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Région de Terre-Neuve et Labrador

Construction of an assessment model for the shrimp (*Pandalus borealis*) stock off Newfoundland and Labrador using a Bayesian production model, first approach

Construction d'un modèle d'évaluation des stocks de crevettes (*Pandalus borealis*) au large de Terre-Neuve-et-Labrador en utilisant d'abord un modèle Bayésien de production

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ABSTRACT

For Illustrative purposes stock status and management advice for the Northern Shrimp, Pandalus borealis, within Shrimp Fishing Area 6 (SFA6) off Newfoundland and Labrador was derived based on a logistic stock-recruitment model with a state-space structure and Bayesian inference. The fishery effect was modelled explicitly while other mortality was included in the parameter for the overall realised population growth rate, *r*, and habitat carrying capacity, *K*. The model included both process and observation error and synthesized information from input priors and three independent series of shrimp biomass indices and a catch series. This model produced reasonable simulations of the observed data. Model results were stated relative to a set of *MSY* (Maximum Sustainable Yield) reference points. The Precautionary Approach limits proposed for stock biomass (*B*) was B_{lim}=0.3B_{msy} and for fishing mortality F_{lim}=1.7F_{msy}. Estimated stock biomass increased from the mid 1990s until 2006 to levels above the optimum, B_{msy}, after which it declined toward B_{msy}. In 2009 there was a 75% probability that the stock biomass was above B_{msy} and that fishing mortality was below the value that maximizes yield (F_{msy}). There was a 0% risk that the resource was below B_{lim} in 2009. The mode of the estimated distribution of maximum annual production surplus, available to the fishery (*MSY*) was at 75 ktons. However, this estimate had wide confidence limits. Future catch options of up to 50 ktons/yr are likely to maintain the stock at its current high level. However, catch options of 60 ktons/yr or higher are under the current low levels of cod predation not likely to drive the stock below optimum levels in the short term either.

RÉSUMÉ

À titre d'exemple, l'état des stocks et les avis concernant la gestion de la crevette nordique, Pandalus borealis, dans la zone de pêche de la crevette 6 (ZPC6) au large de Terre-Neuve-et-Labrador, sont tirés d'un modèle logique stock-recrutement avec une structure état-espace et une inférence bayésienne. L'effet de la pêche a été modélisé explicitement alors que d'autres mortalités ont été incluses dans le paramètre pour le taux global de croissance de la population réalisé, r, et la capacité limite de l'habitat, K. Le modèle comprenait le processus et l'erreur d'observation ainsi que les renseignements synthétisés provenant des données saisies précédemment et de trois séries d'indices de biomasse de crevettes et d'une série de prises. Ce modèle a produit des simulations raisonnables des données observées. Les résultats du modèle ont été comparés à un jeu de points de référence d'un rendement maximal durable *RMD*. Les limites proposées pour l'approche de précaution concernant la biomasse des stocks (B) étaient B_{lim} = 0,3B_{rmd} et concernant la mortalité par la pêche étaient F_{lim} = 1,7F_{rmd}. La biomasse estimée des stocks a augmenté du milieu des années 1990 à 2006 jusqu'au niveau optimalB_{rmd}, pour ensuite diminuer vers B_{rmd}. En 2009, la probabilité était de 75 % que la biomasse des stocks soit supérieure à B_{rms} et que la mortalité par la pêche soit inférieure à la valeur qui maximise le rendement (F_{rmd}). En 2009, la probabilité que la ressource soit inférieure à B_{lim} était de 0 %. Le mode de la distribution estimée du surplus de production annuelle maximale disponible pour la pêche (*RMD*) était de 75 kilotonnes. Cependant, cette estimation comportait des intervalles de confiance importants. Les captures future jusqu'à 50 kilotonnes par année devraient probablement maintenir les stocks à leur niveau élevé actuel. Cependant, des captures égales ou supérieures à 60 kilotonnes par année sont inférieures aux faibles niveaux de prédation de la morue actuels et ne devraient pas amener les stocks sous les niveaux optimaux à court terme.

INTRODUCTION

In the Shrimp Fishing Area 6 (SFA 6) Northern Shrimp (*Pandalus borealis*) is distributed along the eastern coast of Labrador from Hawke Channel, south to Cape Freels and off north eastern Newfoundland. This resource is exploited by a Canadian fleet consisting of approximately 13 large (>500 t) and 300 small (<500 t) vessels. Catches increased from 11,000 t in 1994 to 78,000 t in 2008. The 2009 TAC was set at 85,725 t; however, due to operational and commercial factors only 45,100 t were tan.

Management advice for this stock has been formulated by qualitative assessment of trends in commercial catch rates and research survey indices in response to the catch history. Advice is given as an annual Total Allowable Catch (TAC). Previous initiatives (in 2005 and 2007) to develop a quantitative assessment framework for this stock were unsuccessful, for methodological reasons and due to a relatively short and uninformative history of stock dynamics and exploitation as seen from the stock biomass and catch time series (Table 1).

This paper presents a new attempt to construct an integrated framework for the assessment and management of the SFA6 shrimp stock based on Hvingel and Kingsley (2006) and Hvingel (2006a) that can provide realistic estimates of the uncertainty associated with the assessment conclusions, and convey the information to fishery managers. We use Bayesian inference to estimate model parameters. A significant strength of using Bayesian methods for stocks with low-informative data is their ability to incorporate knowledge outside the data series which can be used directly by the model to assist parameter estimation. The method offers a conceptually elegant way to incorporate such ancillary knowledge in a model as “prior distributions” of model parameters. If informative priors can be constructed, based on ancillary information for one or more of the parameters that are poorly defined by the main data series, it may significantly boost the ability to estimate parameters. Similar assessment models have been accepted within ICES and NAFO for deriving management advice for shrimp off West Greenland (Hvingel 2006a, Hvingel and Kingsley 2002, 2006); Shrimp in the Barents Sea (Hvingel 2006b) and Greenland Halibut off East Greenland, Iceland and the Faeroes (Hvingel et al. 2007).

The results presented here should be regarded as a demonstration of the potential of this modelling framework to provide a quantitative basis for management decision making and should not be taken as a final stock assessment.

MODEL

MODELLING FRAMEWORK

The model was built in a state-space framework (Hvingel and Kingsley 2006, Schnute 1994) with a set of parameters (θ) defining the dynamics of the shrimp stock. The posterior distribution for the parameters of the model, $p(\theta|data)$, given a joint prior distribution, $p(\theta)$, and the likelihood of the data, $p(data|\theta)$, was determined using Bayes’ (1763) theorem:

(1) $$p(\theta \mid data) \propto p(data \mid \theta)\, p(\theta)$$

The posterior was derived by Monte-Carlo-Markov-Chain (MCMC) sampling methods using WinBUGS v.1.4 (www.mrc-bsu.cam.ac.uk/bugs; Spiegelhalter et al. 2003).

State equations

The equation describing the state transition from time t to t+1 was a discrete form of the logistic model of population growth including fishing mortality (e.g. Schaefer (1954), and parameterised in terms of *MSY* (Maximum Sustainable Yield) rather than *r* (intrinsic growth rate) (cf. Fletcher 1978):

(2)
$$B_{t+1} = B_t - C_t + 4MSY\frac{B_t}{K}\left(1-\frac{B_t}{K}\right)$$

K is the carrying capacity, or the equilibrium stock size in the absence of fishing (B_{MSY}=K/2). B_t is the stock biomass. C_t is the catch taken by the fishery.

Absolute biomass estimates of most population-dynamic models are susceptible to large uncertainty if no explicit information is available to scale the biomass indices to real stock size. 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" parameter (the scaler). This was accomplished by dividing equation (2) throughout by B_{MSY}, the biomass that produces MSY (Hvingel and Kingsley 2006). The variability (ratio of the interquartile range to the median) of estimated biomass-ratios were about 67% lower than absolute estimates of B. This reparametrisation also reduced auto-correlation in the chains of values sampled by the Gibbs sampler and thus hastened convergence to the posterior distribution (cf. Meyer and Millar, 1999). Finally a term for the process error was applied and the state equation took the form:

(3)
$$P_{t+1} = \left(P_t - \frac{C_t}{B_{MSY}} + \frac{2\,MSY\,P_t}{B_{MSY}}\left(1-\frac{P_t}{2}\right)\right)\cdot \exp(p_t)$$

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_p^2.

