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A Stock-Dynamic Model of the West Greenland Stock of Northern Shrimp

by

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Summary

A quantitative stock-dynamic model is used in assessing the West Greenland stock of *Pandalus borealis*. It is a simple surplus production model based on a Schaefer model of stock dynamics. The model tracks biomass indices provided by standardized series of fishery catch:effort ratios and a research trawl survey executed annually since 1988. It fits changes in stock size to estimated production and removals, which comprise documented catches and predation by Atlantic cod (*Gadus morhua*). Predation is estimated by a functional relationship between predation rate and prey biomass. The model is fitted by Bayesian methods to thirty-year data series. Changes to the model in 2015 included: revised calculation of mortality; linking biomass indices to modelled mid-year stock biomass; less informative prior distributions for parameters of the predation function; and a less informative prior distribution for the initial stock biomass.

The 2015 research trawl survey estimated an increase in stock size. Results from the assessment model reflected that, showing a stock 23% above B_{msy} and exploited in 2015—on the basis of estimated cod biomass and catches for the year—at only 58.6% of Z_{msy}. With moderate estimates of future cod biomass it was estimated that catches up to 90 000 tons would not entail a risk greater than 35% of exceedin Z_{msy}.

Introduction

In 2002 a quantitative assessment framework based on a biological model of shrimp stock dynamics (Hvingel and Kingsley 2002) was adopted by STACFIS and Scientific Council as a contribution to the assessment of the West Greenland stock of the Northern Shrimp *Pandalus borealis*.

The stock-dynamic model is a non-age-structured stock-production model that attempts to fit a Schaefer stock-production relationship to past data on stock size and stock production. Stock-size information is obtained from a research trawl survey and from logbook information on fishery effort and catches. Net stock production is deduced from change in estimated stock size and from removals, which comprise fishery catches and an estimate of predation by Atlantic cod. Other mortality is simply subsumed in the global net production. The predation by cod is treated by fitting a functional relationship between the amount consumed and the biomasses of cod and shrimps; the consumption is estimated as a component of the discrepancy between the biomass predicted by the stock-dynamic function and that fitted to the stock-size observations.

The model is fitted by Bayesian methods using the OpenBUGS platform which produces a complete multivariate posterior distribution of the parameters of the stock dynamics, including the predation function.

Forward predictions of the evolution of the stock are made within the same model, using the entire posterior distribution, based on proposed catch options and likely values for the biomass of the cod predator.

Quantitative Assessment

Parameters relevant for the assessment and management of the stock were estimated by a stochastic version of a surplus-production model that included an explicit term for predation by cod. The model was formulated in a state-space framework, and Bayesian methods were used to construct posterior likelihood distributions of the parameters (Hvingel and Kingsley 2002).

A discrete-time state equation (Pella and Tomlinson 1969) describing the transition of the fishable biomass from the end of year *t-1* to the end of year *t* was:

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

where *MSY* is an annual maximum sustainable yield and B_{MSY} is the fishable biomass yielding it. P_t is the stock biomass relative to biomass at *MSY* (P_t=B_t/B_{MSY}) at the end of 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:

$$P_t = \left(P_{t-1}\left(1 + \frac{MSY}{B_{MSY}}(2 - P_{t-1}) \right) - \left(\frac{C_t + V_t}{B_{MSY}} \right) \right)$$

The 'process errors', *v* are normally, independently and identically distributed with mean 0 and variance σ_v^2 .The chain of biomass indices P_t was fitted to two series of biomass indices, one from a research trawl survey and the other from fishery catch:effort ratios, while the biomass transitions from year to year were fitted to the stock-dynamic equation and to series of fishery catches and predation estimates derived from indices of cod biomass. The ratio, $Z_{MSY} = \frac{MSY}{B_{MSY}}$, the MSY level of mortality, is a key parameter, and is shown to be a discrete-time value—i.e. the ratio between change in biomass and start biomass over a discrete time-step—by rearranging the Schaefer expression:.

$$Z_{MSY} = \frac{P_t - P_{t-1} + R_t}{P_{t-1}(2 - P_{t-1})}$$

where R_t represents the scaled removals from the stock.

The annual discrete-time mortality is given by $Z_t = \frac{C_t + V_t}{P_{t-1} \cdot B_{MSY}}$, so that the Schaefer stock-dynamic equation simplifies to:

$$P_t = P_{t-1}(1 + Z_{MSY}(2 - P_{t-1}) - Z_t)$$

For fitting to the data, a series of identically distributed Normal error terms ν_t is applied to the sequential relationship:

$$P_t = P_{t-1}\left(1 + Z_{MSY}\left(2 - P_{t-1}\right) - Z_t\right) \cdot \exp(\nu_t)$$

These error terms are considered to be, and are fitted as, serially independent both in fitting to past data and in projecting the stock status forward into the future.

The biomass indices P_t are considered to measure stock status at year end. Survey data is obtained in mid-year and the CPUE index is calculated from calendar-year data, so a mid-year biomass index to link to these observed values was constructed as the mean of the start- and end-year values:

$$Pmid_t = \frac{P_{t-1} + P_t}{2}$$

- the survey series of indices of the fishable (i.e. at least 17 mm (oblique) carapace length) biomass index is provided by a research trawl survey executed annually with consistent methods (Wieland 2005; Burmeister et al. 2014); observed values are linked to the mid-year biomass index by a catchability parameter and an error term:

$$surv_t = q_s B_{MSY} Pmid_t \exp(\kappa_t)$$

- CPUE index series are obtained from four fleets: the original Greenland KGH fleet, the modern Greenland offshore and costal fleets, and the Canadian fleet fishing in the Canadian EEZ which composes about 3% of the stock area. Linear models are fitted to the four sets of catch and effort data to create series of CPUE indices which are then (Kingsley 2008a; Hammeken Arboe 2014b) unified into a single series by a separate model. The resulting unified series gives greatest weight to the historical 'KGH' fleet in the early days of the fishery and in more recent times to the offshore fleet of large trawlers. Relative weights for the offshore and coastal Greenland fleets were re-calculated in 2014 from the distribution of haul positions in 2013 and slightly revised. CPUE data for the calendar year was linked to the mid-year biomass index by:

