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A Provisional Assessment of the Shrimp Stock off West Greenland in 2013

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 commercial fishing fleets, biomass and stock-composition information from a research trawl survey, catch data, and information on stock demographics and 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, although 19% higher than in 2012, remains at a low level compared with the most recent 20 years. Offshore, the fishable biomass has increased by nearly 50% compared with 2012, but is still very low; this is most marked in the central and southern areas while the northern areas have an above-average proportion of the biomass. The fishable biomass inshore, in Disko Bay and Vaigat, 12% lower than in 2012, is still moderately high when compared with its history. As a result of this contrast, the proportion of biomass in the inshore area is still high.

Both inshore and offshore the number of two-year-old shrimps, although 50% higher than in 2012, is small, both absolutely and in relation to survey biomass. The fishable biomass in 2013 is high in relation to the survey biomass and both inshore and offshore comprises a high proportion of females. Recruitment prospects are low, and fishing on the stock in its present state will disproportionally hit the spawning stock of females. The stock composition inshore, historically characterised by a higher proportion of young shrimps than that offshore, is in 2013 closer to the stock structure offshore than to its past average values.

The quantitative assessment model—backed up by survey data—estimates that the stock has decreased in 8 of the 9 years 2004–12. Predation by a cod stock that is estimated to be at its highest level since the late 1980s is an additional stress. However, with catches projected at 100 Kt in 2013 the median estimate of total mortality is not expected to exceed the MSY level of mortality and the stock is projected to remain above its MSY level to the year end. It is estimated that catches of 80–85 Kt in 2014–15 would keep the mortality risk below 35%.

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 comprise a swept-area index of fishable biomass from an annual research trawl survey, a series of standardised indices of fishery CPUE, past catches, and an index of the biomass of Atlantic cod, an important predator. The model was modified in 2011 to give more weight to the survey index of biomass and less to the fishery CPU (Kingsley 2011). This document presents the results of applying it to the updated available data series of shrimp catches and shrimp and cod biomass, to evaluate management options for the West Greenland shrimp stock.

Short-term (1-year) and medium-term (three-year) projections of stock development were made for annual catches at 5 000-ton intervals from 70 000 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 40 000 tons, the estimate for 2013 being 36 000 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 2013). The assessment also refers to indices that summarise survey information on the distribution of the stock and its structure (Kingsley 2008b; Burmeister et al. 2013).

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. 2013). 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 85 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 and 2013 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 late 1980s (Siegstad and Kingsley 2013).

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 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, subsequently decreasing equally quickly to reach, by 2008, about the levels of the 1990s (Fig. 1). Compared with average levels of the most recent 20 years stock-size indices are therefore low. Survey biomass overall has increased by 19% over 2012 but is still 47% less than the temporary maximum of 2010. In 2013, the number and biomass of females are both one-third higher than they were in 2012, and are now near to their 20-year medians. It is this increase in the female component of the stock that has generated the overall increase—the number and biomass of males have hardly changed since 2012 and remain not far above their 20-year minimums (Burmeister et al. 2013).

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[1] 'German survey' estimate revised in 2012.

Survey Measures of Stock Size

	Biomass (Kt)					Number (bn)		
	Survey							
	Disko B. & Vaigat	Offshore	Total	Fishable	Female	Male	Female	Age 2
2013 value[1]	81.4	152.4	233.8	218.1	103.9	31.1	12.0	3.16
20-year[2] upper quartile	92.6	286.4	367.2	344.5	127.1	66.4	15.2	7.57
20-year median	72.6	220.4	280.3	258.9	102.6	42.5	11.8	5.23
20-year lower quartile	49.2	195.4	234.3	221.5	87.2	37.3	9.0	3.39
2013 rank	13.0/20	3.0/20	5.6/20	5.2/20	10.8/20	3.6/20	12.0/20	4.8/20
2012 value	92.5	103.7	196.2	178.7	77.2	29.7	9.0	2.07

[1] corrections for unsurveyed strata (C0 in 2011–12, W1-4 in 2011) applied to measures of stock size were 3.7% for 2011 and 3.1% for 2012.
[2] 20-year percentiles, and 2013 rank, are referred to the 20 preceding years, i.e. 1993–2012.

In the inshore area comprising Disko Bay and Vaigat the survey biomass decreased by 12% from 2012 to a value below its 20-year upper quartile. The offshore biomass collectively, in 2012 at its lowest for 20 years, was nearly half as large again in 2013, although still well below its 20-year lower quartile. Relative to stock size and previous values, it could be seen in 2012 that large pre-recruits were numerous, especially offshore (Kingsley 2012), and the increase in the offshore fishable biomass might be associated with recruitment of these shrimps. The absolute number at age 2 is 50% higher than in 2012, but still low relative to past values (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
2013 value	13.5	22.3	93.3	48.9	44.4	47.6
Upper quartile[1]	24.7	27.8	93.8	57.9	37.4	39.8
Median[1]	16.7	25.5	92.1	56.9	35.5	38.3
Lower quartile[1]	11.7	23.7	90.7	54.2	34.9	37.5
2013 rank[1]	8.8/20	2.3/8	13.3/20	1.0/20	21/20	21/20
2012 value	10.9	31.7	91.1	51.7	39.4	43.2

[1] quartiles and 2013 rank generally referred to 20 preceding years 1993–2012;
[2] quartiles and 2013 rank referred to 8 preceding years 2005–2012 (for which data is available);

The overall stock composition in 2013 is marked 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 below its 20-yr median and the number of large pre-recruits is below an 8-yr lower quartile, so there are not good prospects for either short- or medium-term recruitment.

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
2013 value	13.6	27.0	91.6	48.7	42.9	46.9
Upper quartile[1]	36.3	40.4	90.8	56.3	35.2	40.2
Median[1]	27.2	32.3	89.5	53.7	33.8	38.6
Lower quartile[1]	14.1	30.5	86.1	50.2	32.5	37.6
2013 rank[1]	4.4/20	0/8	16.3/20	2.0/8	9/8	9/8
2012 value	14.4	31.8	90.7	56.5	34.2	37.7

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
2013 value	13.5	19.7	94.2	49.0	45.3	48.0
Upper quartile[1]	21.1	24.2	94.9	57.9	41.5	43.7
Median[1]	14.2	20.4	93.6	55.6	38.4	41.1
Lower quartile[1]	7.4	13.4	92.1	52.1	36.8	38.6
2013 rank[1]	8.9/20	3.9/8	14.1/20	2.0/8	9/8	7.7/8
2012 value	7.6	31.7	91.5	47.3	44.2	48.3

Differences between the stock composition 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. Thoughout 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.

However, in 2013 some of these differences are less evident than in 2012 or in the past averages. For example, in 2012 the female proportion of the biomass was 10 percentage points higher offshore; in 2013 one percentage point. Relative to survey biomass, age-2s were twice as numerous inshore as offshore in 2012—consistent with past differences—but in 2013 the values are equal. I.e it seems that in 2013 the inshore stock has in some ways converged on the offshore structure: its values are more like the offshore values than like its own past.

