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A Provisional Assessment of the Shrimp Stock off West Greenland in 2012

by

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## Abstract

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-structure 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 structure are extreme in several respects. Offshore, the fishable biomass is at by far its lowest level for the last 20 years, but the biomass inshore, in Disko Bay and Vaigat, is high when compared with its history. As a result of this contrast, the proportion of biomass in the inshore area is extraordinarily high. Overall, the biomass is at its second lowest level in 20 years. Offshore, the biomass decrease is most marked in the central and southern areas: the northern area has an above-average proportion of the biomass.

Both inshore and offshore the number of two-year-old shrimps is small, both absolutely and in relation to survey biomass. Offshore, there are relatively large numbers of large pre-recruits at 14–16.5 mm, giving some promise for recruitment to the fishable biomass in the near future. However, the fishable biomass in 2012 is low in relation to the survey biomass, and the biomass of fishable males is exceptionally low so that fishing on the offshore stock in its present state will disproportionally hit the spawning stock of females. Inshore, the stock structure is in general closer to its past average values than it is offshore.

The quantitative assessment model estimates that the stock is close to its MSY level, having decreased for 7 of the last 9 years, and has been fished over its MSY catch rate in 2011, with catches of 124 Kt, and 2012, with catches projected at 110 Kt. It estimates that catches of 80–85 Kt would keep the mortality risk below 40%.

## 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 has been restricted to Div. 0A since 1981.

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. 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 75 000 to 100 000 tons under assumptions that the cod stock, allowance made for its overlap with shrimp distribution, might be at 20 000 tons or 25 000 tons, the estimate for 2012 being 22 300 tons. 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 2012). The assessment also refers to indices that summarise survey information on the distribution of the stock and its structure (Kingsley 2008b; Kingsley et al. 2012).

## 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. This is continuing.

The estimated survey biomass of a main predator, the Atlantic cod, was less than 10 Kt from 1991 to 2004. It increased briefly in 2006–7 to near 200 Kt, 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 concentrated in northerly areas where there was a higher density of shrimps, and the ‘effective’ cod stock appeared to have increased significantly. In 2012, while the survey biomass of cod has increased again to 74 Kt, it is again mostly distributed in more southerly areas, its index of overlap with the shrimp stock is less, and the ‘effective’ cod stock has declined slightly from the 2011 value. However, 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, Distribution and Structure

*Survey measures of stock size*

| | Biomass (Kt) | | | | | Number (bn) | | |
|---|---|---|---|---|---|---|---|---|
| | Survey | | | | | | | |
| | Disko B. & Vaigat | Offshore | Total | Fishable | Female | Male | Female | Age 2 |
| 2012 value[1] | 92.5 | 103.7 | 196.2 | 178.7 | 77.2 | 29.7 | 9.0 | 2.07 |
| 20-year[2] upper quartile | 87.6 | 286.4 | 367.2 | 344.5 | 127.1 | 66.4 | 15.18 | 8.38 |
| 20-year median | 71.1 | 220.4 | 280.3 | 258.9 | 102.6 | 42.5 | 11.80 | 5.27 |
| 20-year lower quartile | 44.3 | 195.4 | 234.3 | 221.5 | 87.2 | 37.3 | 8.75 | 3.58 |
| 2012 rank | 15.9/20 | 0.0/20 | 2.4/20 | 1.7/20 | 4.6/20 | 2.5/20 | 6.1/20 | 0.0/19 |

1 corrections for unsurveyed strata (C0 in 2011–12, W1-4 in 2011) applied to measures of stock size (except age-2 numbers) were 3.7% for 2011 and 3.1% for 2012.
2 20-year percentiles, and 2012 rank, are referred to the 20 preceding years, i.e. 1992–2011; (19 years 1993–2011 for age-2 numbers.)

*Measures of survey biomass distribution within SA1*

| | Of offshore (%) | | | | | | Of total (%) |
|---|---|---|---|---|---|---|---|
| | North | W1–2 | W3–4 | W5–7 | W8–9 | Distribution Index | Disko B. and Vaigat |
| 2012 value | 34.3 | 34.6 | 7.2 | 23.6 | 0.4 | 3.4 | 48.6 |
| 18-year[1] upper quartile | 24.5 | 36.4 | 23.1 | 28.6 | 9.2 | 4.0 | 25.1 |
| 18-year median | 15.1 | 30.8 | 19.1 | 21.5 | 3.5 | 3.3 | 21.7 |
| 18-year lower quartile | 4.7 | 26.8 | 18.5 | 14.1 | 0.6 | 3.1 | 20.1 |
| 2012 rank | 16.1/18 | 12.9/18 | 1.6/18 | 11.1/18 | 2.6/18 | 9.7/18 | 19.0/18 |
| 2011 rank[2] | 15.2/17 | 15.2/17 | 0.0/17 | 7.2/17 | 6.5/17 | 4.3/17 | 18.0/17 |

[1] percentiles and 2012 rank are referred to the 18 preceding years, i.e. 1994–2011, with stable survey coverage.
[2] referred to the 17 preceding years, i.e. 1994–2010.

Survey biomass has decreased continuously, with one interruption in 2010, since reaching a high level in 2003, and overall measures of stock size, and most of the individual measures, are about as low as they have been in the last 20 years. The survey biomass is 27% less than in 2011, and 45% less than the temporary maximum of 2010. The low biomass is not uniform. The inshore area comprising Disko Bay and Vaigat has survey biomass well above its 20-year upper quartile point, while the offshore area collectively has its lowest biomass for 20 years. Owing to these divergent trajectories, the inshore area has a proportion of the survey biomass in 2012 which is the highest ever and nearly twice its upper quartile point.

Even within the offshore area as a whole, the trajectories have been different. The southernmost area had collapsed already in 2004–2007 and W3–4, around Store Hellefiskebanke, collapsed in 2011 and remained empty in 2012. The northern area and W1–2 off the mouth of Disko Bay 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, is somewhat above its median, but the 2012 estimate is largely due to a small number of large catches and is relatively imprecise.

The proportions in W1 and 2, W3 and 4, and Disko had been relatively constant over the preceding 18 years: the inter-quartile ranges were about one quarter of the medians. The deviations in 2012, especially for Disko (upward) and W3–4 (downward) are, by comparison with this earlier stability, especially remarkable. Comparing the 2012 rank with that for 2011 it is seen that the W3–4 proportion was already low last year, and that for Disko already high, but that the decrease in W1–2 is new.

The low level of survey biomass is more marked for males, near their 20-year minimum, than for females, which by number are close to the lower quartile. The age-2 index is the lowest so far.

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 made a large increase. The CPU index did not follow that jump but increased more slowly; but also it has not suffered the sustained decrease of the survey index from 2003 through 2012. Instead it has stayed close to its level of 2004 without major changes. In 2012 it decreased from its 2011 value, but only by 7½%. It is above its median of the previous 20 years, although below its upper quartile point, and still above a minimum reached in 2010. That CPU 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.