Observation equations

The available data for this shrimp stock covers two regimes of high and low cod abundance (Table1). Abundance of cod has been associated with dynamics of shrimp stocks (Hvingel 2006a and references therein) and should be considered as a possible explicit factor in a shrimp stock assessment model. In this first approach we didn't want to include cod as an explicit factor and we therefore chose to only use data collected since 1994, i.e. from the recent period of low cod abundance. For this period and the period predicted by the model we assume that the 'cod effect' is relatively small and varying without trend.

The model synthesized information from input priors and three independent series of shrimp biomass indices and one series of shrimp catches (Table 1). The three series of shrimp biomass indices were: a standardised series of annual large vessel catch rates for 1994–2009, $CPUEL_t$ (Orr et al.., in press), a standardised series of annual small vessel catch rates for 1998–2009, $CPUES_t$ (Orr et al.., in press); and a trawl-survey biomass index for 1996–2009, $surv_t$, (Orr et al.., in press). These indices were scaled to true biomass by catchability parameters, q_{CL}, q_{CS} and q_S. Lognormal observation errors, ω, κ and ε were applied, giving:

(4)
$$CPUEL_t = q_{CL} B_{MSY} P_t \exp(\omega_t)$$
$$CPUES_t = q_{CS} B_{MSY} P_t \exp(\kappa_t)$$

$$survE_t = q_E B_{MSY} P_t \exp(\varepsilon_t)$$

The error terms, ω and κ are normally, independently and identically distributed with mean 0 and variance σ^2_ω and σ^2_κ and σ^2_ε.

Total reported catch in SFA6 (1994-2009) was used as yield data (Table 1). The fishery is considered to have no major discarding problems or variable misreporting; therefore reported catches were entered into the model as error-free.

Priors

Bayesian philosophy considers that an observer maintains a model—perhaps mental or conceptual—of reality that is subject to being modified—updated—by observations (Hvingel and Kingsley 2006). As a quantitative version of this, Bayesian statistics considers that quantitative observations (data) can be used to update pre-existing probability distributions of the values of parameters defining a quantitative model. The prior distribution for a parameter should incorporate all the information that is already available, but if none can be identified a low-information or "reference" prior (Kass and Wasserman 1996) is used.

Initial stock size: It seemed unlikely that stock size at the beginning of the time series could have been at a high level (close to K) as the stock had just been exposed to a long period with high cod abundance. On the other hand the catch rates of the shrimp fishery prior to 1994 were not particularly bad so the shrimp stock could not have been at a low level either. The ”initial” stock biomass in 1994, P_1, was therefore given a normal distribution with mean=0.75 and sigma=0.22, i.e. a distribution covering values between 0.3 and 1.2 (95%) (Fig. 3, Table 2).

To provide the model with information on the order of magnitude of *K*, its prior was constructed based on an estimated posterior for this parameter from a shrimp stock with similar biology at West Greenland (Hvingel and Kingsley 2006). This had a median of 728 ktons and 95% of the distribution between 300 and 2200 ktons. The area of SFA6 was estimated to be about 1.5 times that of the West Greenland area and thus the prior was approximated by a lognormal distribution with median of 1115 ktons and 95% confidence limits at about 500 and 2500 ktons (Table 2).

The uncertainty of the survey input data series (CV) were given a gamma distributed prior with a 95% range of 10-30%, thought to be the typical range for such data. The CPUE data was given a similar prior but with a 95% range of 16-45% to take into account that commercial CPUE data is often thought to be less reflective of stock dynamics than independent survey data. In the future, these priors could be refined with reliable estimates of the survey and CPUE CVs.

Reference priors (low-information priors) were given to the other parameters of the model (Table 2) as we had little or no information as to 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 was 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 be similar. 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

Fishing mortality, F, is scaled to F_{MSY} (fishing mortality that yields MSY) for the same reasons as relative biomass was used instead of absolute. The equations added for generating posterior distributions of the F ratio were:

$$F\mathrm{ratio}_{\mathrm{t}} = \frac{F_{\mathrm{t}}}{F_{MSY}} = \frac{C_t / B_t}{MSY / B_{MSY}}$$

The risk of a parameter transgressing a reference point is the relative frequency of the MCMC sampled values that are smaller (or larger –depending on type) than the reference points.

Precautionary approach considerations

We proposed to use limit reference points as B_{lim}=0.3B_{msy} and $F_{lim}=1.7F_{msy}$ based on the following considerations:

B_{lim}: The biomass limit reference point can be set in relation to the time it takes for the stock to recover from this point (cf. Cadrin 1999). The time needed to rebuild an overfished stock from B_{lim} back to B_{msy} depends on the stock size at B_{lim}, the rate of biomass growth and the rate of fishing mortality.

At 0.3B_{msy} production is reduced to 50% of its maximum (Fig. 4, upper panel). This is equivalent to the SSB-level (spawning stock biomass) at 50% R_{max} (maximum recruitment). The rate of potential stock increase of the SFA6 shrimp stock was estimated (Table 5). This implies that even without fishery it would take some in the order of 3-15 years to rebuild the stock from 30%B_{msy} to B_{msy} (calculated by using the 10^{th} and 90^{th} percentile of the estimate of r) (Fig. 5 *right*).

Once fished down to low levels the stock will, due to the predicted slow recovery potential, spend proportionally longer time at low levels once a recovery plan is implemented and fishing pressure is relaxed. Longer time at low levels means higher risk of “bad things” happening which could destabilise the stock. We therefore propose that the B_{lim} be set no lower than 30% B_{msy}. This limit reference is also implemented for the West Greenland and Barents Sea shrimp stocks.

F_{lim}: An F-ratio (F/F_{msy}) corresponding to a yield of 50%MSY (50%R_{max}) at a stock biomass of 30%B_{msy} (suggested B_{lim}) may be derived from equation 3 as follows:

$$\frac{production}{B_{MSY}} = \frac{2\,MSY\,P_t}{B_{MSY}}\left(1-\frac{P_t}{2}\right),$$

$$\text{at equilibrium: } C = production \text{ and}$$

$$F = \frac{C}{B} = \frac{C}{B_{MSY}}\frac{B_{MSY}}{B} \Rightarrow$$

$$F = \frac{2\,MSY\,P_t}{B_{MSY}}\left(1-\frac{P_t}{2}\right)\frac{1}{P}, \quad \text{as } F_{MSY} = \frac{MSY}{B_{MSY}} \Rightarrow$$

$$\frac{F}{F_{MSY}} = Fratio = 2 - P$$

if B_{lim} is 30%B_{msy} (P=0.3) then the corresponding F-ratio is 1.7 (Fig. 4). The proposed F_{lim} at 1.7F_{msy} is the fishing mortality that will drive the stock biomass to B_{lim}.

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 1 million iterations. Only each 100th value of the sampled chains for the model parameters was stored and used for further analyses in order to remove within-chain autocorrelation (Fig. 1). After 100 stored iterations the sampler had converged to the target distribution (Fig. 2) leaving 9900 samples for each parameter for the final analysis.

The initial hypothesis of the SFA6 shrimp stock dynamics represented by the set of priors of the parameters of the model was updated by adding information contained in the available data series (Fig. 3). Taking into account that the data series were not that well correlated in certain periods, the model nevertheless produced a reasonable representation of the observations (Fig. 6), however some pattern in the residuals can be observed. The probabilities of getting more extreme observations than the realised ones given in the data series on stock size showed a few observations outside the 0.05-0.95 range i.e. in the tails of their posterior distributions (Table 4). The trends of the small vessel CPUE and the survey were generally better estimated than that of the large vessel CPUE. However, as suggested by the diagnostics (Fig. 6, Table 4), the 2006-peak value and the sharp decrease in 2009 in the survey series were too optimistic and too pessimistic respectively.

In this first approach towards an assessment model all available data series were used in spite of their sometime conflicting trends. The model cannot portray all the series well and trends in residuals are inevitable for that reason alone. In future work more consideration should be given to the selection of input data. Also, the Schaeffer model tracks longer term changes rather than abrupt year to year ones which tends to create patterns in the residuals. This is a limitation of the model, but it does not necessarily invalidate the results.