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 2013, 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, 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, are scarce both inshore and offshore in 2013.

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. Therefore, perhaps, the inshore stock-composition history provides safer criteria than that of the offshore and if in 2013 the inshore stock composition is moving closer to the offshore history it could be a danger signal. The stock seems at the moment to be at, or outside, the limits of where it has been in the past. The danger points appear to be: few age-2 shrimps anywhere even relative to stock size; 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
2013 value	35.6	34.0	24.6	5.7	0.1	3.3	34.9
19-year[1] upper quartile	27.6	35.8	23.0	28.4	9.1	3.9	25.4
19-year median	16.6	30.8	19.0	21.6	3.2	3.4	22.3
19-year lower quartile	4.9	27.0	16.6	15.0	0.5	3.1	20.3
2013 rank	17.1/19	12.6/19	15.4/19	1.0/19	0.0/19	7.4/19	17.9/19
2012 value	34.3	34.6	7.2	23.6	0.4	3.4	48.6

[1] percentiles and 2013 rank are referred to the 19 preceding years with stable survey coverage, i.e. 1994–2012.

Compared with values for the previous 20 years, the offshore biomass is low and the inshore biomass relatively high, so the proportion inshore is still near to its 20-year maximum, although lower than the extreme value of 2012.

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 median values. The proportion in the south-central offshore area W5–7, extending from the Lille Hellefiskebanke to Kobberminebugten, was above its median in 2012, owing to a small number of large catches. In the results from the 2013 survey, W3–4 has regained its past position, while W5–7 has now only a small proportion of the survey biomass (Burmeister et al. 2013).

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 2012, especially for Disko (upward) and W3–4 (downward) were, by comparison with this earlier stability, especially remarkable. The 2013 distribution is somewhat a return to the distribution before 2012.

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 sustained decrease of the survey index from 2003 through 2012. Instead it continued to increase, more slowly, until 2008, after which it 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 there is no clear 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 one state, t, to the next, t+1 was:

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

where *MSY* is an annualised value of the instantaneous maximum sustainable yield rate. P_t is the stock biomass relative to biomass at *MSY* ($P_t=B_t/B_{MSY}$) in year *t*. C_t is the catch taken by the fishery and O_t is the consumption by cod, in year *t*. *m* is a shape parameter for the 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 (1988–2013) 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; 2004; Burmeister et al. 2013);
- CPUE indices spanning, among them, 1984 through 2013 (Kingsley 2008a; Hammeken Arboe 2013); and unified into a single series by a separate model (Hammeken Arboe and Kingsley 2013); 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;
- the a 30-year series of catches by the fishery with corrections for past overpacking (Hvingel 2004; Hammeken Arboe 2013);
- a 30-year series of 'effective' cod biomass estimates (i.e. allowance made for the partial overlap of the two stocks) (Hvingel and Kingsley 2002; Wieland and Storr-Paulsen 2004; Siegstad and Kingsley 2013);
- and a short series (4 years) 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.

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 100 000 t. Canadian catches had been zero in 2008 and small in 2009, but the Canadian fishery took about 5 500 t in 2010. Canadian catches for 2011 were reported at 1296 t and in 2012 were negligible. There appears to have been very little fishing in Canadian SFA1 in the first part of 2013 and the year's catches are projected to be negligible.

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 updated with the most recent estimates of effective cod stock (Siegstad and Kingsley 2013).

The data link functions for the biomass indices were:

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

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:

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

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). The error term, τ , is 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.

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:

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

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 iterations and then run for 10 000 000, every 100th being retained. Of the resulting 100 000 iterations every 10th was used in the final calculations, giving sample sizes of 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 and the smaller range of the year-to-year change in shrimp biomass.

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).

The median estimate of the *MSY* was 138 Kt, with quartiles at 109 and 171 Kt; an estimated mode is at 117 Kt.

Results of the Quantitative Assessment

[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 model estimates that the stock decreased in 2010, 11 and 12, given the decrease in the survey estimate of fishable biomass as well as the drop in fishery CPUE, and projects fishable biomass at end 2013 at close to the 2012 level, now estimated to be about 9% above B_{msy}. The catches recorded in 2011 are estimated to have been sustainable, but total mortality in 2012 is now estimated to have been unsustainable with a median estimate 10% above the MSY level (Fig. 7, Fig. 8). With an estimated lower cod stock and lower projected catches, total mortality in 2013 is estimated to be below the MSY level, but the mortality risk at 44% exceeds a management critierion of 35%.

The median estimate of *MSY*—138 000 t—is more uncertain than in earlier assessments: the e.c.v. of the mean is 53% and the relative interquartile range 45%. The distribution of the estimate is skewed and the most likely value for the MSY is estimated at 117 000 t. This implies that all values between 138 000 and 117 000 t, as well as some values less than 117 000 t, are more likely than 138 000 t (Table 2).

The stock is projected to be above B_{msy} at the end of 2013, and the risk of its going below this level in 2014 is below 40% at all the catch levels considered. Risks[3] associated with six possible catch levels for 2014, with an 'effective' cod stock at 30 000 t[4], are estimated to be:

30 000 t cod	Catch option ('000 tons)						
Risk of:	65	70	75	80	85	90	95
falling below B_{msy} end 2014 (%)	35.0	35.6	36.1	36.8	37.3	38.0	38.0
falling below B_{lim} end 2014 (%)	1.5	1.7	1.7	1.6	1.8	1.5	1.7
exceeding Z_{msy} in 2014 (%)	21.9	24.3	26.7	29.5	32.0	35.6	38.7
exceeding Z_{msy} in 2015 (%)	22.2	24.6	27.4	29.9	33.0	36.0	39.4

and with an 'effective' cod stock at 40 000 t:

40 000 t cod	Catch option ('000 tons)						
Risk of:	65	70	75	80	85	90	95
falling below B_{msy} end 2014 (%)	36.1	36.2	36.4	37.5	37.6	38.3	38.9
falling below B_{lim} end 2014 (%)	1.9	1.8	1.7	2.0	1.8	1.9	1.9
exceeding Z_{msy} in 2014 (%)	24.7	26.5	29.0	32.3	36.3	39.2	42.4
exceeding Z_{msy} in 2015 (%)	25.1	27.2	30.3	33.6	36.7	40.1	43.4

If a mortality risk (i.e. of exceeding Z_{msy}) criterion of 35% is observed, catches of 80–85 Kt might be sustainable, depending on the expected level of future cod stocks.

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, and recent signs of increase have not been maintained. 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. However, if cod are distributed over only a part of the range of distribution of the shrimp stock so that the opportunities for interaction between the two species are reduced, a different model might be appropriate.

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. Five levels of annual catch were investigated from 70 000 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

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

[4] the estimate for 2013 is 36 200 tons.

biomass and the fishery have contracted towards the north, so indices of the breadth of distribution of both survey biomass and catch weight have decreased, while indices of latitude have increased. From the data available for 2013 it appears that this contraction is continuing (Figs 3–4).

