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A Provisional Assessment of the Shrimp Stock off West Greenland in 2014

by

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Summary

The West Greenland Stock of *Pandalus borealis* was assessed from indices of biomass density based on catch and effort data from fishing fleets, biomass and stock-composition information from a research trawl survey, catch data, and information on the distribution of the stock as revealed by fishery logbooks. The assessment framework incorporates a logistic stock-recruitment model, fitted by Bayesian methods, that uses CPUE and survey series as biomass indicators, and includes as removals catch data, assumed free of error, as well as a term for predation by Atlantic cod, using available series of cod biomass.

Overall, the stock biomass, distribution and composition are extreme in several respects. Survey total biomass remains at a low level compared with the most recent 20 years. Offshore, the fishable biomass has decreased by nearly 50% compared with 2013 to one of the lowest levels of the most recent 20 years; areas north of the northern margin of Store Hellefiskebanke have three-quarters of the offshore biomass. The fishable biomass inshore, in Disko Bay and Vaigat, 15% higher than in 2013, is high when compared with its history. As a result of this contrast, the proportion of biomass in the inshore area is at a 20-year maximum.

The number of two-year-old shrimps, 50% higher in 2013 than in 2012, has increased again in 2014 and is near its 20-year median; in relation to survey biomass it is high. However, the proportion of large pre-recruits of 14.5–16 mm carapace length remains small both inshore and offshore, menacing prospects for short-term recruitment to the fishable stock. Overall, in 2014 the proportion fishable of the survey biomass is about average for the last 20 years, but its proportion of females is at a 20-year record value and fishable males are few. Fishing on the stock in its present state will disproportionally hit the spawning stock of females, prospects for recruitment which are also low.

The stock composition inshore has historically been characterised by a higher proportion of young shrimps than that offshore, but in 2013 was closer to the stock structure offshore than to its past average values. In 2014 the difference has been re-established: there are twice as many age-2 shrimps a survey ton inshore as offshore, and large pre-recruits are about 65% higher.

The quantitative assessment adopted by NAFO shows a stock that has been declining for a decade—albeit from levels that were probably not sustainable—has probably been fished over its MSY mortality for the most recent four years, and is now probably below its MSY biomass.

Introduction

The stock of the Northern shrimp (*Pandalus borealis*) off West Greenland is distributed in NAFO Subarea 1 and the eastern margin of NAFO Div. 0A, and within this area is assessed as one unit. A Greenlandic fishery exploits the stock in Subarea 1 (Divs 1A–1F); a Canadian fishery is restricted to Div. 0A.

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. Input data series include a swept-area index of fishable biomass from an annual research trawl survey, a series of standardised indices of fishery CPUE and the series of past catches. The model was modified in 2011 to give more weight to the survey index of biomass and less to the fishery CPU (Kingsley 2011).

Up to 2014 an externally calculated index series of 'effective' biomasses of Atlantic cod —i.e. corrected for the partial overlap of its distribution with that of the shrimps—was also included. In 2014 this was replaced by the inclusion of the four biomass index series on which it had been based as well as the series of overlap indices (Kingsley 2014). The biomass indices are combined within the assessment model to generate a series of estimated biomasses, and this is multiplied by the overlap series to generate a series of 'effective' biomasses that are used in estimating the amount cod remove from the stock each year.

The quantitative model was fitted to the input data and short-term (1-year) and medium-term (three-year) projections of stock development were made for annual catches from 50 000 to 90 000 tons under assumptions that the cod stock, allowance made for its overlap with shrimp distribution, might be at 30 000 tons or 50 000 tons. The median estimate of effective cod biomass for 2014 was 44 100 tons (Siegstad and Kingsley 2013). The associated risks of transgressing reference parameters—maximum sustainable yield levels of biomass (B_{msy}) and mortality (Z_{msy})—as well as a precautionary limit set at 30% of B_{msy} were estimated.

This assessment refers also, although qualitatively, to information on the distribution of the Greenland fishery derived from logbooks. Trawl time, and catches, were assigned to statistical areas covering the West Greenland shrimp grounds, and series of indices of how widely the fishery was distributed were calculated (Hammeken Arboe 2014). The assessment also refers to indices that summarise survey information on the distribution of the stock and its structure (Kingsley 2008b; Burmeister et al. 2014).

Environment

The survey mean bottom temperature—weighted by area, not by shrimp stock density—increased quite abruptly from a mean of 1.83°C in 1990–96 to 3.12°C in 1997–2012. At about the same time as the mean bottom temperature increased, the shrimp stock started a more protracted shift in its distribution, into shallower water and into more northerly areas. In the mid-90s, most of the survey biomass was between 300 and 400 m, with a significant amount deeper than 400 m. Now, a majority is between 200 and 300 m, with a significant amount between 300 and 400 m (Burmeister et al. 2014). This move into shallower water looks like a continuing trend since the early 2000s.

The estimated biomass of a main predator, the Atlantic cod, was less than 10 Kt from 1991 to 2004. It increased briefly in 2006–7 to about 87 Kt[1], distributed mostly in southern West Greenland, before declining again. In 2011 there was a smaller increase, but in that year the fish appeared to be more widely distributed into northerly areas where there was a higher density of shrimps, and the 'effective' cod stock appeared to have increased significantly. In 2012–2014 the biomass of cod has increased considerably, and although it is mostly distributed in more southerly areas so its index of overlap with the shrimp stock has been less the 'effective' cod stock has been greater than at any time since the start of the 1990s (Siegstad and Kingsley 2014).

Stocks of Atlantic cod in West Greenland continue to fluctuate and while forecasting the biomass and distribution of cod on the West Greenland shrimp ground is important in predicting the dynamics of the stock of Northern shrimp

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[1] 'German survey' estimate revised in 2014.

and in managing the fishery, it remains an insoluble problem. The stock-dynamic model used in the assessment allows for flexible and comprehensive consideration of possible developments of the cod stock.

Stock Size, Composition and Distribution

Survey biomass increased by 130% in 1999–2003. It has since decreased by 70% and is at nearly its lowest level in 20 years (Fig. 1); an overall increase from 2012 to 2013 was not maintained. Compared with the most recent 20 years almost all stock-size indices are therefore low. In 2014, the number and biomass of females are 20–25% lower than they were in 2013, and are now below their 20-year lower quartiles, while the number of males is at its lowest for 20 years (Burmeister et al. 2014).

Survey Measures of Stock Size

	Biomass (Kt)					Number (bn)		
	Survey							
	Disko B. & Vaigat	Offshore	Total	Fishable	Female	Male	Female	Age 2
2014 value[1]	93.5	89.3	182.8	170.0	87.6	23.2	9.4	4.88
20-year[2] upper quartile	92.6	291.7	372.5	344.4	127.1	66.4	15.2	7.6
20-year median	76.0	220.4	280.3	258.8	104.4	42.5	11.9	5.1
20-year lower quartile	51.5	174.1	235.0	221.9	90.4	36.3	9.7	3.1
2014 rank	16.1	0.6	1.4	1.3	4.9	0.0	5.5	9.8
2013 value	81.4	152.4	233.8	218.1	103.9	31.1	12.0	4.06[3]

[1] survey estimates of stock size for 2011, 2012, and 2014 were adjusted for incomplete coverage of the offshore strata by applying the mean offshore density to the survey strata not covered, and adding the corrected offshore estimate to that for Disko Bay and Vaigat

[2] 20-year percentiles, and 2014 rank, are referred to the 20 preceding years, i.e. 1994–2013.

[3] value recalculated in 2014

In the inshore area comprising Disko Bay and Vaigat the estimated survey biomass increased by 15% from 2013 to a 2014 value above its 20-year upper quartile. The offshore biomass collectively, in 2012 at its lowest for 20 years but nearly half as large again in 2013, dropped by 43% in 2014 to a new 20-year low value. In a contrary trend, the absolute number at age 2, 50% higher in 2013 than in 2012, increased again in 2014 to near, although still below, its 20-year median (Fig. 2a).