$$CPUE_t = \ln\left(q_c Pmid_t\right) + \omega_t$$

Catch data was obtained variously from fishery logbooks, fishery reports to, and quota drawdowns entered by the Greenland Fishery control agency, Canadian observer logbooks, Canadian Atlantic quota reports, and national statistical reports to STATLANT. Catches have been corrected for past misreporting of various kinds (Hvingel 2004; Kingsley 2008a; Hammeken Arboe 2014); past catches are assumed error-free in the model. Uncertainty in the projected catch for the present year was treated by fitting

$$C_t = b \cdot R_t \cdot \exp\left(\zeta_t\right)$$

to a short recent series of past projected, *R*, and realised, *C*, catches, thereby estimating both a correction factor *b* for the current year's projected catch and also an uncertainty for the corrected value.

- four series of cod biomass estimates by VPA and survey, of different lengths and covering different periods (Siegstad and Kingsley 2014; Kingsley 2014) are included. The research trawl surveys were 'ICES', 'Greenland Skjervøy' and 'Greenland Cosmos.' For each series, a correction factor and an error variance were fitted

$$Cod_{s,t} = f_s \cdot T_t \cdot \exp(\rho_{t,s})$$

T being the series of 'true' biomass values, Cod being the index estimate from VPA or survey, f a correction factor, and the error terms ρ normally distributed. The correction factor for the ICES survey was fixed at 0.6 to allow the factor for the short VPA series to be close to unity.

- a series of estimates of the overlap between the shrimp and cod distributions (Wieland and Storr-Paulsen 2004) using an index of colocation based on density at trawl-survey stations was calculated outside the assessment model and multiplied by the 'true' cod biomass estimates to arrive at a series of 'effective' cod biomass estimates E_t.

Predation by cod was modelled as a Holling (1959) type III functional relationship:

$$V_t = E_t \frac{V_{\max} P_{t-1}^2}{P_{t-1}^2 + P_{50\%}^2} \exp(\tau_t)$$

The parameters V_{max} and $P_{50\%}$ were estimated largely through fitting the biomass trajectory to the biomass index data, but an additional 4-year (1988—91) series of estimates of the shrimp biomass consumed by cod (Hvingel and Kingsley 2002) based on stomach analyses (Grunwald 1998) (Table 1; Fig. 6) with its own associated series of cod biomass estimates was also used to fit the same parameters, but with a different error variance.

The ratio of the discrete-time total mortality Z_t to the discrete-time MSY level of mortality was modelled as:

$$\frac{Z_t}{Z_{msy}} = \frac{C_t + O_t}{P_{t-1} \cdot B_{msy} \cdot Z_{msy}}$$

The model was fitted by Bayesian methods, the integration being carried out by Markov Chain Monte Carlo sampling. The sampling was burnt in for 50 000 or 100 000 iterations and then run for 8 000 000 or 10 000 000, every 100th being retained. Of the resulting 80 000 or 100 000 retained iterations every 10th was used in the final calculations, giving sample sizes of 8 000 or 10 000.

This model was reviewed and approved by Scientific Council and taken into use in 2004. In the ensuing period the following changes have been made and retained; some other tested changes were abandoned and not implemented.

2006. An 'effective' cod biomass series, allowing for partial overlap between stocks of the prey and the predator, was introduced (Wieland and Storr-Paulsen 2004; Storr-Paulsen et al. 2006).

2007. The Grunwald cod-predation relationship was coded separately from the main cod predation block and a separate cod biomass series was associated with it. This solved the then-existing problem that changing the main cod biomass series destabilised the model (Kingsley 2007). Error terms τ were included in the main cod-predation model.

2007. The Pella-Tomlinson stock-dynamic function was abandoned in favour of the Schaefer simplification.

2009. Coding was changed so that P_t became the biomass index at the end of year t instead of at the start. When the model was approved, P_t was documented as the biomass 'in' year t. The catch and estimated predation for year t were employed in transferring the stock from its state 'in' year t to its state 'in' year t+1, implying that 'in' meant 'at the start of.' The stock state 'in' the first forecast year was therefore at its start, so at the end of the current (assessment) year. With this change, the stock status at the end of the current year was still a forecast, not linked to a data point, but the reported forecast period started with the year after the assessment.

2011. The modelled biomass index trajectory was required, by constraining the relative precisions, to follow the survey series at least as closely as the CPUE series. When the model was approved, it was free to fit the stock biomass trajectory to the data series and the stock-dynamic equation as it wished, estimating the error variances in accordance. The result was that the trajectory was fitted closely to the relatively smooth CPUE series with small process error and small error variance of the CPUE observations. The model largely ignored the more variable survey series, assigning a survey error variance that was greater than that calculated for the survey results.

2011. The data series were shortened to 30 years. This data horizon still includes the entire survey series.

2013. Uncertainty in the projected catch for the current year was treated by introducing a series of past projected catches and comparing them with the realised catch for the year, instead of as formerly considering the assessment year's projected catch as being known without error. This increased uncertainty as to stock status at the end of the assessment year.

2013. Fishery catch:effort data from a most northerly statistical area 0 was included in the calculation of the input CPU series.

2014. Four separate indices of the cod biomass (an early VPA analysis, a groundfish research trawl survey carried out by Germany, and two Greenland research trawl series using different gears), not all overlapping in time, were introduced (Kingsley 2014a). The previous practice had been to calculate a single cod-stock biomass series outside the assessment model. Uncertainty as to the cod biomass, and therefore predation, in the assessment year increased the uncertainty associated with the condition of the shrimp stock at the end of the assessment year.

2015. A biomass index at the middle of the year was constructed as the mean of values at the year start and end. Biomass-index data (i.e. survey and CPUE) was linked to the mid-year biomass index instead of to the index at the start of the year. This reduced the uncertainty associated with the forecast of shrimp stock condition at the end of the assessment year.