The present assessment based on the existing modelling approach estimates a stock close to B_{msy}, reduced by several years of large catches that have exceeded the MSY level of mortality. CPUE remains relatively high, even after the high catches of the past decade, but is now starting to decrease. The fishery is now more concentrated than in 1992–2003 (Fig. 3, 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 fishery between 2003 and 2009 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 moderately low.

Conclusions

The stock is estimated to be above its MSY level in 1013, but recruitment prospects in the medium term as indicated by numbers at age 2 continue to be poor. The risk of exceeding Z_{msy} should probably not exceed 35%. A quantitative assessment indicates that catches below 80–85 Kt would keep the risk of exceeding Z_{msy} below 35%.

Acknowledgements

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.

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Table 1. *Pandalus borealis* in West Greenland: input data series 1984–2013 for stock-dynamic assessment model.

	Effective cod biomass[5] (Kt)	Catch (Kt)	Provisional catch (Kt)	Survey index of fishable biomass (Kt)	Predation estimate[6] (Kt)	Cod-stock estimate[7] (Kt)	ln CPUE (1990=0)
1984	37.8	52.8					0.180
1985	25.0	66.2					0.247
1986	19.6	76.9					0.288
1987	282.1	77.9					0.428
1988	297.3	73.6		223.2			0.137
1989	149.1	80.7		209.0	213.7	470.9	0.048
1990	10.9	84.0		207.0	27.8	184.1	0.000
1991	1.9	91.5		146.0	2.7	19.8	0.036
1992	0.3	105.5		194.2	0.8	2.9	0.118
1993	0.2	91.0		216.5			0.096
1994	0.1	92.8		223.1			0.099
1995	0.0	87.4		183.2			0.194
1996	0.1	84.1		192.1			0.243
1997	0.1	78.1		167.1			0.214
1998	0.0	80.5		244.3			0.356
1999	0.1	92.2		237.3			0.487
2000	0.4	98.0		280.3			0.579
2001	1.1	102.9		280.5			0.550
2002	0.6	135.2		369.5			0.686
2003	0.9	130.2		548.3			0.761
2004	1.6	149.3		528.3			0.863
2005	1.8	156.9	140.5	494.2*			0.900
2006	31.8	157.3	140.2	451.0*			0.879
2007	21.5	144.2	135.2	336.1			0.921
2008	8.9	153.9	131.6	262.6			0.951
2009	2.2	135.5	108.8	255.1			0.839
2010	5.9	134.0	138.5	318.7			0.820
2011	22.7	124.0	128.0	247.8#			0.850
2012	54.9	116.0	110.0	178.7#			0.767
2013	36.2	—	100.0	218.1			0.630

* demographic analyses for 2005–2010 were 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);

\# the survey estimate of fishable biomass in 2011, 238 990 t, was adjusted upwards by 3.7% to compensate for the survey's having missed area C0 and sub-stratum W1-4 owing to hindrance by sea ice;

\# the survey estimate of fishable biomass in 2012, 173 300 t, was adjusted upwards by 3.1% to compensate for the survey's having missed area C0 owing to hindrance by sea ice.

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[5] Wieland and Storr-Paulsen (2004) updated by Sünksen (2009) and Siegstad and Kingsley (2013).

[6] Grunwald (1998).

[7] the estimate of cod stock biomass associated with Grunwald's estimate of predation.

Table 2. *Pandalus borealis* in West Greenland: summary of estimates of selected parameters from Bayesian fitting of a surplus production model, 2013.

	Mean	S.D.	25%	Median	75%	Est. mode	Median (2012)
Max. sustainable yield (Kt)	148	79	109	138	171	117	132
B/B_{msy}, end current yr (proj.)	1.11	0.31	0.91	1.09	1.29	1.04	1.00
Biom. risk, end current yr (%)	37.3	48.4	–	–	–	–	—
Z/Z_{msy}, current yr (proj.)	3.92	59.55	0.64	0.93	1.33	-5.05	1.08
Carrying capacity	4118	3185	2158	3162	4972	1250	2767
M.S.Y. ratio (%)	9.8	5.7	5.6	9.3	13.3	8.4	10.1
Survey catchability (%)	16.6	11.1	8.4	14.0	21.7	8.8	17.4
CPUE catchability	1.0	0.7	0.5	0.9	1.4	0.6	1.1
$P_{50\%}$	8.5	5.4	5.1	7.4	10.6	5.0	6.3
V_{max}	3.0	0.3	2.8	3.0	3.2	3.0	3.0
CV of process (%)	11.9	2.7	10.0	11.6	13.6	11.0	11.9
CV of survey fit (%)	15.0	2.0	13.7	15.0	16.4	15.0	14.5
CV of CPUE fit (%)	17.7	2.5	15.9	17.4	19.0	16.7	16.9
CV of predation fit (%)	127.5	84.7	58.5	112.4	180.2	82.2	106.7
Start biomass ratio	0.90	0.16	0.78	0.88	0.99	0.85	0.90

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

	Start biom. ratio	*CV pred*	*CV cpu*	*CV s*	*CV proc*	*V_{max}*	*P50%*	*Qc*	*Qs*	*MSY ratio*	*K*
Max. sustainable yield		17						-14	-14	22	19
Carrying capacity	13	24			7		9	-54	-54	-54	
Max. sustainable yield ratio (%)	-27	-23			-10		-19	85	85		
Survey catchability (%)	-43	-30			-12		-30	100			
CPUE catchability	-44	-30			-12		-30				
P50%	50	16			15	18					
Vmax											
CV of process (%)	17		19	-13							
CV of survey fit (%)			29								
CV of CPUE fit (%)											
CV of predation fit (%)	12										

[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 30 or 40 Kt.

Catch	Prob. biomass < B_{msy} (%)		Prob. biomass< B_{lim} (%)		Prob. mort > Z_{msy} (%)	
(Kt/yr)	30 Kt	40 Kt	30 Kt	40 Kt	30 Kt	40 Kt
70	32.8	34.4	2.8	3.2	24.3	28.1
75	33.5	35.4	2.8	3.5	26.4	30.9
80	34.6	37.6	2.9	3.6	29.4	34.2
85	36.2	38.6	2.9	3.4	32.7	37.3
90	38.2	39.7	3.0	3.7	36.7	40.7

