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A Provisional Assessment of the Shrimp Stock off West Greenland in 2011

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 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.

The standard formulation of the model is free to estimate uncertainties of stock-dynamic and predation processes and with biomass indices. It has fitted a biomass trajectory closely to the CPUE series and not closely to the survey series, being unable to fit the large excursions of the survey series to its simple stock-recruitment expression. Since CPUE has been at high levels in recent years, in spite of high catches, this formulation of the model estimates that the stock has a high MSY, estimated in 2011 at 155 Kt (median estimate), and that it is in good condition, having been above B_{msy} and with total mortality below Z_{msy} since 2001.

This assessment of stock status is at variance with the trajectory of the survey index of fishable biomass, which in 2011 is 45% of a 2003 maximum. Furthermore, the model assigns to the survey index a level of uncertainty that is at variance with its high serial correlation, and in relying on CPUE as a linear index of biomass the model ignores a contraction of the fished area that has continued since 2003.

Therefore, another formulation of the assessment model was run in which the uncertainty of the survey index of biomass was constrained to be no greater than that assigned to the CPUE index. The resulting biomass trajectory lay between those of the CPUE series and the survey series. The uncertainties (error CVs) attached to the stock-production process and the CPUE index were increased from 8.4% to 11.1% and from 4.3% to 15%, while that of the survey series decreased from 23% to 13.1%. The MSY was estimated at 135 Kt (median estimate). The stock was estimated to be in worse condition, only 8% above Bmsy and decreasing since 2003–04, while mortality was estimated to have averaged 6% above Zmsy since 2006.

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. The shrimp stock 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. This document presents the results of applying this model to the updated available data series of shrimp catches and shrimp and cod biomass, to evaluate management options for the West Greenland shrimp stock. The model was modified to give more weight to the survey index of biomass and the results obtained from the modified model are given in an Appendix.

Short-term (1-year) and medium-term (three-year) projections of stock development were made for annual catches at 10 000-ton intervals from 80 000 to 130 000 tons under assumptions that the cod stock, allowance made for its overlap with shrimp distribution, increases from the levels of the recent years and either remains near the present level of 20 000 tons or increases to 30 000 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.

Stocks of Atlantic cod in West Greenland continue to fluctuate and there are no signs of a maintained increase in the stock, but the most recent survey results show a wider distribution, with more cod further north, than in other recent resurgences of the species. The stock-dynamic model used in the assessment allows for flexible and comprehensive consideration of possible developments of the cod stock, but the uncertain evolution of the stock in recent years gives little direction for investigations of its future development.

Estimation of Parameters

Parameters relevant for the assessment and management of the stock were estimated, based on 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 had high variances. 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}. 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[1]. The ‘process errors’, *v* are normally, independently and identically distributed with mean 0 and variance σ_ν^2.

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. 2011); 4 series of CPUE indices spanning, among them, 1976 through 2011 (Kingsley, 2008a; Kingsley, 2011); and unified into a single series by a separate model (Hvingel and Kingsley, 2002); a 57-year series of catches by the fishery with corrections for past overpacking (Hvingel, 2004; Kingsley 2011); a 57-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 2011); and a short series (4

[1] earlier analyses had estimated a stock-recruitment curve that was very close to logistic (*m* at 1.62, where the logistic would have 2, and the ratio of B_{msy} to *K* at 0.46, where the logistic would have 0.5), so recent, and this, years’ analyses have been carried out with *m* fixed at 2. This greatly speeds up model fitting.

years) of estimates of the shrimp biomass consumed by cod (Hvingel and Kingsley, 2002) based on stomach analyses (Grunwald, 1998) (Table 1; Fig. 1).

The four available 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 data from 2003 and earlier, 15% was added to reported catches of 'large' shrimp and 42% to catches of 'small' and 'unsorted' (Kingsley 2008a; Kingsley, 201q1).

Catch data were updated from available sources, including logbooks, STATLANT 21A, and quota reports from Greenland and Canadian sources (Kingsley 2011). The estimation of total catch for the current year tends to be important in short-term forecasting of stock status in the next. 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 124 000 t. Canadian catches had been zero in 2008 and 2009, but the fishery had taken about 5 500 t in 2010 and was active again in 2011. A projected catch of 2000 t in the Canadian EEZ was included.

Recent survey data, as well as the present distribution of fishing, showed that densities of shrimp in southerly areas have 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 2011).

The data link functions for the biomass indices were:

$$CPUE_t = q_c P_t \exp(\omega) \ \text{, for } \ t \in (t_1, t_2, ,..., ..N-1), \quad CPUE_N = q_c P_N \exp(1.5\omega)$$
$$surv_t = q_s B_{MSY} P_t \exp(\kappa) \ \text{, for } \ t \in (2,3,..,..N), \quad surv_1 = q_s B_{MSY} P_1 \exp(1.5\kappa)$$

The catch rate ($CPUE_{,t}$) and survey ($surv_t$) indices were scaled to the biomass index by catchability constants q_c and q_s. Their error terms, ω and κ, were assumed normally, independently and identically distributed with mean 0 and variance σ_c^2 and σ_κ^2. The standard error for 2011 for the CPUE index series was assumed to be 1.5 times the error for the rest of the series, as this data point is an interim one based on partial data for the year (the annual assessment takes place in November). The first year of the survey was also assigned a 50% larger error than the rest of the series to allow for a possible learning process.

Estimates of annual consumption rate of shrimp by cod were linked to the equations of shrimp stock dynamics through a Holling type III functional response function (Holling, 1959) and a series of cod biomass:

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

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, τ, is normally, independently and identically distributed with mean 0 and variance σ_τ^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[2].

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:

[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.

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

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 60 000 000, every 400th being retained. Of the resulting 100 000 iterations, every 10th was used in the final calculations giving sample sizes of 10 000.

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 (Kingsley, 2011). The assessment also refers to indices that summarise survey information on the distribution of the stock (Kingsley et al., 2011).

Data from the annual West Greenland trawl survey (Kingsley et al. 2011) on the size structure of the stock and of numbers in pre-recruitment year-classes of small shrimps gave information on the likely future development of the stock.