2015. Wider (non-informative) priors were used for the parameters of the predation function (Kingsley 2014b). Hitherto, the maximum predation rate (w/w) was fixed at 3, but this level was incompatible with the Greenland data and would never be reached. The effect was to reduce estimated predation when both shrimp and cod biomasses were high, compensated by a lower estimate of MSY. Risk levels for future catches were thereby reduced when cod stocks were forecast to be high and the shrimp stock was also high.

2015. A wider prior—precision of 15 instead of 25—was used for the biomass index at the start of the first modelled year. (Precisions even lower caused the model to run slowly and hesitantly.)

2015. Realised mortality, both historically and in future projections, was calculated as a discrete-time value instead of, as formerly, an instantaneous rate which could not properly be compared with the discrete-time productivity used in the stock-dynamic equation. The effect, by reducing calculated future mortalities, was to decrease mortality risk levels associated with future catches.

An outstanding problem is the treatment of cod predation, which in the present model coding is associated with two series of error terms, the ν_t and the τ_t. It is expected that this problem will be resolved in 2016 by removing the τ_t from the model coding, so that the uncertainty in predation is expressed entirely by the uncertainty in the parameters of the functional relationship.

Results, Model Performance

The model fitted fairly well to the observed data series (Fig. 1), but the error term for cod predation was large (Table 1). This could be due to the interaction between the large dynamic range of the cod biomass estimates, including many very small values while cod was largely absent from the offshore shrimp range, and the smaller range of the year-to-year change in shrimp biomass, or it could be due to the model's applying both process error and a separate cod-predation error term to the predicted predation when calculating the stock dynamic transfer from one year to the next.

Some parameters of the supposed stock dynamic system are implicitly difficult to estimate. Notable among them are the carrying capacity and the MSY level of biomass. Consequently, the survey and CPUE catchabilities are also poorly determined, as is the ratio of MSY to MSYL. This cascade of poor estimations generates high correlations among these parameters (Table 3).

In verifying that the thinning of the Markov chains had been effective, most attention was paid to the auto-correlation in the chains for the forward projection values, and less to the stock-dynamic parameters.

In using surplus-production models like this one for forecasting future trajectories of the stock under various different harvesting scenarios, there is reason to be concerned about serial correlation in the errors, especially the process error. In calculating forward projections and their uncertainties, process error is sampled and applied independently each year with the variance calculated from the history of the stock and the fit of its dynamics to the data under an assumption of independent process errors. If, however, the history of the stock shows year-on-year serial correlation of process errors, the forward projections should ideally be made using the same serially correlated structure. Process error serial correlation was calculated for the assessment model using the following code:

```
      Proc.Err[i] <-  log(P[i]) - P.med[i] # P.med being the log of P.pred

#Serial Correlation of Process.Error

for (i in 1:Past.Years)
{  Proc.Err.Dev.One[i] <- Proc.Err[i] - mean(Proc.Err[1:Past.Years])
   P.E.D.O.sq[i] <- Proc.Err.Dev.One[i] * Proc.Err.Dev.One[i]
}
for (i in 2:Present.Year)
{  Proc.Err.Dev.Two[i-1] <- Proc.Err[i] - mean(Proc.Err[2:Present.Year])
   P.E.D.T.sq[i-1] <- Proc.Err.Dev.Two[i-1] * Proc.Err.Dev.Two[i-1]
}

Proc.Err.Corr <- inprod(Proc.Err.Dev.One[], Proc.Err.Dev.Two[]) /
sqrt(sum(P.E.D.O.sq[])*sum(P.E.D.T.sq[]))
```

This resulted in a median estimate of the serial correlation of the process error for the 30-year data series 1986–2015 at -0.1% with quartile points at ± 12.4%. Given the large excursion of the stock to high biomass values in the early 2000s, this is a surprisingly small value, but the inference is that going forward to make future predictions with an assumption of serially independent process errors will not cause serious problems.

Results of the Quantitative Assessment

In every respect, the results of the quantitative assessment reflected the remarkable change in stock biomass estimated by the trawl survey. The median estimate of the *MSY* was 141Kt—i.e. 10 Kt more than the estimate made in 2014—with quartiles at 106 and 187 Kt; an estimated mode is at 109 Kt. The model estimates that the stock biomass has decreased in every year from 2004 to 2013 even though catches since 1990 appear to have been sustainable. Fishable biomass at end 2015 is projected above the 2014 value and 23% above B_{msy}. The low catches projected for 2015 are expected to hold total mortality in 2015 below 60% of Z_{msy}.

Risks associated with eight possible catch levels for 2016, with an ‘effective’ cod stock at 45 000 t , are estimated to be:

45 000 t cod	Catch option ('000 tons)							
Risk of:	60	70	75	80	85	90	95	100
falling below Bmsy end 2016 (%)	23.5	24.6	25.0	25.5	25.9	26.2	27.0	26.7
falling below Blim end 2016 (%)	0.9	1.0	1.0	1.1	0.9	1.1	0.8	1.1
exceeding Zmsy in 2016 (%)	19.1	22.5	24.2	25.8	28.3	30.1	32.3	34.5
exceeding Zmsy in 2017 (%)	20.2	23.5	25.5	27.7	29.4	31.4	34.1	36.8

with an 'effective' cod stock at 55 000 t (close to the 2015 estimate):

55 000 t cod	Catch option ('000 tons)							
Risk of:	60	70	75	80	85	90	95	100
falling below Bmsy end 2016 (%)	25.0	25.0	25.4	26.2	26.6	26.6	27.0	27.2
falling below Blim end 2016 (%)	1.2	1.3	1.1	1.3	1.4	1.1	1.2	1.2
exceeding Zmsy in 2016 (%)	21.7	24.5	26.6	28.2	30.7	32.3	34.7	36.9
exceeding Zmsy in 2017 (%)	23.0	26.3	27.6	29.4	31.9	33.4	36.8	38.8

and with an 'effective' cod stock at 65 000 t:

65 000 t cod	Catch option ('000 tons)							
Risk of:	60	70	75	80	85	90	95	100
falling below Bmsy end 2016 (%)	25.0	25.9	26.3	26.8	26.9	27.4	27.9	28.3
falling below Blim end 2016 (%)	1.4	1.4	1.3	1.4	1.4	1.4	1.4	1.5
exceeding Zmsy in 2016 (%)	23.6	26.6	28.3	30.5	32.0	34.1	36.4	39.3
exceeding Zmsy in 2017 (%)	25.3	28.0	30.0	32.3	34.5	36.7	38.7	40.9

If a mortality risk (i.e. of exceeding Z_{msy}) criterion of 35% is observed, catches of 90–95 Kt are predicted to be sustainable, provided that the effective cod biomass does not make further large gains in the coming years. However, if the total TAC decided for 2015 was 73 000 t, a catch smoothing rule limiting change in TAC to ±12½% would impose a limit of 82 125 t on the allowable catch for 2016.

