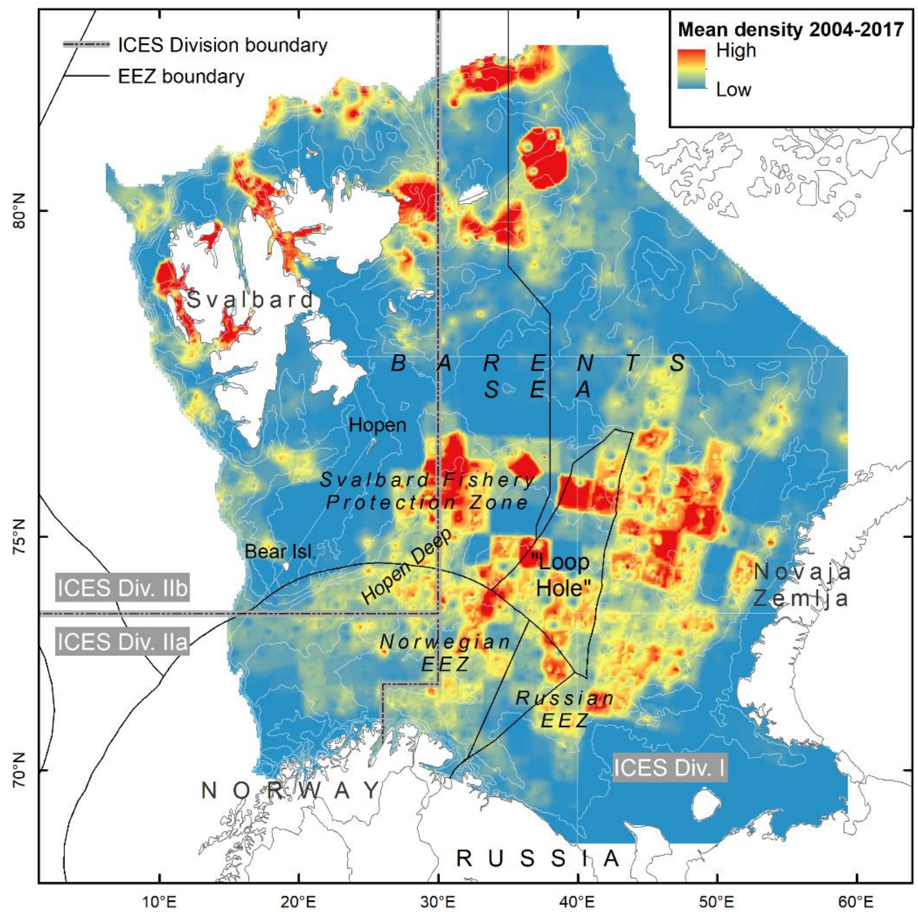


Figure 1. Shrimp in ICES SA 1 and 2: Stock distribution. Survey density index (kg/km2).

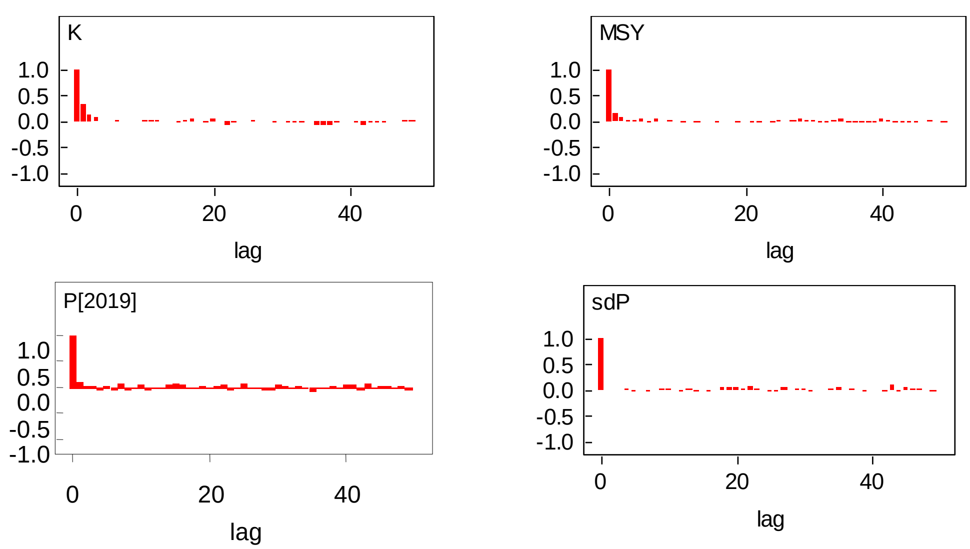


Figure 2. Autocorrelation function of values sampled for four selected variables out to lag 50. K is the carrying capacity, P[2019] is the relative biomass in year 2019, MSY is maximum sustainable yield and sdP is the process error.