Results, Model Performance

The model fitted fairly well to the observed data series (Fig. 2); parameter estimates are similar to values estimated in previous assessments, but error CVs and uncertainties increased. Most of the error CV parameters were greater than in 2010; the increase in the CPUE index goes against the decrease in the survey result. The median estimate of the precision parameter for the research trawl survey index was equivalent to an error CV of about 23%. This is greater than the scatter of residuals in a first-order autoregressive model of the survey results. The precision parameter for the unified CPU series was about equivalent to an error CV of 4.3% and the process variation was about 8½%, indicating that the model could fit a biomass trajectory very closely to the CPUE series, even at the cost of a slightly worse fit to the stock-dynamic equation. The cod predation terms had error CVs considerably greater than in 2010.

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 155 Kt, with quartiles at 140 and 175 Kt; the estimated mode is at 134 Kt.

Assessment Results

The median *MSY* of 155 000 t is uncertain; the e.c.v. of the mean is 30% and the relative interquartile range 23%. The distribution of the estimate is highly skewed and the most likely value for the MSY is estimated at 134 000 t. This implies that all values between 155 000 and 134 000 t, as well as some values *less* than 134 000 t, are more likely than 155 000 t. However, the increase in the CPUE index and the concomitant increase in the modelled MSY induces the model to be more confident about the present state of the stock, and the median estimate of stock size at start of 2011 in this year's assessment was 25% above *MSYL* where in the 2010 assessment it had been projected at 15% above *MSYL*. This difference is only in small part due to the error in projecting 2010 catches at 138.5 Kt, 4.5 Kt over the realised 134 Kt.

The model estimated the yearly consumption of shrimp by cod to be relatively constant between about 30 and 100 000 tons all the way from 1957 to about 1983 (Fig. 3). The estimated consumption declined after 1960 as a result of a decline in cod abundance at West Greenland, but a short-lived resurgence of the cod stock in the late

1980s caused modelled consumption estimates to increase dramatically—median 210 000 t in 1987 and 97 000 t in 1988. The cod disappeared again at the beginning of the 1990s and estimates of consumption went to near zero (Fig. 4). In the most recent years occasional slight increases in cod abundance have been noted in research trawl surveys in West Greenland, but have not been maintained. The present assessment estimates that cod consumed only about 1500 tons of shrimp in 2004; median estimates of predation increased to about 31 000 t and 22 000 t in 2006 and 2007 owing again to an increase in survey estimates of cod. Cod stocks have continued to fluctuate with no clear pattern; in 2011 the effective cod biomass has increased again, in large part owing to a broadening of its distribution rather than an increase in nominal biomass.

From the late 1970s to the mid-80s the estimated trajectory of the median estimate of 'biomass-ratio' (B_t/B_{MSY}) plotted against 'mortality-ratio' (Z_t/Z_{MSY}) (Fig. 4) was stable in a region of biomass 0.6-0.9 times B_{MSY} and mortality 0.7 to 1.2 times Z_{MSY}. A brief return of high cod stocks in the late 1980s caused a short episode of high mortality, with a corresponding decrease in the stock biomass. A steep decline in CPUE was noted at this time. After the cod collapsed again the mortality decreased, and after the late 1990s the biomass increased. Median estimates of biomass were 1.29–1.31 times B_{MSY} at end of years 2004–07, since decreasing, while annual (median estimate) *Z*-ratio has been stable near 90%. Associated with an increase in the cod stock and high catches in 2005–06, mortality is modelled to have increased; future catches even at present levels, if accompanied by significant predation, are forecast to bring biomass ratio down (Fig. 4). The median estimate of the Z-ratio for 2011, with catches projected at 128 Kt, is 0.87, with a 31% risk that it exceeds 1.

The present assessment is more sanguine about the stock status than the 2010 assessment. The 2010 assessment projected that relative biomass (B/B_{msy}) at the end of that year would be 115%; in 2010 we estimate that it was only 125%. In 2010 we projected that year's removals at 92% of Z_{msy}, but in 2011 we estimate they were 87%. Catches in 2010 were 4 500 tons lower than our projection and projected catches for 2011 are lower again than the recorded catches in 2010. However, the modelled stock trajectory also reflects an increase in the effective cod stock. The present assessment expects the stock status at end 2011 (1.25, 0.88) to be the same as we now estimate that it was at the end of 2010 (1.24, 0.87).

The stock is now estimated above B_{msy}, the risk that it will fall below this level within the next year is not high. Risks[3] associated with five possible catch levels for 2011, with an 'effective' cod stock at 20 000 tons, are estimated to be:

20 000 t cod	Catch option ('000 tons)				
Risk (%), in 2012, of:	90	100	110	120	130
falling below B_{msy}	21	22	22	24	25
falling below B_{lim}	<1	<1	<1	<1	<1
exceeding Z_{msy}	4	8	14	22	32

and with an 'effective' cod stock at 30 000 t:

30 000 t cod	Catch option ('000 tons)				
Risk (%), in 2012, of:	90	100	110	120	130
falling below B_{msy}	21	23	24	25	26
falling below B_{lim}	<1	<1	<1	<1	<1
exceeding Z_{msy}	9	14	22	31	41

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

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

cod predation is bedevilled by the difficulty of foreseeing the evolution of the stock and complicated by uncertainty as to the overlap between 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.

3-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: 90 000, 100 000, 110 000, 120 000 and 130 000 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 2011 it appears that this contraction is continuing (Fig. 10, Fig. 11).

Survey indices show that the stock continued to contract until 2007 (Fig. 11; Ziemer et al. 2010). The most recent survey result estimates a fishable biomass that is at 45% of its 2003 peak and 13% below the series mean (Table 1). Survey estimates of numbers at age 2 have been at low levels for the last 5 years and in 2011 have decreased, so recruitment prospects appear still 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 still slightly over 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.

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Table 1. *Pandalus borealis* in West Greenland: input data series for stock-dynamic assessment model 1955–2011.

