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Assessment, Prediction and Risk Analysis: Stock Development and Production of Northern Shrimp off West Greenland

by

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Abstract

An assessment of the West Greenland stock of *Pandalus borealis* was carried out, and management advice formulated, using the new framework for assessment and advice adopted by STACFIS and Scientific Council in 2002.

The estimated stock biomass has increased since the early 1990s, reached a record high in 2003, and is now well above the estimate of maximum sustainable yield level (B_{MSY}). Total mortality by the fishery and cod predation (Z_{MSY}) is well below the value that maximizes yield. A median estimate of the maximum annual production surplus, available to both the fishery and cod, was 132 000 tons. Projections showed that catches of 130 000 tons/yr are not likely to drive the stock below B_{MSY} in the short to medium term (<5 years), but might not be sustainable in the longer term.

The stock size in 2003 was estimated to be close to carrying capacity and surplus production therefore low. Consequently, stock biomass is expected to decline in coming years, which might reduce catch rates.

Introduction

The shrimp (*Pandalus borealis*) stock off West Greenland is distributed in Div. 0A and Subarea 1. Shrimp within this area is assessed as a single population. The Greenland fishery exploits the stock in Subarea 1 (Div. 1A to 1F) in offshore and inshore areas (primarily Disko Bay). The Canadian fishery has been restricted to Div. 0A since 1981.

Until 2002 management advice for this stock was basically formulated by qualitative assessment of trends in various indices of stock condition in response to the catch history (Anon., 2001). Management advice was given as an annual Total Allowable Catch (TAC) and a statement about the sustainability of the applied fishing practice as consented by the assessment board.

In 2002 a quantitative assessment framework (Hvingel and Kingsley, 2002) based on a biological model of shrimp stock dynamics was adopted by STACFIS and Scientific Council. This paper presents the results of applying this model to the updated data series of shrimp catches and shrimp and cod biomass, to generate the management advice for, the West Greenland shrimp stock.

Short-term (1-year) and medium-term (ten-year) projections of stock development are made for five levels of annual catch: 110, 120, 130, 140 and 150 thousand tons under the assumption that the cod stock remain at its current low level. The associated risk of transgressing the reference parameters maximum sustainable yield level of biomass (B_{MSY}) and mortality (Z_{MSY}) are estimated.

Estimation of Parameters

Parameters relevant for the assessment and management of the stock were estimated, based on a stochastic version of a surplus-production model that included an explicit term for predation by cod (*Gadus morhua*). The model was formulated in a state-space framework and Bayesian methods were used to construct "posterior" likelihood distributions of the parameters. Model background, formulation, checking, validation and further details are given in Hvingel and Kingsley, 2002.

Absolute biomass estimates had relatively high variances. For management purposes therefore it is desirable to work with biomass on a relative scale in order to cancel out the uncertainty of the "catchability" parameters (the parameters that scale absolute stock size). Biomass, B, is thus measured relative to the biomass that yields Maximum Sustainable Yield, B_{MSY}. The state equation describing the transition of shrimp biomass from one state, t, to the next, t+1 was:

$$P_{t+1} = \left(P_t - \left(\frac{C_t + O_t}{B_{MSY}} \right) + \frac{mMSYP_t}{B_{MSY}(m-1)} \left(1 - \frac{P_t^{m-1}}{m} \right) \right) \cdot \exp(\nu)$$

where MSY is the annualized value of the instantaneous maximum sustainable yield rate. P_t is the stock biomass relative to biomass at MSY (P_t=B_t/B_{MSY}) in year t. C_t is the catch taken by the fishery and O_t is the consumption by cod, in year t. m is a shape parameter for the stock–recruitment curve: a value of 2 gives the standard logistic, or Schaefer (1954), trajectory. The ‘process errors’, v are normally, independently and identically distributed with mean 0 and variance σ_v^2 .

The model synthesized information from input priors (Hvingel and Kingsley, 2002) and the following data: a 16-year series of a survey biomass indices of shrimp ≥17 mm CL. (Kanneworff and Wieland, 2003); a 28-year series of combined CPUE indices (Hvingel, 2003); a 49 year series of catches by the fishery (Hvingel, 2003; Hvingel and Kingsley, 2002); a 49-year series of a cod biomass estimates (Hvingel and Kingsley, 2002); and a short series (4 years) of estimates of the shrimp biomass consumed by cod (Hvingel and Kingsley, 2002) based on stomach analysis (Grunwald, 1998) (see Fig. 1). The data link functions of the biomass indices were:

$$CPUE_t = q_c B_{MSY} P_t \exp(\omega) \ \text{, for} \ \ t \in (1,2,..,..N-1)\,, \ \ CPUE_N = q_c B_{MSY} P_N \exp(1.5\omega)$$
$$surv_t = q_s B_{MSY} P_t \exp(\kappa) \ \text{, for} \ \ t \in (2,3,..,..N)\,, \ \ surv_1 = q_s B_{MSY} P_1 \exp(1.5\kappa)$$

The CPUE ($CPUE_t$) and survey ($surv_t$) indices were scaled to true biomass by the catchability constants, q_c and q_s. The error terms, ω and κ, are normally, independently and identically distributed with mean 0 and variance σ_ω^2 and σ_κ^2 . The error for the final year, N, of the CPUE index was assumed to be 1.5 times the error for the rest of the series, as this data point is an interim one based on fishery data until October (the annual assessment takes place in November). Likewise the first year of the survey was assigned a 50% larger error than the rest of the series to allow for a learning process.