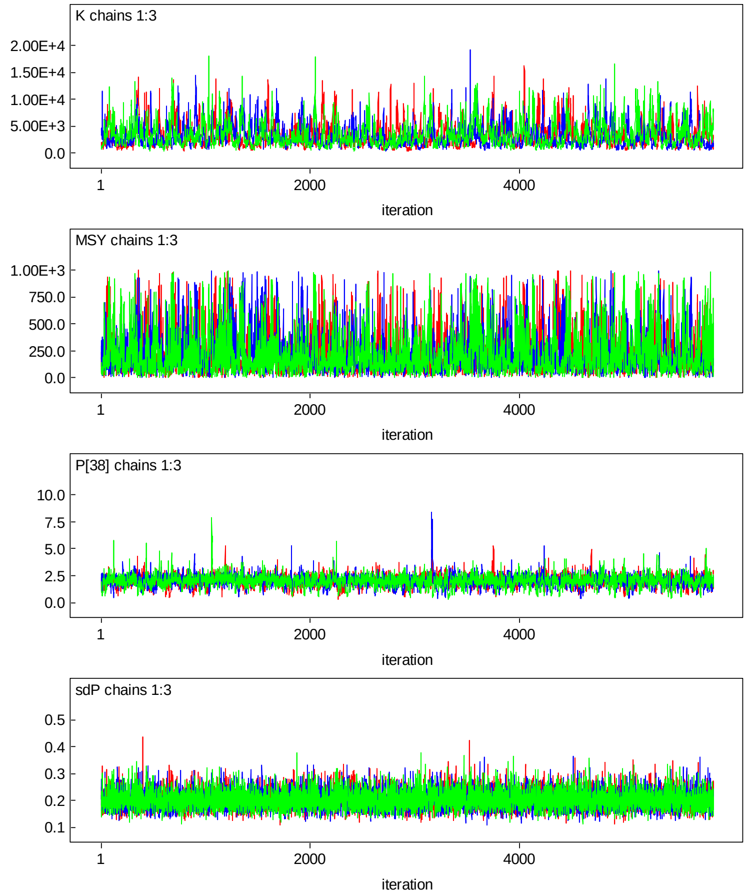


Figure 3. Three traces (red, green, blue) with different initial values of four selected variables. K is the carrying capacity, P[38] is the relative biomass in year 2007, MSY is maximum sustainable yield and sdP is the process error.