* limit biomass is 30% of B_{msy}

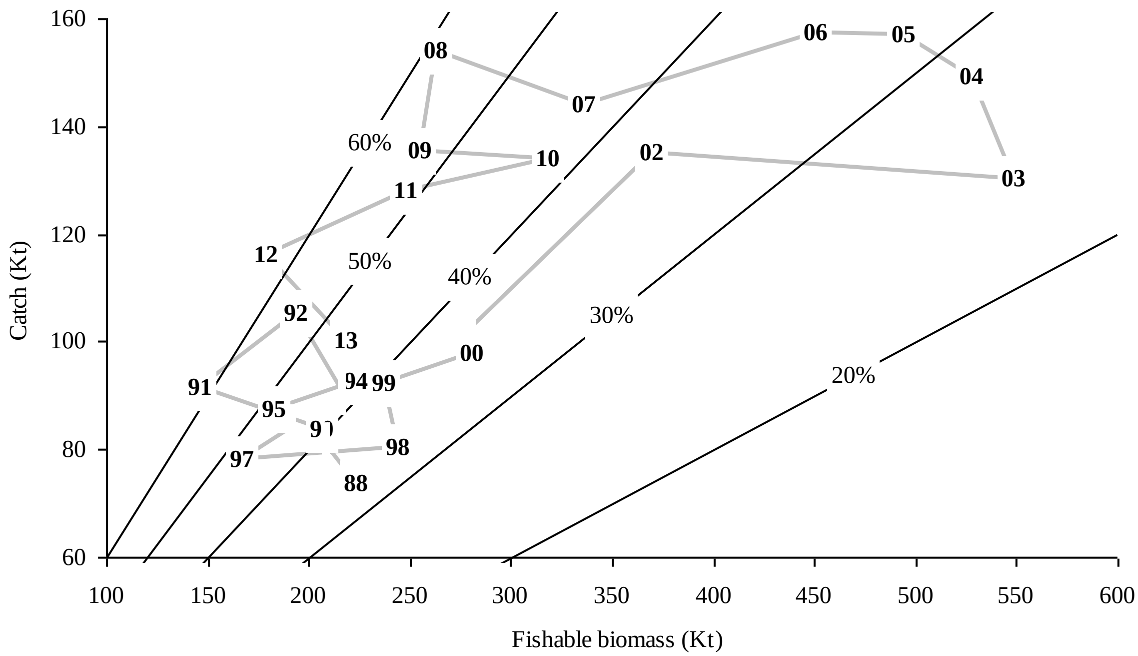

Fig. 1. *Pandalus borealis* in West Greenland: catch, fishable biomass and exploitation index, 1988–2013 (2013 catch is provisional).

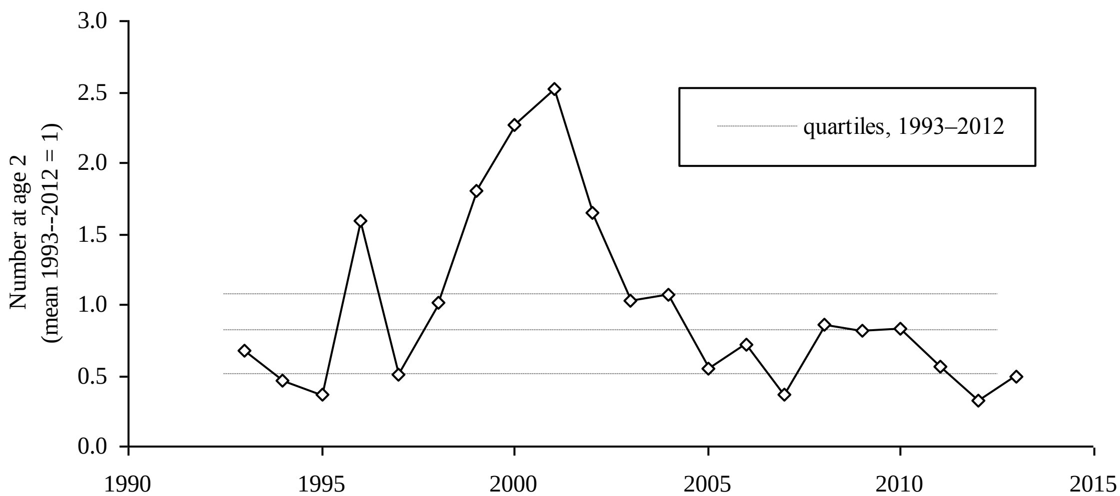

Fig. 2a. *Pandalus borealis* in West Greenland: relative number at age 2 from research trawl survey, 1993–2013.

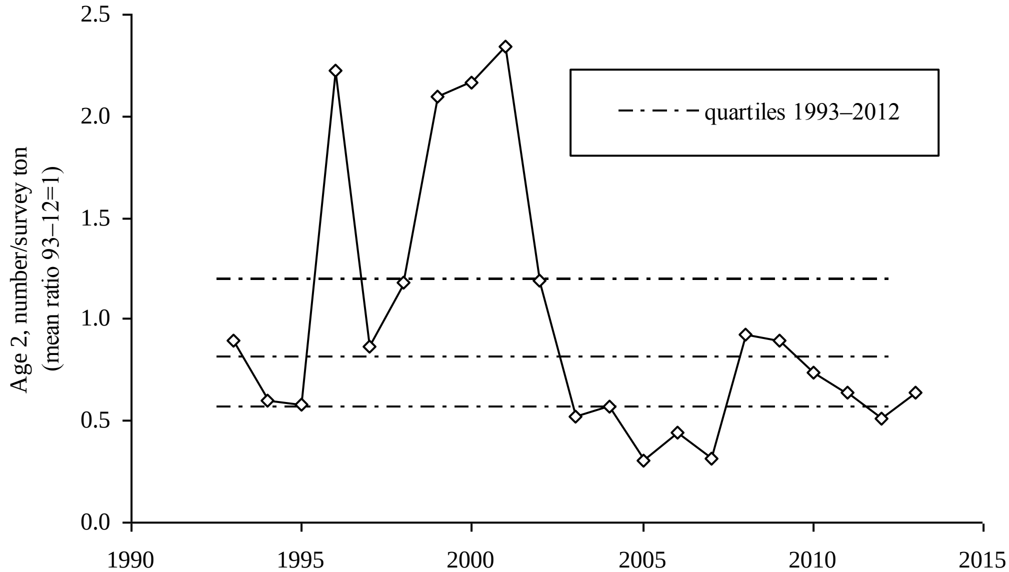

Fig. 2b. *Pandalus borealis* in West Greenland: number at age 2 relative to survey biomass, from research trawl survey 1993–2013.

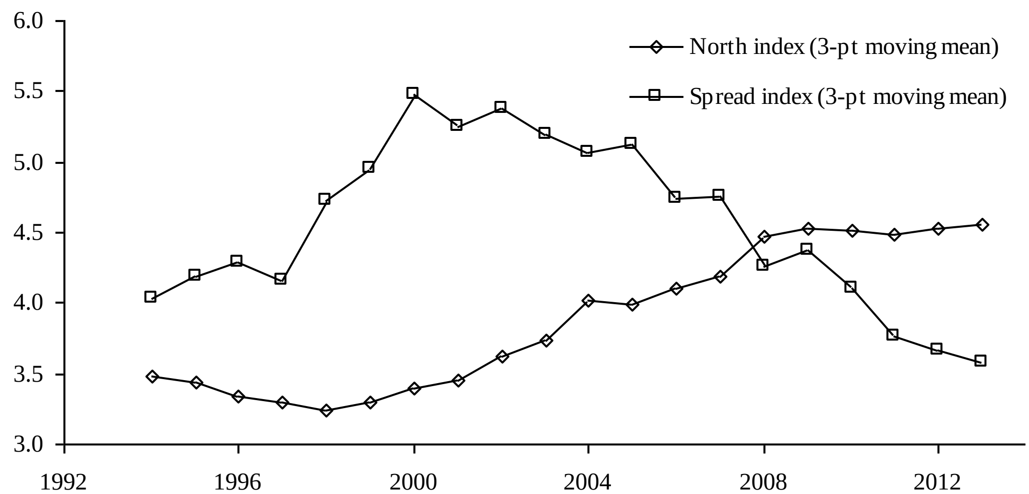

Fig. 3. *Pandalus borealis* in West Greenland: indices of distribution of the survey biomass, 1994–2013 (3-point moving means.)