Estimates of annual consumption rate of shrimp by cod were linked to the equations of shrimp stock dynamics through a Holling type III functional response function (Holling, 1959) and a series of cod biomass:

$$O_t = cod_t \frac{V_{\max} P_t^2}{P_t^2 + P_{50\%}^2} \exp(\tau)$$

where O_t is total consumption in year t, V_{max} is the maximum consumption of prey per predator (kg·kg^{-1}) reached at large prey biomass, and $P_{50\%}$ is the prey biomass index at which the consumption is half of the maximum. cod_t is biomass of cod in year t. The error term, τ , is normally, independently and identically distributed with mean 0 and variance σ_τ^2 .

The mortality caused by cod predation and fishery, *Z*, is scaled to Z_{MSY} (the combined fishing and predation mortality that yields *MSY*) for the same reasons as relative biomass was used instead of absolute. The equations for generating posteriors of the *Z-ratio* were:

$$Zratio_t = \frac{Z_t}{Z_{MSY}} = \frac{-\ln\left(\frac{B_t-(C_t+O_t)}{B_t}\right)}{\frac{MSY}{B_{MSY}}}$$

Results, Model Performance

The addition of an extra year of data did not change the model diagnostics and derived conclusions about model performance reported in Hvingel and Kingsley (2002). The model was able to produce a reasonable simulation of the observed data (Fig. 2). The probabilities of getting a more extreme observation than the realized ones given in the two data series on stock size (Table 1) showed that except for the 2003 survey biomass index value the observations did not lie in the tails of their posterior distributions. The survey series was generally less well estimated; the 1991 and 2003 values had the largest residuals and smallest CPOs (Conditional Predctive Ordinate).

Some of the parameters showed high linear correlations (Table 2). The catchabilities of the CPUE series, q_c and of the survey series, q_s, were negatively correlated with the parameter for carrying capacity, *K*, and Maximum Sustainable Yield, *MSY*.

For the parameters P_1 (Biomass ratio of year 1), τ(CV of consumption by cod) and O_{max} (maximum predation rate) the posterior distributions tended to approximate the input priors (Fig. 3). The distribution of the carrying capacity, *K*, showed a mode around 9 230 000 tons (Fig. 3) but had a long tail towards higher values. The catchabilities, q_s and q_c, showed peaks at 0.49 and 0.0014, respectively, but had relatively wide posterior distributions. However, the posterior for *MSY* was determined with a distinct mode at 117 000 and a smooth distribution skewed to the right (Fig. 3).

The estimated CV of the observed CPUE series, ω, had a median of about 8.0% and for the survey series, κ, of 16.4%. The process error, ν, had a median of 11.3% (Table 3). The parameter set to be the main determinant of cod predation rate, $P_{50\%}$ (biomass ratio at which the predator is 50% saturated), was markedly updated with a posterior showing a mode at 3.26 (Fig. 3).

Assessment Results

The model estimated the median annual consumption by cod 1956-2003 in the range of 200 tons to about 116 000 tons (Fig. 4), which is in the same order of magnitude as the catches taken by the fishery. The estimated consumption declined since 1960 as a result of a decline in cod abundance at West Greenland. A short-lived resurgence of the cod stock in the late-1980s caused consumption to increase. The cod disappeared in the beginning of the 1990s and estimates of consumption went to zero (Fig. 4).

The trajectory of the median estimate of 'biomass-ratio' (B_t/B_{MSY}) plotted against 'mortality-ratio' (Z_t/Z_{MSY}) (Fig. 5) starts in 1956 at half the optimum biomass ratio and at a mortality-ratio well above 1. The stock maintained itself in this region during the years when cod were abundant. When the cod stock declined in the late-1960s, and predation pressure was lifted (Fig. 4), shrimp stock biomass increases and eventually began cycling in the left upper corner of the graph (Fig. 5) during the current regime of low cod abundance.

Since the early-1970s the estimated median biomass-ratio ranged from about 0.96 to 1.92 (Fig. 5) and the probability that it had been below the optimum level was small for most years (Fig. 6), i.e. it seemed likely that the stock had been at or above its MSY-level throughout the modern fishery. A steep decline in CPUE was noted in the late-1980s and early-1990s following a short-lived resurgence of the cod stock and the median estimate of biomass-ratio dipped just below the optimum in 1990-1991 (Fig. 5). The stock has increased since then and reached its highest level ever in 2003 with a median estimate of biomass-ratio of 1.92, corresponding to about 87% of estimated median carrying capacity. The estimated risk of stock biomass being below B_{MSY} was 0.01 (Fig. 6). At the current stock size surplus production is only xx% of MSY and a decling trend is …………CPUE decline.

The mortality ratio (Z-ratio, which includes mortality by fishing and predation by cod) has been below 1 for most of the time since 1970, except for the period of high cod predation in the late- 1980s (Fig. 5). Since 1997, annual median Z-ratio has been stable at approximately 0.6, i.e. well below the value that maximizes yield. The median of estimate for 2003 is 0.59 with a risk of only 0.04 of being above 1 (Fig. 6).