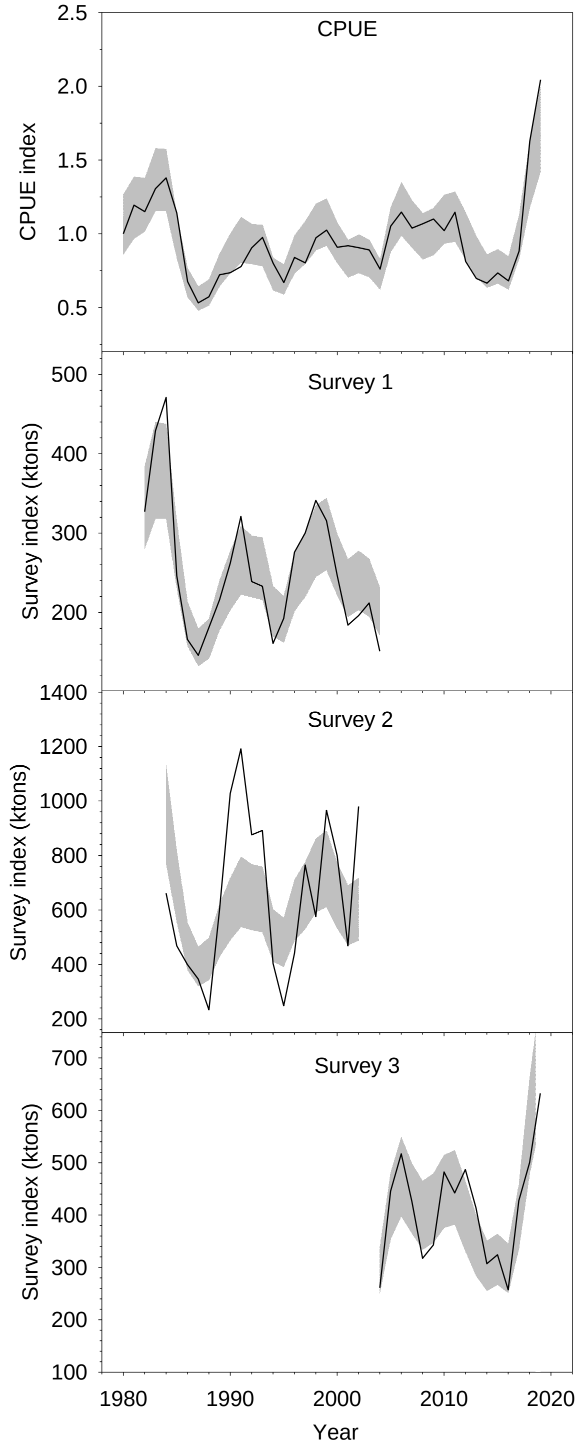


Figure 4. Shrimp in ICES SA I and II: Observed (solid line) and estimated (shaded) series of the included biomass indices: the standardized catch-per-unit-effort (CPUE), the 1982–2004 shrimp survey (survey 1), a Russian survey index discontinued in 2005 (Survey 2) and the Joint Norwegian-Russian Ecosystem Survey (survey 3) since 2004. Grey shaded areas cover the 90% probability interval of their posteriors.

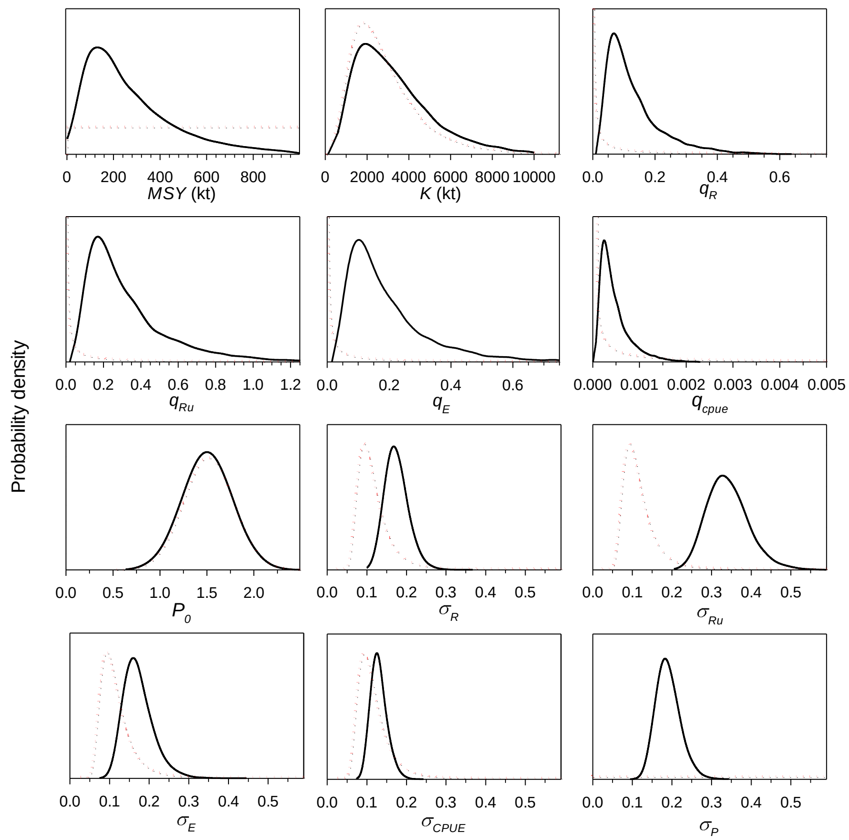
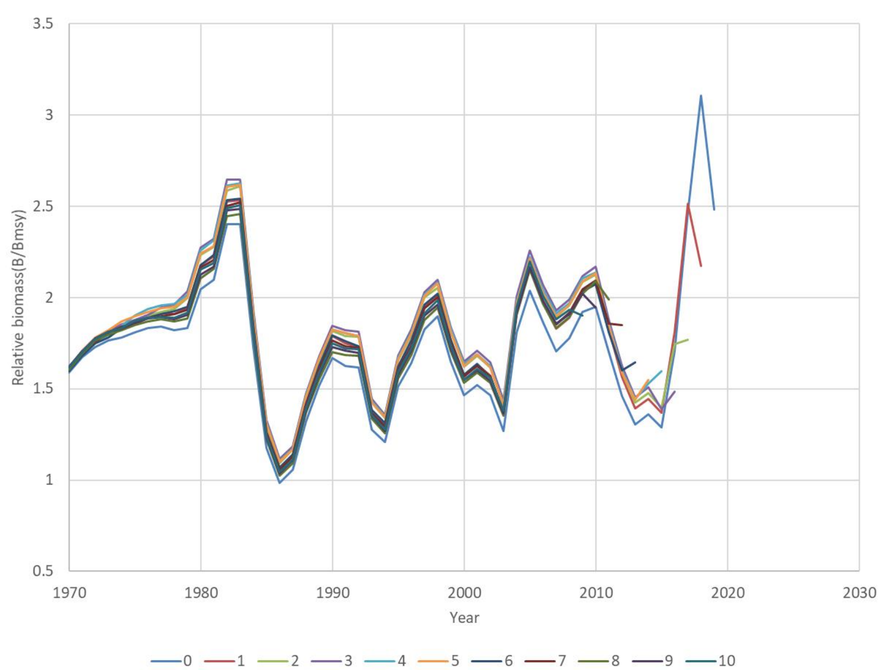


Figure 5. Probability density distributions of model parameters: estimated posterior (solid line) and prior



(broken line) distributions.