The retrospective pattern of relative biomass series estimated by consecutively leaving out from 0 to 10 years of data did reveal some problems with sensitivity of the model when more than 5 years of data is deleted (Fig. 7). This is however to be expected due to the short time series available so that each data point represents a large part of the total information to the model. When just 1-5 years are left out the model was relatively stable.

The survey catchability, q_s, indicated that the survey on average sees about 50% of the stock (Table 5). The estimated CVs for the survey series had a median at about 16% while that for the CPUE series was close to 17%. The process error, σ_v^2, had a median of 11%.

Preliminary assessment results

Since the mid 1990s, the estimated median biomass-ratio has increased from around 0.9B_{msy} (Fig. 8) to 1.7B_{msy} in 2006. However, by 2009 the median stock size had decreased to 1.25B_{msy} and the risk of the stock being below B_{msy} was 25% (Table 6). The median fishing mortality ratio (*F-ratio*) had been below 1 throughout the series (Fig. 8). Note, however, that the estimates of the *F-ratios* have high uncertainties (Fig. 10). In 2009 there was a 13% risk of the *F-ratio* being above 1 (Table 6). The posterior for *MSY* was positively skewed with a mode at 75 ktons (Fig. 3) with lower and upper quartiles at 65 ktons and 144 ktons respectively (Table 5).

Risk associated with six optional catch levels for 2010 are given in Table 6. Within a one-year perspective the sensitivity of the stock biomass to alternative catch options seems rather low, i.e. the risk of exceeding B_{msy} increases only slightly with increasing catches. The risk of stock biomass falling below B_{lim} within a one-year perspective is low irrespective of catch level.

The risk profile associated with ten-year projections of stock development assuming annual catch of 30-90 ktons were investigated (Fig. 11). Given the relatively high stock level, the risk of going below $\mathrm{B_{lim}}$ is less than 5% over the next 4 years even at catches at 90 ktons. However, at 90 ktons the stock is expected to decline. The median biomass ratio is projected to increase with catches of up to 70 ktons. However, the risk of going below Bmsy increases from the current 25% if catches exceed 60 ktons/yr. Catch options of up to 60 ktons/yr have a 22 % risk of exceeding F_{msy}, i.e. a 22% risk that this catch level may not be sustainable in the longer term. However, this risk is of the same magnitude as that estimated of all years since 2000 (Fig. 10), a period where catches have been below MSY and allowed the stock to exceed B_{msy}.
Catch options of up to 50 ktons have a less than 10% risk of exceeding F_{msy} in the long term and are likely to allow for stock increase and a decreased risk of going below B_{msy}.

Rebuilding potential

At 30%B_{msy} (B_{lim}) production is reduced to 50% of its maximum. The estimate of *r* (intrinsic rate of increase) had 90% confidence intervals ranging from 0.12 to 0.58 (Fig. 5 *left*). Thus without fishing it would take 3-15 years or more to rebuild the stock from B_{lim} to B_{msy} (Fig. 5 right).

Stock status 2009

- Stock size:
  - Stock biomass 1.25B_{msy} (median)
  - 25% probability of being below B_{msy}
  - 0% risk of being below B_{lim}
- Stock production:

  - MSY = 65 – 144ktons (inter-quartile range)
  - Actual ≈ 0.95MSY (median)
- Exploitation:
  - 45 ktons
  - 0.58F_{msy} (median)
  - ≈4% risk of exceeding F_{lim} (1.7F_{msy})
  - ≈13% risk of exceeding F_{msy}

Predictions for 2010

- Risk of exceeding Blim
  - As the stock is estimated to be at a relatively high level there is a low risk of exceeding this reference point at any catch.
- Catch option of 70-90 ktons/yr
  - Median fishing mortality is projected to stay below F_{msy}, however, there is still a high >28% risk of being above.
  - Stock biomass is not projected to change significantly from the 2009 median value.
- Catch option of 60 ktons/yr
  - Stock biomass is projected to remain close to its current value.
  - F median is projected to decrease well below F_{msy}, however due to the uncertainties in the estimation of F there is still a ca. 22% risk of exceeding F_{msy} .
- Catch option of 50 ktons/yr
  - Stock biomass is projected to increase slightly.
  - F median is projected to decrease further and the risk of exceeding F_{msy} is 16%.
- Moratorium
  - In the order of 3-15 years or more to rebuild from B_{lim} to B_{msy}

ADDITIONAL CONSIDERATIONS

Predation

Both stock development and the rate at which changes might take place can be affected by changes in predation - in particular by cod. If predation on shrimp were to increase rapidly outside the range previously experienced by the shrimp stock within the modelled period (1994–2009), the shrimp stock might decrease in size more than the model results have indicated as likely. The 2J3KL cod stock has shown signs of resent increases (Table 1). Cod predation effects can be included in the model as an explicit effect. This will be explored in future work.

Recruitment/reaction time of the assessment model

The model used is best at describing trends in stock development and will have some inertia in its response to year-to-year changes. Large and sudden changes in recruitment may therefore not be fully captured in model predictions.

Stock structure

The shrimp resource off the eastern coasts of Newfoundland and Labrador is not confined to SFA6 but forms a continuous band from Baffin Island to the southeastern edge of NAFO Division 3L, and shrimp that hatch in the north most likely move to the south on the Labrador Current. It might therefore be appropriate to model shrimp in the entire area as one stock rather than separate management units.

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Table 1. Model input data series (greyed area, see text for further explanation): Catch by the fishery; three indices of fishable biomass – a standardized catch rate index based on fishery data from large >500 GRT vessels (CPUE L), a standardized catch rate index based on fishery data from small <500 GRT vessels (CPUE S) and a research survey index (Survey 1). The cod series is survey biomass from the fall 2J3KL groundfish bottom trawl survey.

Year	Catch (tons)	CPUE L (index)	Survey 1 (ktons)	CPUE S (index)	Cod (ktons)
1977	1	-	-	-	-
1978	0	-	-	-	-
1979	5	-	-	-	-
1980	0	-	-	-	-
1981	135	-	-	-	-
1982	1	-	-	-	-
1983	0	-	-	-	1 444
1984	0	-	-	-	1 416
1985	0	-	-	-	1 050
1986	0	-	-	-	2 642
1987	1 845	-	-	-	1 079
1988	7 849	-	-	-	1 092
1989	6 662	0.86	-	-	1 416
1990	5 598	0.60	-	-	1 159
1991	5 500	0.49	-	-	739
1992	6 609	0.50	-	-	174
1993	8 035	0.70	-	-	44
1994	10 978	0.93	-	-	10
1995	10 914	1.25	-	-	12
1996	10 923	1.32	315	-	16
1997	21 018	1.61	310	-	17
1998	46 337	1.39	359	0.88	17
1999	51 260	1.37	412	0.87	28
2000	62 581	1.53	417	1.00	30
2001	52 590	1.53	521	1.00	31
2002	60 384	1.33	491	0.89	23
2003	71 227	1.32	433	0.91	13
2004	77 820	1.31	455	1.30	20
2005	75 231	1.35	505	1.37	28
2006	75 673	1.51	670	1.37	62
2007	80 736	1.42	566	1.43	103
2008	75 080	1.28	510	1.26	148
2009	45 108	1.00	311	1.00	143

Table 2. Priors used in the model. ~ means "distributed as..", dunif = uniform-, dlnorm = lognormal-, dnorm= normal- and dgamma = gamma distributed. Symbols as in text.

Parameter		Prior	
Name	Symbol	Type	Distribution
Maximal Suatainable Yield	MSY	reference	~dunif(1,300)
Carrying capacity	K	informative	~dlnorm(7.02,6)
Catchability survey	q_S	reference	$\ln(q_R)$~dunif(-10,1)
Catchability CPUE L	q_C	reference	$\ln(q_C)$~dunif(-10,1)
Catchability CPUE S	q_C	reference	$\ln(q_C)$~dunif(-10,1)
Initial biomass ratio	P_1	informative	~dnorm(0.75,20)
Precision survey	$1/\sigma_S{}^2$	informative	~dgamma(4,0.1125)
Precision CPUE L	$1/\sigma_C{}^2$	informative	~dgamma(4,0.1125)/2
Precision CPUE S	$1/\sigma_C{}^2$	informative	~dgamma(4,0.1125)/2
Precision model	$1/\sigma_P{}^2$	reference	~dgamma(0.01,0.01)

Table 3. Correlations among selected model parameters (for explanation of symbols, see text).