Survey Measures of Stock Composition

Overall	Number ('000/survey ton)		Biomass (%)			
	Age 2	14–16.5 mm[2]	Fishable, of survey	Fishable males, of survey	Females, of survey	Females, of fishable
2014 value	26.7	20.3	93.0	45.1	47.9	51.5
Upper quartile[1]	24.7	26.4	93.6	57.8	37.7	40.2
Median[1]	14.9	25.2	92.1	56.8	35.6	38.5
Lower quartile[1]	10.8	22.3	90.7	53.9	34.9	37.5
2014 rank[1]	16.1/20	0.0/9	12.3/20	0.0/20	21/20	21/20
2013 value	17.4[3]	22.3	93.3	48.9	44.4	47.6

[1] quartiles and 2014 rank generally referred to 20 preceding years 1994–2012;

[2] quartiles and 2014 rank referred to 9 preceding years 2005–2013 (for which data is available);

[3] value recalculated in 2014

The overall stock composition in 2014 is marked, even more than in 2013, by a high proportion of females, both in the survey and in the fishable biomass; males compose a low proportion of the fishable biomass. Relative to stock size the number of age-2 shrimps is above its 20-yr upper quartile. The relative number of large pre-recruits is at a ten-year minimum, so prospects for short-term recruitment are poor; this is true both in Disko and offshore as well.

Disko Bay and Vaigat	Number ('000/survey ton)		Biomass (%)			
	Age 2	14–16.5 mm	Fishable, of survey	Fishable males, of survey	Females, of survey	Females, of fishable
2014 value	35.3	25.2	91.5	46.4	45.0	49.2
Upper quartile[1]	36.3	34.0	90.8	56.2	38.1	42.5
Median[1]	27.7	31.8	89.5	51.5	34.2	39.2
Lower quartile[1]	15.8	30.2	86.1	48.7	32.8	37.7
2014 rank[1]	15.1/20	0.0/9	16.8/20	0.0/9	10/9	10/9
2013 value	13.6	27.0	91.6	48.7	42.9	46.9

Offshore	Number ('000/survey ton)		Biomass (%)			
	Age 2	14–16.5 mm	Fishable, of survey	Fishable males, of survey	Females, of survey	Females, of fishable
2014 value	17.7	15.2	94.5	43.7	50.8	53.8
Upper quartile[1]	20.0	24.3	94.9	57.5	44.0	47.3
Median[1]	13.6	21.0	93.7	55.2	39.1	42.3
Lower quartile[1]	8.1	19.7	92.0	49.0	36.6	38.7
2014 rank[1]	13.9/20	1.1/9	14.5/20	2.0/9	10/9	10/9
2013 value	13.3	19.7	94.2	49.0	45.3	48.0

Differences between the stock compositions offshore and inshore—in Disko Bay and Vaigat—have tended to be maintained over time. The inshore averages higher proportions of smaller shrimps. For the age-2 index, relative to survey biomass, the inshore quartile points have about twice the values of the offshore. Quartiles of the relative number of 14–16.5-mm shrimps are about half as big again inshore as offshore. In keeping with having fewer small shrimps the fishable, female and fishable-male proportions of the survey biomass have averaged larger offshore, and the female proportion of the fishable biomass has also averaged slightly larger offshore. Throughout the size distribution, the offshore stock has been biased toward comprising larger shrimps, while the Disko component has had higher proportions of smaller and younger shrimps.

In 2013 some of these differences were less evident than in 2012 or in the past averages, and the inshore stock had in some ways converged on the offshore structure: its values were more like the offshore values than like its own past. This has not been maintained, and in 2014 there are again marked differences in composition between the stock in Disko Bay and that offshore.

In both regions females compose by far the highest proportion of the biomass, both survey and fishable, seen in the years for which we have data and males a low proportion. In 2014, while males are still a low proportion of the fishable biomass, the fishable biomass is a high proportion of survey biomass and comprises a high proportion of females. Even more than in 2012 or in 2013, the stock both offshore and inshore is 'all females'. The length classes of large pre-recruits, which in 2012 were, relative to stock size, near their median inshore and abundant offshore, have been scarce both inshore and offshore in 2013 and again in 2014.

We don't know what are the limits for any of these stock-composition parameters to conduce to a 'healthy' stock with good potential for maintaining itself. For some of the statistics, past information is limited to 2005–12—a period characterised by a 75% decline in the offshore stock while the inshore has fluctuated. The stock seems at the moment to be at, or outside, the limits of where it has been in the past. There are few large pre-recruits; few fishable males to recruit to the spawning stock; and, concomitantly, exceptionally high proportions of spawning females in the fishable biomass. The fishable stock is a high proportion of the total, so if the fishable stock gets fished, there won't be much left.

Measures of Biomass Distribution within SA1

	Of offshore (%)						Of total (%)
	North	W1–2	W3–4	W5–7	W8–9	Distribution Index	Disko B. and Vaigat
2014 value	34.0	39.9	14.0	12.1	0.0	3.2	52.0
20-year[1] upper quartile	30.9	35.2	23.6	28.2	9.0	3.9	25.6
20-year median	19.4	31.4	19.1	21.5	2.6	3.3	22.3
20-year lower quartile	5.0	27.1	17.5	12.4	0.5	3.1	20.5
2014 rank	16.8	17.1	4.7	5.7	0.0	6.9	21.0
2013 value	35.6	34.0	24.6	5.7	0.1	3.3	48.6

[1] percentiles and 2014 rank are referred to the 20 preceding years, i.e. 1994–2013.

Compared with values for the previous 20 years, the offshore biomass is very low and the inshore biomass relatively high, so the proportion inshore is at a 21-year maximum.

Within the offshore area as a whole, the trajectories have been different and since 2000 the distribution of the survey biomass has contracted and moved northwards (Fig. 3). The southernmost area had collapsed already in 2004–2007 and W3–4, around Store Hellefiskebanke, collapsed in 2011 and were empty in 2012. The North area and W1–2, off the mouth of Disko Bay, continue to hold proportions of the offshore biomass that are well above their 20-year upper quartiles. In the results from the 2014 survey, all the areas south of Disko Bay continue to have small proportions of the survey biomass.

The proportions in W1–2, W3–4, and Disko had been relatively constant over the preceding 19 years: the inter-quartile ranges were about one quarter of the medians. The deviations in, and since, 2012, especially for Disko (upward) and W3–4 (downward) were, by comparison with this earlier stability, especially remarkable.

Fishery

The trajectory of the fishery CPU agreed with that of the survey estimate of fishable biomass from 1988 until about 2002, when the survey index suddenly increased. The CPU index did not follow that jump but increased more slowly; but also did not suffered the rapid and sustained decrease of the survey index from 2003 through 2012. Instead it continued to increase, more slowly, until 2008, after which it also has continually declined. From 2007 through 2013 the CPUE index of relative biomass has remained significantly above the survey index. That CPUE can be maintained while the survey index declines might be due to shrinking of the area over which the stock, and the fishery, is distributed, although we have not been able to find a satisfactory relationship between the difference between the two indices and any measure of stock distribution.

The distribution of the fishery, like that of the survey biomass, has varied over time (Fig. 4). In the 1990s over half the catches were taken south of Holsteinsborg Dybde, but southern areas have subsequently lost their shrimp stock and the fishery in Greenland waters is now concentrated in NAFO Divisions 1A and 1B. In recent years, the offshore fishery has been extending its range northwards and recent years have seen some exploitation of grounds even north of 73° N (Hammeken Arboe and Kingsley 2013).

Between 1997 and 2003 the exploitation ratio—of catch to fishable biomass—declined from about 50% to about 25% (Fig. 1) as the catches, although steadily increasing, failed to keep up with the more rapidly increasing biomass (Fig. 6). While catches were high in 2004–2008 the ratio increased as biomass declined while catches did not, and since 2008 it has stayed above average as catches have not been brought down to match the lowness of recent biomass estimates.

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). In the context of the present assessment, the model behaviour was not checked in great detail.

Absolute biomass estimates, and all related parameters, had high variances and were difficult to estimate. 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}. , which is consistent with catch control rules that are directed by such a relative measure. The state equation describing the transition of shrimp biomass from the end of year *t-1* to the end of year *t* was:

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

where *MSY* is an annualised value of the instantaneous maximum sustainable yield rate. P_t is the stock biomass relative to biomass at *MSY* ($P_t=B_t/B_{MSY}$) 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 Pella-Tomlinson (1969) stock–recruitment curve: a value of 2 gives the standard logistic, or Schaefer (1954), trajectory. The 'process errors', *ν* are normally, independently and identically distributed with mean 0 and variance σ_ν^2 .

Input data series were shortened to 30 years on a trial basis in 2011 (Kingsley 2011), and the formulation with shorter series has subsequently been retained as the main assessment model.