The median estimate of the maximum annual production surplus, available equally to the fishery the cod (*MSY*) was estimated to 132 000 tons (Table 3). The posterior showed a mode at 117 000 tons and upper and lower quartiles at 167 000 and 117 000 tons (Fig. 7). The risk function relating the probability of exceeding *MSY* to the combined removal by fishery and cod predation is given as the integral of this distribution (Fig. 7 right panel).

The catch input series has been corrected for "overpacking" (Hvingel, 2003a) and input annual catch data values were therefore increased by on average 23% as compared to the assessment in 2002. As catches are important in scaling shrimp stock production, the model estimate of *MSY* would thus increase proportionally. The increase of MSY summarized in its median from 101 000 tons (Hvingel, 2002) in last years' assessment to 132 000 tons in the current is therefore mainly caused by the revision of the catch series.

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 five optional catch levels for 2004 are as follows:

Catch option ('000 tons)	110	120	130	140	150
Risk of falling below B_{MSY}	2%	2%	2%	3%	3%
Risk of exceeding Z_{MSY}	2%	3%	9%	14%	21%

Predation by cod can be significant (Fig. 4) and have a major impact on shrimp stock size. Currently the cod stock at West Greenland is at a very low level. A large cod stock that would significantly increase shrimp mortality could be established in two ways: Either by a slowly rebuilding process or by immigration of one or two large year-classes from areas around Iceland as seen in the late-1980s. An increase in cod abundance through growth of the existing stock would, however, be noted in an early phase during routine monitoring programs. No such signals were found in 2003. All though the biological end environmental conditions for immigration of cod from Icelandic areas have seemed favorable in recent years, no indications of such events were registered in the annual surveys.

Ten-year projections of stock development were therefore made under the assumption that the cod stock will remain at its current low abundance. Five levels of annual catch: 110 000, 120 000, 130 000, 140 000 and 150 000 tons were investigated (Fig. 8).

The investigated catch options of 110 000 and 120 000 ton/yr have a small risk of being above *MSY* (Fig. 7) and the stock is therefore likely to remain above B_{MSY} (Fig. 8) during the ten years of projection. The combined relative fishing and cod predation mortality, Z_t/Z_{MSY}, has a high probability of being below 1 within this period (Fig. 9).

A catch option of 130 000 tons/yr will just about meet the estimated median *MSY* and is not likely to drive the stock below B_{MSY} in the short to medium term (Fig. 8), i.e. the risk is less than 10% within the first four years and just above 25% after year 10 (Fig. 9). However, this level of exploitation might not be sustainable in the longer term, as risk of exceeding B_{MSY} continues to increase through time.

Fishing 140000 or 150 000 tons/yr bears a 60% and 70% risk respectively of being above *MSY* (Fig. 7), thus these catch levels are not likely to be sustainable in the longer term. Owing to the current high stock level the risk of exceeding B_{MSY} is no more than 20% after five years at 150 000 tons/yr, although after 10 years it is close to 50% (Fig. 9).

If on the other hand an abrupt increase in cod biomass resulting from immigration from other areas changes of shrimp stock condition may be much more rapid. Preliminary investigations of the event of an immigration of two large year-classes of cod were made by simulating a repetition of the short-lived resurgence of the cod stock seen in the late-1980s. The simulation showed that predation could within a 3-4 year period go from negligible to between 80 000 and 140 000 tons (upper and lower quartiles) (Fig.10).

Precautionary Approach

The "Precautionary Approach" framework developed by Scientific Council defined a limit reference point for fishing mortality, F_{lim}, as equal to F_{MSY}. The limit reference point for stock size measured in units of biomass, B_{lim}, is the spawning stock biomass below which unknown or "low" recruitment is expected. Buffer reference points, B_{buf} and F_{buf}, are also requested to provide a safety margin that will ensure a small risk of exceeding the limits.

The limit reference point for mortality in the current assessment framework is Z_{MSY}, i.e. Z-ratio =1 and the risk of exceeding this point is given in this assessment. B_{lim} could not be defined. For one thing stock-recruitment figures were only available for relative high stock sizes and extrapolation to define an area of "low recruitment" were not readily justified. Buffer reference points are not needed in this framework as the risk of exceeding the limit reference can be directly calculated and uncertainty associated with the entire process is taken into account.

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Table 1. Model diagnostics: residuals (% of observed value), probability of getting a more extreme observation (p.extr.), conditional predictive ordinate (CPO).