	K	P_{1994}	P_{2009}	q_{CL}	q_{CS}	q_s	σ_{CL}	σ_{CS}	σ_P	σ_s
MSY	0.17	0.36	0.59	-0.47	-0.47	-0.47	0.03	0.02	0.02	0.07
P_{1994}	-0.03	1.00	0.72	-0.50	-0.48	-0.50	-0.12	0.03	-0.06	0.09
P_{2009}	-0.06	0.72	1.00	-0.54	-0.54	-0.55	0.05	0.00	-0.18	0.12
q_{CL}	-0.66	-0.50	-0.54	1.00	0.98	0.98	-0.04	0.03	0.09	0.00
q_{CS}	-0.65	-0.48	-0.54	0.98	1.00	0.98	-0.06	0.03	0.09	0.01
q_s	-0.65	-0.50	-0.55	0.98	0.98	1.00	-0.05	0.03	0.09	0.00
σ_{CL}	0.05	-0.12	0.05	-0.04	-0.06	-0.05	1.00	-0.08	0.09	-0.15
σ_{CS}	-0.05	0.03	0.00	0.03	0.03	0.03	-0.08	1.00	-0.03	0.08
σ_P	-0.06	-0.06	-0.18	0.09	0.09	0.09	0.09	-0.03	1.00	-0.15
σ_s	-0.04	0.09	0.12	0.00	0.01	0.00	-0.15	0.08	-0.15	1.00

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

	CPUE L		Survey		CPUE S	
Year	resid (%)	Pr	resid (%)	Pr	resid (%)	Pr
1994	-2.20	0.58	-	-	-	-
1995	-14.10	0.91	-	-	-	-
1996	-13.23	0.93	14.43	0.10	-	-
1997	-24.11	1.00	24.16	0.02	-	-
1998	-9.10	0.86	10.74	0.13	9.54	0.19
1999	-4.25	0.70	0.26	0.50	15.01	0.07
2000	-9.38	0.88	4.74	0.30	5.74	0.28
2001	-5.38	0.75	-12.52	0.95	10.39	0.15
2002	5.76	0.28	-9.87	0.90	20.51	0.02
2003	5.32	0.29	1.11	0.46	16.50	0.05
2004	12.99	0.09	2.42	0.40	-13.19	0.95
2005	16.41	0.05	-2.12	0.61	-12.54	0.94
2006	12.06	0.13	-20.52	0.99	-5.84	0.75
2007	14.11	0.09	-9.97	0.89	-13.61	0.94
2008	13.86	0.08	-10.09	0.90	-11.81	0.92
2009	22.50	0.03	24.04	0.02	-6.60	0.76

*Table 5. **S**ummary of parameter estimates: mean, standard deviation (sd) and 25, 50, and 75 percentiles of the posterior distribution of selected parameters (symbols are as in the text).*

	Mean	sd	25 %	Median	75 %
MSY (ktons)	111	63	65	94	144
K (ktons)	1482	559	1086	1375	1763
r	0.33	0.20	0.19	0.29	0.43
q_S	0.51	0.22	0.35	0.47	0.63
q_{CL}	1.63E-03	7.04E-04	1.11E-03	1.48E-03	2.00E-03
q_{CS}	1.24E-03	5.44E-04	8.44E-04	1.14E-03	1.52E-03
P_{1994}	0.89	0.19	0.77	0.90	1.03
P_{2009}	1.22	0.31	1.00	1.24	1.46
σ_S	0.16	0.03	0.14	0.16	0.18
σ_{CL}	0.20	0.04	0.17	0.19	0.22
σ_{CS}	0.20	0.04	0.17	0.19	0.22
σ_P	0.12	0.04	0.09	0.12	0.14

Table 6. Upper: stock status for 2008 and 2009. Lower: predictions for 2010 given catch options ranging from 30 to 90 ktons.

Status	2008	2009
Risk of falling below B_{lim}	0.0 %	0.0 %
Risk of falling below B_{MSY}	12.4 %	25.0 %
Risk of exceeding F_{MSY}	24.4 %	13.0 %
Risk of exceeding 1.7F_{MSY}	8.4 %	3.9 %
Stock size (B/Bmsy), median	1.46	1.22
Fishing mortality (F/Fmsy),	0.82	0.58
Productivity (% of MSY)	79 %	95 %

Catch option 2010 (ktons)	30	40	50	60	70	90
Risk of falling below B_{lim}	0.1 %	0.1 %	0.2 %	0.1 %	0.2 %	0.3 %
Risk of falling below B_{MSY}	20.8 %	21.6 %	22.7 %	23.4 %	25.0 %	27.1 %
Risk of exceeding F_{MSY}	5.5 %	9.9 %	15.7 %	21.8 %	28.0 %	38.9 %
Risk of exceeding 1.7F_{MSY}	2.0 %	3.5 %	5.9 %	8.8 %	12.5 %	20.6 %
Stock size (B/Bmsy), median	1.37	1.37	1.35	1.33	1.32	1.29
Fishing mortality (F/Fmsy),	0.22	0.30	0.38	0.47	0.56	0.75
Productivity (% of MSY)	86 %	87 %	88 %	89 %	90 %	92 %

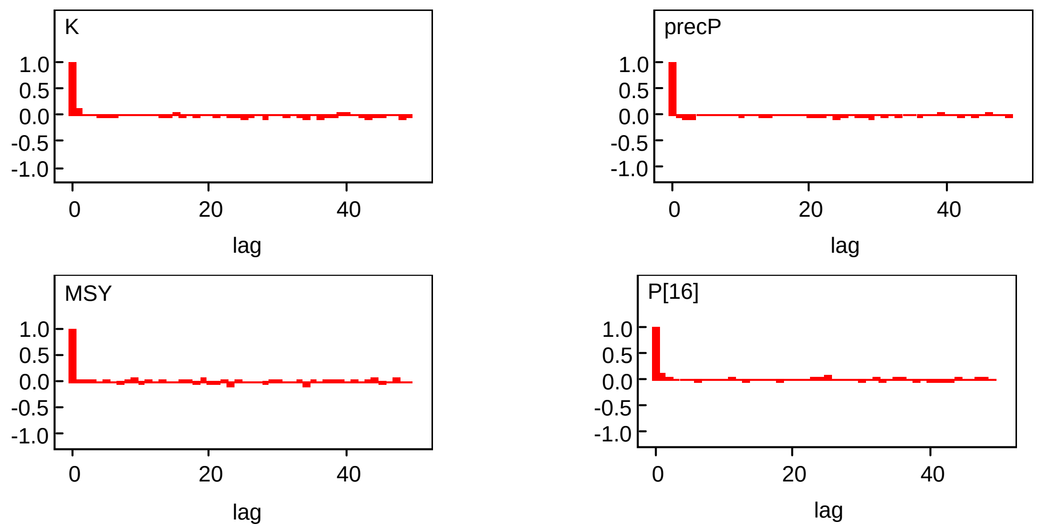

Figure 1. Autocorrelation function of values sampled for four selected variables out to lag 50. K is the carrying capacity, P[16] is the relative biomass in year 2009, MSY is maximum sustainable yield and precP is the process precision (1/ process error).