Predation by cod can be significant and have a major impact on shrimp stocks. Currently the cod stock at West Greenland is at a low level, but recent years have seen slow, but progressive, increases. A large cod stock that would significantly increase shrimp mortality could be established in two ways: either by a slow rebuilding process or by immigration of one or two large year-classes from areas around Iceland, as in the late 1980s. The question of cod predation is bedevilled by the difficulty of foreseeing the evolution of the stock and complicated by uncertainty as to the overlap between the two species.

Projections of stock development were made under the assumption that the 'effective' cod stock will remain at levels consistent with recent estimates, and that parameters of the stock-dynamic and predation processes, including their uncertainties, will retain the values estimated from the 30-year data series. Eight levels of annual catch were investigated from 60 000 to 1000 000 tons (Figs 10–12, Table 4; Appendix).

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 a 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} was set at 30% of B_{msy}. The risks of transgressing B_{lim} under scenarios of different future catches have been estimated (Table 4) and are low.

Conclusions

The stock is predicted to remain well above its *MSY* level at end 2015. Given the uncertainty of both stock status and stock-dynamic parameters, the risk of exceeding Z_{msy} should probably not exceed 35%. A quantitative assessment indicates that catches below 90 Kt would keep the risk of exceeding Z_{msy} below 35%, assuming certain limits on the evolution of the biomass of Atlantic cod.

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Table 1. *Pandalus borealis* in West Greenland: input data series 1986–2015 for stock-dynamic assessment model.

	Effective cod biomass[1] (Kt)	Catch (Kt)	Provisional catch (Kt)	Survey index of fishable biomass (Kt)	Predation estimate[2] (Kt)	Cod-stock estimate[2] (Kt)	ln CPUE (1990=0)
1986	25.9	76.9					0.289
1987	329.9	73.6					0.432
1988	313.5	77.9		223.2			0.144
1989	146.5	80.7		209	213.7	470.9	0.048
1990	10.1	84.0		207	27.8	184.1	0.000
1991	1.8	91.5		146	2.7	19.8	0.042
1992	0.3	105.5		194.2	0.8	2.9	0.115
1993	0.2	91.0		216.5			0.106
1994	0.1	92.8		223.1			0.108
1995	0.1	87.4		183.2			0.201
1996	0.1	84.1		192.1			0.248
1997	0.1	78.1		167.1			0.218
1998	0.1	80.5		244.3			0.358
1999	0.1	92.2		237.3			0.469
2000	0.4	98.0		280.3			0.572
2001	0.8	102.9		280.5			0.530
2002	0.7	135.2		369.5			0.697
2003	0.9	130.2		548.3			0.758
2004	1.4	149.3		528.3			0.859
2005	2.7	156.9	140.5	494.2			0.902
2006	21.8	157.3	140.2	451			0.880
2007	15.0	144.2	135.2	336.1			0.948
2008	8.4	153.9	131.6	262.6			0.978
2009	2.5	135.5	108.8	255.1			0.860
2010	5.4	134.0	138.5	318.7			0.833
2011	24.2	124.0	128.0	245.7[3]			0.863
2012	39.7	116.0	110.0	176.4[3]			0.784
2013	37.7	95.4	100.0	218.1[3]			0.655
2014	58.3	88.8	90.0	170			0.749
2015	55.9	—	65.0	255.5[3]			0.758

[1] 'effective cod biomass' was not an input data series in 2015; instead, four series of cod survey biomass indices were input and used to estimate a cod biomass series which was multiplied by an input overlap series to generate an 'effective cod' series; tabulated are the median resulting estimates (see Kingsley 2014).
[2] Grunwald (1998).
[3] survey estimates of fishable biomass for 2011, 2012, 2014 and 2015were adjusted for incomplete coverage of offshore strata.

Table 2. *Pandalus borealis* in West Greenland: summary of estimates of selected parameters from Bayesian fitting of a surplus production model, 2015.

	Mean	S.D.	25%	Median	75%	Est. mode	Median (2014)
Max. sustainable yield (Kt)	155.3	94.7	104.7	140.2	186.2	110.0	131.3
B/B_{msy}, end current yr (proj.)	126.9	35.7	102.0	123.0	147.3	115.2	97.3
Biom. risk, end current yr (%)	23.0	42.1	–	–	–	–	–
Z/Z_{msy}, current yr (proj.)	–	–	37.4	58.6	94.1	–	103.1
Carrying capacity	4255	3166	2226	3365	5257	1585	3126
M.S.Y. ratio (%)	10.1	6.6	5.2	9.2	13.8	7.5	9.0
Survey catchability (%)	15.8	12.6	7.3	12.3	20.2	5.1	14.1
CPUE catchability	1.0	0.8	0.5	0.8	1.3	0.3	0.9
Effective cod biomass 2014 (Kt)	75.2	88.4	36.1	55.9	84.5	17.2	44.3
$P_{50\%}$	4.5	10.6	0.2	1.1	4.7	-5.9	7.2
V_{max}	1.5	2.0	0.3	0.6	1.8	-1.2	3.0
CV of process (%)	14.2	3.7	11.5	13.7	16.4	12.7	12.1
CV of survey fit (%)	16.4	1.8	15.2	16.5	17.8	16.6	15.9
CV of CPUE fit (%)	19.3	2.7	17.5	19.0	20.6	18.3	19.0
CV of predation fit (%)	139.9	90.5	66.1	124.7	198.2	94.3	115.4

Table 3. *Pandalus borealis* in West Greenland: selected[1] correlations (%) between model parameters, 2015.