*Survey Measures of Stock Structure*

| Overall | Numbers ('000/survey ton) | | Biomass (%) | | | |
|---|---|---|---|---|---|---|
| | Age 2 | 14–16.5 mm[2] | Fishable, of survey | Fishable males, of survey | Females, of survey | Females, of fishable |
| 2012 | 10.9 | 31.7 | 91.1 | 51.7 | 39.4 | 43.2 |
| Upper quartile[1] | 24.7 | 26.1 | 93.9 | 58.4 | 36.9 | 39.8 |
| Median[1] | 18.1 | 25.3 | 92.8 | 57.0 | 35.4 | 38.2 |
| Lower quartile[1] | 12.1 | 22.9 | 90.7 | 54.9 | 34.4 | 37.0 |
| 2012 rank[1] | 4.0/19 | 6.3/7 | 6.0/20 | 1.7/20 | 19.1/20 | 19.3/20 |

[1] percentiles and 2012 rank generally referred to 20 preceding years 1992–2011;
[2] percentiles and 2012 rank referred to 7 preceding years 2005–2011 (for which data is available);

| Disko Bay and Vaigat | Numbers ('000/survey ton) | | Biomass (%) | | | |
|---|---|---|---|---|---|---|
| | Age 2 | 14–16.5 mm | Fishable, of survey | Fishable males, of survey | Females, of survey | Females, of fishable |
| 2012 | 14.4 | 31.8 | 90.7 | 56.5 | 34.2 | 37.7 |
| Upper quartile[1] | 38.1 | 46.8 | 91.6 | 56.1 | 36.2 | 41.0 |
| Median[1] | 28.2 | 32.9 | 89.5 | 51.5 | 33.4 | 39.2 |
| Lower quartile[1] | 15.5 | 30.4 | 86.1 | 49.7 | 32.2 | 37.6 |
| 2012 rank[1] | 5.2/19 | 3.5/7 | 14.7/20 | 6.1/7 | 5.0/7 | 2.6/7 |

| Offshore | Numbers ('000/survey ton) | | Biomass (%) | | | |
|---|---|---|---|---|---|---|
| | Age 2 | 14–16.5 mm | Fishable, of survey | Fishable males, of survey | Females, of survey | Females, of fishable |
| 2012 | 7.6 | 31.7 | 91.5 | 47.3 | 44.2 | 48.3 |
| Upper quartile[1] | 21.5 | 24.2 | 94.9 | 58.3 | 39.9 | 42.4 |
| Median[1] | 14.5 | 21.0 | 93.7 | 55.7 | 37.6 | 39.9 |
| Lower quartile[1] | 9.0 | 18.8 | 92.5 | 54.3 | 36.6 | 38.5 |
| 2012 rank[1] | 5.1/19 | 8.0/7 | 4.6/20 | 0.0/7 | 8.0/7 | 8.0/7 |

The overall stock structure in 2012 is marked by a high biomass proportion of females, both in the survey and in the fishable biomass, and males composing a low proportion of the fishable biomass. There are big differences between the stock structures offshore and inshore in Disko Bay and Vaigat, but some of these differences between their stock structures have tended to be maintained over time.

Over the most recent 19 years, the inshore has an evident tendency to have higher proportions of smaller shrimps. For the age-2 index, relative to survey biomass, the inshore quartile points have twice the value of the offshore. Quartiles of the distribution of the number of 14–16.5-mm shrimps are about half as big again inshore as offshore. In keeping with having fewer small shrimps, the female and fishable-male proportions of the survey biomass are both consistently larger offshore, but the female proportion of the fishable biomass appears to average about the same inshore as offshore.

In 2012, compared with other years, females offshore compose the highest proportion of the biomass, both survey and fishable, seen in the years for which we have data. Males constitute a very low proportion of both the survey and the fishable biomasses and the fishable biomass in total is a relatively low fraction of the survey biomass. However, it appears that offshore, numbers from 14 through 16.5 mm CPL, relative to survey biomass, are well above their upper quartile and the highest we have data for. These length classes represent short-term recruitment potential to the fishable stock. Thus, it appears that there is now a gap in the length distribution offshore in the fishable-male length classes, which is why the fishable biomass is both a low proportion of the survey biomass—relative to usual offshore values—and has a small fraction of males. This could mean that fishing offshore in the near future would be mostly on the spawning stock, recruitment to which would be limited by a scarcity of large males.

The stock structure in Disko Bay and Vaigat in 2012 is not the same as it is offshore and deviates from its standard pattern in different ways from the offshore. Relative to its past, the fishable biomass is a fairly high proportion of the survey biomass, not a low one, and has a high proportion of males, not females. This should mean good short-term prospects for recruitment to the spawning stock. But relative to survey biomass, the 14–16.5-mm length classes are, for the inshore, at an average level, not, as they are offshore, more numerous than usual.

Both inshore and offshore the number at age 2, relative to survey biomass, is a bit below its lower quartile, and higher than only 5 of 19 foregoing values.

We don't know what are the limits for any of these stock-structure parameters to conduce to a 'healthy' stock with good potential for maintaining itself. But 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; offshore, few fishable males to recruit to the spawning stock and, concomitantly, a high proportion of spawning females in the fishable biomass.

## 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', $v$ are normally, independently and identically distributed with mean 0 and variance $\sigma_v^2$ .

Input data series were shortened to 30 years on a trial basis in 2011 (Kingsley 2011), and the formulation with shorter series was retained as the main assessment model in 2012.

The model synthesised information from input priors (Hvingel and Kingsley 2002) (Fig. 3) and the following data: a 24-year (1988–2011) series of a survey estimate of the 'fishable' (i.e. at least 17 mm CL) stock biomass index (Wieland *et al*., 2004; Kingsley et al. 2012); CPUE indices spanning, among them, 1983 through 2012 (Kingsley 2008a; Hammeken Arboe 2012); and unified into a single series by a separate model (Hvingel and Kingsley 2002); a 30-year series of catches by the fishery with corrections for past overpacking (Hvingel 2004; Hammeken Arboe 2012); a 30-year series of 'effective' cod biomass estimates (i.e. allowance made for the imperfect overlap of the two stocks) (Hvingel and Kingsley 2002; Wieland and Storr-Paulsen 2004; Retzel 2012); 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. 1).

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 much 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 2012).

Catch data were updated from available sources, including logbooks, STATLANT 21A, and quota reports from Greenland and Canadian sources (Kingsley and Hammeken Arboe 2012). 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 110 000 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, but it was not possible to find that there had been any fishing in Canadian SFA1 in 2012.

The estimation of total catch for the current year tends to be important in short-term forecasting of stock status in the next, and projected current-year catches have hitherto been assumed free from uncertainty. The model was modified in 2012 to add the 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 series, 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 2012.

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 (Retzel 2012).

The data link functions for the biomass indices were:

$$CPUE_t = q_c P_t \exp(\omega) \ , \text{ for } \ t \in (t_1, t_2, ,..,..N-1), \ \ CPUE_N = q_c P_N \exp(1.5\omega)$$

$$surv_t = q_s B_{MSY} P_t \exp(\kappa) \ , \text{ for } \ t \in (2,3,..,..N), \ \ surv_1 = q_s B_{MSY} P_1 \exp(1.5\kappa)$$

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

where $O_t$ is total consumption in year *t*, $V_{max}$ is the maximum consumption of prey per predator (kg·kg$^{-1}$) reached at large prey biomass, and $P_{50\%}$ is the prey biomass index at which the consumption is half of the maximum. $cod_t$ is biomass of cod in year *t*. The error term, $\tau$ , is normally, independently and identically distributed with mean 0 and variance $\sigma_\tau^2$ . The predation estimates from Grunwald (1998) were associated with a separate short series of cod biomass estimates that she had used in her calculations, but were related by the same predation function and the same parameter values[1].

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:

[1] 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 had not been retained.

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

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 18 000 000, every 300$^{th}$ being retained. Of the resulting 60 000 iterations every 4$^{th}$ was used in the final calculations, giving sample sizes of 15 000.