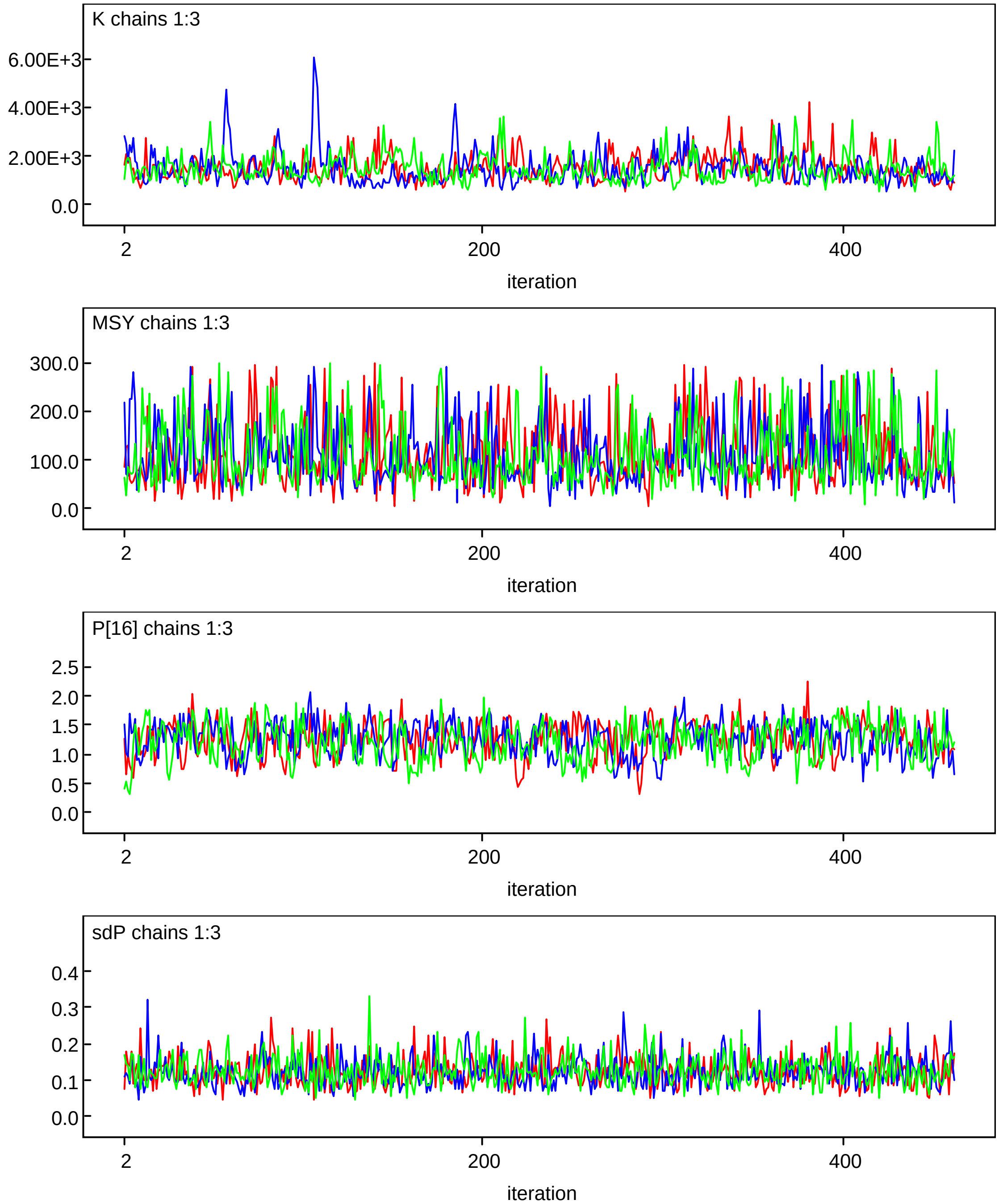

Figure 2. Three traces (red, green, blue) with different initial values of dour selected variables. K is the carrying capacity, P[16] is the relative biomass in year 2009, MSY is maximum sustainable yield and sdP is the process error.

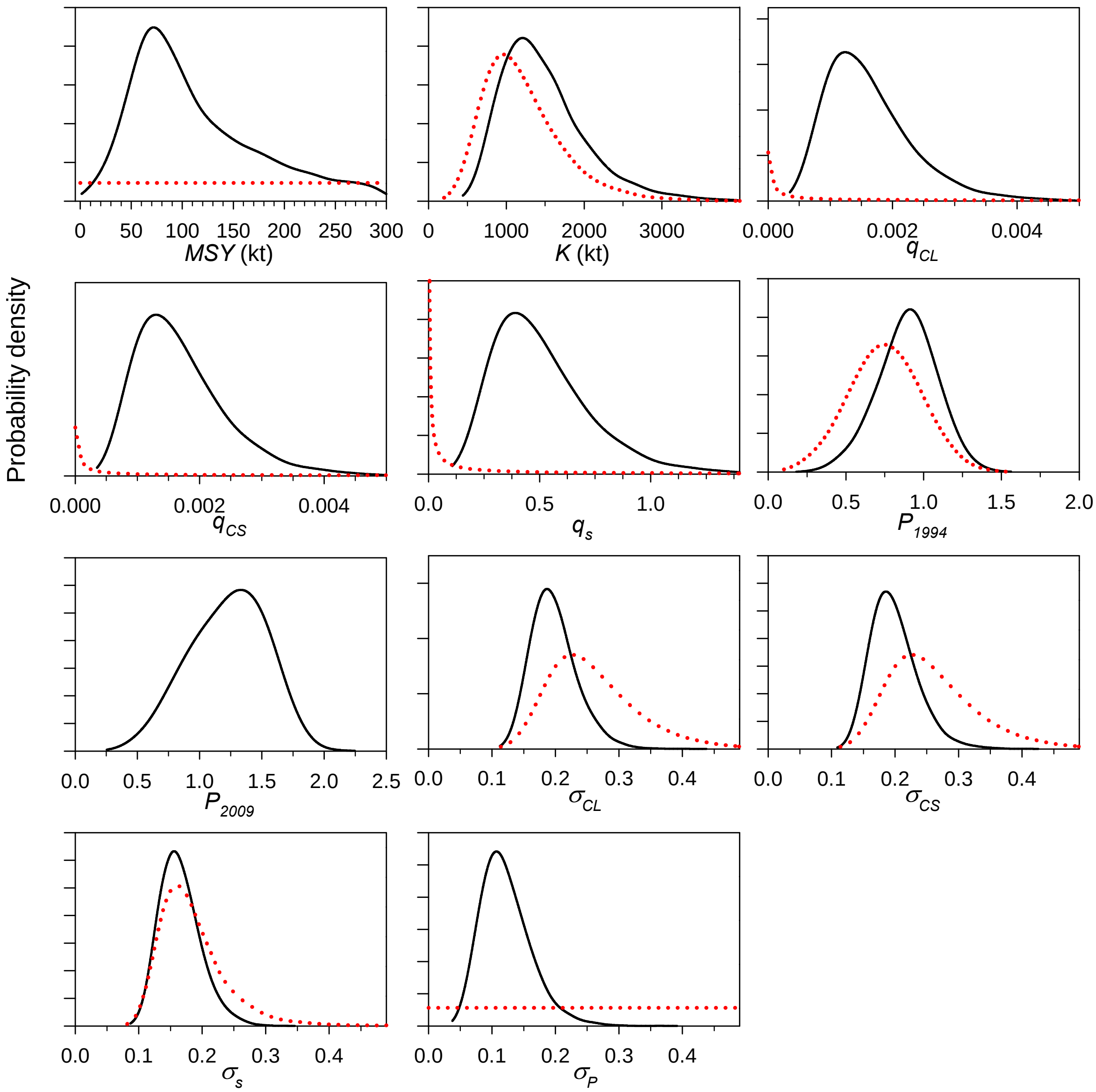

Figure 3 Probability density distributions of model parameters: estimated: posterior (solid line) and prior (broken line) distributions if relevant.