The model synthesised information from input priors (Hvingel and Kingsley 2002) (Fig. 3) and the following data:

- a 26-year (1988–2014) series of estimates of the 'fishable' (i.e. at least 17 mm CL) stock biomass index obtained from a research survey executed annually with consistent methods (Wieland 2005; Burmeister et al. 2014);
- CPUE index series spanning, among them, 1985 through 2014 (Kingsley 2008a; Hammeken Arboe 2014) and unified into a single series by a separate model (Hammeken Arboe and Kingsley 2014); in 2013, for the first time, catch and effort data from statistical area 0 was included in calculating the series for the offshore fleet and for the fishery as a whole;
- a 30-year series of catches by the fishery with corrections for past overpacking (Hvingel 2004; Hammeken Arboe 2014);
- four series of cod biomass estimates by VPA and survey, of different lengths and covering different periods (Siegstad and Kingsley 2014; Kingsley 2014);
- a series of estimates of the overlap between the shrimp and cod distributions (Wieland and Storr-Paulsen 2004);
- and a 4-year series of estimates of the shrimp biomass consumed by cod (Hvingel and Kingsley 2002) based on stomach analyses (Grunwald 1998) (Table 1; Fig. 6).

CPUE series were unified in a separate step, applying assigned weights based on an estimate of the areas fished by the different fleet components. The resulting unified series gives greatest weight to the historical 'KGH' fleet from 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.

Logbook data was corrected for earlier overpacking and associated underreporting before calculating the standardised CPUE index for the Greenland offshore fleet: for 2003 and earlier, 15% was added to reported catches of 'large' shrimp and 42% to catches of 'small' and 'unsorted' (Kingsley 2008a; Hammeken Arboe and Kingsley 2013).

Catch data were updated from available sources, including logbooks, STATLANT 21A, and quota reports from Greenland and Canadian sources (Hammeken Arboe and Kingsley 2013). A forecast for the Greenland catch provided by industry observers was that the year's final catch would be close to the enacted TAC, including the EU quota, at 90 000 t (Hammeken Arboe 2014). Canadian catches had been zero in 2008 and small in 2009, but the Canadian fishery took about 5 500 t in 2010. Canadian catches were reported at 1296 t for 2011 and have since been negligible; this goes for the projected catch in 2014 as well.

The estimation of total catch for the current year is important in short-term forecasting of stock status in the next. The assessment model was modified in 2012 to add uncertainty in current-year catch forecasting to the other uncertainties about stock status. The series of past estimates of current-year catch was added to the input data, and the final known catches were modelled as having a constant ratio to the initial projections, with an error term. This uncertainty was then applied to this year's projection to calculate an uncertain catch to use in estimating stock status at the end of the current year.

Densities of shrimp in southerly areas decreased in recent years. Cod biomass estimates in some recent surveys increased from the very low levels that prevailed throughout the 1990s. The most recent survey results have shown a wide distribution for cod and an increasing overlap with the distribution of the Northern shrimp. The 'effective' cod series of Storr-Paulsen et al. (2006) was replaced by a procedure within the quantitative assessment model to unify a set of different survey and VPA series and multiply the consensus biomass by an input series of overlap factors (Siegstad and Kingsley 2014; Kingsley 2014 a and b).

The data link functions for the biomass indices were:

$$CPUE_t = \ln\left(q_c P_{t-1}\right) + \omega_t \text{ and}$$
$$surv_t = q_s B_{MSY} P_{t-1} \exp(\kappa_t)$$

I.e. the fishery CPUE and the survey estimate in year t are modelled as being predicted by the stock biomass at the end of the preceding year. The error terms ω_t and κ_t were considered to have Normal distributions, each series with uniform variance except that for the survey series the first term was given a larger variance to allow for inexperience among the survey crew, and for the CPUE series the last term was given a larger variance because it is based on part-year's data. The error variance associated with the CPUE series was constrained to be at least as large as that of the survey series, to reflect confidence among assessment scientists that the designed survey—although based on far fewer hauls—is at least as good an index of biomass as CPUE.

Predation by cod was modelled as:

$$O_t = cod_t \frac{V_{\max} P_{t-1}^2}{P_{t-1}^2 + P_{50\%}^2} \exp(\tau)$$

where O_t is total consumption in year *t*, V_{max} is the maximum consumption (weight for weight) reached at large prey biomass, and $P_{50\%}$ is the prey biomass index at which the consumption would be half the maximum. cod_t is biomass of cod in year *t* (Holling 1959). As for survey and CPUE biomass indices, the shrimp biomass regulating predation in year t is that at the end of the previous year. The error terms, τ , are normally, independently and identically distributed with mean 0 and variance σ_τ^2 . Predation estimates from Grunwald (1998) were related by the same predation function and the same parameter values[2].to a separate short series of cod biomass estimates that she had used in her calculations.

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[2] in 2008, as a test, the model had been allowed to fit a multiplier to the cod biomass series that Grunwald used to calculate total consumption; its median estimate was close to 1 and the uncertainty large, so this modification to the model was not retained.

The mortality caused by cod predation and fishery, Z, was 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:

$$Zratio_t = \frac{Z_t}{Z_{MSY}} = \frac{-\ln\left(\frac{B_{t-1} - C_t - O_t}{B_{t-1}}\right)}{\frac{MSY}{B_{MSY}}}$$

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.

Results, Model Performance

The model fitted fairly well to the observed data series (Fig. 7), but the error term for cod predation was large (Table 2). This is probably an inevitable consequence of 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. The prior distribution on V_{max} is so tight that it is not being updated. As a result, the parameter $P_{50\%}{}^2$ must take high values to fit cod predation to the stock dynamics, and the functional has become essentially a one-parameter relationship (Kingsley 2014.) It will be appropriate either to replace the present Holling type III function with a simpler one-parameter Holling type I, or to investigate whether a different set of priors would be more suitable.

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 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 at 8.8% with quartile points at – 2.9% and 20.4%. Given the large excursion of the stock to high biomass values in the early 2000s, this is a surprisingly small value.

Results of the Quantitative Assessment

The median estimate of the *MSY* was 131 Kt—i.e. 7 Kt less than the estimate made in 2013—with quartiles at 103 and 165 Kt; an estimated mode is at 113 Kt.

The model estimates that the stock biomass has decreased in every year from 2004 to 2013 (except for 2009 with a 0.5% increase), even though it estimated catches up to 2010 as sustainable. Relative to B_{msy}, fishable biomass at end 2014 is projected at close to the 2013 value, but that estimate has been revised downward to 97.3% of B_{msy}, catches in 2011–2013 all now estimated to have been unsustainable. With a high cod biomass, even with catches projected at 90 000 t, total mortality in 2014 is estimated to be slightly above the MSY level and the mortality risk at 52% exceeds a management threshold of 35%.

The median estimate of *MSY* is more uncertain than in earlier assessments: the e.c.v. of the mean is 54% and the relative interquartile range 47%. The distribution of the estimate is skewed and the most likely value for the MSY is estimated at 113 000 t. This implies that all values between 131 000 and 113 000 t, as well as some values less than that, are more likely than 131 000 t (Table 2).

The stock is projected to be below B_{msy} at the end of 2014, and the risk of its staying below this level in 2015 is very close to or over 50% at all the catch levels considered. Risks[3] associated with six possible catch levels for 2015, with an 'effective' cod stock at 30 000 t[4], are estimated to be:

30 000 t cod	Catch option ('000 tons)						
Risk of:	50	55	60	65	70	80	90
falling below Bmsy end 2015 (%)	49.1	49.7	50.1	50.2	50.9	52.3	52.7
falling below Blim end 2015 (%)	2.4	2.4	2.3	2.5	2.5	2.5	2.7
exceeding Zmsy in 2015 (%)	21.2	23.8	26.3	29.8	32.8	39.9	47.5
exceeding Zmsy in 2016 (%)	21.6	24.1	26.4	29.2	32.7	40.7	47.7

and with an 'effective' cod stock at 50 000 t:

50 000 t cod	Catch option ('000 tons)						
Risk of:	50	55	60	65	70	80	90
falling below Bmsy end 2015 (%)	50.3	51.3	51.4	51.9	52.0	53.4	53.7
falling below Blim end 2015 (%)	2.7	2.9	2.8	2.9	2.9	2.9	2.9
exceeding Zmsy in 2015 (%)	26.8	30.0	31.8	35.6	38.7	46.6	53.1
exceeding Zmsy in 2016 (%)	27.6	30.4	32.9	36.8	39.8	46.6	54.3

If a mortality risk (i.e. of exceeding Z_{msy}) criterion of 35% is observed, catches of 60–70 Kt might be sustainable, provided that the effective cod biomass does not make further large gains in the coming years.