### Results, Model Performance

The model fitted fairly well to the observed data series (Fig. 2).

Some parameter pairs were highly correlated (Table 3). The major parameters of stock size and productivity—*K* and *MSY*—were positively correlated. Both were negatively correlated with $Z_{msy}$, but as would be expected, *K* had a much larger negative correlation with *Z* than *MSY* did. Since the *MSY* was estimated with only a moderate uncertainty, the *MSY* ratio ($Z_{msy} = MSY//B_{msy}$) was negatively correlated with carrying capacity *K*, but it was also negatively correlated with MSY itself, which was unexpected.

The median estimate of the *MSY* was 132 Kt, with quartiles at 108 and 160 Kt; the estimated mode is at 118 Kt.

### Results of the Quantitative Assessment

The model estimates that the stock decreased in 2011, given the great decrease in the survey estimate of fishable biomass as well as the smaller drop in fishery CPUE between 2011 and 2012. The modelled decrease is from about 120% of $B_{msy}$ to $B_{msy}$, a drop of about 16%. The catches recorded in 2011 and projected for 2012 are estimated to have been unsustainable with total mortality above the MSY level.

The median *MSY* of 132 000 t is uncertain; the e.c.v. of the mean is 48% and the relative interquartile range 39%. The distribution of the estimate is skewed and the most likely value for the MSY is estimated at 118 000 t. This implies that all values between 132 000 and 118 000 t, as well as some values less than 118 000 t, are more likely than 132 000 t.

The stock is projected to be very close to $B_{msy}$ at the end of 2012, and the risk of its going below this level is high at all catch levels considered. Risks[2] associated with six possible catch levels for 2013, with an 'effective' cod stock at 20 000 tons[3], are estimated to be:

| 20 000 t cod | Catch option ('000 tons) | | | | | |
|---|---|---|---|---|---|---|
| Risk of: | 75 | 80 | 85 | 90 | 95 | 100 |
| falling below $B_{msy}$ end 2013 (%) | 47.3 | 47.5 | 48.6 | 48.7 | 49.1 | 49.8 |
| falling below $B_{lim}$ end 2013 (%) | 1.2 | 1.3 | 1.4 | 1.4 | 1.4 | 1.5 |
| exceeding $Z_{msy}$ during 2013 (%) | 28.9 | 32.1 | 36.2 | 40.4 | 44.4 | 48.5 |
| exceeding $Z_{msy}$ during 2014 (%) | 28.7 | 31.7 | 36.0 | 39.9 | 44.0 | 48.0 |

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

[3] the estimate for 2012 is 22 700 tons.

and with an 'effective' cod stock at 25 000 t:

| 25 000 t cod | Catch option ('000 tons) | | | | | |
|---|---|---|---|---|---|---|
| Risk of: | 75 | 80 | 85 | 90 | 95 | 100 |
| falling below $B_{msy}$ end 2013 (%) | 47.6 | 47.8 | 48.7 | 48.9 | 49.8 | 50.9 |
| falling below $B_{lim}$ end 2013 (%) | 1.4 | 1.4 | 1.4 | 1.4 | 1.5 | 1.6 |
| exceeding $Z_{msy}$ during 2013 (%) | 30.9 | 34.1 | 38.4 | 43.0 | 47.2 | 50.7 |
| exceeding $Z_{msy}$ during 2014 (%) | 30.8 | 34.4 | 38.2 | 42.5 | 46.7 | 50.9 |

Predation by cod can be significant (Fig. 2) 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. The effect of a cod stock widely distributed over the shrimp-fishing area off West Greenland waters might be reasonably well modelled by the process used here. 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.

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 100 000 tons (Figs 6–8).

*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, 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 2012 it appears that this contraction is continuing (Fig. 10, Fig. 11).

The most recent survey result estimates a fishable biomass that is at 33% of its 2003 peak and 13% below the series mean (Table 1). Survey estimates of numbers at age 2 have been low for the most recent 5 years and in both 2011 and 2012 have decreased, so recruitment prospects still appear to be poor (Fig. 9).

The ratio of catch to survey fishable biomass declined fairly steadily from 1991 to 2003 as the catches, although steadily increasing, never kept up with the more rapidly increasing survey biomass. During a short period of high catches in 2004–2006 this ratio stayed below its mean level, although increasing as survey biomass declined. Since 2007 it has been above average as catches have not been brought down enough to match the lowness of recent biomass estimates.

The present assessment based on the existing modelling approach estimates a stock very close to $B_{msy}$, although reduced by several years of large catches, and large carrying capacity. CPUE remains relatively high, even after the high catches of the past decade, but may now be starting to decrease. The fishery is now more concentrated than in 1992–2003 (Fig. 10), 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 2005 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 5) and are low.

## Conclusions

The stock is at a low level and recruitment prospects in the medium term as indicated by numbers at age 2 continue to be poor. A quantitative assessment indicates that catches below 85 Kt would keep the risk of exceeding $Z_{msy}$ below 40%.

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**Table 1.** *Pandalus borealis* in West Greenland: input data series for stock-dynamic assessment model 1983–2012.

| | Effective cod biomass[4] (Kt) | Catch (Kt) | Provisional catch (Kt) | Survey index of fishable biomass (Kt) | Predation estimate[5] (Kt) | Cod-stock estimate[6] (Kt) | CPUE (1990=1) |
|---|---|---|---|---|---|---|---|
| 1983 | 61.7 | 56.2 | | | | | 1.376 |
| 1984 | 37.8 | 52.8 | | | | | 1.289 |
| 1985 | 25 | 66.2 | | | | | 1.381 |
| 1986 | 19.6 | 76.9 | | | | | 1.438 |
| 1987 | 282.1 | 77.9 | | | | | 1.656 |
| 1988 | 297.3 | 73.6 | | 223.2 | | | 1.197 |
| 1989 | 149.1 | 80.7 | | 209.0 | 213.7 | 470.9 | 1.040 |
| 1990 | 12.2 | 84.0 | | 207.0 | 27.8 | 184.1 | 1.000 |
| 1991 | 2.1 | 91.5 | | 146.0 | 2.7 | 19.8 | 1.032 |
| 1992 | 0.4 | 105.5 | | 194.2 | 0.8 | 2.9 | 1.138 |
| 1993 | 0.3 | 91.0 | | 216.5 | | | 1.096 |
| 1994 | 0.1 | 92.8 | | 223.1 | | | 1.094 |
| 1995 | 0.1 | 87.4 | | 183.2 | | | 1.213 |
| 1996 | 0.1 | 84.1 | | 192.1 | | | 1.272 |
| 1997 | 0.1 | 78.1 | | 167.1 | | | 1.233 |
| 1998 | 0.1 | 80.5 | | 244.3 | | | 1.419 |
| 1999 | 0.1 | 92.2 | | 237.3 | | | 1.595 |
| 2000 | 0.4 | 98.0 | | 280.3 | | | 1.751 |
| 2001 | 1.2 | 102.9 | | 280.5 | | | 1.673 |
| 2002 | 0.7 | 135.2 | | 369.5 | | | 1.992 |
| 2003 | 1.0 | 130.2 | | 548.3 | | | 2.129 |
| 2004 | 1.7 | 149.3 | | 528.3 | | | 2.362 |
| 2005 | 2 | 156.9 | 140.5 | 494.2* | | | 2.465 |
| 2006 | 35.7 | 157.3 | 140.2 | 451.0* | | | 2.413 |
| 2007 | 24 | 144.2 | 135.2 | 336.1 | | | 2.480 |
| 2008 | 6.4 | 153.9 | 131.6 | 262.6 | | | 2.588 |
| 2009 | 2.4 | 135.5 | 108.8 | 255.1 | | | 2.223 |
| 2010 | 6.5 | 134.0 | 138.5 | 318.7 | | | 2.129 |
| 2011 | 25.5 | 124.0 | 128.0 | 247.8# | | | 2.401 |
| 2012 | 22.7 | — | 110.0 | 178.7# | | | 2.223 |

* 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.