Figure 6. Retrospective plot of median relative biomass (B/B_{msy}). Relative biomass series are estimated by consecutively leaving out from 0 to 10 years of data.

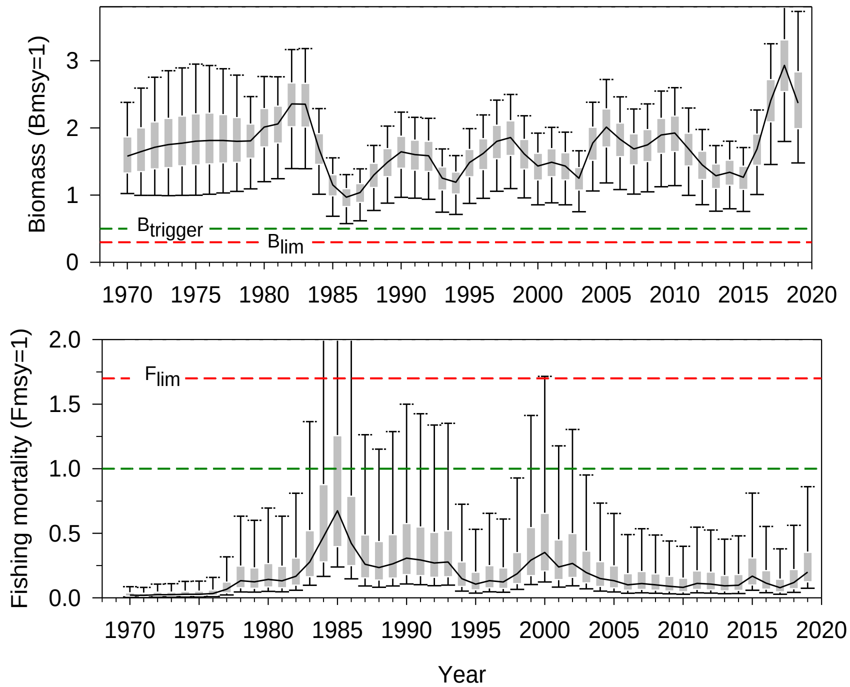


Figure 7. Shrimp in ICES SA 1 and 2: Estimated relative biomass (B/B_{msy}) and fishing mortality (F/F_{msy}) since 1970. Boxes represent inter-quartile ranges and the solid black line in the middle of each box is the median; the arms of each box cover the central 90% of the distribution. The broken lines indicate *MSY* and precautionary approach reference points.

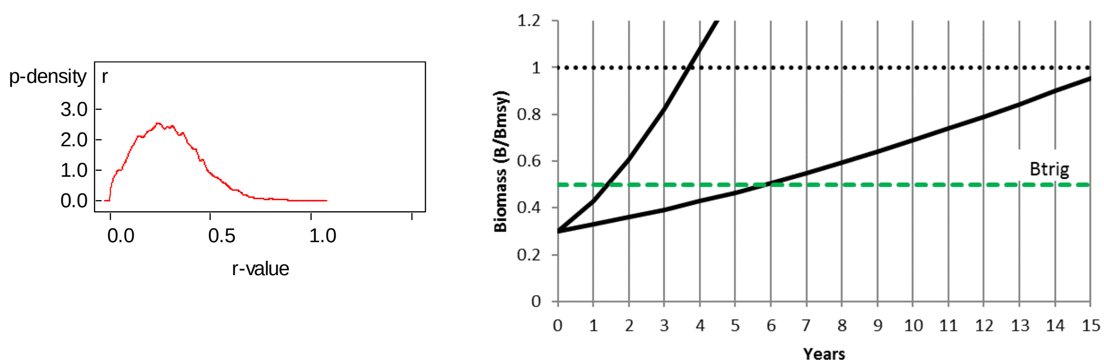


Figure 8. Shrimp in ICES SA 1 and 2: The posterior probability density distribution of r, the intrinsic rate of growth (left). Right: estimated recovery time from B_{lim} ($0.3B_{msy}$) to B_{msy} (relative biomass = 1) given r values ranging within the 80% conf. lim. of the posterior (left figure) and no fishing mortality.