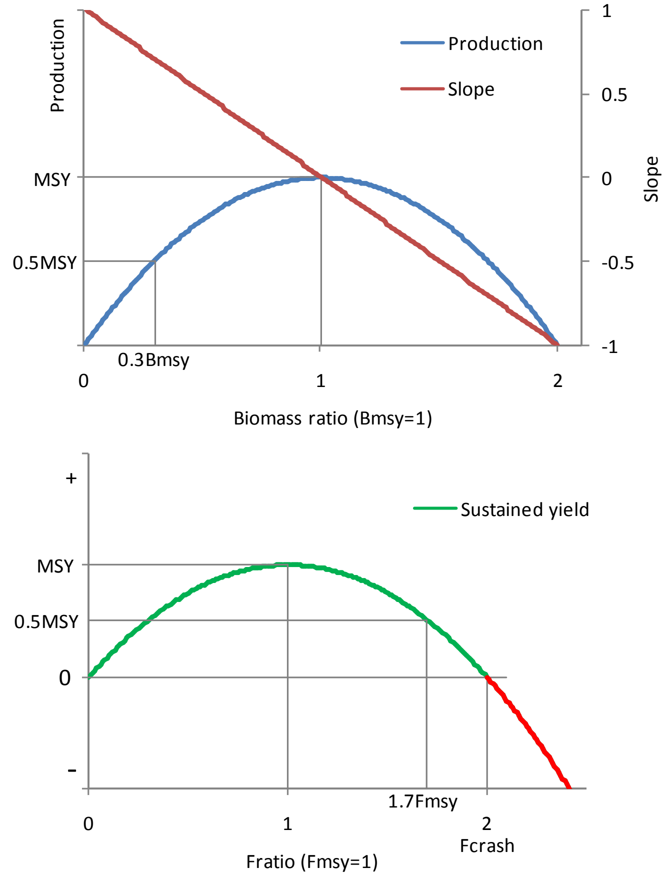

Figure 4. The logistic production curve in relation to stock biomass (B/B_{msy}) (upper) and fishing mortality (F/F_{msy}) (lower). Upper: points of maximum sustainable yield (MSY) and corresponding stock size are shown as well as the slope (red line) of the production curve (blue line); lower: points of MSY and corresponding fishing mortality and F_{crash} ($F \geq F_{crash}$ do not have stable equilibriums and will drive the stock to zero).

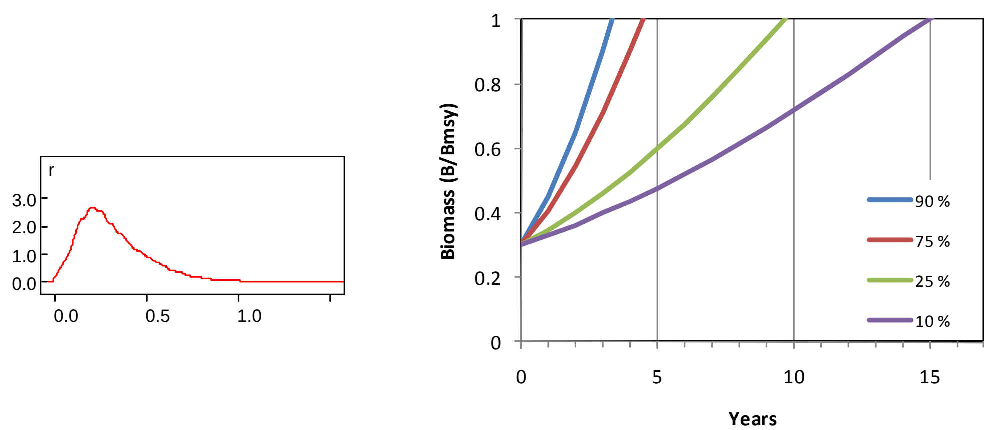

Figure 5. Left: The posterior probability density distribution of r, the intrinsic rate of growth. Right: estimated recovery time from B_{lim} ($0.3B_{msy}$) to B_{msy} (relative biomass = 1) given r values ranging within the 90% conf. lim. of the posterior (left figure) and no fishing mortality.

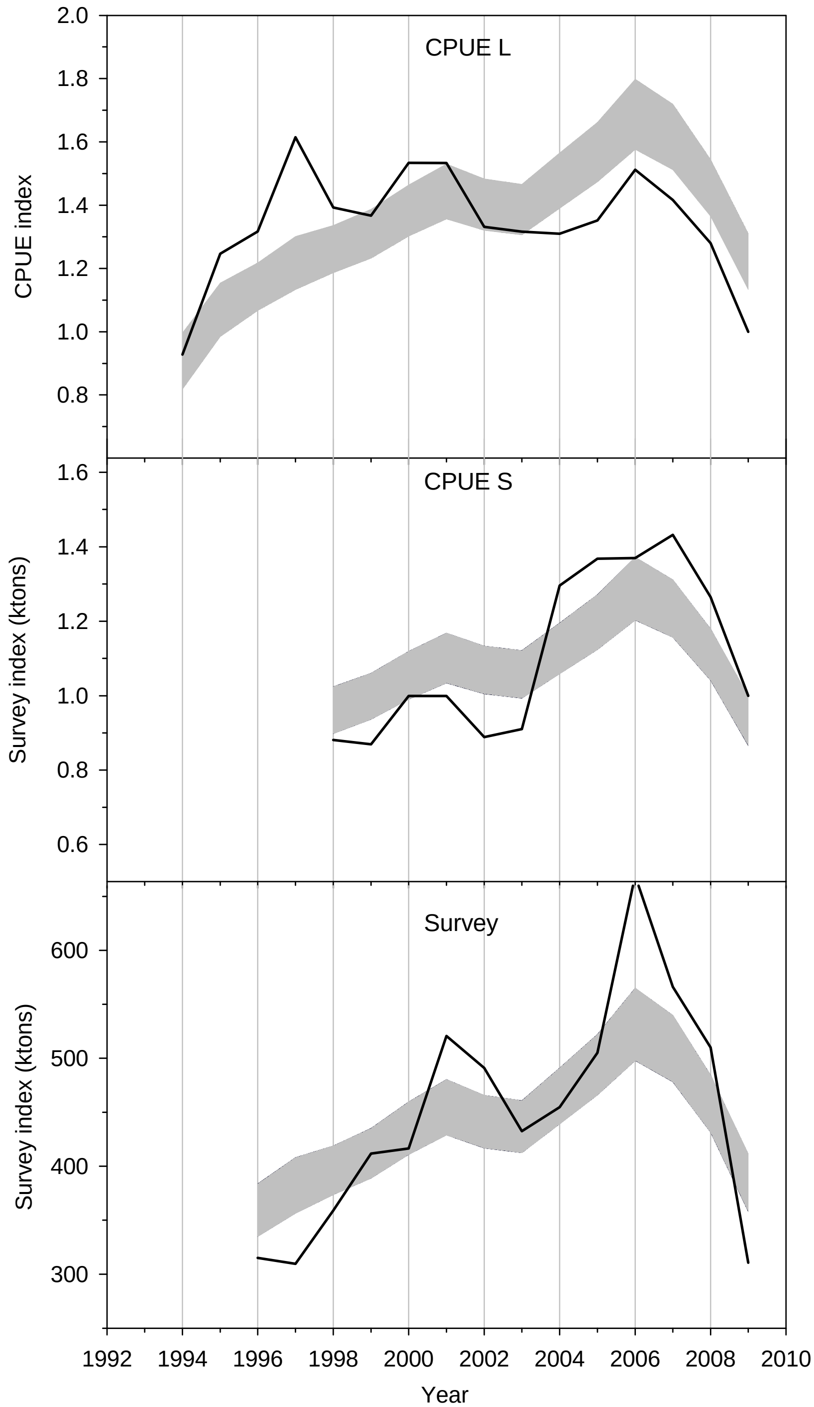

Figure 6. Observed (solid line) and predicted (shaded) series of the biomass indices used as input to the model (the shaded areas are inter-quartile range of the estimated posteriors).