**Table 2.** *Pandalus borealis* in West Greenland: summary of estimates of selected parameters from Bayesian fitting of a surplus production model, 2012.

| | Mean | S.D. | 25% | Median | 75% | Est. mode | Median (2011) |
|---|---|---|---|---|---|---|---|
| *Max. sustainable yield (Kt)* | 139 | 67 | 108 | 132 | 160 | 118 | 136 |
| *$B/B_{msy}$, end current yr (proj.)* | 1.02 | 0.29 | 0.83 | 1.00 | 1.19 | 0.95 | 1.08 |
| *Biom. risk, end current yr (%)* | 51 | 50 | 0.0 | 100 | 100 | — | — |
| *$Z/Z_{msy}$, current yr (proj.)* | 2.86 | 26.82 | 0.77 | 1.08 | 1.51 | -2.48 | 1.09 |
| *Carrying capacity* | 3776 | 3418 | 1861 | 2767 | 4427 | 749 | 2661 |
| *M.S.Y. ratio (%)* | 10.7 | 6.3 | 6.0 | 10.1 | 14.6 | 8.9 | 10.7 |
| *Survey catchability (%)* | 20.5 | 13.7 | 10.3 | 17.4 | 27.4 | 11.2 | 20.3 |

[4] Wieland and Storr-Paulsen (2004) updated by Sünksen (2009) and Retzel (2011 and 2012).
[5] Grunwald (1998).
[6] the estimate of cod stock biomass associated with Grunwald's estimate of predation.

| | Mean | S.D. | 25% | Median | 75% | Est. mode | Median (2011) |
|---|---|---|---|---|---|---|---|
| *CPUE catchability* | 1.3 | 0.8 | 0.6 | 1.1 | 1.7 | 0.7 | 1.2 |
| $P_{50\%}$ | 7.3 | 4.6 | 4.3 | 6.3 | 9.1 | 4.2 | 4.9 |
| $O_{max}$ | 3.0 | 0.3 | 2.8 | 3.0 | 3.2 | 3.0 | 3.0 |
| *CV of process (%)* | 12.2 | 2.9 | 10.2 | 11.9 | 14.0 | 11.3 | 11.0 |
| *CV of survey fit (%)* | 14.5 | 2.0 | 13.2 | 14.5 | 15.8 | 14.4 | 13.1 |
| *CV of CPUE fit (%)* | 17.2 | 2.5 | 15.5 | 16.9 | 18.6 | 16.3 | 14.9 |
| *CV of predation fit (%)* | 123.2 | 82.8 | 57.3 | 106.7 | 174.6 | 73.7 | 93.7 |
| *Start biomass ratio* | 0.91 | 0.17 | 0.79 | 0.90 | 1.02 | 0.86 | 0.92 |

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

| | *Start biom. ratio* | *CV pred* | *CV cpu* | *CV s* | *CV proc* | *Omax* | *P50%* | *Qc* | *Qs* | *MSY ratio* | *K* |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *Max. sustainable yield* | | 17 | | | -7 | | | -14 | -14 | 23 | 21 |
| *Carrying capacity* | 16 | 26 | | | 6 | | 12 | -60 | -59 | -58 | |
| *Max. sustainable yield ratio (%)* | -27 | -22 | | | -10 | | -20 | 85 | 84 | | |
| *Survey catchability (%)* | -42 | -29 | | | -9 | | -31 | 100 | | | |
| *CPUE catchability* | -43 | -29 | | | -9 | | -31 | | | | |
| *P50%* | 51 | 16 | | | 14 | 17 | | | | | |
| *Omax* | | | | | | | | | | | |
| *CV of process (%)* | 17 | | 18 | -17 | | | | | | | |
| *CV of survey fit (%)* | | | 29 | | | | | | | | |
| *CV of CPUE fit (%)* | | | | | | | | | | | |
| *CV of predation fit (%)* | 11 | | | | | | | | | | |

[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 20 or 25 Kt.

| Catch | Prob. biomass < $B_{msy}$ (%) | | Prob. biomass< $B_{lim}$ (%) | | Prob. mort > $Z_{msy}$ (%) | |
|---|---|---|---|---|---|---|
| (Kt/yr) | 20 Kt | 25 Kt | 20 Kt | 25 Kt | 20 Kt | 25 Kt |
| 70 | 36.7 | 37.9 | 3.6 | 3.9 | 25.4 | 28.2 |
| 75 | 38.8 | 40.3 | 3.7 | 4.1 | 28.2 | 31.4 |
| 80 | 40.5 | 42.1 | 3.6 | 4.4 | 31.9 | 34.6 |
| 85 | 43.0 | 43.7 | 4.2 | 4.6 | 35.8 | 38.3 |
| 90 | 44.6 | 46.2 | 4.6 | 4.8 | 40.2 | 42.3 |

[*] limit biomass is 30% of $B_{msy}$

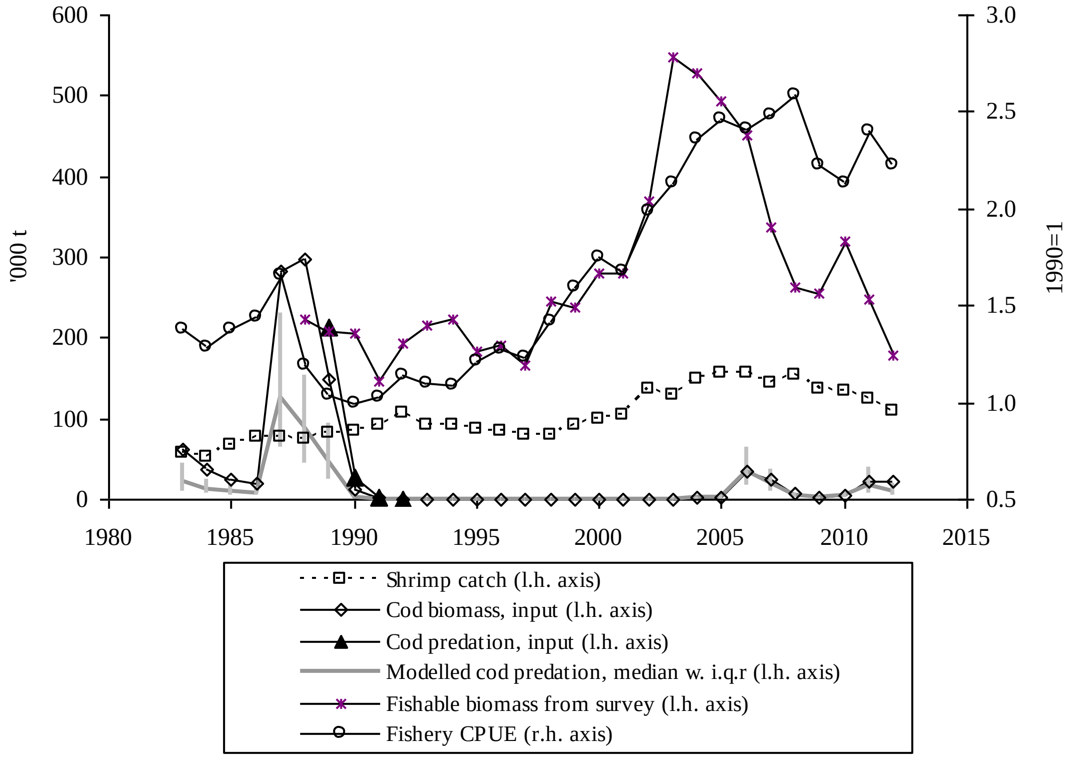


**Fig. 1.** *Pandalus borealis* in West Greenland: data series providing information for the assessment model, and cod predation estimated by the model.