3 'risk' in this document includes all three of uncertainty of knowledge, uncertainty of prediction, and uncertainty of outcome.

4 the median estimate for 2014 is 44 300 tons.

Predation by cod can be significant and have a major impact on shrimp stocks. 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.

Three- and five-year projections of stock development were made under the assumption that the ‘effective’ cod stock will remain at levels consistent with recent estimates, and under assumptions that constants governing the predation mechanism will retain the values estimated from the 30-year data series of the interaction between the two species. Seven levels of annual catch were investigated from 50 000 to 90 000 tons (Figs 10–12, Table 4; Appendix).

P. borealis in West Greenland spread more widely after 1990, the fishery extended into more southerly areas, and the annual trawl survey was extended to southern West Greenland. However, since the late 1990s both the survey biomass and the fishery have contracted towards the north. While the contraction appears to have continued and the stock distribution to be shrinking into a core range, the shift northward appears from both survey and fishery data to have stopped since about 2008 (Figs 3–5).

The present assessment based on the existing modelling approach estimates a stock that has been decreasing for a decade and is below B_{msy}. CPUE has had a downward trend since about 2008. The fishery is now more concentrated than in 1992–2003 (Fig. 4), so CPUEs that indicate high densities in the fished areas do not necessarily translate to an equally high biomass. The contraction of the biomass distribution, and the fishery, is continuing. The assessment model does not take the distribution of the fishery into account, but considers CPUE in fished areas to be a linear index of stock biomass. It might therefore under present conditions be overly sanguine in its evaluation of stock status.

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 still moderately low, although higher than we have seen in past assessments.

Conclusions

The stock is estimated to be below its MSY level at end 2014, and prospects for short-term recruitment to the fishable stock, as indicated by numbers of large pre-recruits, have been low for two years. Fishable males compose an unusually small proportion of the fishable stock, presaging poor recruitment to the spawning stock of females. 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 60–70 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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Thanks are due to Helle Siegstad for updating the information on the behaviour of the cod stock in southern West Greenland, and to Mads Rossing Lund of the Greenland Fishery and Licence Control for information on the fishery. Dr Carsten Hvingel developed the initial version of the surplus-production model and wrote the WinBUGS coding for it.

References

BURMEISTER, AD., M.C.S. KINGSLEY and H. SIEGSTAD. 2014. The West Greenland trawl survey for *Pandalus borealis*, 2014, with reference to earlier results. *NAFO SCR Doc*. 14/052, Ser. No. N6354. 37 pp.

GRUNWALD, E. 1998. Nahrungsökologishe Untersuchungen an Fischbeständen im Seegebiet vor Westgrönland. Ph.D. Dissertation, Christian-Albrechts-Universität, Kiel, Germany. 208 pp.

HAMMEKEN ARBOE, N. 2014. Catch table update for the West Greenland shrimp fishery. *NAFO SCR Doc*. 14/046 Ser. No. N6338. 5 pp.

HAMMEKEN ARBOE, N. 2014. The Fishery for Northern Shrimp (*Pandalus borealis*) off West Greenland, 1970–2014. *NAFO SCR Doc.* 14/061, Ser. No. N6363. 45 pp.

HOLLING, C.S. 1959. Some characteristics of simple types of predation and parasitism. *Can. Entomol.* **91**: 385–398.

HVINGEL, C. 2004. The fishery for northern shrimp (*Pandalus borealis*) off West Greenland, 1970–2004. *NAFO SCR Doc.* 04/75, Ser. No. N5045.

HVINGEL, C. and M.C.S. KINGSLEY. 2002. A framework for the development of management advice on a shrimp stock using a Bayesian approach. *NAFO SCR Doc.* 02/158, Ser. No. N4787.

KINGSLEY, M.C.S. 2008a. CPU Series for the West Greenland Shrimp Fishery. *NAFO SCR Doc*. 08/62 Ser. No. N5591. 6 pp.

KINGSLEY, M.C.S. 2008b. Indices of distribution and location of shrimp biomass for the West Greenland research trawl survey. *NAFO SCR Doc*. 08/78 Ser. No. N5610. 4 pp.

KINGSLEY, M.C.S. 2011. A provisional assessment of the shrimp stock off West Greenland in 2011. *NAFO SCR Doc*. 11/058, Ser. No. N5983. 23 pp.

KINGSLEY, M.C.S. 2012. A provisional assessment of the shrimp stock off West Greenland in 2012. *NAFO SCR Doc*. 12/046, Ser. No. N6107. 23 pp.

KINGSLEY, M.C.S. 2014. Revised treatment of cod survey data in assessing the West Greenland stock of *P. borealis*. NAFO SCR Doc. 14/062. Ser. No. N6364. 4 pp.

PELLA, J.S. and P.K. TOMLINSON. 1969. A generalised stock-production model. *Bull. Inter-Am. Trop. Tuna Comm.* 13: 421–496.

SCHAEFER, M.B. 1954. Some aspects of the dynamics of populations important to the management of the commercial marine fisheries. *Bull. Inter-Am. Trop. Tuna Comm.*, **1**: 27–56.

STORR-PAULSEN, M., J. CARL and K. WIELAND. 2006. The importance of Atlantic Cod (*Gadus morhua*) predation on Northern Shrimp (*Pandalus borealis*) in Greenland waters 2005. *NAFO SCR Doc*. 06/68. Ser. No. N5318. 16 pp.

WIELAND, K. 2005. Conversion of northern shrimp (*Pandalus borealis*) biomass, recruitment and mean size from previous years (1988–2004) to the new standard trawl used in the Greenland bottom trawl survey at West Greenland in 2005. *NAFO SCR Doc.* 05/75, Ser. No. N5180. 6pp.

WIELAND, K. and M. STORR-PAULSEN. 2004. A comparison of different time series of Atlantic cod (*Gadus morhua*) biomass at West Greenland and their potential use for the assessment of Northern shrimp (*Pandalus borealis*) in NAFO Subareas 0+1. *NAFO SCR Doc.* 04/71, Ser. No. N5041.

Table 1. *Pandalus borealis* in West Greenland: input data series 1985–2014 for stock-dynamic assessment model.

	Effective cod biomass[1] (Kt)	Catch (Kt)	Provisional catch (Kt)	Survey index of fishable biomass (Kt)	Predation estimate2 (Kt)	Cod-stock estimate2 (Kt)	ln CPUE (1990=0)
1985	20.4	66.2					0.247
1986	23.3	76.9					0.285
1987	289.2	77.9					0.422
1988	303.3	73.6		223.2			0.139
1989	136.6	80.7		209.0			0.050
1990	10.0	84.0		207.0	213.7	470.9	0.000
1991	1.8	91.5		146.0	27.8	184.1	0.038
1992	0.3	105.5		194.2	2.7	19.8	0.119
1993	0.2	91.0		216.5	0.8	2.9	0.103
1994	0.1	92.8		223.1			0.098
1995	0.1	87.4		183.2			0.190
1996	0.1	84.1		192.1			0.235
1997	0.1	78.1		167.1			0.211
1998	0.1	80.5		244.3			0.354
1999	0.1	92.2		237.3			0.465
2000	0.4	98.0		280.3			0.566
2001	0.7	102.9		280.5			0.529
2002	0.7	135.2		369.5			0.698
2003	0.9	130.2		548.3			0.766
2004	1.3	149.3		528.3			0.864
2005	2.8	156.9	140.5	494.2[3]			0.897
2006	21.7	157.3	140.2	451.0[3]			0.885
2007	14.7	144.2	135.2	336.1			0.936
2008	8.3	153.9	131.6	262.6			0.972
2009	2.5	135.5	108.8	255.1			0.854
2010	5.3	134.0	138.5	318.7			0.828
2011	24.0	124.0	128.0	245.7[4]			0.865
2012	38.8	116.0	110.0	176.4[4]			0.781
2013	37.2	95.4	100.0	218.1			0.651
2014	44.3	—	90.0	170.0[4]			0.767

1 'effective cod biomass' was not an input data series in 2014; 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 a series of 'effective cod' estimates; tabulated are the median estimates (see Kingsley 2014; Siegstad and Kingsley 2014, Renzel 2014).