	Start biom. ratio	*CV pred*	*CV cpu*	*CV s*	*CV proc*	*V_{max}*	*P50%*	*Qc*	*Qs*	*MSY ratio*	*K*
Max. sustainable yield		15						-17	-17	32	25
Carrying capacity	17	20						-61	-61	-57	
Max. sustainable yield ratio (%)	-28	-12						77	77		
Survey catchability (%)	-39	-21					-8	100			
CPUE catchability	-40	-21					-8				
P50%	11					68					
Vmax	-7	-5									
CV of process (%)	13		18	-12							
CV of survey fit (%)			15								
CV of CPUE fit (%)											
CV of predation fit (%)	7										

[1] those over 5%

Table 4. *Pandalus borealis* in West Greenland: risks (%) of exceeding limit mortality in 2016 and of falling below B_{msy} or limit* biomass at the end of 2016 assuming effective cod biomass 55 or 65 Kt.

Catch (Kt/yr)	Prob. biomass < B_{msy} (%)		Prob. biomass< B_{lim} (%)		Prob. mort > Z_{msy} (%)	
	55 Kt	65 Kt	55 Kt	65 Kt	55 Kt	65 Kt
60	25.0	25.0	1.2	1.4	21.7	23.6
70	25.0	25.9	1.3	1.4	24.5	26.6
75	25.4	26.3	1.1	1.3	26.6	28.3
80	26.2	26.8	1.3	1.4	28.2	30.5
85	26.6	26.9	1.4	1.4	30.7	32.0
90	26.6	27.4	1.1	1.4	32.3	34.1
95	27.0	27.9	1.2	1.4	34.7	36.4
100	27.2	28.3	1.2	1.5	36.9	39.3

* limit biomass is 30% of B_{msy}

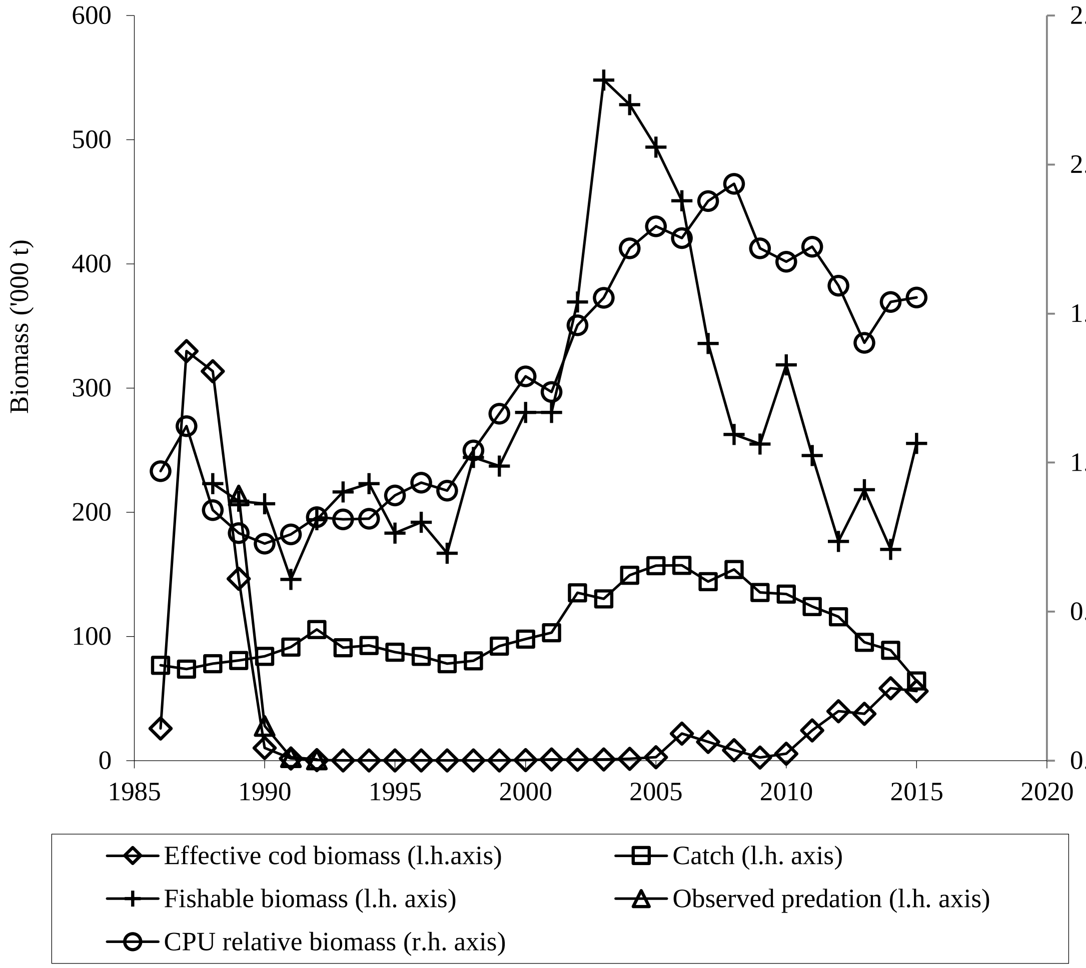

Fig. 1. *Pandalus borealis* in West Greenland: thirty-year data series providing information for the assessment model. (2015 catch is projected; effective cod biomass is synthesised from four biomass index series and a series of overlap indices between distributions of cod and shrimps.)