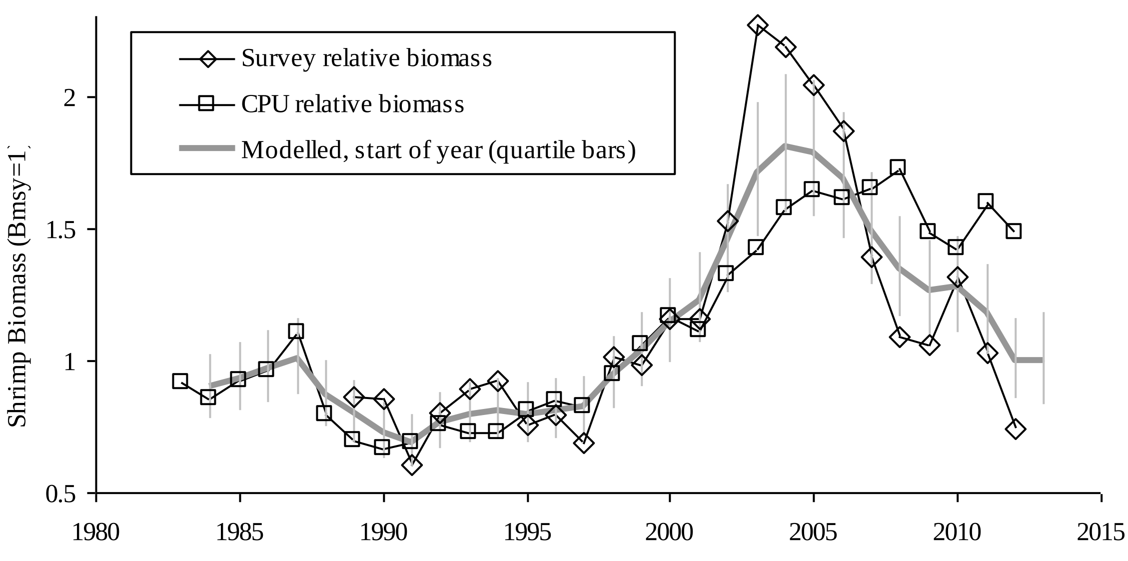


**Fig. 2.** *Pandalus borealis* in West Greenland: modelled shrimp standing stock fitted to survey and CPUE indices, 1983–2012.

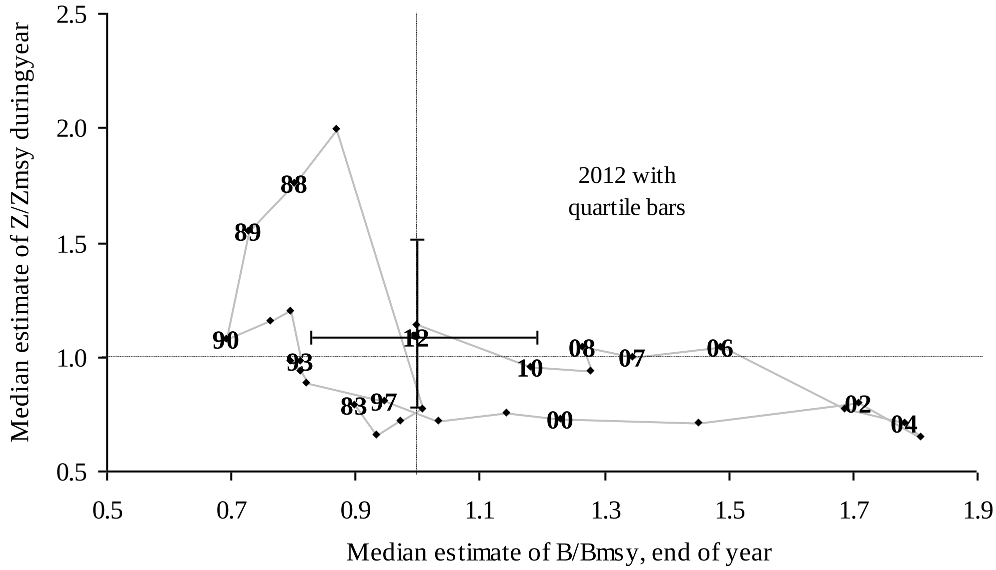


**Fig. 3.** *Pandalus borealis* in West Greenland: median estimates of biomass ratio ($B/B_{msy}$) and mortality ratio ($Z/Z_{msy}$) 1983–2012.

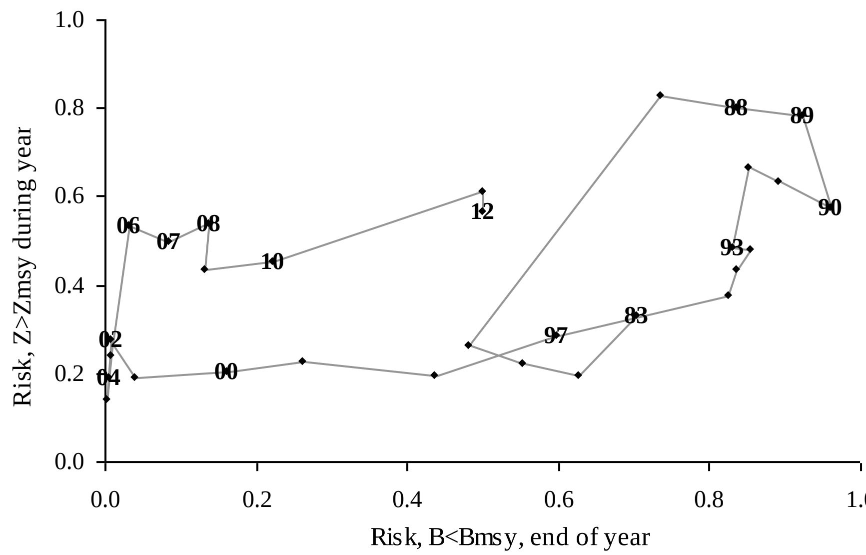


**Fig. 4.** *Pandalus borealis* in West Greenland: annual likelihood that biomass has been below $B_{msy}$ and that mortality caused by fishing and cod predation has been above $Z_{msy}$ 1983–2011.