	Effective cod biomass[4]	Catch	Survey index of fishable biomass	Predation estimate[5]	Cod-stock estimate[6]	CPUE
1955	1919.1	6.1				
1956	1592.7	6.1				
1957	1392.9	6.1				
1958	1258.3	6.1				
1959	1212.6	6.1				
1960	1287.3	6.1				
1961	1263.1	6.1				
1962	1051.3	6.1				
1963	911.2	6.1				
1964	898.1	6.1				
1965	950.2	6.1				
1966	889.2	6.1				
1967	797.4	6.1				
1968	578.1	6.1				
1969	389.7	6.1				
1970	244.9	10.5				
1971	218.7	11.6				
1972	191.9	11.9				
1973	115.4	15.5				
1974	84.7	27.0				
1975	68.2	46.5				
1976	132.5	61.4				1.745
1977	144.5	51.6				1.569
1978	170.3	42.3				1.23
1979	145.6	42.8				1.109
1980	163.4	55.9				1.344
1981	110.4	53.8				1.266
1982	98.8	54.3				1.626
1983	61.7	56.2				1.427
1984	37.8	52.8				1.338
1985	25	66.2				1.437
1986	19.6	76.9				1.5
1987	282.1	77.9				1.681
1988	297.3	73.6	223.2			1.207
1989	149.1	80.7	209.0	213.7	470.9	1.053
1990	12.2	84.0	207.0	27.8	184.1	1
1991	2.1	91.5	146.0	2.7	19.8	1.041
1992	0.4	105.5	194.2	0.8	2.9	1.151
1993	0.3	91.0	216.5			1.109
1994	0.1	92.8	223.1			1.107
1995	0	87.4	183.2			1.225
1996	0.1	84.1	192.1			1.288
1997	0.1	78.1	167.1			1.249

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

	Effective cod biomass[4]	Catch	Survey index of fishable biomass	Predation estimate[5]	Cod-stock estimate[6]	CPUE
1998	0	80.5	244.3			1.444
1999	0.1	92.2	237.3			1.616
2000	0.4	98.0	280.3			1.774
2001	1.2	102.9	280.5			1.698
2002	0.7	135.2	369.5			2.019
2003	1	130.2	548.3			2.153
2004	1.7	149.3	528.3			2.376
2005	2	156.9	494.2*			2.478
2006	35.7	157.3	451.0*			2.432
2007	24	144.2	336.1			2.497
2008	6.4	153.9	262.6			2.605
2009	2.4	135.5	255.1			2.236
2010	4.4	134.0	318.7			2.142
2011	21.8	128.0	247.8#			2.575

* demographic analyses for 2005–2010 have 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).
# 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.

Table 2. *Pandalus borealis* in West Greenland: summary of estimates of selected parameters from Bayesian fitting of a surplus production model, 2011.

	Mean	S.D.	25%	Median	75%	Est. mode	Median (2010)
Max. sustainable yield	165	50	140	155	175	134	147
B/B_{msy}, end current year (proj.)	1.25	0.35	1.01	1.22	1.46	1.18	1.16
Z/Z_{msy}, current year (proj.)	0.90	0.90	0.69	0.87	1.04	0.81	0.92
Carrying capacity	2741	2800	1631	2034	2854	621	2123
Max. sustainable yield ratio (%)	14.9	4.7	11.9	15.2	18.1	15.6	13.9
Survey catchability (%)	31.8	14.2	21.6	31.0	41.0	29.5	28
CPUE catchability	2.0	0.9	1.3	1.9	2.5	1.9	1.6
$P_{50\%}$	4.3	2.7	2.6	3.7	5.2	2.6	4.1
O_{max}	3.0	0.31	2.8	3.0	3.2	3.0	3
CV of process (%)	8.4	2.4	6.7	8.4	10.1	8.4	8.9
CV of survey fit (%)	23.5	3.9	20.8	23.0	25.8	22.0	20.5
CV of CPUE fit (%)	4.4	1.6	3.2	4.3	5.5	4.0	3.6
CV of predation fit (%)	55.1	33.6	31.0	53.8	74.6	51.3	42.2
Start biomass ratio	0.92	0.19	0.78	0.90	1.04	0.86	0.9

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

	Start biom .ratio	*CV pred*	*CV s*	*CV cpu*	*CV proc*	*Omax*	*P50%*	*Qc*	*Qs*	*MSY ratio*	*K*
Max.sustainable yield	9.0	27.2					-15.0	-32.9	-32.7	-33.8	62.3
Carrying capacity	11.0	8.9			16.7			-52.2	-51.9	-63.8	
Max. sustainable yield ratio %	-14.9		-9.2		-26.0		-23.3	84.2	83.7		
Survey catchability (%)	-13.5				-36.7		-42.4	99.2			
CPUE catchability	-13.6				-36.9		-42.8				
$P_{50\%}$	5.6	-5.7			32.7	#N/A					
O_{max}											
CV of process (%)		-45.9	-28.7								
CV of survey fit (%)			-17.2								
CV of CPUE fit (%)											
CV of predation fit (%)	9.3										

[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 20 or 30 Kt.

Catch (Kt/yr)	Prob. biomass < B_{msy} (%)		Prob. biomass< B_{lim} (%)		Prob. mort > Z_{msy} (%)	
	20 Kt	30 Kt	20 Kt	30 Kt	20 Kt	30 Kt
90	12.0	14.2	0.2	0.2	3.1	7.5
100	14.2	19.5	0.2	0.4	6.0	13.4
110	19.0	24.2	0.2	0.4	12.7	23.4
120	23.8	30.1	0.2	0.4	23.6	36.2
130	29.0	36.4	0.3	0.4	37.1	49.2