2 Grunwald (1998).

3 demographic analyses for 2005–2010 had been re-run in 2011 and resulted in especially large changes in the survey estimates of fishable biomass for 2005 (3.1% increase) and 2006 (3.1% increase);

4 survey estimates of fishable biomass for 2011, 2012, and 2014 were adjusted for incomplete coverage of the offshore strata by applying the mean offshore density to the survey strata not covered, and adding the corrected offshore estimate to that for Disko Bay and Vaigat.

Table 2. *Pandalus borealis* in West Greenland: summary of estimates of selected parameters from Bayesian fitting of a surplus production model, 2014.

	Mean	S.D.	25%	Median	75%	Est. mode	Median (2013)
Max. sustainable yield (Kt)	140.5	76.5	102.9	131.3	165.0	112.9	138.0
B/B_{msy}, end current yr (proj.)	98.9	30.6	79.5	97.3	117.2	94.0	109.0
Biom. risk, end current yr (%)	53.7	49.9	–	–	–	–	–
Z/Z_{msy}, current yr (proj.)	–	–	69.2	103.1	161.8	–	93.0
Carrying capacity	4216	3710	2042	3126	5057	946	3162
M.S.Y. ratio (%)	9.8	6.1	5.1	9.0	13.5	7.6	9.3
Survey catchability (%)	17.4	12.6	8.3	14.1	23.1	7.5	14.0
CPUE catchability	1.1	0.8	0.5	0.9	1.5	0.5	0.9
Effective cod biomass 2014 (Kt)	65.1	116.2	27.5	44.3	69.4	2.9	–
$P_{50\%}$	8.4	5.2	5.0	7.2	10.5	4.8	7.4
V_{max}	3.0	0.3	2.8	3.0	3.2	3.0	3.0
CV of process (%)	12.4	2.9	10.4	12.1	14.1	11.4	11.6
CV of survey fit (%)	15.8	2.1	14.4	15.9	17.3	16.1	15.0
CV of CPUE fit (%)	19.4	2.9	17.4	19.0	20.9	18.1	17.4
CV of predation fit (%)	131.0	87.5	59.5	115.4	185.3	84.2	112.4

Table 3. *Pandalus borealis* in West Greenland: selected[1] correlations (%) between model parameters, 2014.

	Start biom. ratio	*CV pred*	*CV cpu*	*CV s*	*CV proc*	V_{max}	*P50%*	*Qc*	*Qs*	*MSY ratio*	*K*
Max. sustainable yield		15		6	-6			-13	-13	27	20
Carrying capacity	14	23			5		11	-59	-58	-56	
Max. sustainable yield ratio (%)	-26	-18			-10		-19	83	83		
Survey catchability (%)	-40	-26			-10		-30	100			
CPUE catchability	-40	-26			-10		-30				
P50%	49	13			13	17					
Vmax											
CV of process (%)	14		25	-21							
CV of survey fit (%)											
CV of CPUE fit (%)											
CV of predation fit (%)	8										

[1] those over 5%

Table 4. *Pandalus borealis* in West Greenland: risks (%) of exceeding limit mortality in 2017 and of falling below B_{msy} or limit* biomass at the end of 2017 assuming effective cod biomass 30 or 50 Kt.

Catch	Prob. biomass < B_{msy} (%)		Prob. biomass< B_{lim} (%)		Prob. mort > Z_{msy} (%)	
(Kt/yr)	30 Kt	50 Kt	30 Kt	50 Kt	30 Kt	50 Kt
50	41.6	44.5	3.7	4.7	22.1	28.4
55	42.1	46.2	3.8	5.0	24.9	31.1
60	43.6	46.7	3.6	4.9	26.6	34.2
65	45.4	48.3	4.0	5.1	30.2	36.5
70	45.8	48.6	3.9	5.3	32.4	40.6
80	48.5	51.7	4.1	5.0	40.3	46.7
90	51.1	53.8	4.3	5.7	47.3	55.0

* limit biomass is 30% of B_{msy}

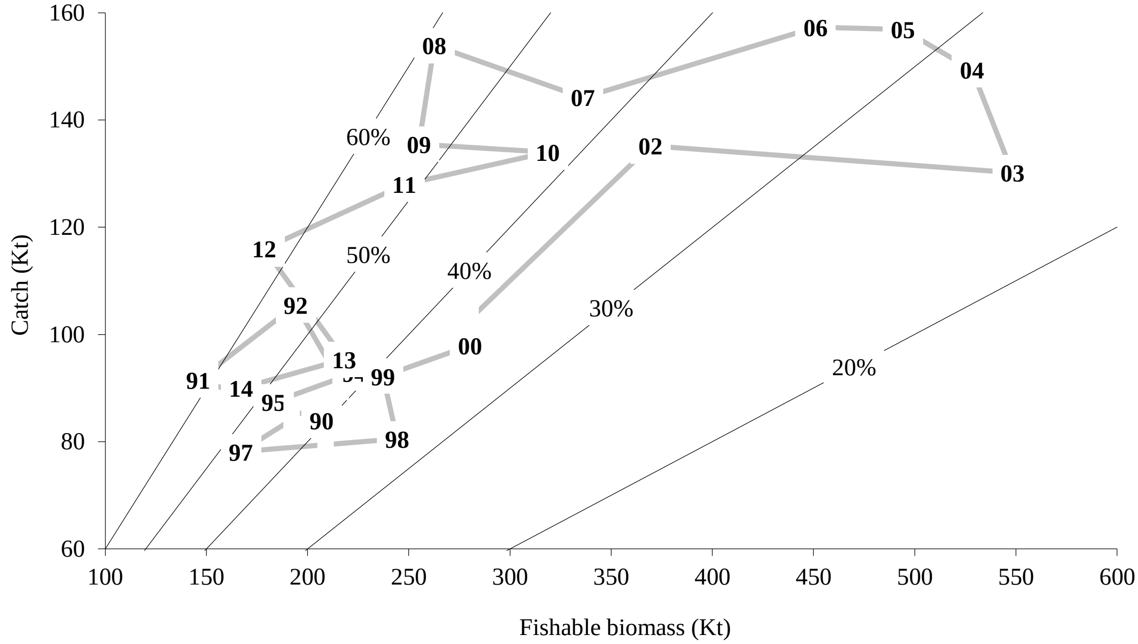

Fig. 1. *Pandalus borealis* in West Greenland: catch, fishable biomass and exploitation index, 1988–2014 (2014 catch is provisional).

Fig. 2a. *Pandalus borealis* in West Greenland: number at age 2 from research trawl survey, 1994–2014.

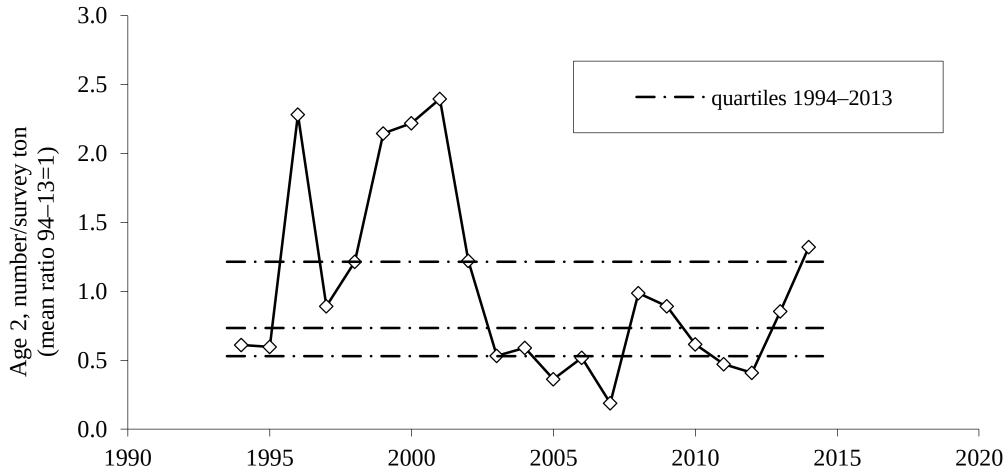

Fig. 2b. *Pandalus borealis* in West Greenland: number at age 2 relative to survey biomass, from research trawl survey 1994–2014.