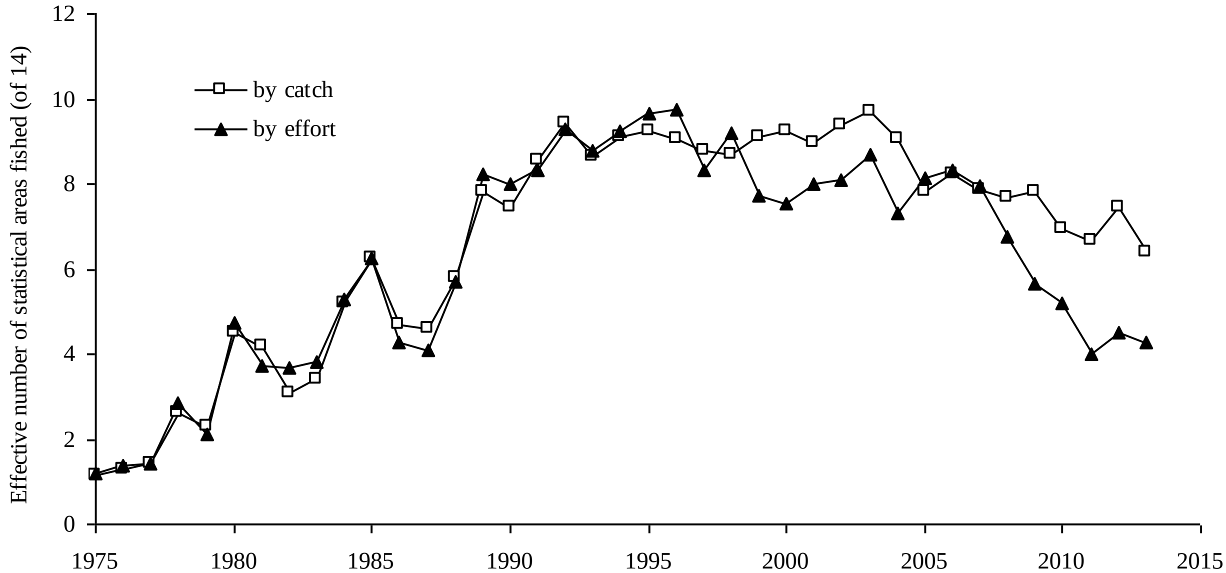

Fig. 4. *Pandalus borealis* in West Greenland: indices of the breadth of distribution of the Greenlandic fishery among 14 statistical areas, from logbook records, 1975–2013.

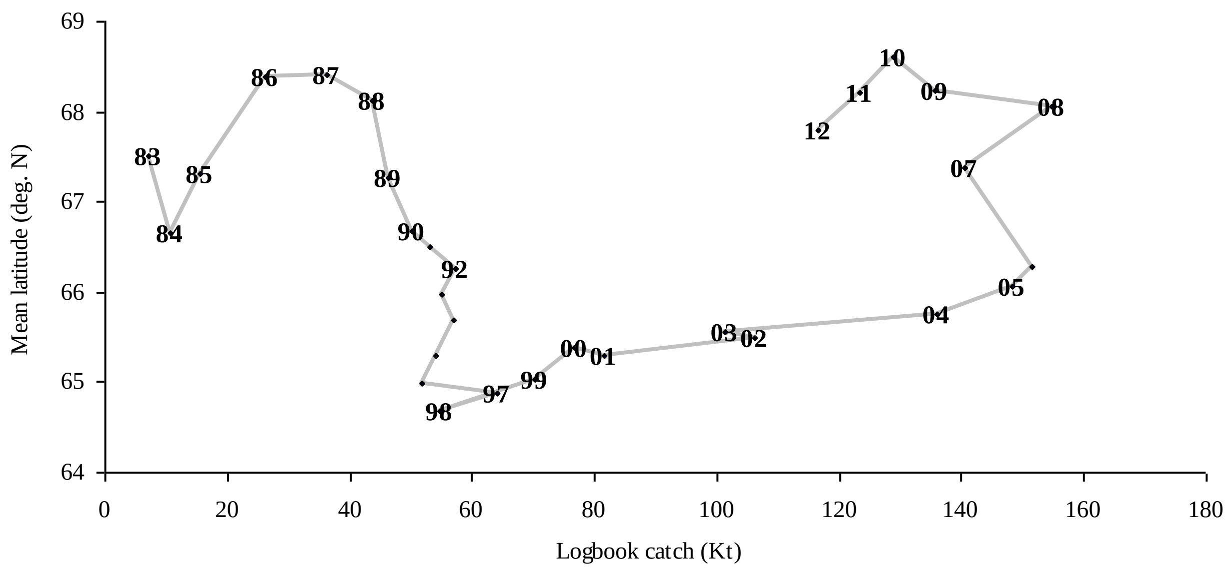

Fig. 5. *Pandalus borealis* in West Greenland: mean latitude by weight vs. total weight, for logbook-recorded catch in the Greenland fishery, 1983–2012 (only partial data is available for 2013 and is misleading).