* limit biomass is 30% of B_{msy}

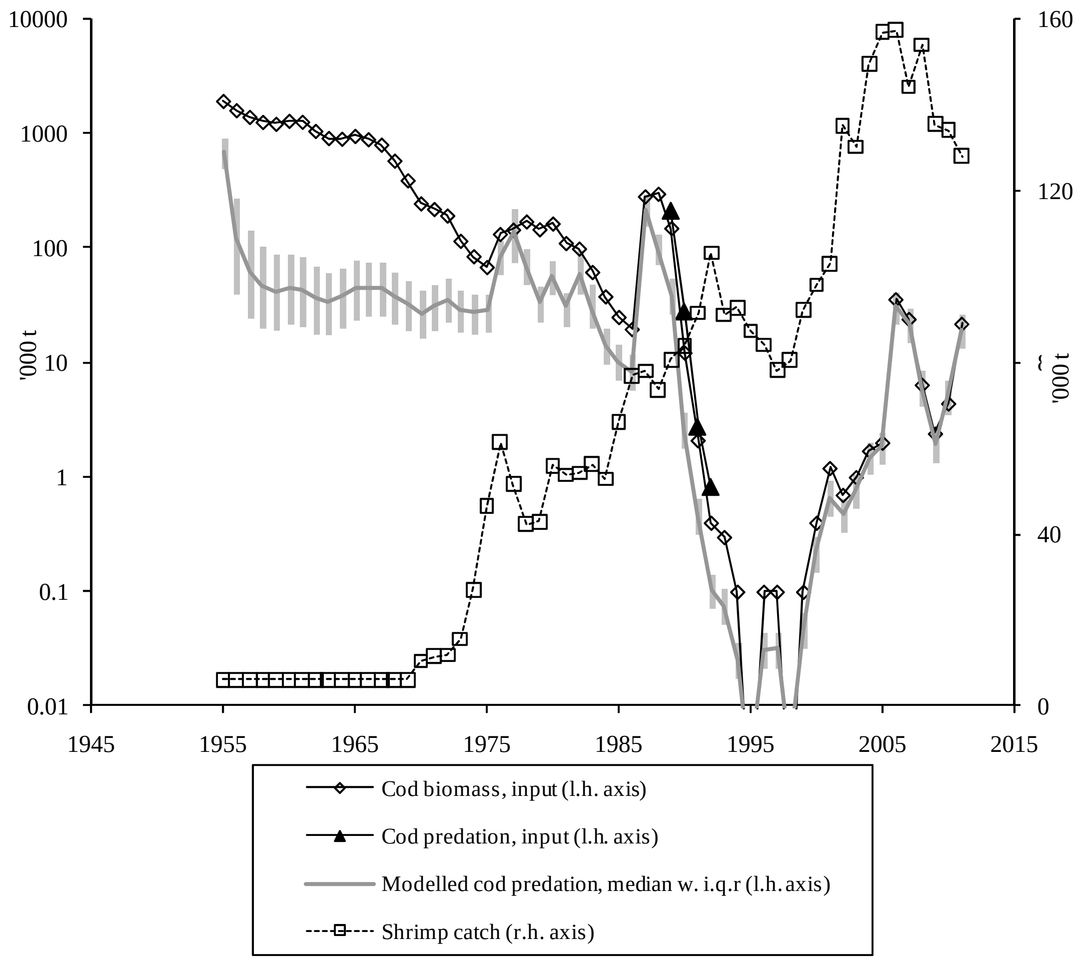


Fig. 1. *Pandalus borealis* in West Greenland: data series providing information for the assessment model, and cod predation estimated by the model.

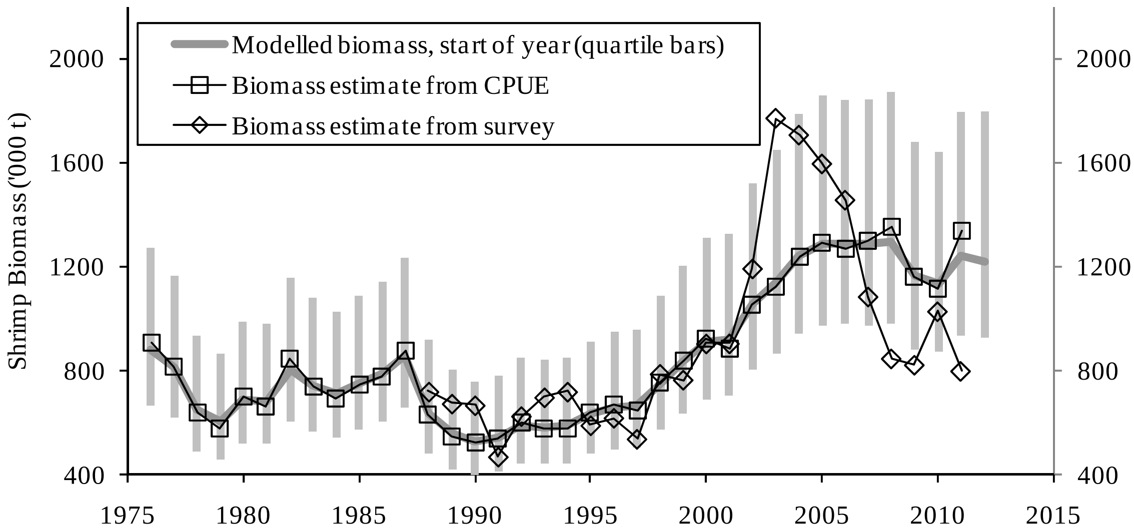


Fig. 2. *Pandalus borealis* in West Greenland: modelled shrimp standing stock fitted to survey and CPUE indices, 1976–2011.

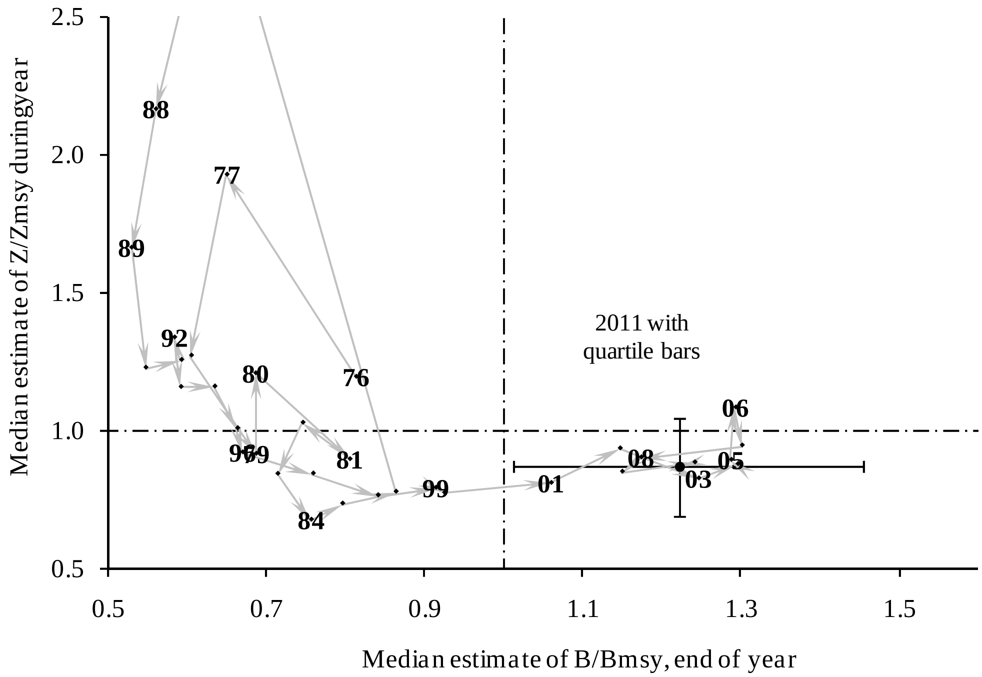


Fig. 3. *Pandalus borealis* in West Greenland: median estimates of biomass ratio (B/B_{msy}) and mortality ratio (Z/Z_{msy}) 1976–2011.