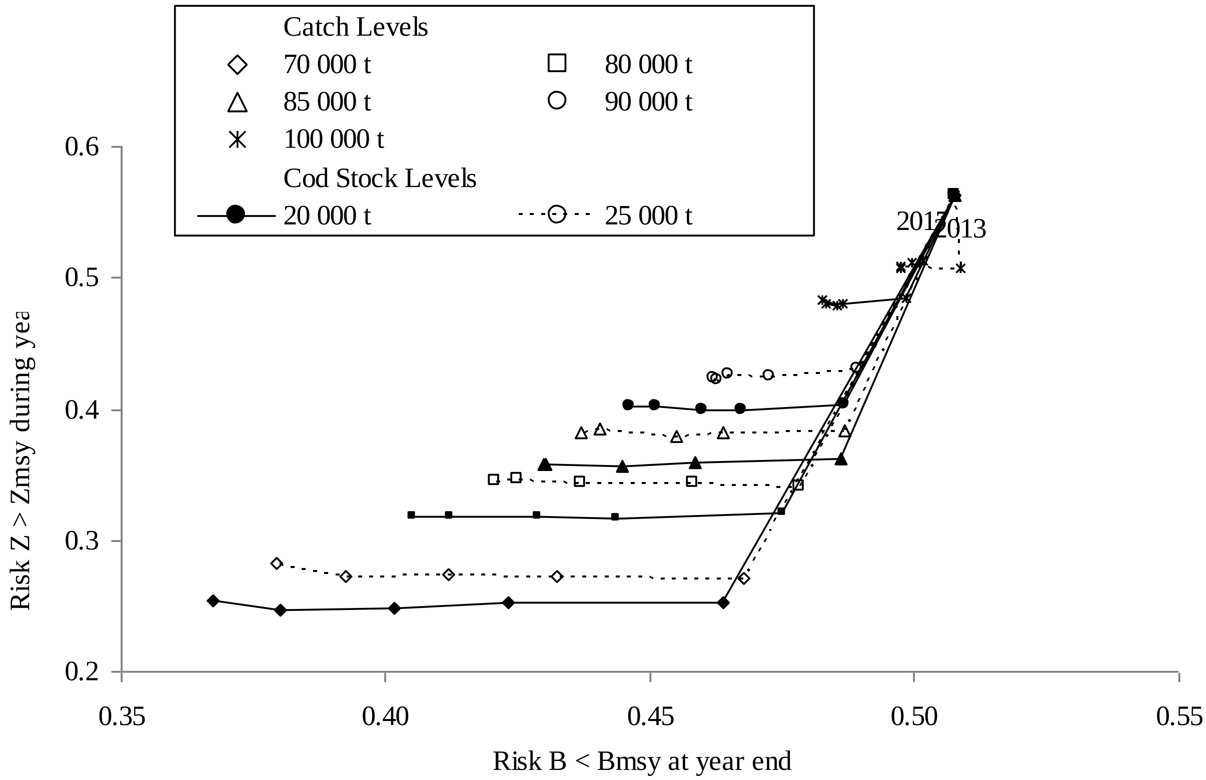


**Fig. 6.** *Pandalus borealis* in West Greenland: joint 5-year plot 2012–17 of the risks of transgressing $B_{msy}$ and $Z_{msy}$ at catch levels 70–100 Kt/yr; with effective cod biomass 20 and 25 Kt.

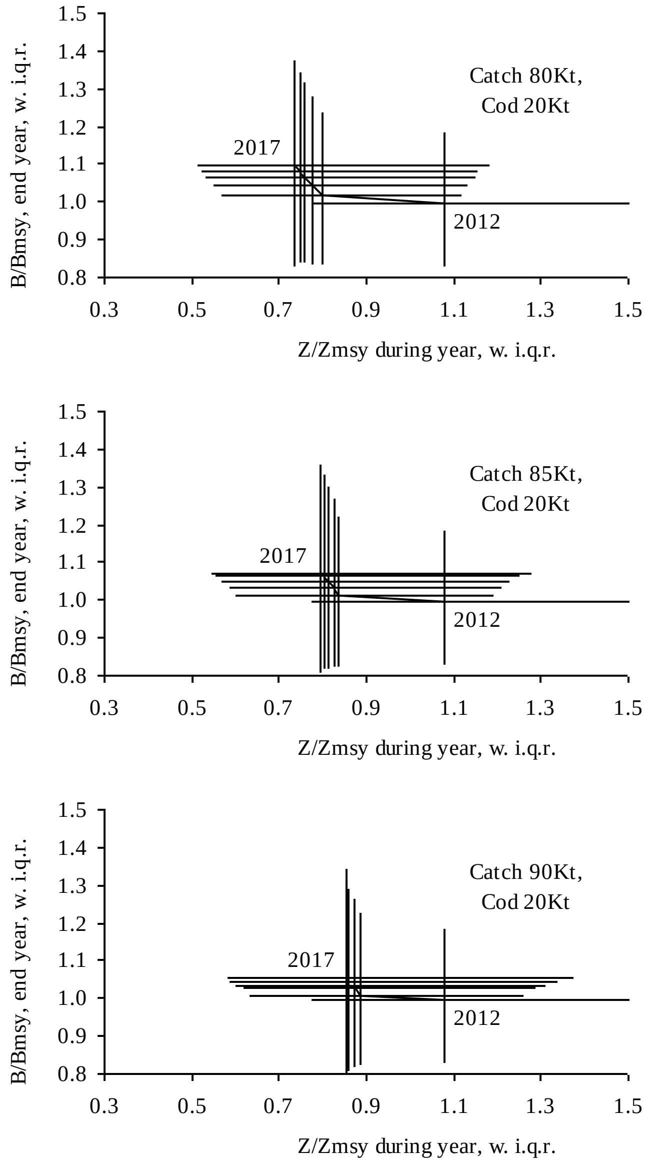


**Fig. 7.** *Pandalus borealis* in West Greenland: projections of stock development for 2013–2017 with effective cod biomass assumed at 20 000 t: median estimates with quartile error bars.

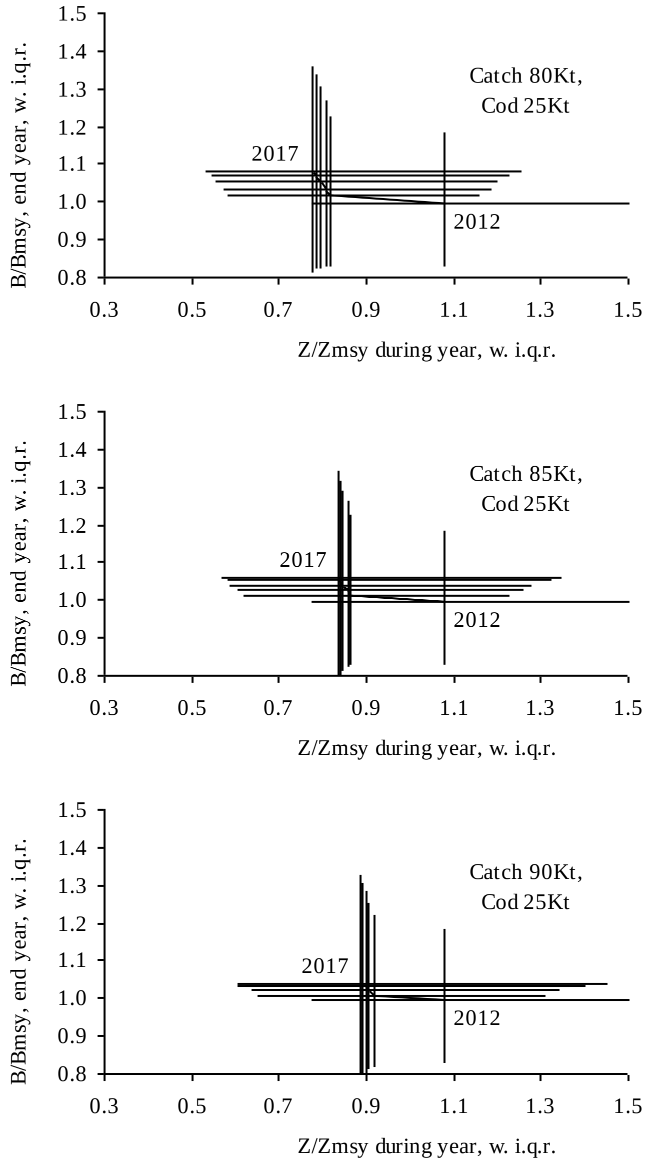


**Fig. 8.** *Pandalus borealis* in West Greenland: projections of stock development for 2013–2017 with effective cod biomass assumed at 25 000 t: median estimates with quartile error bars.