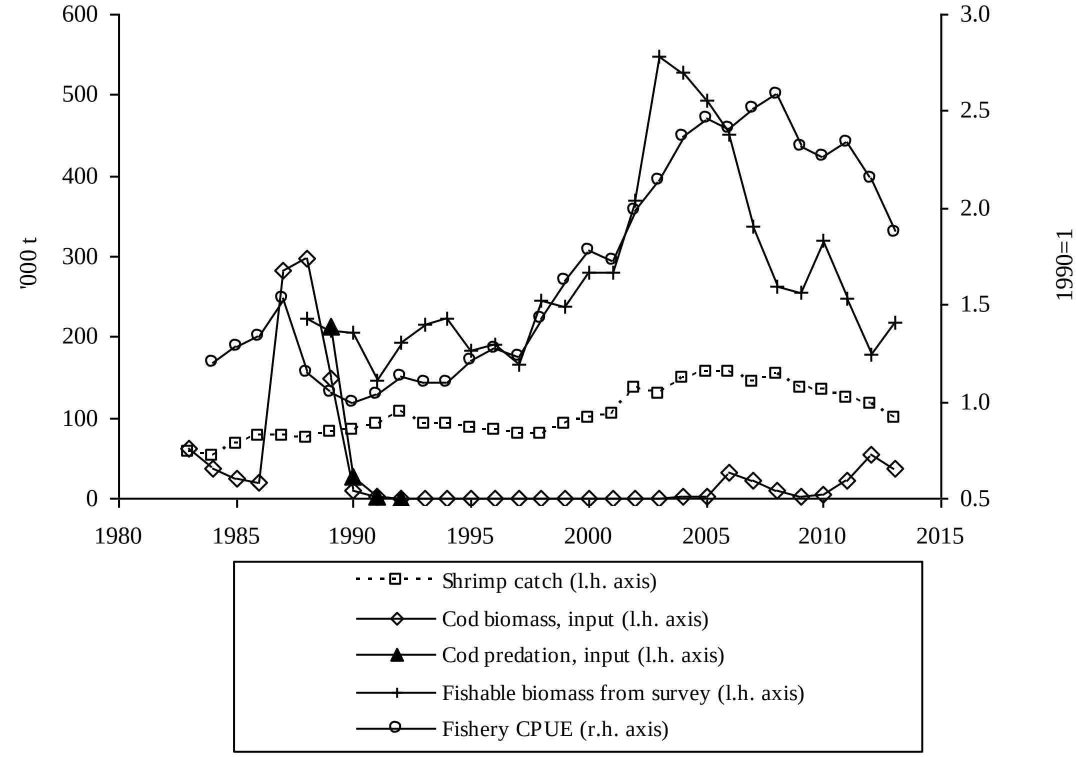

Fig. 6. *Pandalus borealis* in West Greenland: data series providing information for the assessment model.

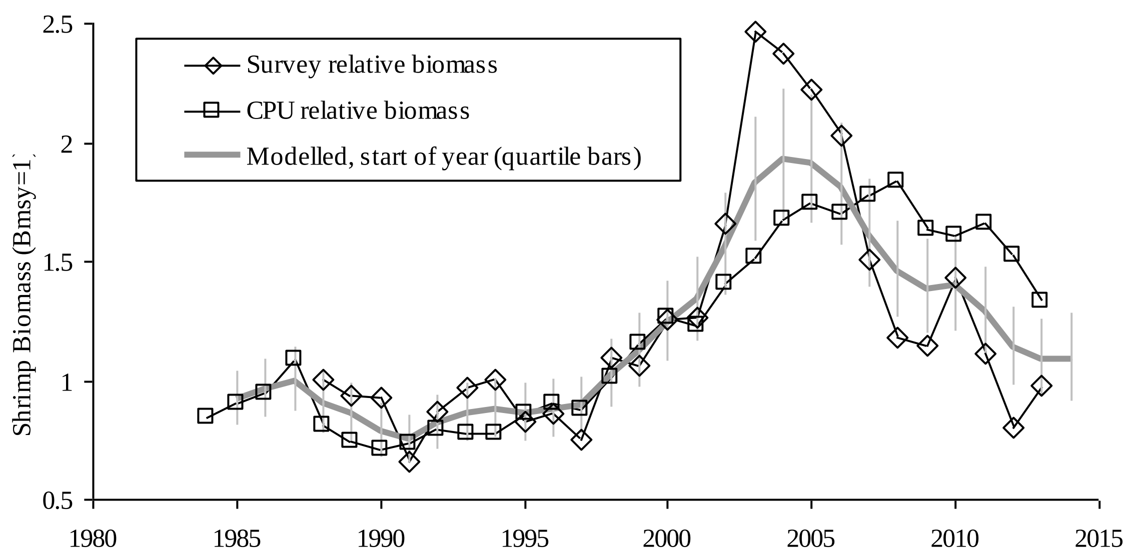

Fig. 7. *Pandalus borealis* in West Greenland: modelled shrimp standing stock fitted to survey and CPUE indices, 1984–2013.

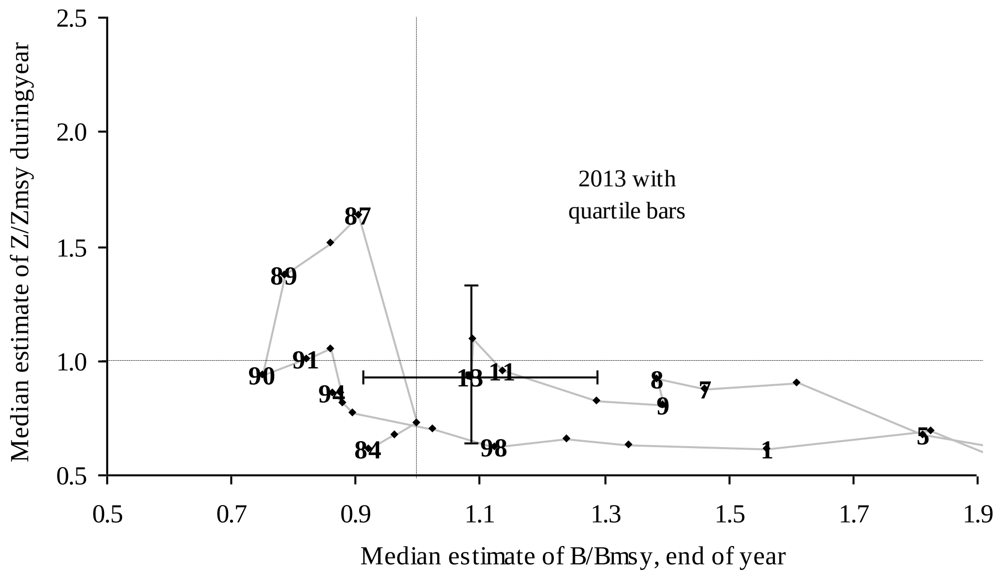

Fig. 8. *Pandalus borealis* in West Greenland: median estimates of biomass ratio (B/B_{msy}) and mortality ratio (Z/Z_{msy}) 1984–2013.

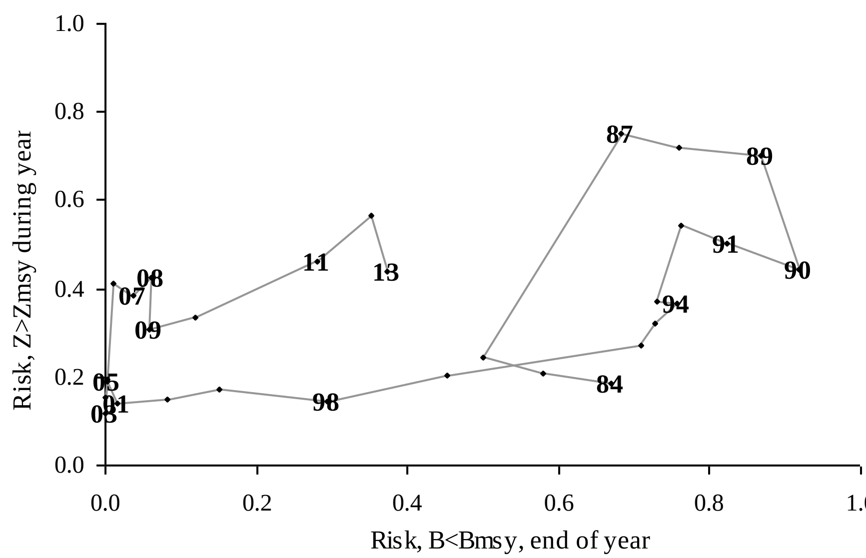

Fig. 9. *Pandalus borealis* in West Greenland: annual likelihood that biomass has been below B_{msy} and that mortality caused by fishing and cod predation has been above Z_{msy} 1984–2013.