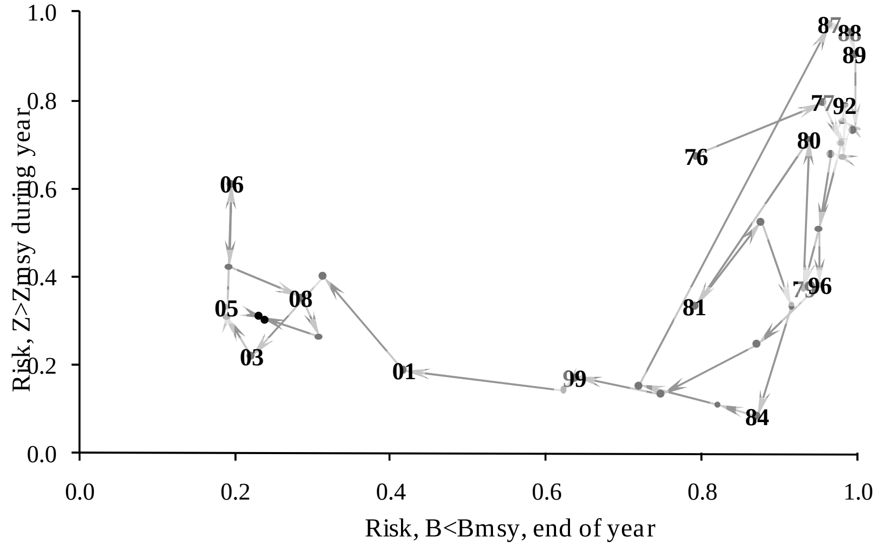


Fig. 4. *Pandalus borealis* in West Greenland: annual likelihood that biomass has been below B_{msy} and that mortality caused by fishing and cod predation has been above Z_{msy} 1976–2011.

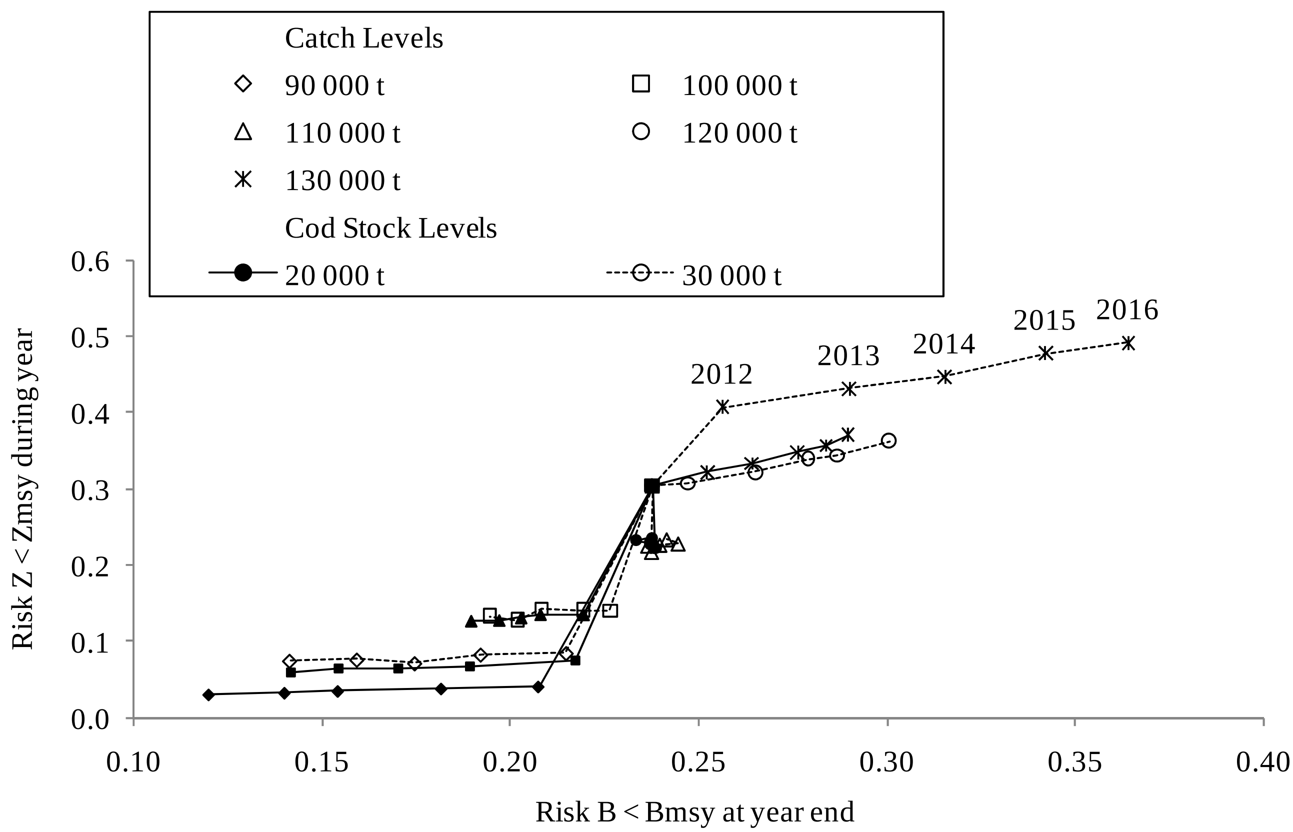
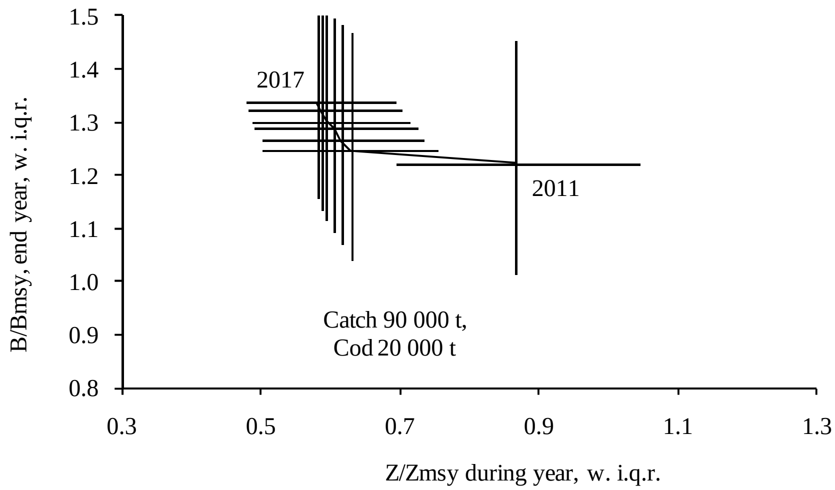
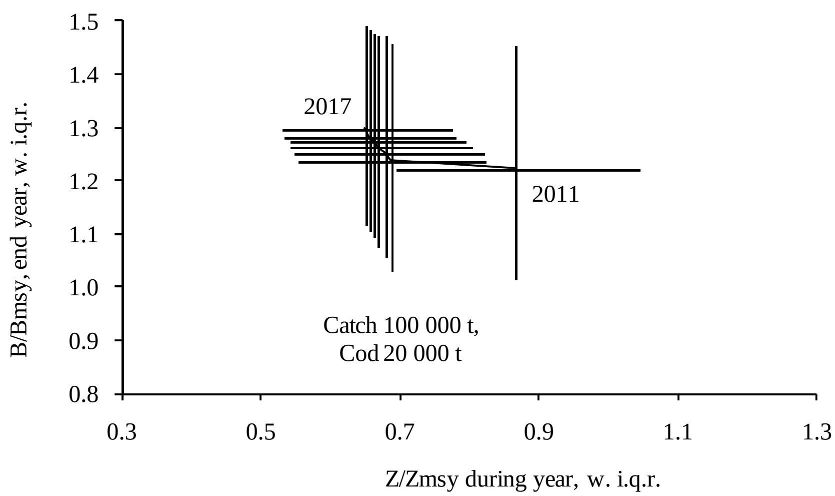
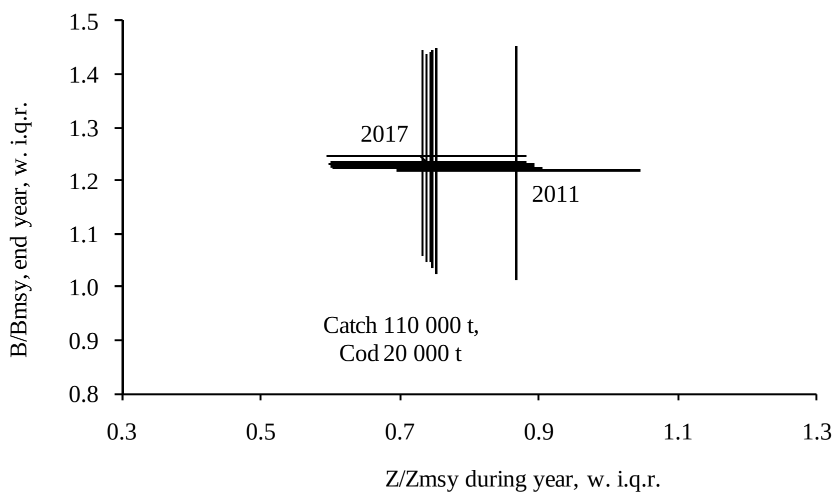