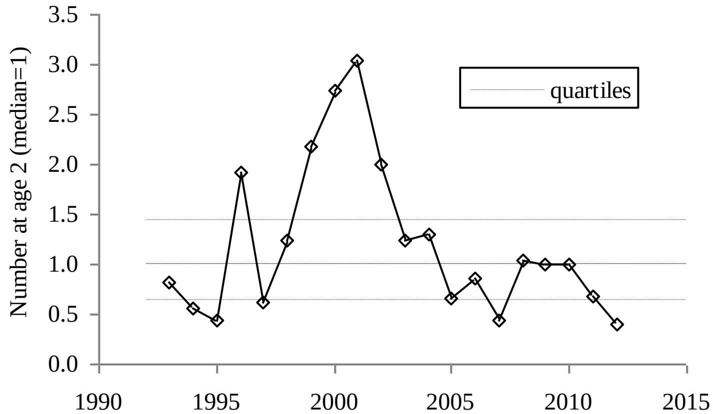


**Fig. 9.** *Pandalus borealis* in West Greenland: number at age 2 from research trawl survey, 1993–2012.

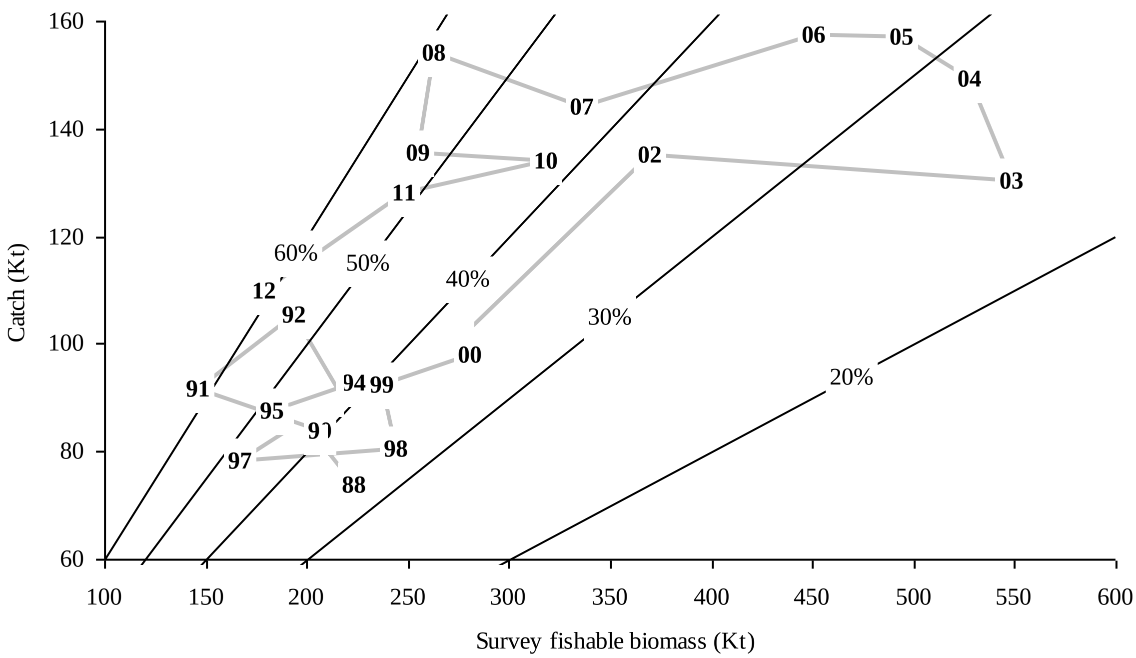


**Fig. 10.** *Pandalus borealis* in West Greenland: catch, fishable biomass and exploitation index, 1988–2012.

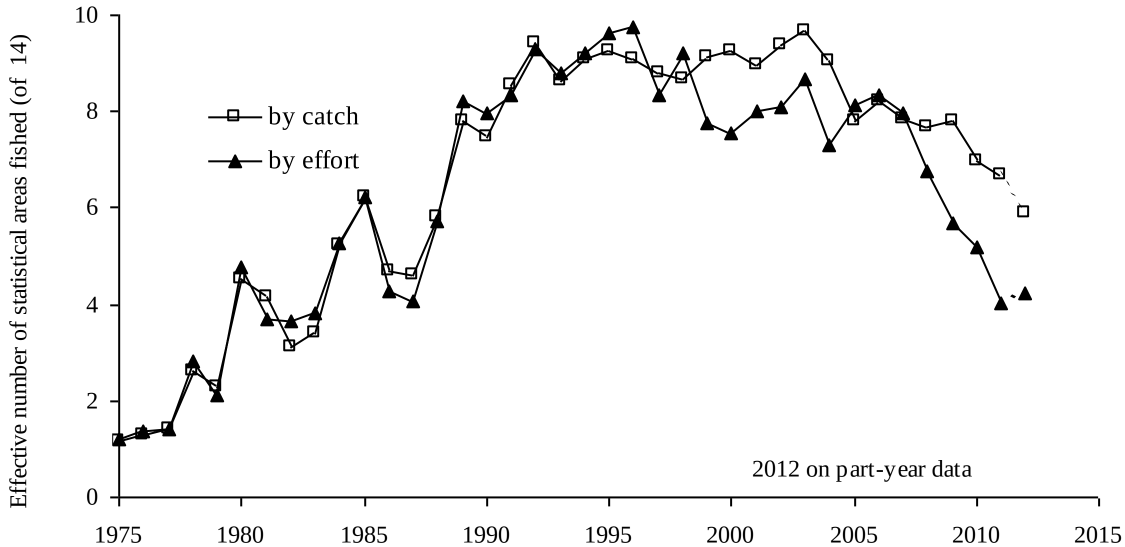


**Fig. 11.** *Pandalus borealis* in West Greenland: indices of the breadth of distribution of the Greenlandic fishery among 14 statistical areas, from logbook records, 1975–2012.

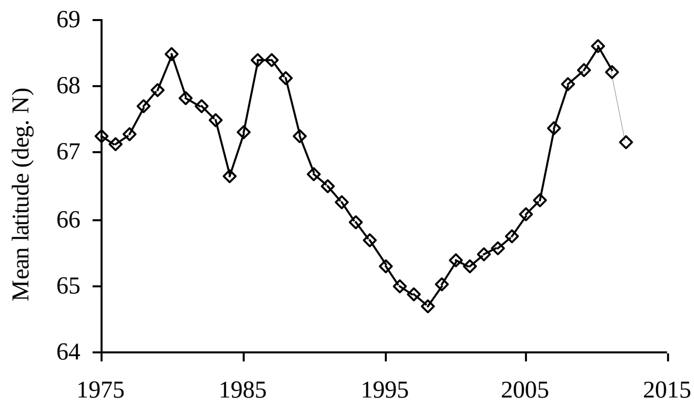


**Figure 12.** *Pandalus borealis* in West Greenland: mean latitude by weight of the logbook-recorded catch in the Greenland fishery, 1975–2012.