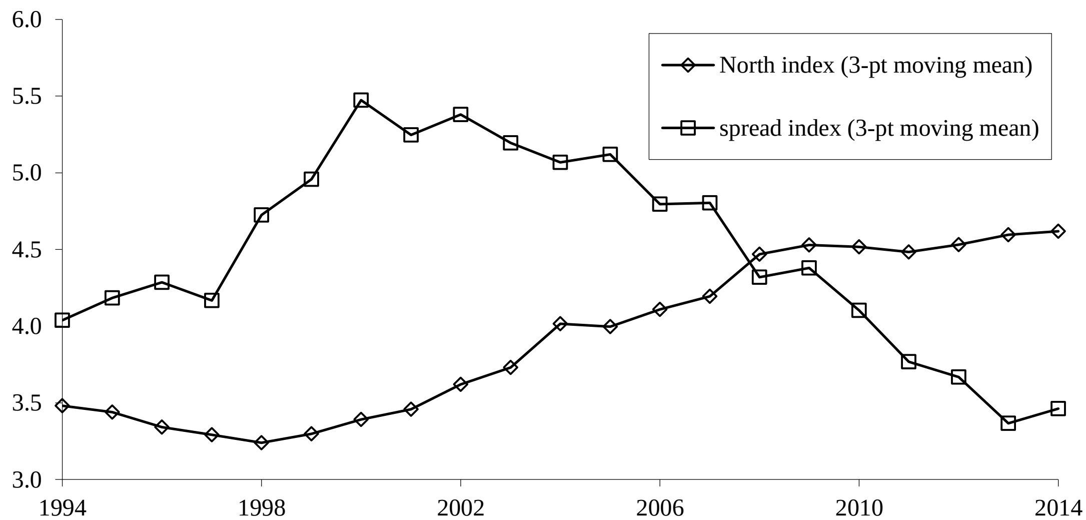

Fig. 3. *Pandalus borealis* in West Greenland: indices of distribution of the survey biomass, 1994–2014 (3-point moving means.)

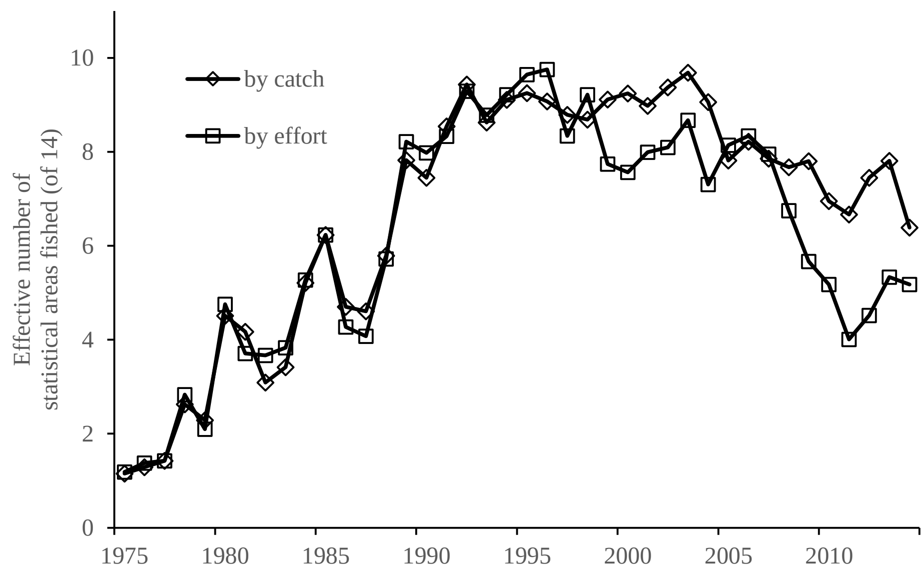

Fig. 4. *Pandalus borealis* in West Greenland: indices of the breadth of distribution of the Greenlandic fishery among 14 statistical areas, from logbook records, 1975–2014 (2014 on part-year's data).

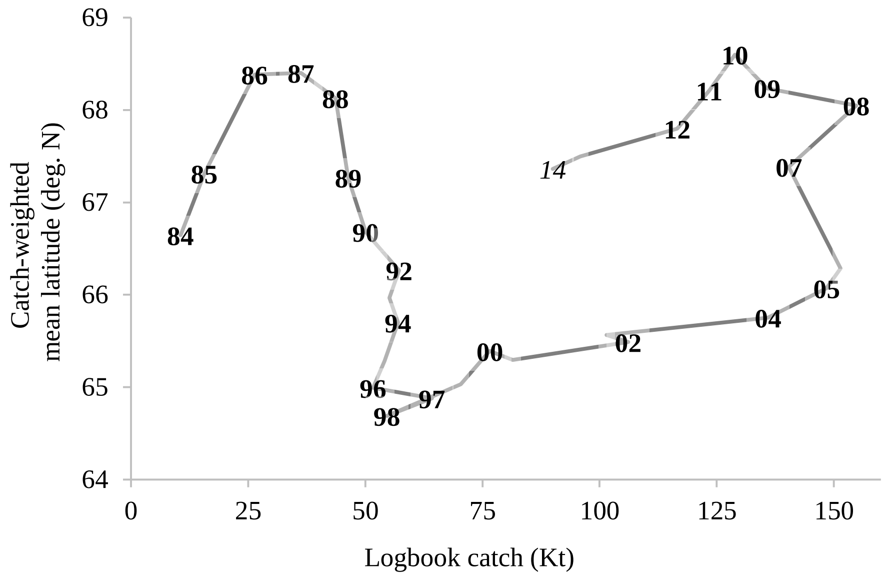

Fig. 5. *Pandalus borealis* in West Greenland: mean latitude by weight vs. total weight, for logbook-recorded catch in the Greenland fishery, 1984–2014 (2014 is represented by a projected catch and a part-year mean latitude).

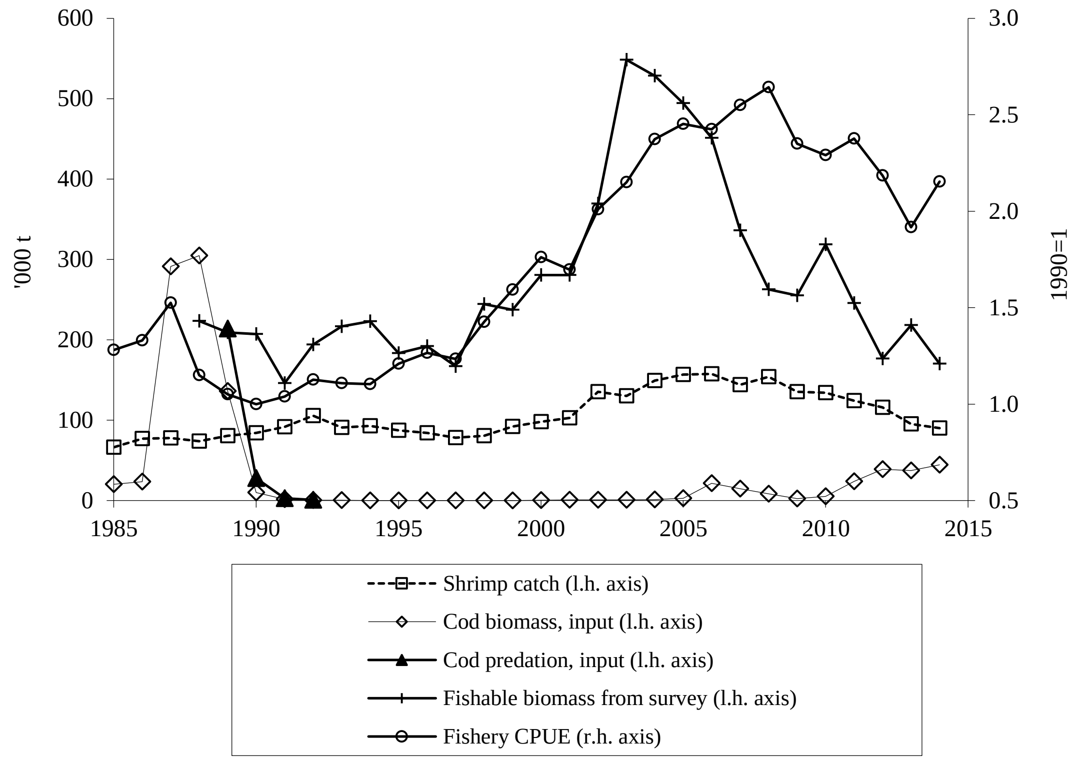

Fig. 6. *Pandalus borealis* in West Greenland: thirty-year data series providing information for the assessment model. (2014 catch is projected; effective cod biomass is synthesised from four biomass index series and a series of overlap indices between distributions of cod and shrimps.)