	CPUE-series			Survey-series		
Year	resid.(%)	p.extr.	CPO	resid.(%)	p.extr.	CPO
1976	-4.9	0.32	1.27			
1977	-4.1	0.34	2.33			
1978	4.0	0.36	3.18			
1979	8.2	0.23	1.4			
1980	-1.9	0.42	3.51			
1981	4.2	0.34	2.88			
1982	-6.9	0.25	1.18			
1983	0.8	0.47	3.71			
1984	2.6	0.40	2.99			
1985	0.8	0.47	3.7			
1986	4.2	0.35	2.79			
1987	-9.1	0.19	0.46			
1988	4.0	0.35	3.55	13.2	0.25	0.68
1989	3.6	0.36	4.26	8.3	0.32	0.93
1990	-0.9	0.46	6.05	-9.6	0.28	0.8
1991	-5.1	0.30	2.88	28.5	0.08	0.37
1992	-2.4	0.40	5.19	4.0	0.41	1.04
1993	0.7	0.47	5.1	-8.3	0.32	0.79
1994	3.9	0.35	4.29	-13.0	0.22	0.56
1995	-2.2	0.41	4.77	9.7	0.31	0.89
1996	-2.0	0.42	4.85	6.0	0.38	0.95
1997	1.0	0.45	5.13	20.9	0.15	0.52
1998	0.7	0.47	4.56	-4.4	0.41	0.78
1999	-1.1	0.45	4.07	8.9	0.31	0.73
2000	-1.1	0.46	3.78	-1.1	0.48	0.72
2001	4.7	0.32	2.76	1.3	0.47	0.71
2002	0.7	0.47	3.05	-8.9	0.30	0.45
2003	0.4	0.49	0.37	-31.6	0.03	0.10

Table 2. Correlations among selected model parameters.

	MSY	K	q_s	q_c	$B_{MSY} \cdot K^{-1}$	$P_{50\%}$	O_{max}	ω	κ	ν	τ
K	0.69										
q_s	-0.66	-0.78									
q_c	-0.67	-0.78	0.99								
$B_{MSY} \cdot K^{-1}$	0.19	0.13	-0.20	-0.20							
$P_{50\%}$	0.38	0.01	-0.24	-0.25	-0.12						
O_{max}	0.00	-0.03	0.02	0.02	0.01	0.07					
ω	0.07	0.14	-0.13	-0.13	-0.01	-0.04	0.01				
κ	-0.06	-0.12	0.12	0.12	0.00	0.06	0.01	-0.02			
ν	0.35	0.32	-0.37	-0.37	0.18	0.15	-0.02	0.00	-0.21		
τ	0.00	-0.02	0.01	0.01	0.00	-0.02	0.00	-0.04	0.02	-0.06	
P_1	0.16	0.17	-0.29	-0.29	0.04	0.21	-0.02	0.03	-0.02	0.15	-0.02

Table 3. Summary of parameter estimates: Mean, standard deviation (sd) and 25, 50, and 75 percentiles of the posterior distribution of selected parameters.

	Mean	sd	25%	Median	75%
MSY	156	66	117	132	167
K	1810	1262	942	1320	2167
q_s	0.365	0.189	0.208	0.364	0.507
q_c	0.00106	0.00055	0.00061	0.00106	0.00148
$B_{MSY} \cdot K^{-1}$	0.46	0.07	0.40	0.45	0.50
$P_{50\%}$	3.52	0.90	2.94	3.40	4.01
O_{max}	3.00	0.099	2.93	3.00	3.07
ω	0.082	0.016	0.070	0.080	0.091
ν	0.167	0.030	0.146	0.164	0.184
κ	0.115	0.028	0.096	0.113	0.132
τ	0.300	0.067	0.253	0.290	0.336
P_1	0.923	0.184	0.792	0.906	1.032