Fig. 6. *Pandalus borealis* in West Greenland: joint 5-year plot 2012–16 of the risks of transgressing B_{msy} and Z_{msy} at catch levels 90–130 Kt/yr; with effective cod biomass 20 and 30 Kt.


1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
B/Bmsy, end year, w. i.q.r.
2017
2011
Catch 90 000 t,
Cod 20 000 t
0.3
0.5
0.7
0.9
1.1
1.3
Z/Zmsy during year, w. i.q.r.


1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
B/Bmsy, end year, w. i.q.r.
2017
2011
Catch 100 000 t,
Cod 20 000 t
0.3
0.5
0.7
0.9
1.1
1.3
Z/Zmsy during year, w. i.q.r.


1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
B/Bmsy, end year, w. i.q.r.
2017
2011
Catch 110 000 t,
Cod 20 000 t
0.3
0.5
0.7
0.9
1.1
1.3
Z/Zmsy during year, w. i.q.r.

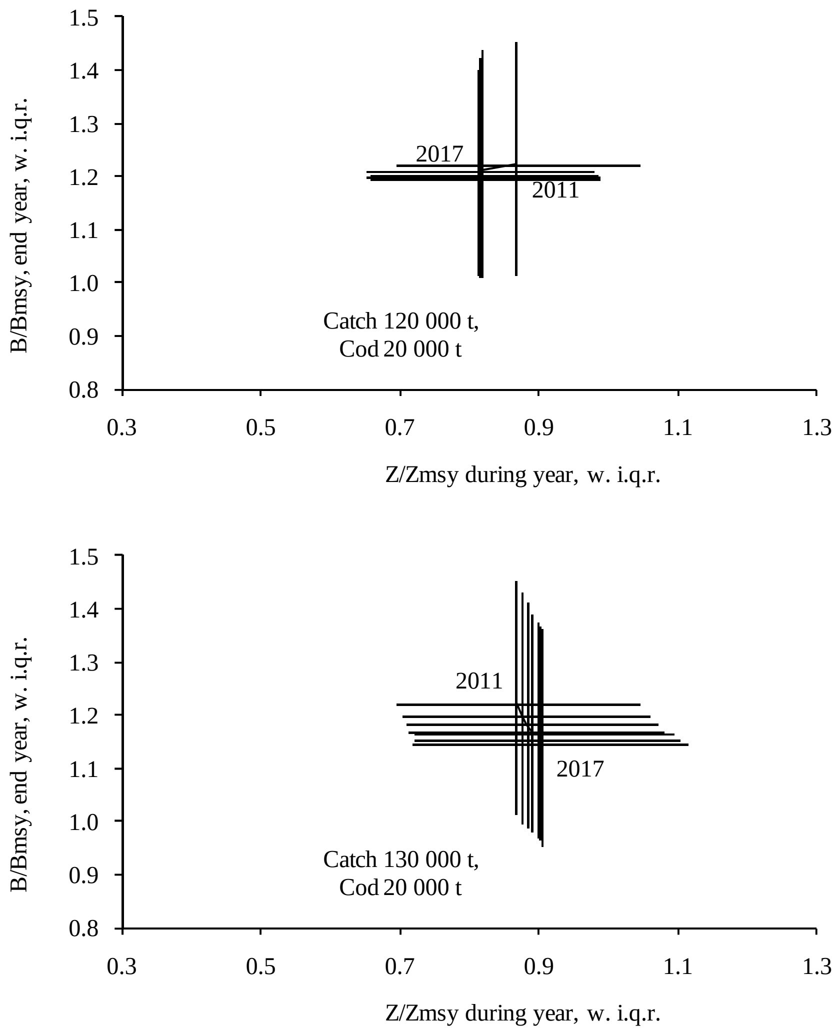


Fig. 7. *Pandalus borealis* in West Greenland: projections of stock development for the period 2011–2017 with effective cod biomass assumed at 20 000 t: median estimates with quartile error bars.