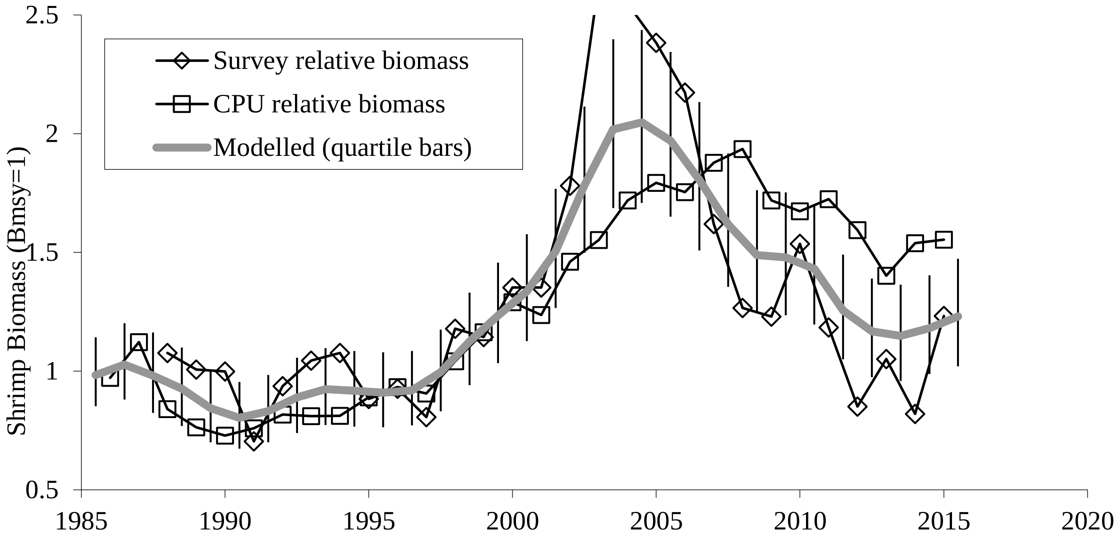

Fig. 2. *Pandalus borealis* in West Greenland: modelled shrimp standing stock fitted to survey and CPUE indices, 1986–2015.

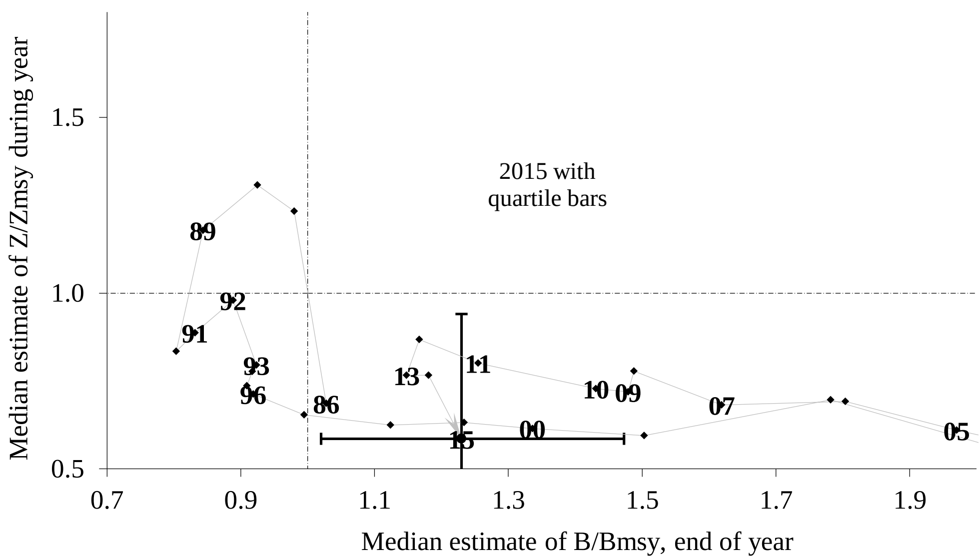

Fig. 3. *Pandalus borealis* in West Greenland: median estimates of biomass ratio (B/B_{msy}) and mortality ratio (Z/Z_{msy}) 1986–2015.

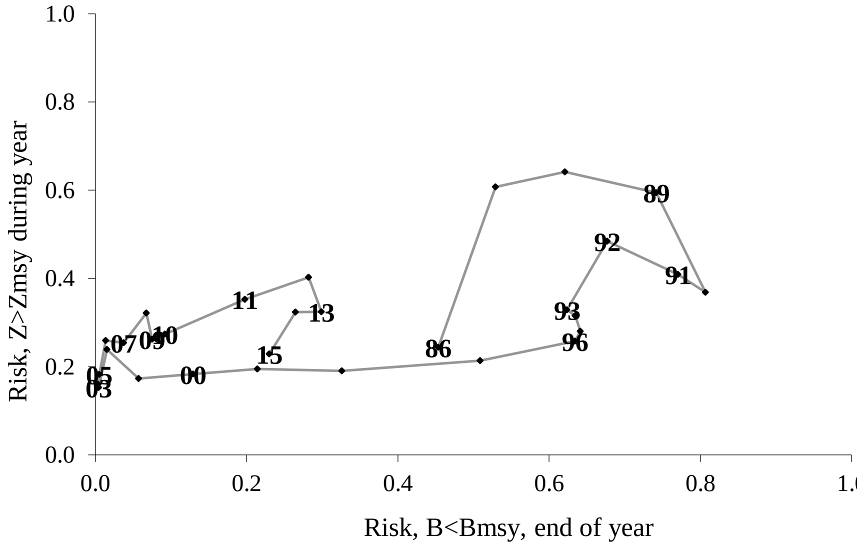

Fig. 4. *Pandalus borealis* in West Greenland: annual likelihood that biomass has been below B_{msy} and that mortality caused by fishing and cod predation has been above Z_{msy} 1986–2015.