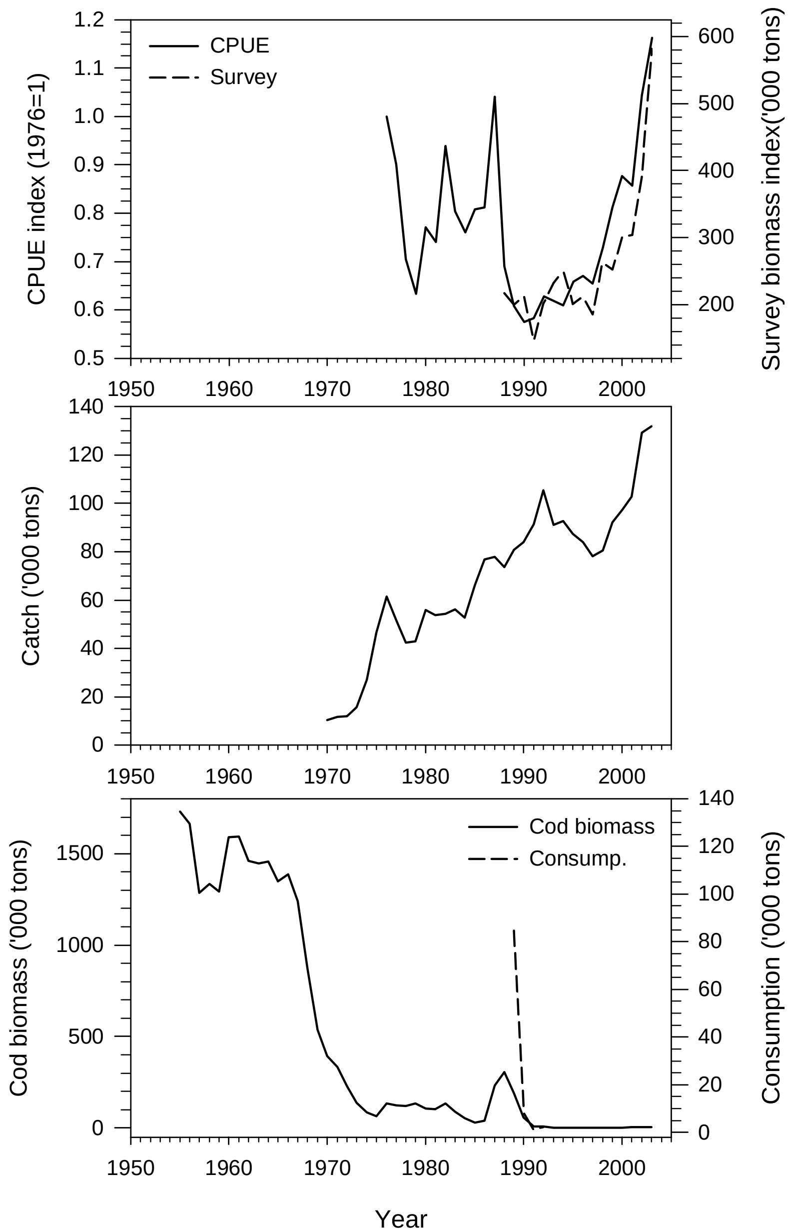

Fig. 1. Shrimp in Subareas 0 and 1: data series providing information for the assessment model. Upper panel: Shrimp biomass (≤17 mm CL) indices based on 1. standardized commercial catch rates (CPUE-index) and 2. research survey data. Middle panel: Catch by the fishery. Lower panel: absolute biomass estimates of cod and a four year series of consumption estimates based on stomach sampling.

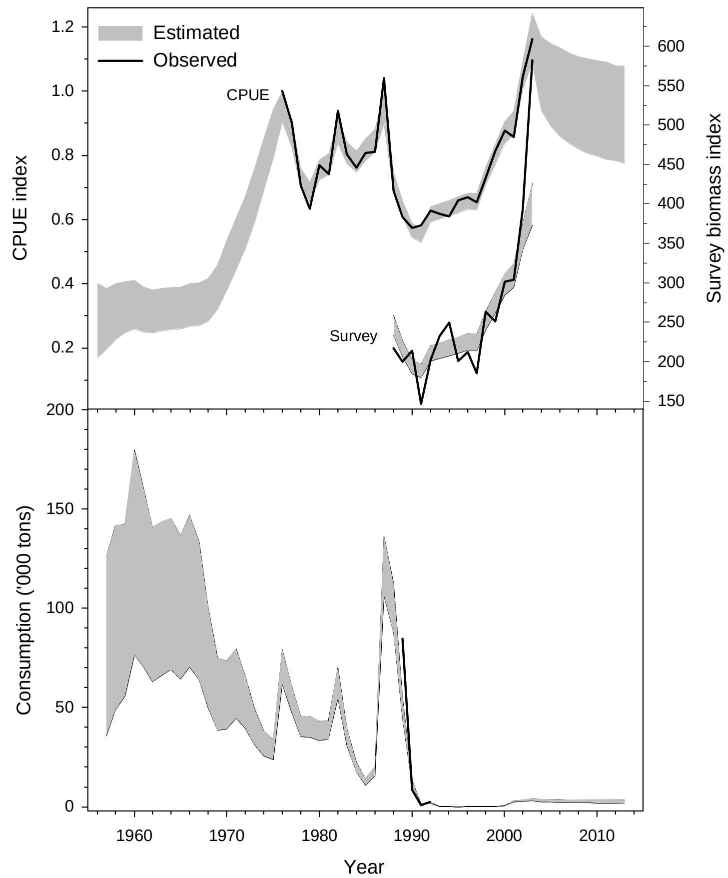

Fig. 2. Comparison of observed and model estimated values: observed values of CPUE and survey stock biomass indices and of shrimp consumption by cod and corresponding estimates by the model (inter-quartile range of the posteriors). Upper panel: estimates of relative stock development in the future and historic to the data series are shown in the scale of the CPUE indices only for improved graphical presentation