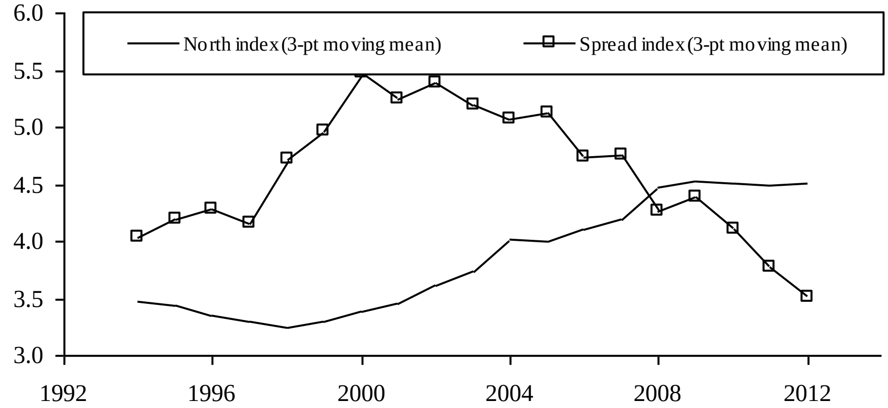


**Fig. 13.** *Pandalus borealis* in West Greenland: indices of distribution of the survey biomass, 1994–2012 (3-point moving means.)

Appendix to the assessment.

The Greenland shrimp fishery has applied to the Marine Stewardship Council for certification. The assessment report on the fishery placed conditions on, *inter alia*, verifying that a harvest control rule was implemented and that it worked effectively to maintain the stock in a safe zone. A management plan for the stock produced by the Greenland Ministry of Fisheries and Agriculture in 2010 included the following harvest control rule:

'harvest control rules are divided into two scenarios:

> 'a) when the stock has shown low rates of recruitment for several years (three years or more) and when the stock's distribution area is reduced (index from survey < 4.5) and,
> 'b) when the stock has shown high rates of recruitment (> two years) and when the stock's distribution area is increased (index from survey > 4.5).

'It has been decided that the following indicators will apply:

> '1. $B_{msy}$: The probability that the biomass < $B_{msy}$ must not exceed 20%. Applies to both scenarios.
> '2. $B_{lim}$: The probability that B< $B_{lim}$ must not exceed 1%. Applies to both scenarios.
> '3. $Z_{msy}$:
> ' 'a) The probability that Z exceeds $Z_{msy}$ must not exceed 10% . Applies in the event of low recruitment rate and small distribution area.
> 'b) The probability that Z exceeds $Z_{msy}$ must not exceed 15%. Applies in the event of high recruitment rate and large distribution area.'

These rules had the foreseeable problems that they do not specify what should be done if the recruitment rate and the distribution area send conflicting signals, and that 'high' and 'low' recruitment rate are not specified. A less foreseeable problem is that biomass, and biomass risk (the probability that the biomass < $B_{msy}$) are not susceptible to being controlled with immediate effect by setting TACs or catch rates—they are as estimated by the assessment and can only be improved, slowly, by the natural growth of the stock. Moreover, the risk levels specified appear at first sight to be excessively conservative and maintaining such low risk levels would probably, under the stock-production model we use, entail keeping the stock close to carrying capacity and in an unproductive zone of stock dynamics.

An alternative that is more practical in application is to set catches to achieve, in the short term, a tolerable level of mortality risk, and one that will in the longer term act to keep the biomass above $B_{msy}$ and the biomass risk below 50%. The level of mortality risk that can be tolerated can be set to respond to the present state of the stock as expressed by the present level of biomass risk. When biomass risk is high—i.e. biomass is low—a lower level of mortality risk could be tolerated than when biomass is high and biomass risk is low; in that case, higher mortality risk could be tolerated.

The following example of a set of harvest control rules considers three divisions of biomass risk: less than 35%; between 35% and 65%; and above 65%. When biomass risk is low, mortality risk can be 45%, which implies fishing at an estimated mortality a little less than $Z_{msy}$. When biomass risk is moderate—i.e. it is estimated that the stock is close to $B_{msy}$ on one side or the other—mortality risk can be no greater than 40%. When biomass risk is high, mortality risk must be even lower, below 35%. It would be possible to adjust allowable mortality risk according to other factors such as recruitment forecasts, provided they were adequately specified. This has not been included in this example set.

An example set of harvest control rules (HCR).

1. The basis for TAC setting is the quantitative stock assessment approved and accepted by NAFO Scientific Council;

2. Advice on total TAC is formulated so that total mortality, including estimated predation, shall not exceed the following limits; in estimating predation pressure, NAFO SC shall use the best available information on the size and trend of predator biomass;

3. NAFO SC may advise catches less than the following limits if, in its opinion, special circumstances or condition of the stock, not fully captured by the quantitative model in use, justify doing so;

4. If it is estimated that the biomass risk (likelihood that the fishable biomass (FB) will be below its MSY level (Bmsy) at the end of the current year) is greater than 65%, then total TAC is to be advised so that the mortality risk (likelihood that total mortality exceeds the MSY rate (Zmsy)) is not greater than 35% in either of the next two years;

5. If it is estimated that the biomass risk is less than 35%, then total TAC is to be advised so that the mortality risk is not greater than 45% in either of the next two years;

6. If it is estimated that the biomass risk is between 35% and 65%, then total TAC is to be advised so that the mortality risk is not greater than 40% in either of the next two years;

7. The total TAC set by Greenland will comprise the Greenland quotas, contractual obligations to other nations and a set-aside for the Canadian fishery on this stock in the Canadian SFA1;

8. The total TAC set by Greenland may be higher than that advised by SC, only in such degree as suffices to avoid year-on-year reduction of the quotas available to the Greenland fleets greater than 12,5%;

9. Notwithstanding any of the foregoing, TAC shall not be advised or enacted such that FB would be brought below Blim (30% of Bmsy) with more than 5% probability in any year if the catch were maintained for 5 years;

These catch control rules were motivated by the following proposal for a harvest strategy:

Harvest Strategy

| | Strategic Element | Notes |
|---|---|---|
| 1) | The principal objective is to maintain the stock in a condition in which it can be most profitably fished (i.e. largest net revenue from the fishery) | a) this is an economic objective; there are no social, environmental or ecological strategic objectives; but<br>b) with a principal objective that seeks to *maintain* the stock, sustainability is implicit and need not be separately specified |
| 2) | As a consequence of 1): harvest control rules should maintain the stock with high probability ABOVE the MSY level | a) HCR will prescribe catch rates and levels according to estimated stock status, as the basis for NAFO SC advice<br>b) NAFO SC can depart from the HCR under special circumstances. |
| 3) | The secondary objective is to avoid sudden large changes in TAC | a) this is a social and economic objective and lies outwith the ambit of NAFO SC concerns;<br>b) ONLY to meet this objective, the Government can deviate from following the NAFO advice;<br>c) HCR can specify how big a change in TAC can be tolerated. |
| 4) | Because of 3), and keeping 1) in view, the HCR of 2) have to be more conservative than they would be if 3) were not present | If you can’t make sharp turns, don’t drive along the edge of the cliff. |