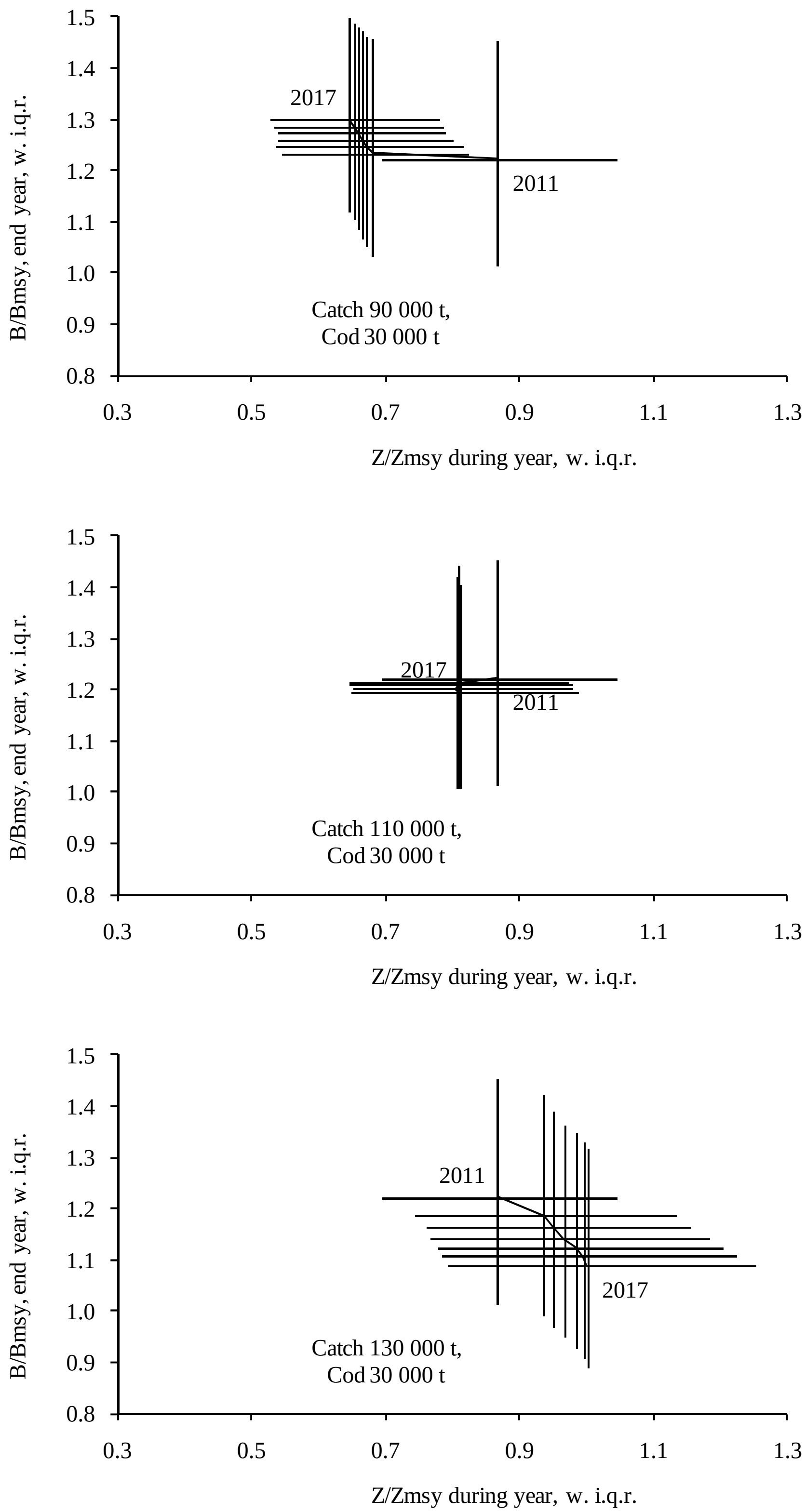


Fig. 8. *Pandalus borealis* in West Greenland: projections of stock development for the period 2011-2017 with effective cod biomass assumed at 30 000 t: median estimates with quartile error bars.

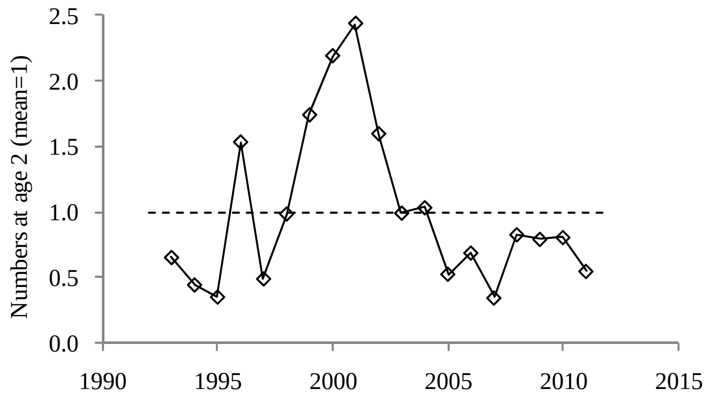


Fig. 9. *Pandalus borealis* in West Greenland: numbers at age 2 from research trawl survey, 1993–2011.