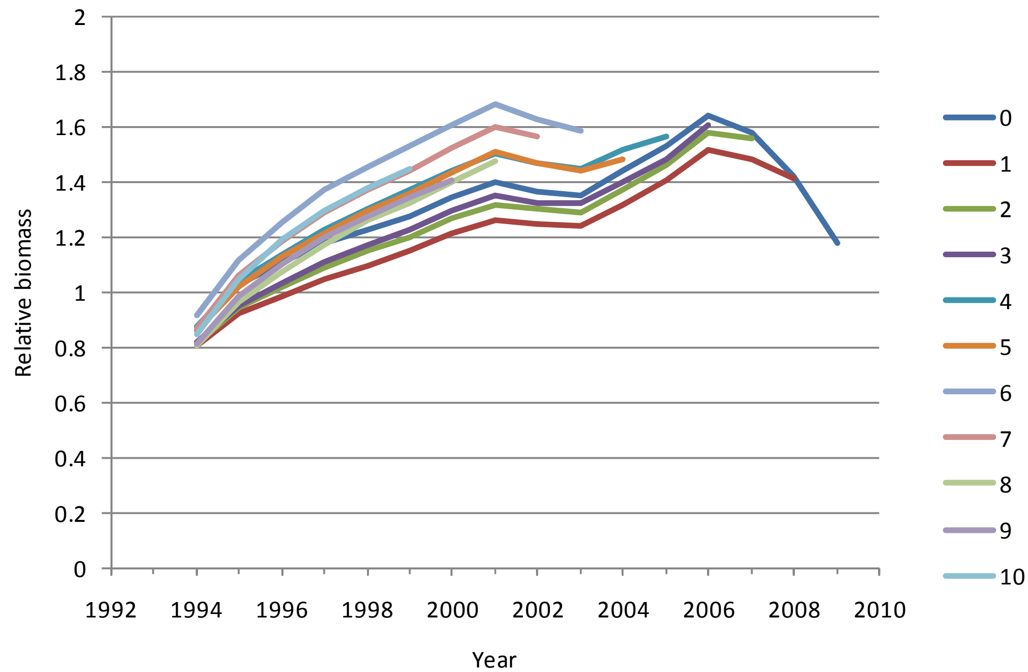

Figure 7. Retrospective plot of median relative biomass (B/B_{msy}). Relative biomass series are estimated by consecutively leaving out from 0 to 10 years of CPUE and survey data (the catch series are kept as original through out).

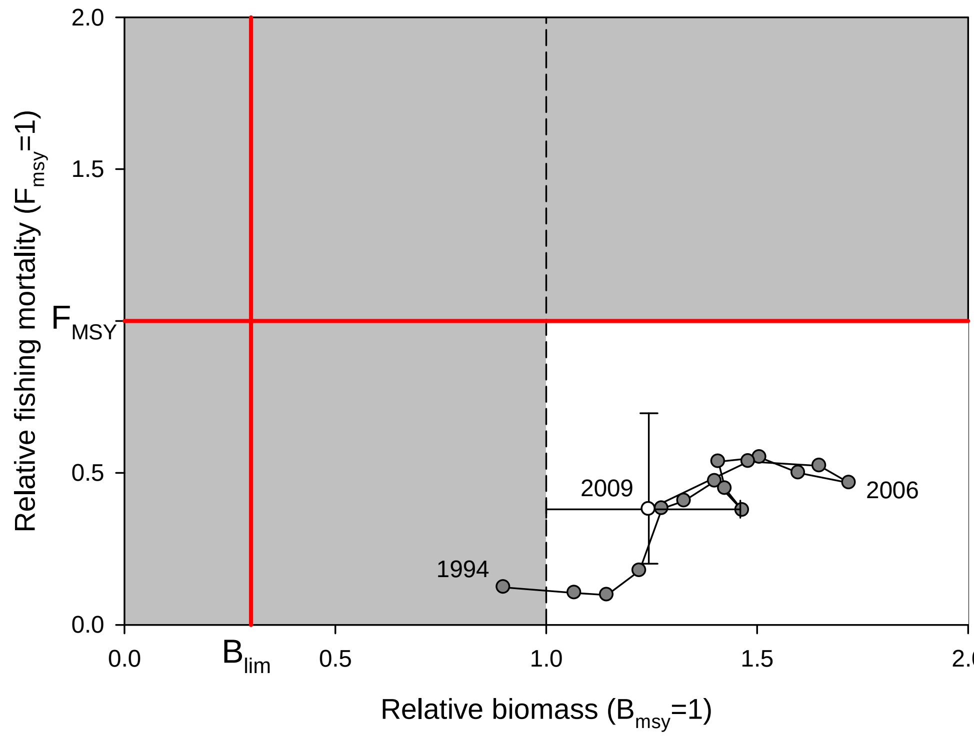

Figure 8. Shrimp in SFA6: estimated annual median biomass-ratio (B/B_{MSY}) and fishing mortality-ratio (F/F_{MSY}) 1994-2009. The reference points for stock biomass, B_{lim}, and fishing mortality, F_{lim}, are indicated by red lines. Error bars on the 2009 value are inter-quartile range

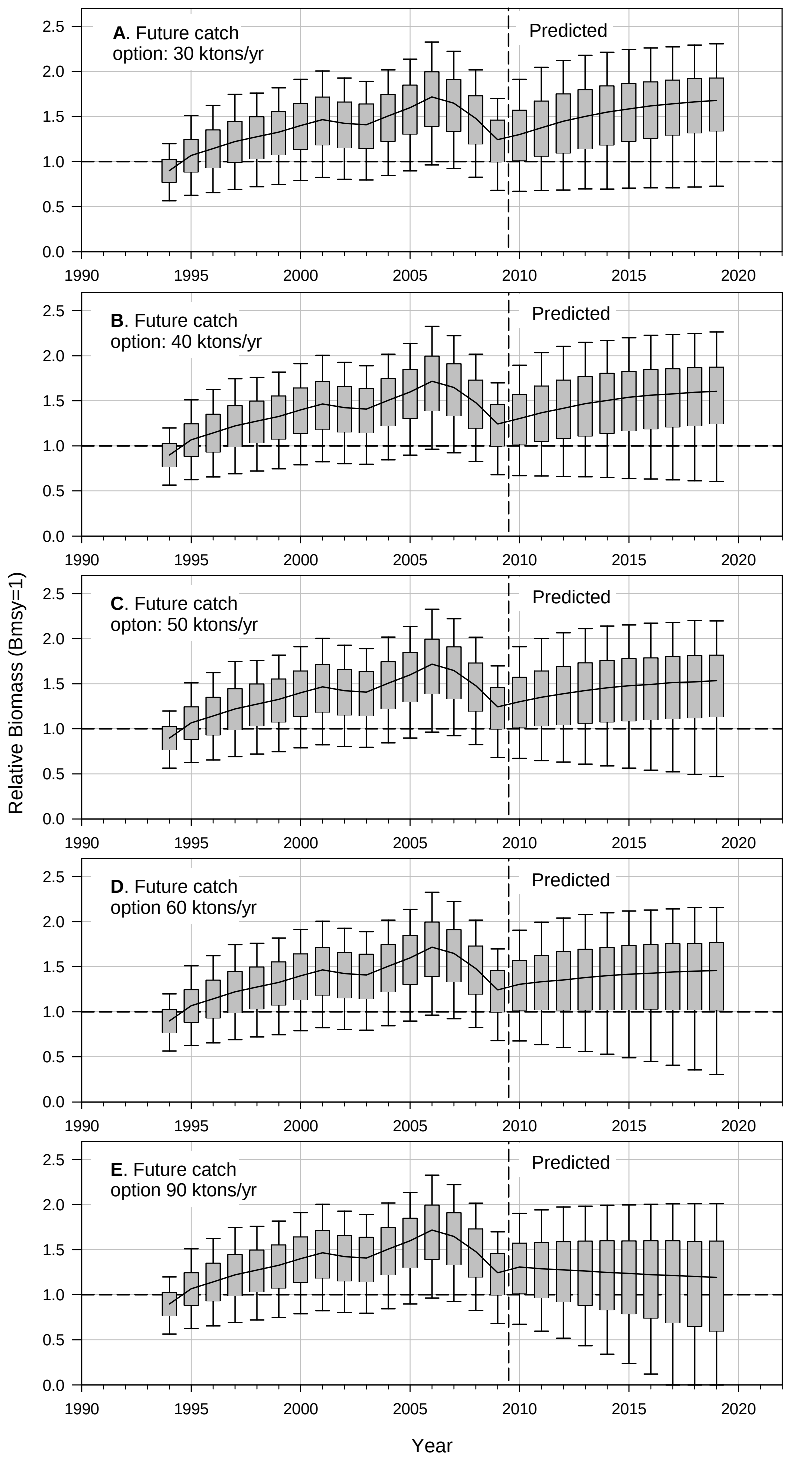

Figure 9. Shrimp in SFA6: Estimated time series of relative biomass (B_t/B_{msy}) 1994-2019. Future development is estimated at five different levels of annual catch (panel A-E). Boxes represent inter-quartile ranges and the solid black line running through the (approximate) centre of each box is the median; the arms of each box extend to cover the central 90 % of the distribution.