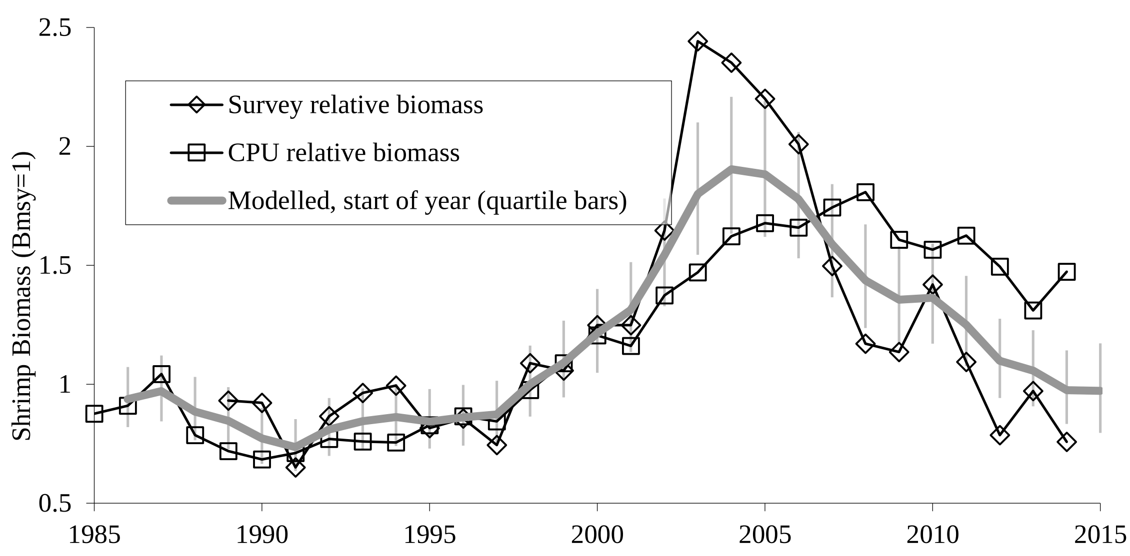

Fig. 7. *Pandalus borealis* in West Greenland: modelled shrimp standing stock fitted to survey and CPUE indices, 1985–2014.

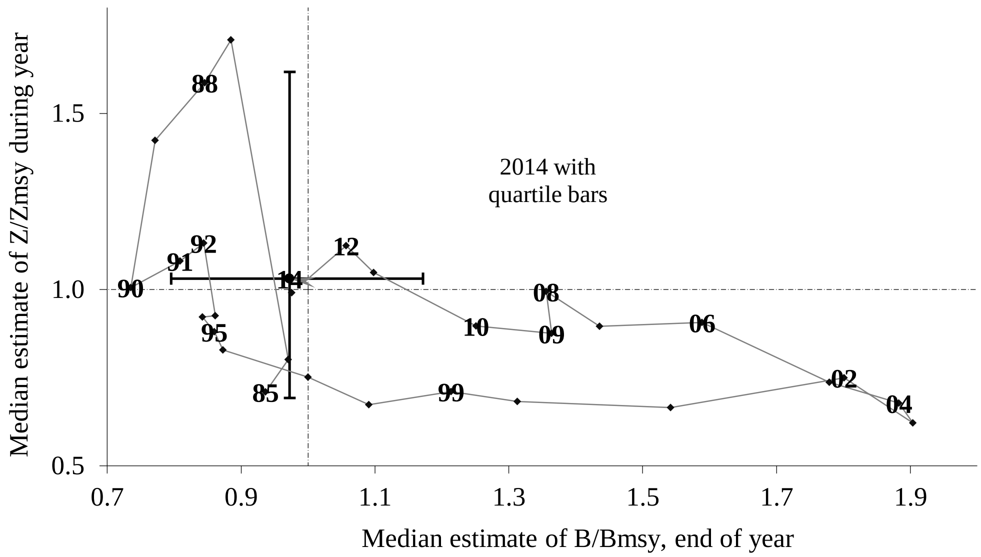

Fig. 8. *Pandalus borealis* in West Greenland: median estimates of biomass ratio (B/B_{msy}) and mortality ratio (Z/Z_{msy}) 1985–2014.

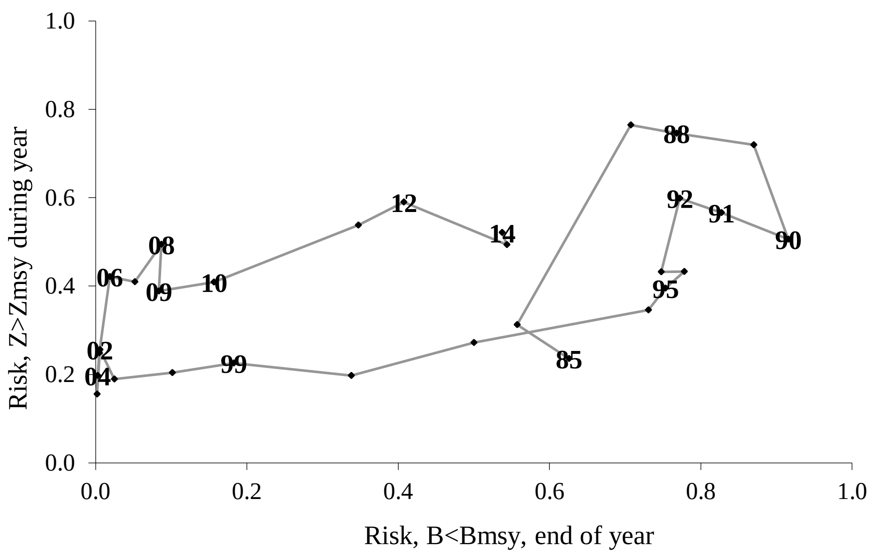

Fig. 9. *Pandalus borealis* in West Greenland: annual likelihood that biomass has been below B_{msy} and that mortality caused by fishing and cod predation has been above Z_{msy} 1985–2014.

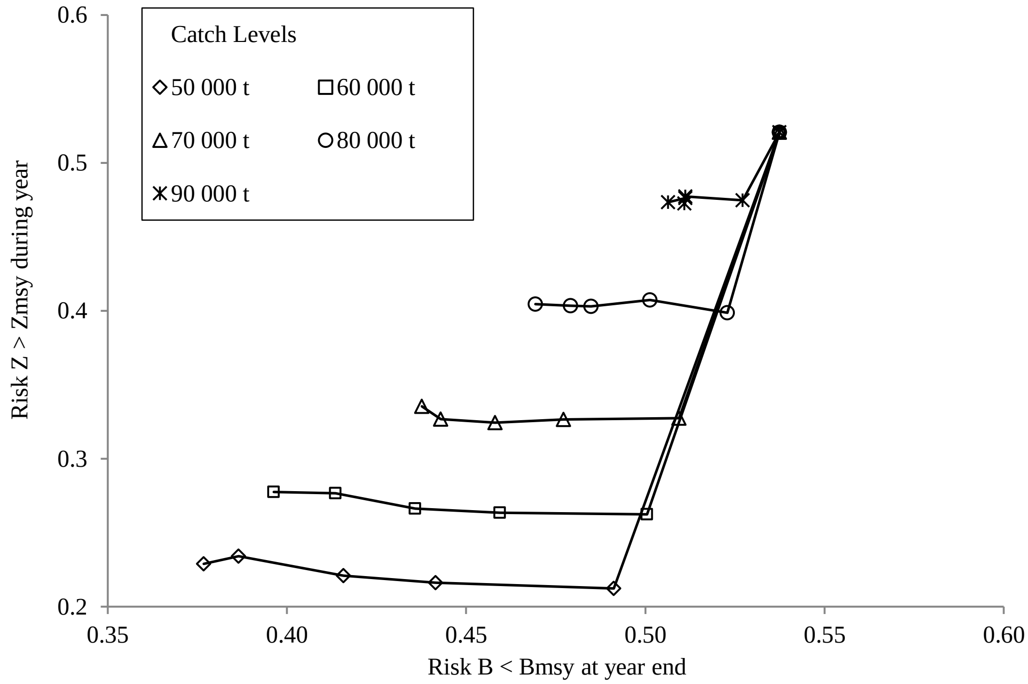

Fig. 10a. *Pandalus borealis* in West Greenland: joint 5-year plot 2015–19 of the risks of transgressing B_{msy} and Z_{msy} at catch levels 50–90 Kt/yr; with effective cod biomass 30 Kt.