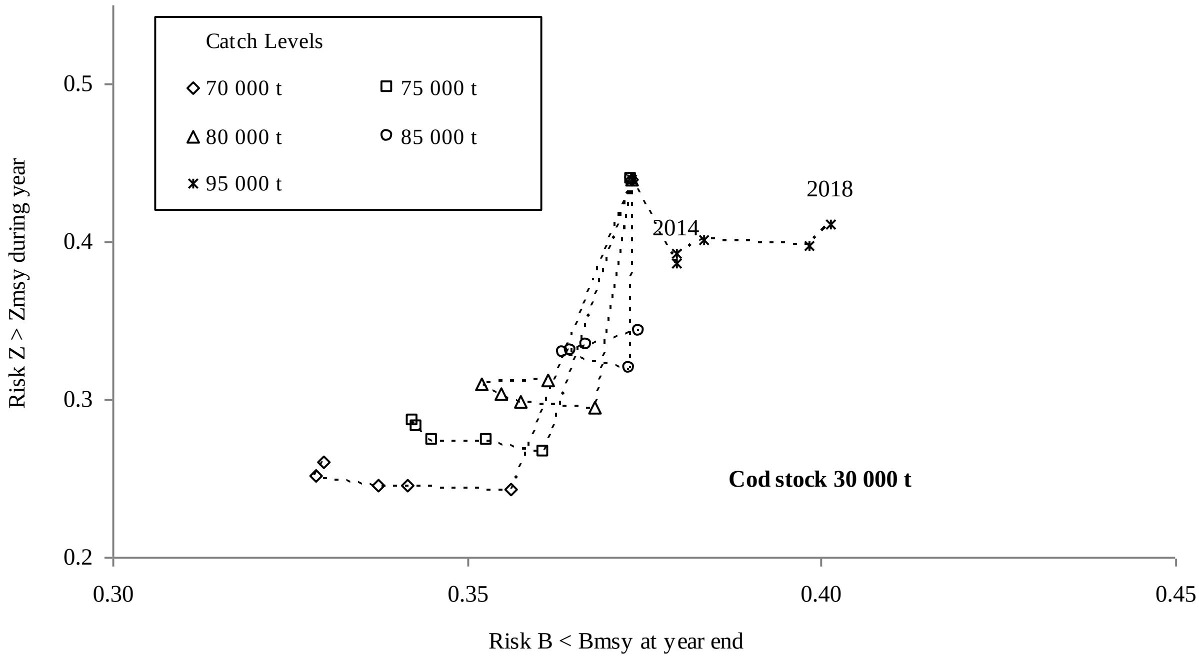

Fig. 10a. *Pandalus borealis* in West Greenland: joint 5-year plot 2014–18 of the risks of transgressing B_{msy} and Z_{msy} at catch levels 70–95 Kt/yr; with effective cod biomass 30 Kt.

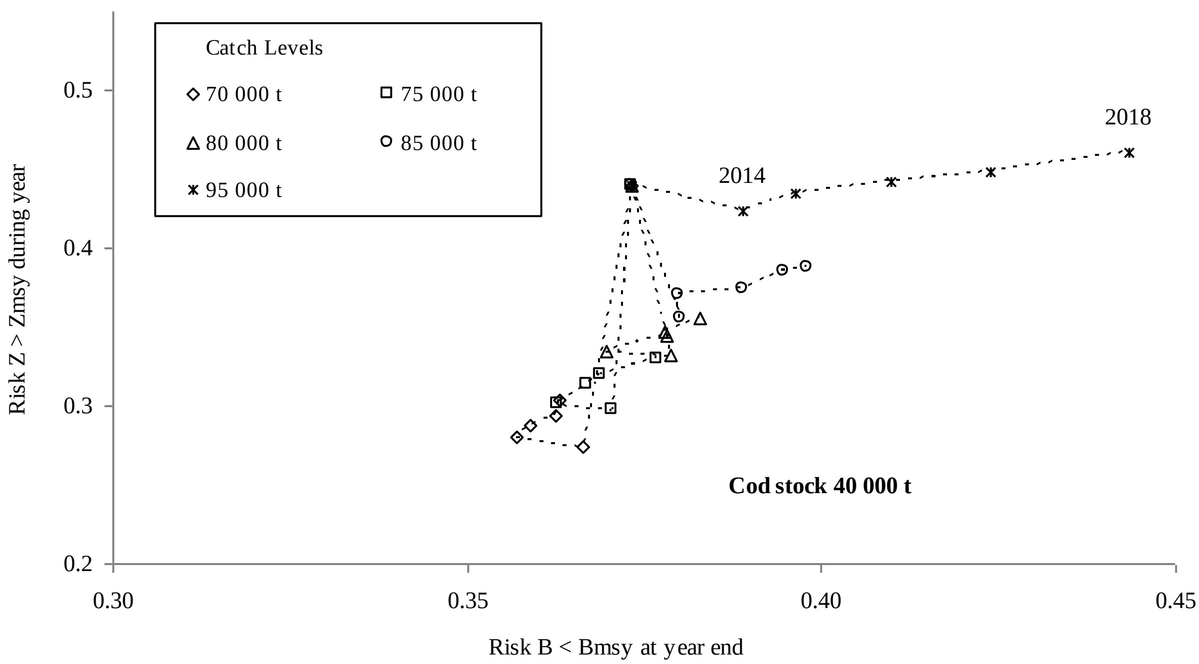

Fig. 10b. *Pandalus borealis* in West Greenland: joint 5-year plot 2014–18 of the risks of transgressing B_{msy} and Z_{msy} at catch levels 70–95 Kt/yr; with effective cod biomass 40 Kt.