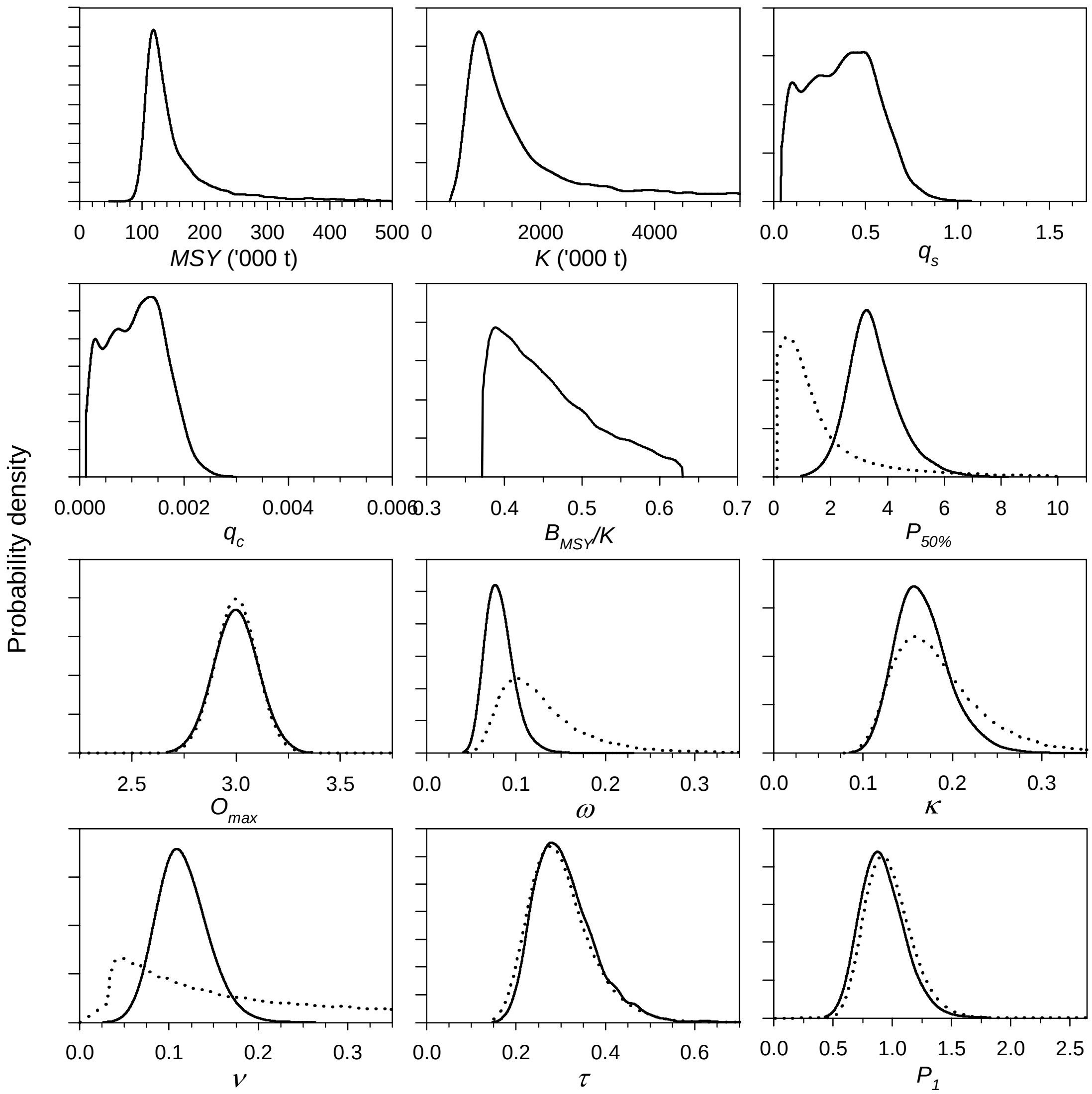

Fig. 3. Probability density distributions of model parameters: estimated: posterior (solid line) and if relevant prior (broken line) distributions.

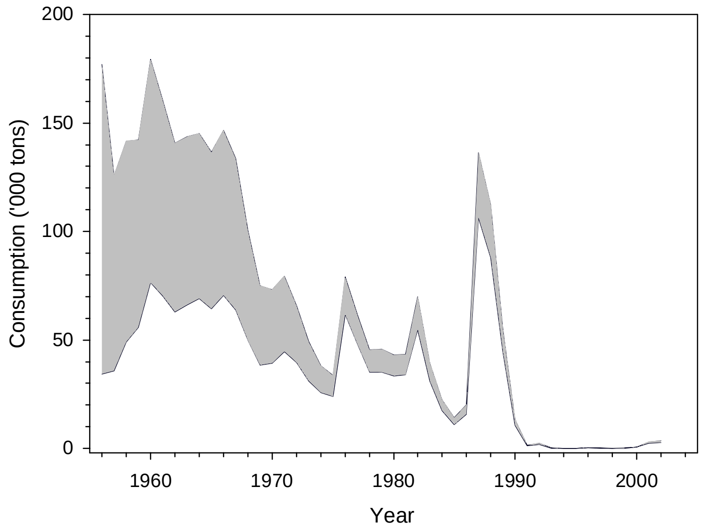

Fig. 4. Shrimp in Subareas 0 and 1: estimated consumption of shrimp by cod. Area borders indicate upper and lower quartiles.

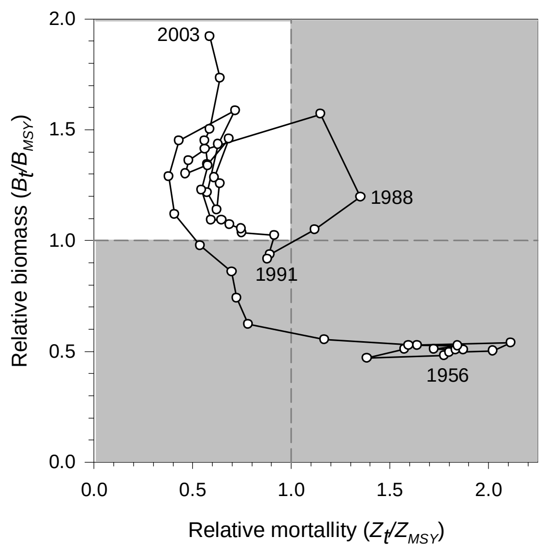

Fig. 5. Shrimp in Subareas 0 and 1: estimated annual median biomass-ratio (B/B_{MSY}) and mortality-ratio (Z/Z_{MSY}) 1956-2003.