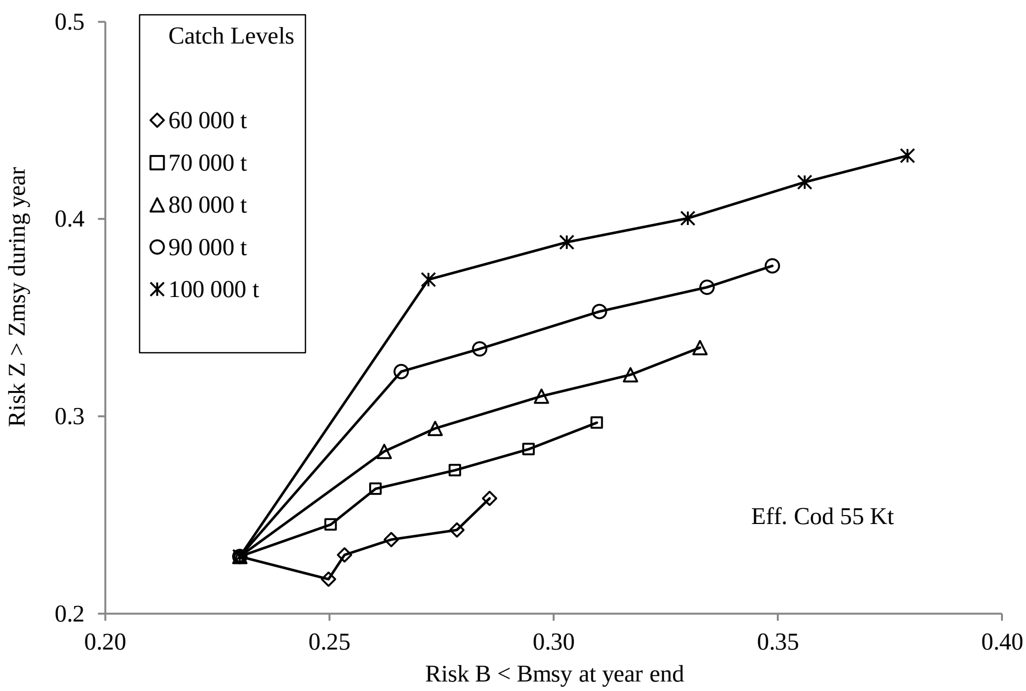

Fig. 5a. *Pandalus borealis* in West Greenland: joint 5-year plot 2016–20 of the risks of transgressing B_{msy} and Z_{msy} at catch levels 60–100 Kt/yr; with effective cod biomass 55 Kt.

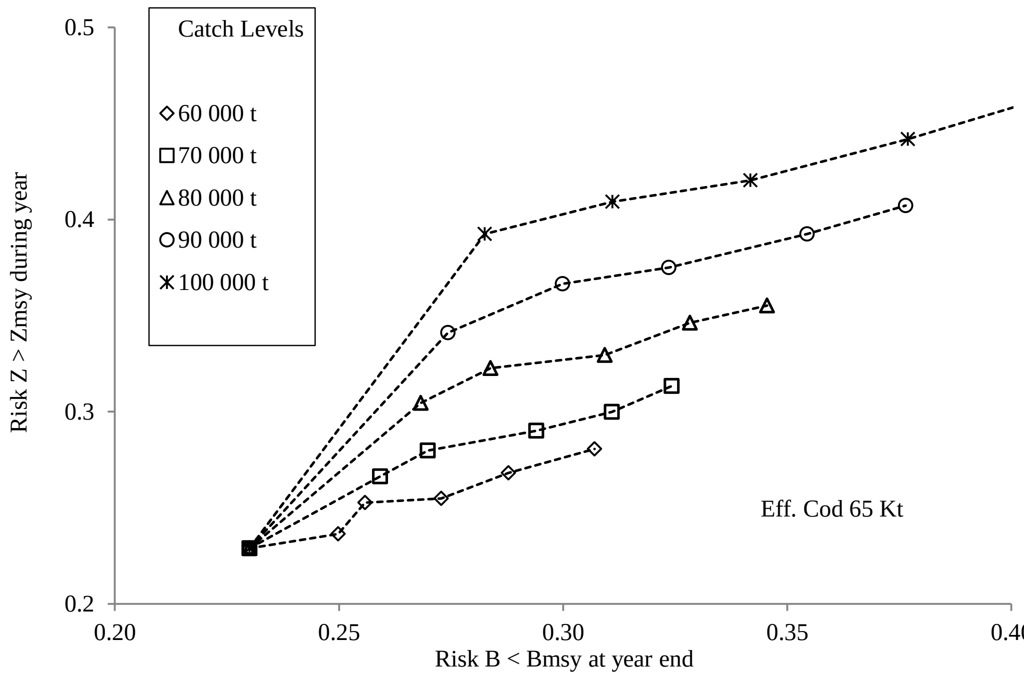

Fig. 5b. *Pandalus borealis* in West Greenland: joint 5-year plot 2016–20 of the risks of transgressing B_{msy} and Z_{msy} at catch levels 60–100 Kt/yr; with effective cod biomass 65 Kt.