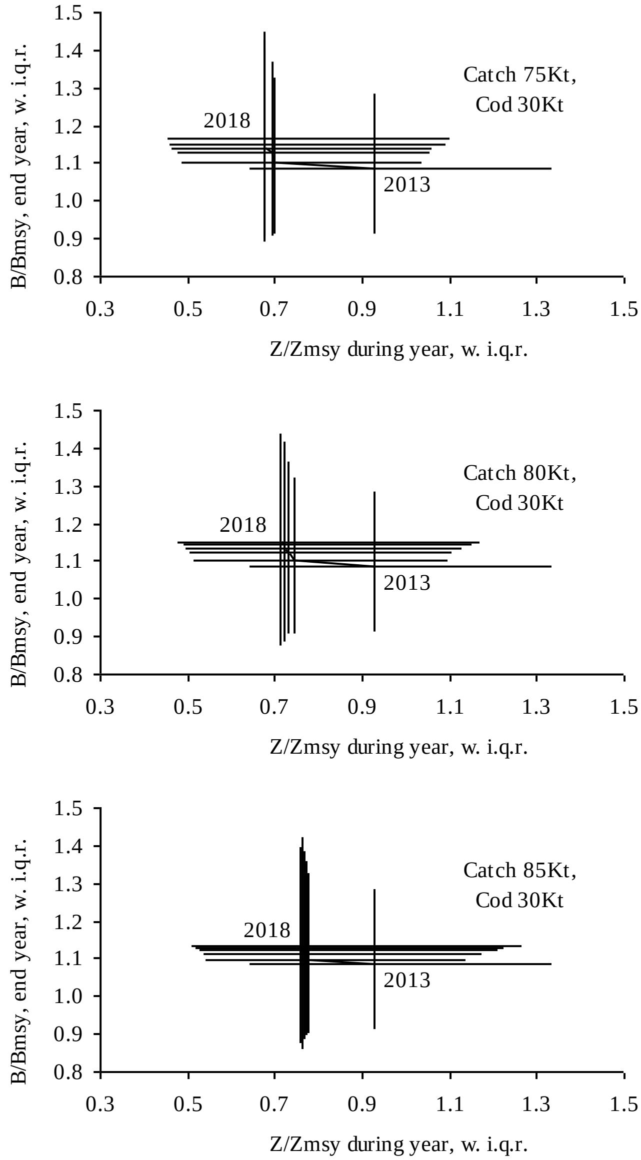

Fig. 11. *Pandalus borealis* in West Greenland: projections of stock development for 2013–2018 with effective cod biomass assumed at 30 000 t: median estimates with quartile error bars.

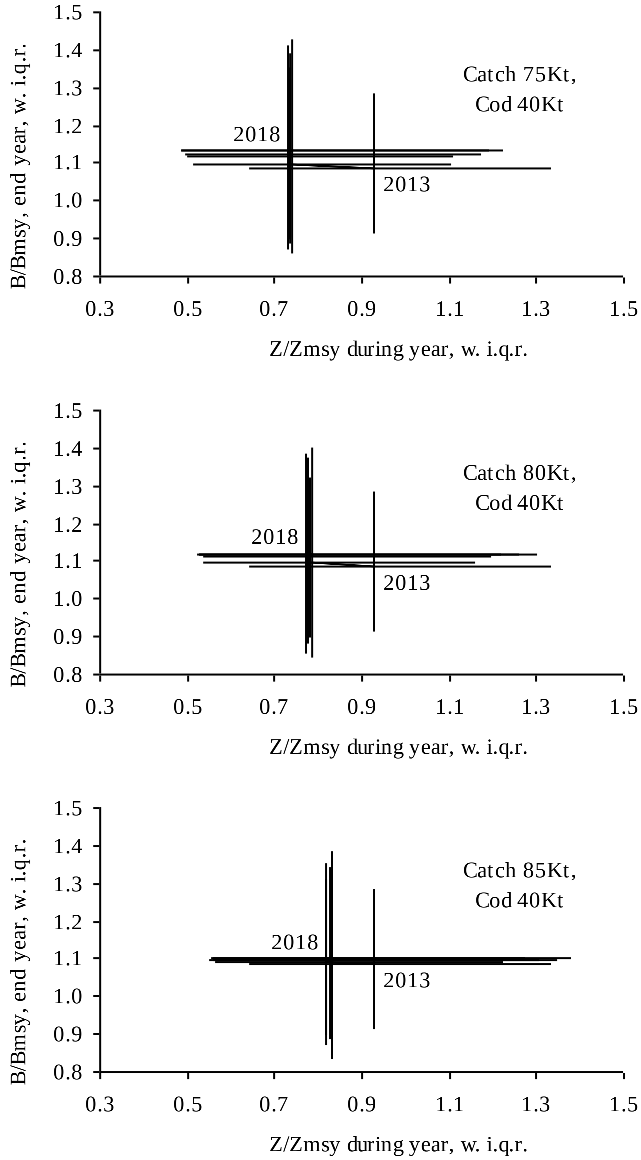

Fig. 12. *Pandalus borealis* in West Greenland: projections of stock development for 2013–2018 with effective cod biomass assumed at 40 000 t: median estimates with quartile error bars.

Appendix to the Assessment—extended tables of catch options and corresponding risks.

The tables in this Appendix present risk levels estimated by the quantitative assessment model associated with an extended range of options for annual catches, from 50 Kt to 110 Kt.

Short-term risks associated with an extended range of six possible catch levels for 2014, with an ‘effective’ cod stock at 30 000 t, are estimated to be:

30 000 t cod	Catch option ('000 tons)						
Risk (%) of:	50	60	70	80	90	100	110
falling below B_{msy} end 2014	33.1	34.3	35.3	36.2	37.6	38.2	39.8
falling below B_{lim} end 2014	1.5	1.5	1.6	1.7	1.6	1.6	1.6
exceeding Z_{msy} in 2014	15.6	19.0	23.1	29.0	35.5	42.2	48.8
exceeding Z_{msy} in 2015	16.0	19.3	24.3	29.3	36.0	42.5	49.7

and with an ‘effective’ cod stock at 40 000 t:

40 000 t cod	Catch option ('000 tons)						
Risk (%) of:	50	60	70	80	90	100	110
falling below B_{msy} end 2014	34.3	35.2	36.2	37.5	38.3	39.3	40.1
falling below B_{lim} end 2014	1.8	1.7	1.8	2.0	1.9	1.7	1.8
exceeding Z_{msy} in 2014	18.3	21.4	26.5	32.3	39.2	45.9	52.1
exceeding Z_{msy} in 2015	18.6	22.4	27.2	33.6	40.1	47.2	53.4

Medium-term risks, i.e. biomass risk after 3 years at constant catch and mortality risk during the third year, are estimated to be:

Catch (Kt/yr)	Prob. biomass < B_{msy} (%)		Prob. biomass< B_{lim} (%)		Prob. mort > Z_{msy} (%)	
	30 Kt	40 Kt	30 Kt	40 Kt	30 Kt	40 Kt
50	27.5	30.1	2.7	3.1	16.8	19.3
60	30.5	31.3	2.6	3.1	19.6	23.2
70	32.8	34.4	2.8	3.2	24.3	28.1
80	34.6	37.6	2.9	3.6	29.4	34.2
90	38.2	39.7	3.0	3.7	36.7	40.7
100	40.0	42.4	3.1	3.6	43.5	47.3
110	42.3	44.5	2.9	3.9	49.9	54.0

Calculated risk levels include uncertainty of prediction and therefore increase with longer-range predictions.