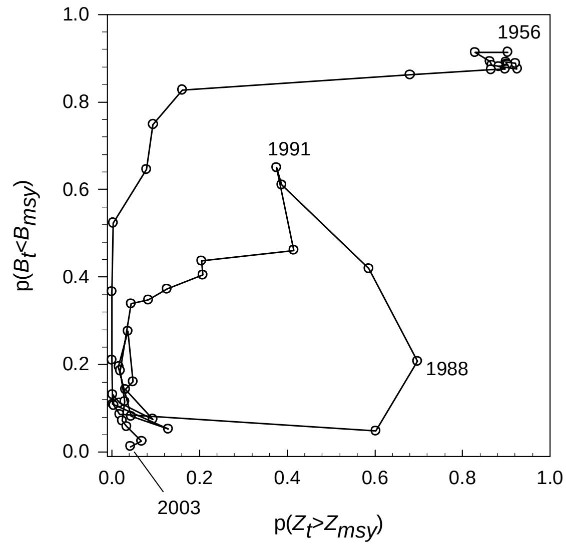

Fig. 6. Shrimp in Subareas 0 and 1: risk of annual biomass being below B_{MSY} and of mortality caused by fishing and cod predation being above Z_{MSY} 1956-2003

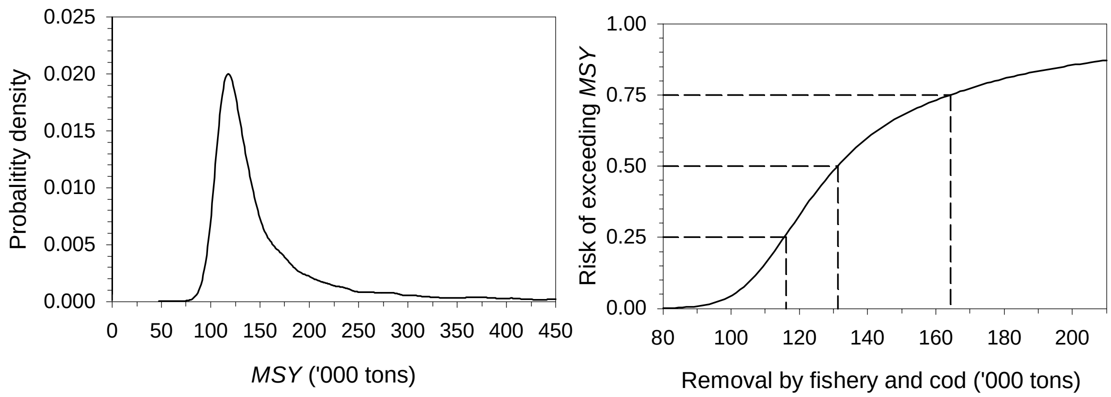

Fig. 7. Shrimp in Subareas 0 and 1: Posterior probability distribution of the maximum annual production surplus, available equally to the fishery the cod (*MSY*) (left panel) and the cumulative probability of exceeding *MSY*.