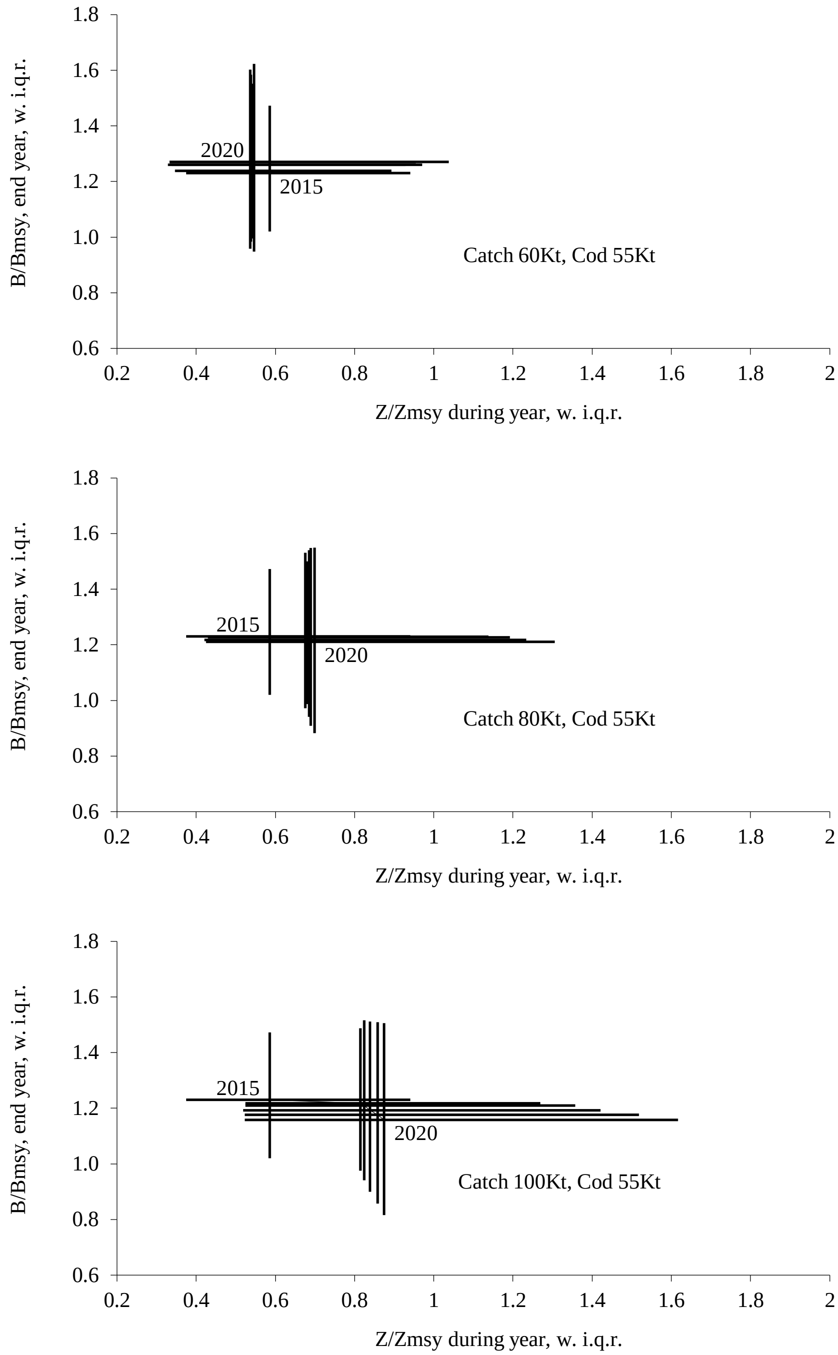

Fig. 6a. *Pandalus borealis* in West Greenland: projections of stock development for 2016–2020 with effective cod biomass assumed at 55 000 t: median estimates with quartile error bars.

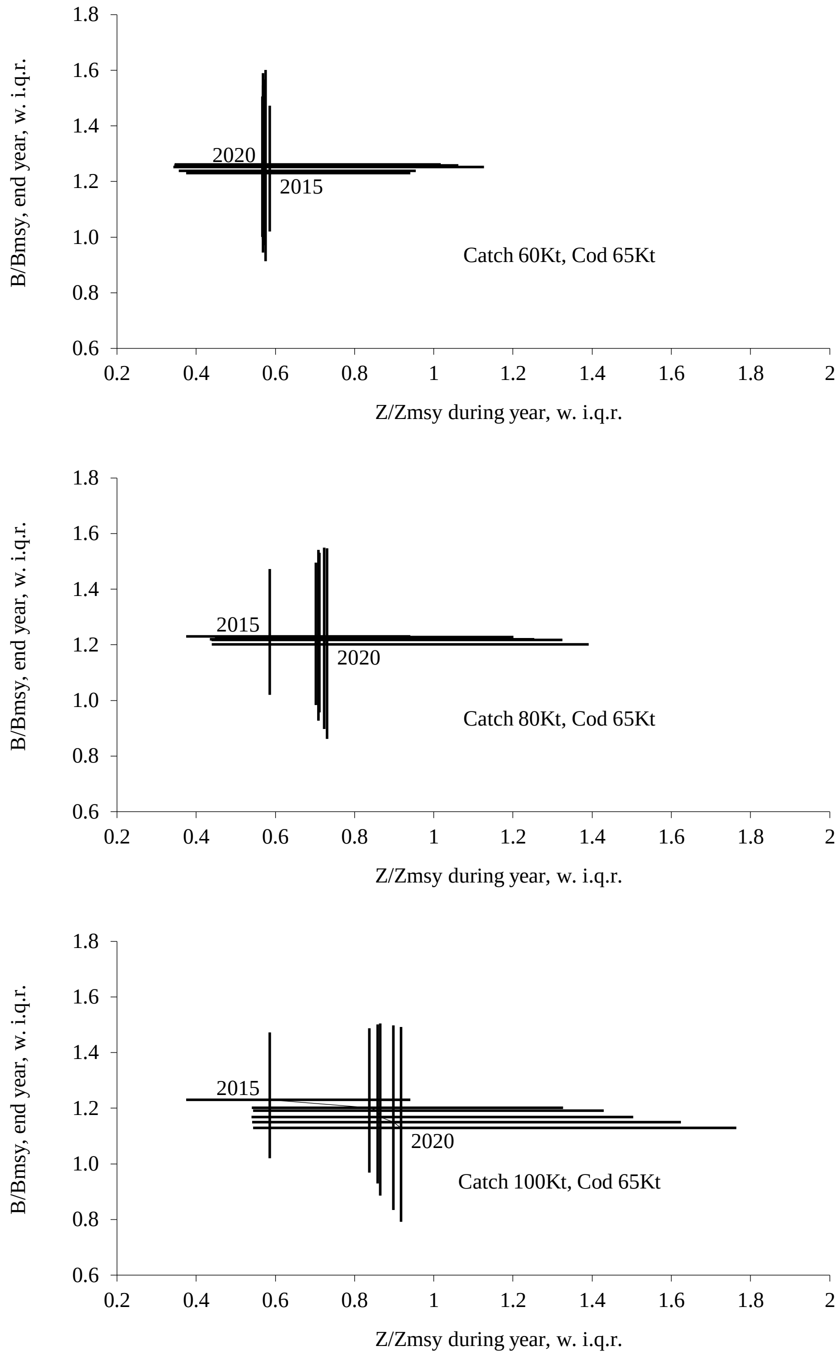

Fig. 6b. *Pandalus borealis* in West Greenland: projections of stock development for 2016–2020 with effective cod biomass assumed at 65 000 t: median estimates with quartile error bars.