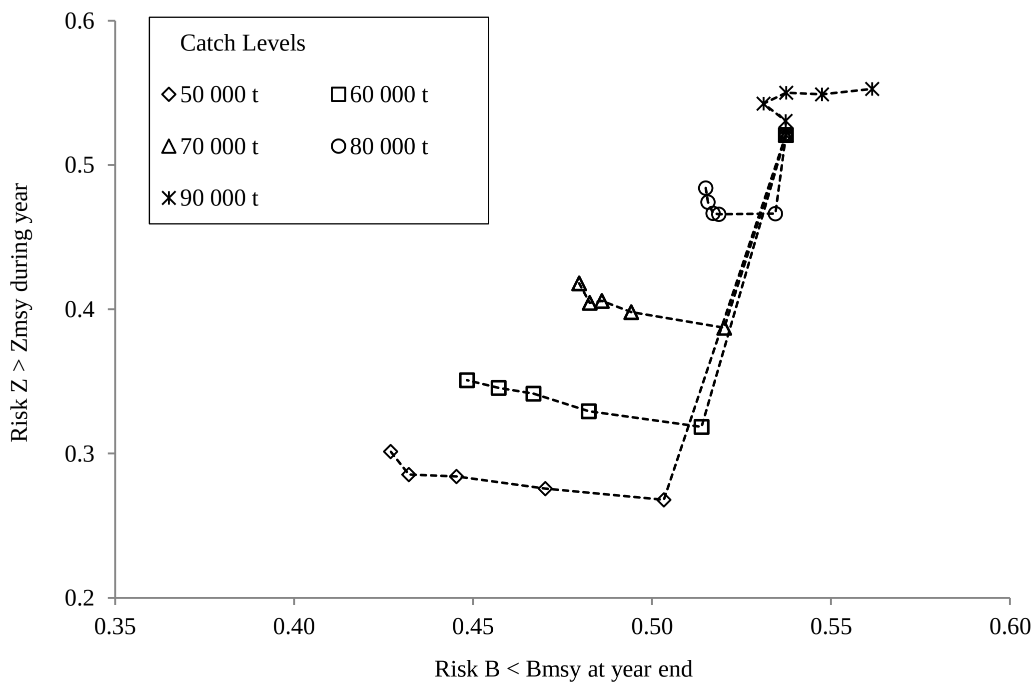

Fig. 10b. *Pandalus borealis* in West Greenland: joint 5-year plot 2015–19 of the risks of transgressing B_{msy} and Z_{msy} at catch levels 50–90 Kt/yr; with effective cod biomass 50 Kt.

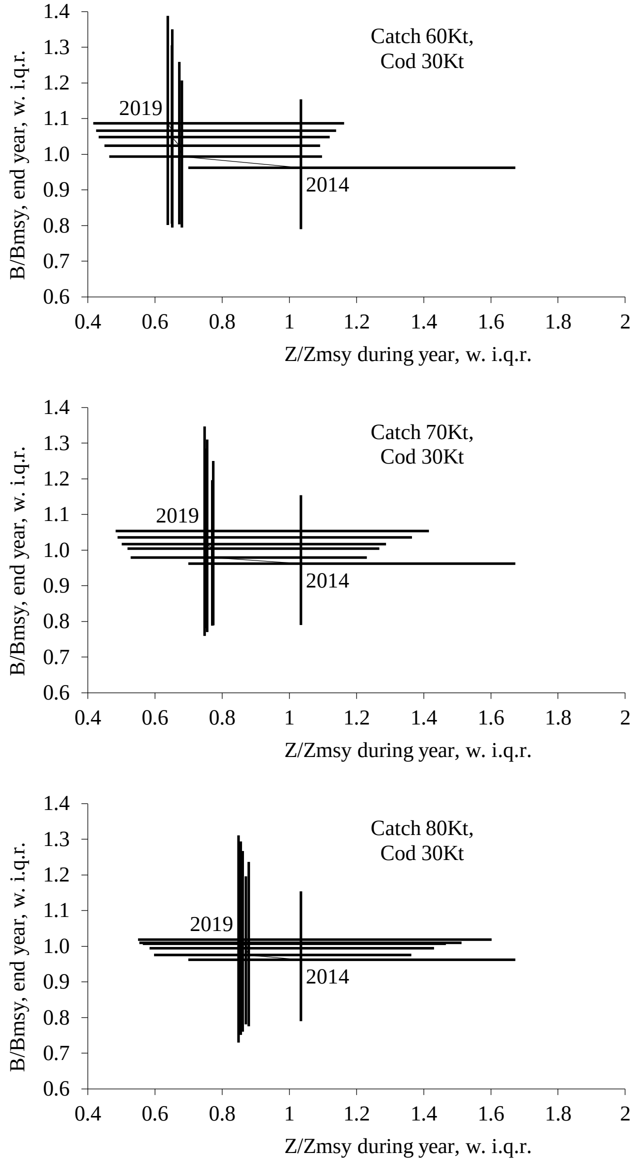

Fig. 11a. *Pandalus borealis* in West Greenland: projections of stock development for 2015–2019 with effective cod biomass assumed at 30 000 t: median estimates with quartile error bars.

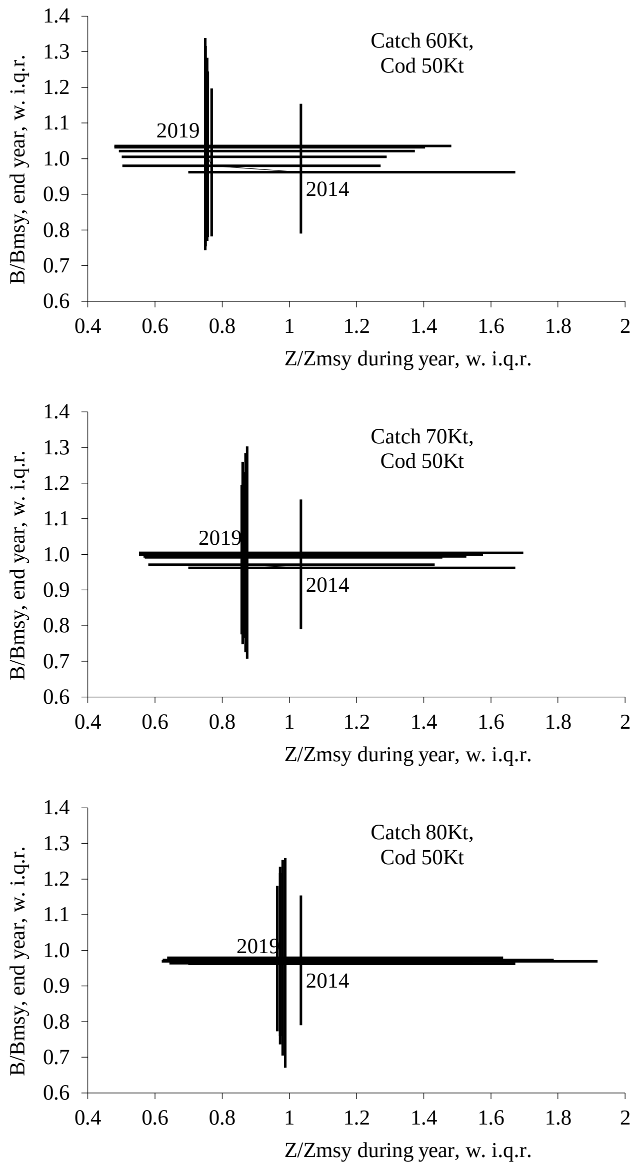

Fig. 11b. *Pandalus borealis* in West Greenland: projections of stock development for 2015–2019 with effective cod biomass assumed at 50 000 t: median estimates with quartile error bars.