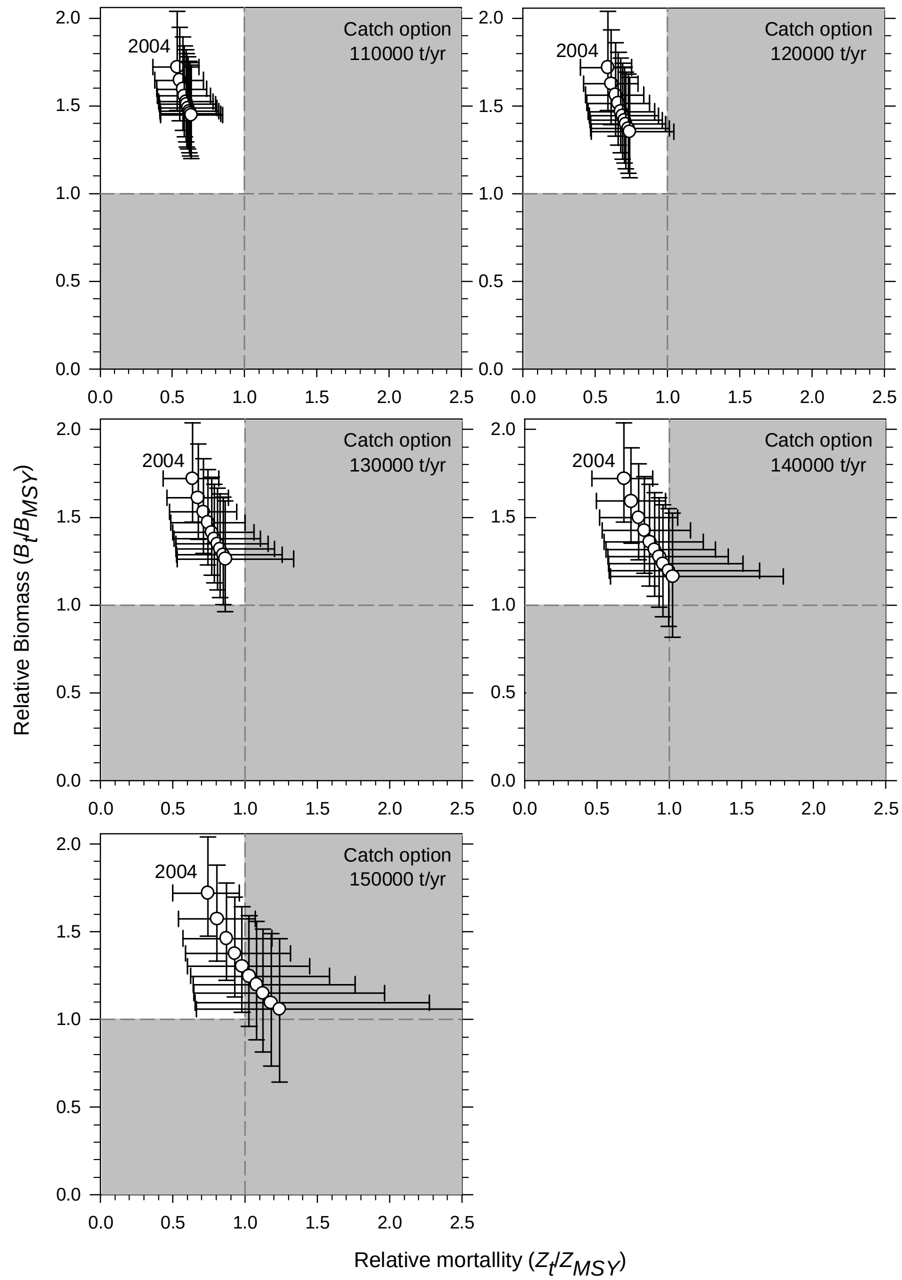

Fig. 8. Shrimp in Subareas 0 and 1: projections of stock development for the period 2004-2013 quantified in a biomass (B/B_{MSY})-mortality (Z/Z_{MSY}) continuum. Dynamics at 100, 110, 120, 130 and 150 thousand tons of fixed annual catch levels are shown as medians with error-bars at the 25th and 75th percentiles. Dashed lines indicate level of biomass and mortality at *MSY*.

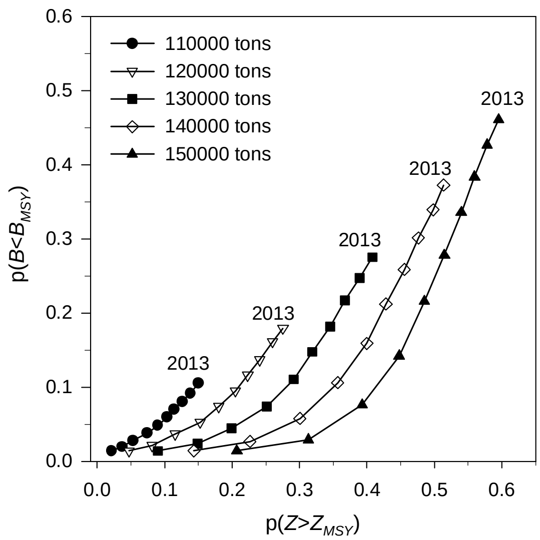

Fig. 9. Shrimp in Subareas 0 and 1: risk of exceeding Z_{MSY} and of driving the stock below B_{MSY} by maintaining optional annual catch levels of 110-150000 tons/yr during the period 2004-2013.

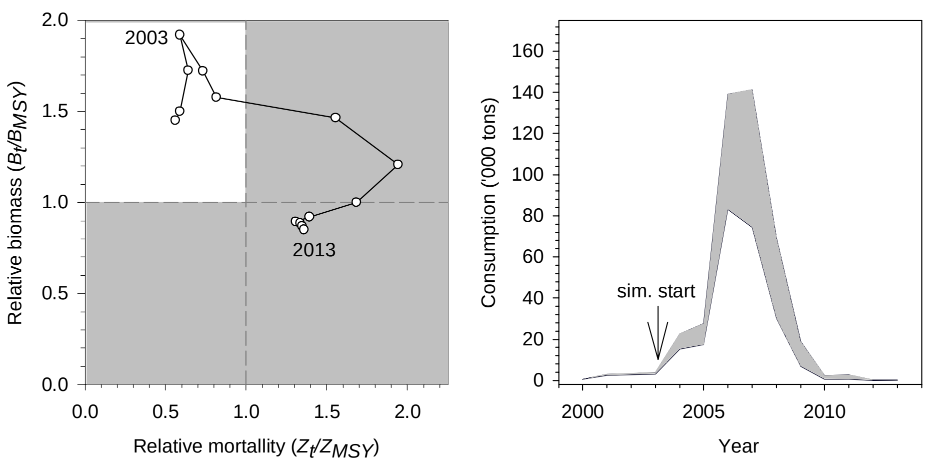

Fig. 10. Simulated annual median biomass-ratio (B/B_{MSY}) and mortality-ratio (Z/Z_{MSY}), and consumption of shrimp by cod 2004-2013. Assumptions: catch by fishery 130000 tons/yr. Cod biomass similar to 1985-1994 period.