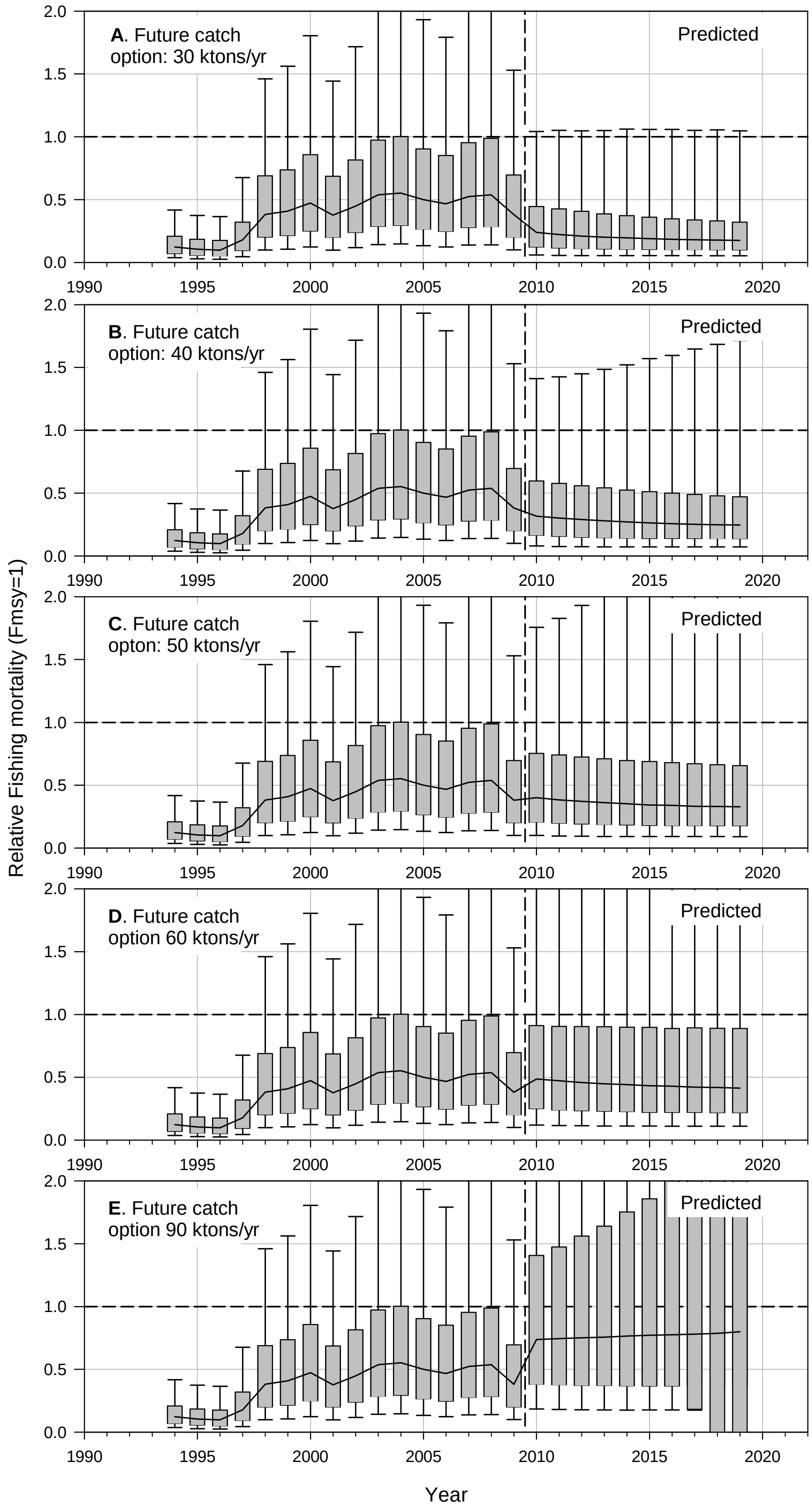

Figure 10. Shrimp in SFA6: Estimated time series of relative fishing mortality (F_t/F_{msy}) 1994-2019. Future development is estimated at five different levels of annual catch (panel A-D). Boxes represent inter-quartile ranges and the solid black line running through the (approximate) centre of each box is the median; the arms of each box extend to cover the central 90 % of the distribution.

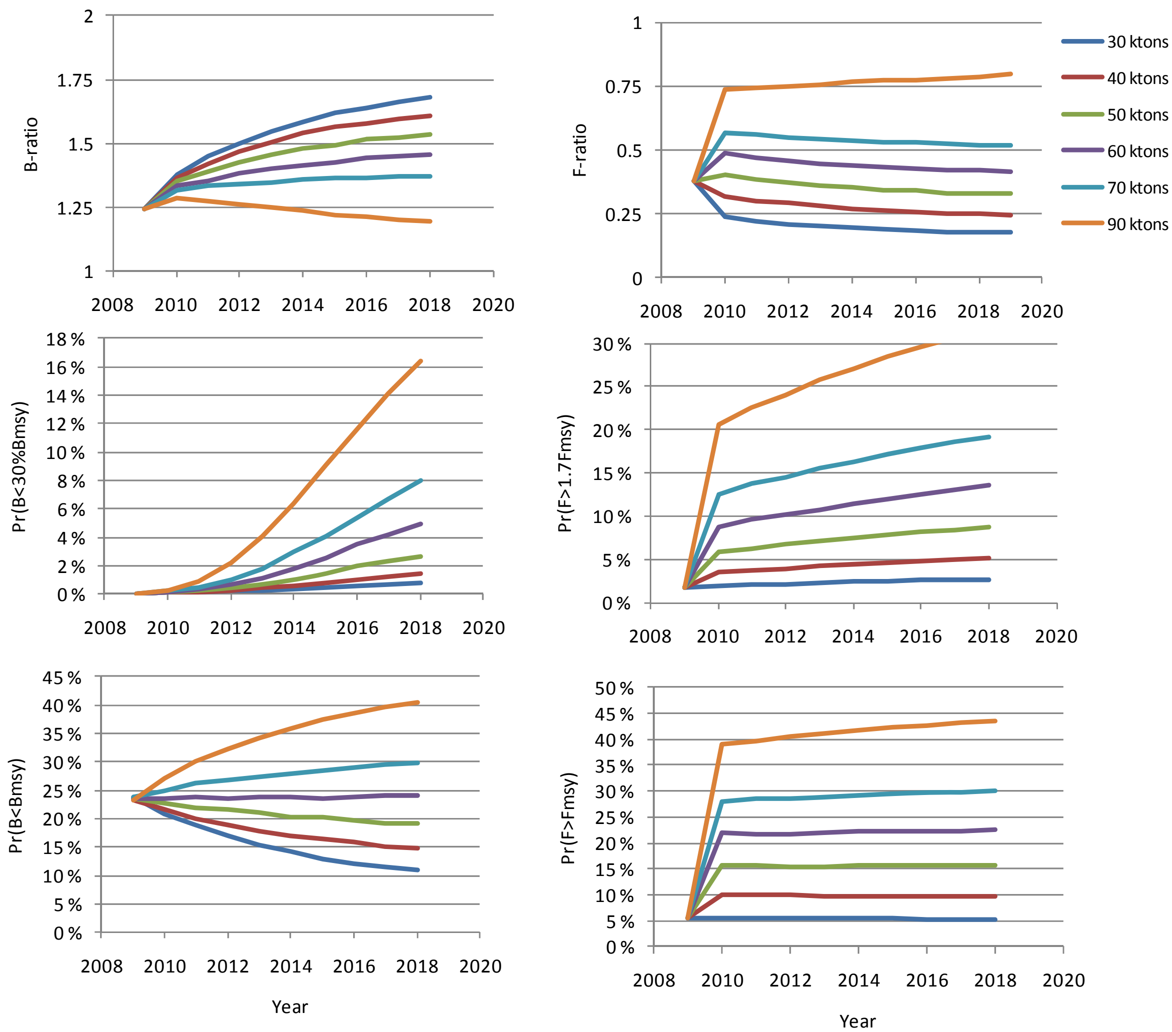

Figure. 11. Projections (left): Medians of estimated posterior biomass ratios and fishing mortality ratios; estimated risk (right and below) of exceeding F_{msy} and F_{lim} ($1.7F_{msy}$) or going below and B_{lim} given a range of 30 to 90 ktons catch options