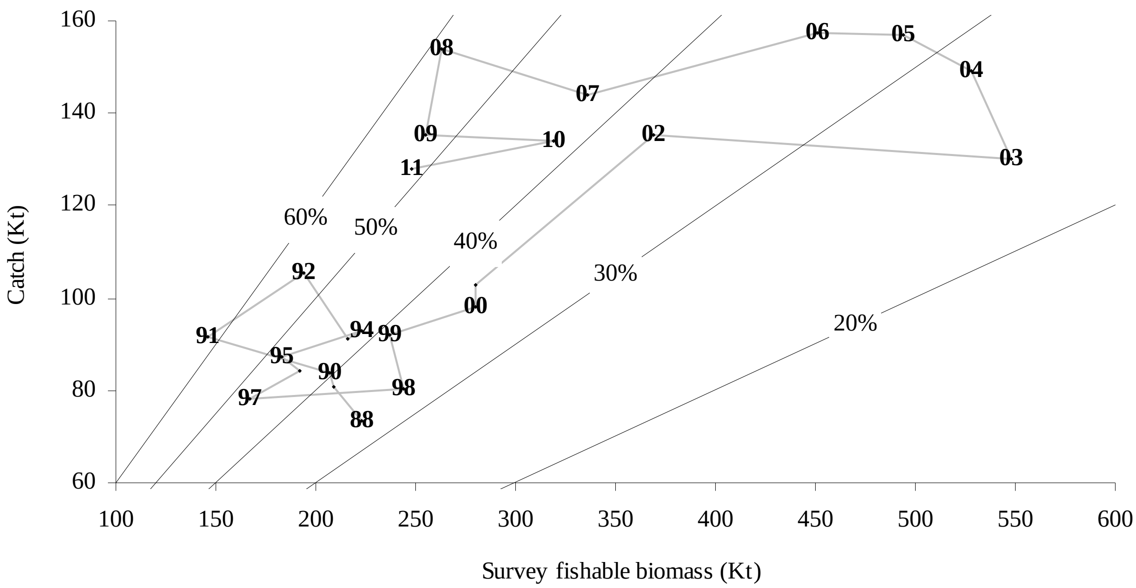


Fig. 10. *Pandalus borealis* in West Greenland: catch, survey estimate of fishable biomass, and exploitation index, 1988–2011.

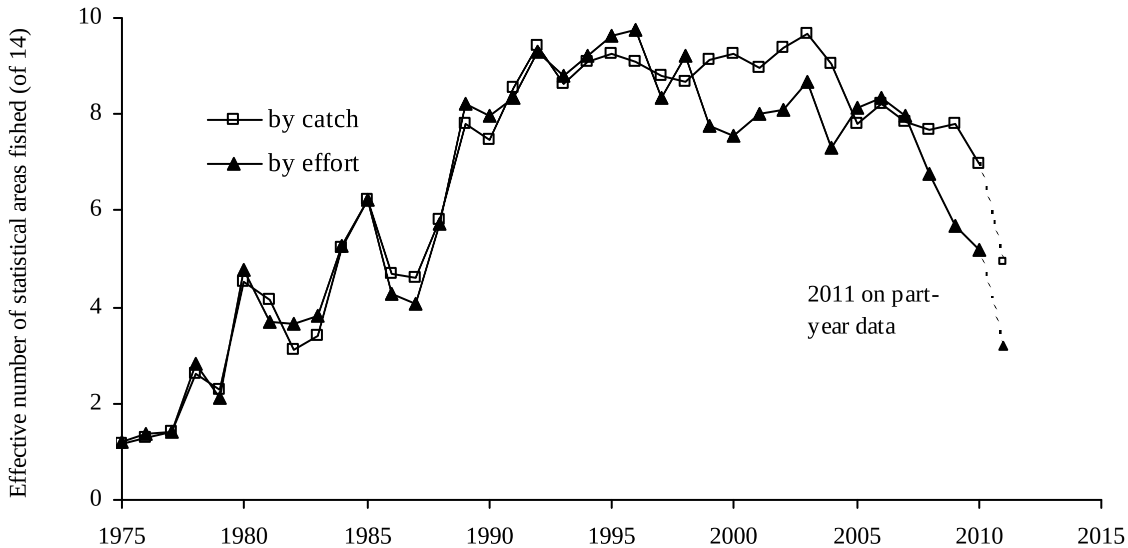


Fig. 11. *Pandalus borealis* in West Greenland: indices of the breadth of distribution of the Greenlandic fishery among 14 statistical areas, from logbook records 1975–2011.

Figure 12. *Pandalus borealis* in West Greenland: mean latitude by weight of the logbook-recorded catch of Northern shrimp by the Greenland fishery, 1975–2011.

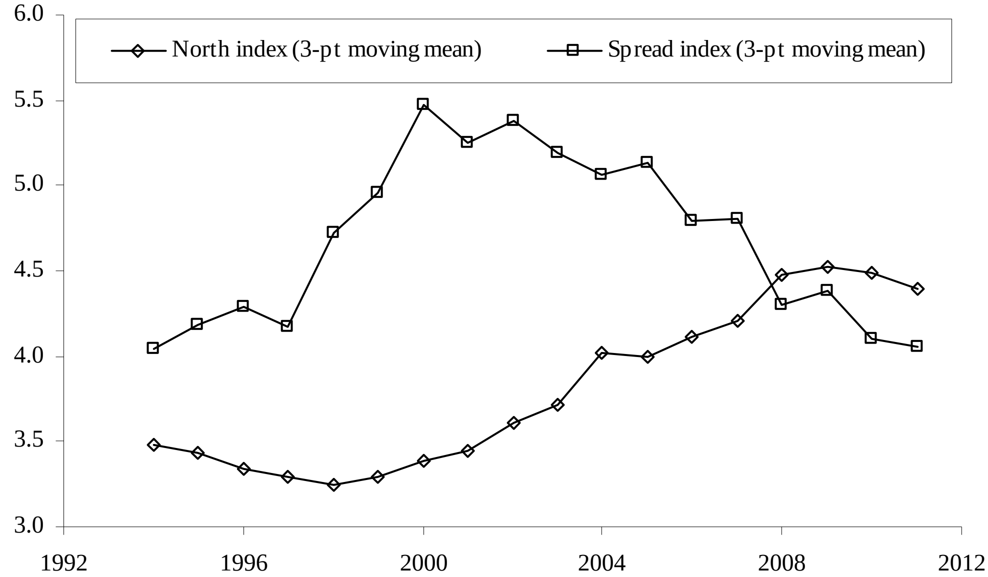


Fig. 13. Shrimp in Subareas 0 and 1: indices of distribution of the survey biomass, 1994–2011 (3-point moving means.)

Appendix to the assessment.

The stock-dynamic model is fitted to biomass index series. It is allowed to make its own decisions as to the reliability to be accorded to the different series without reference to any exogenous estimates of how accurate they might be. If either, or both, of the index series jump around too much from year to year, the model can accommodate their vagaries by adding variability to the stock-dynamic process.

Up to about 2002 the survey and CPUE series followed trajectories that without too much difficulty could be considered similar, both showing a slight increase after the mid-90s. After 2002 the two series diverged—the survey index increased by 95% between 2001 and 2003, and then decreased in 6 consecutive years to reach in 2008 a point that was 6% less than in 2001. The CPUE index also increased, but more slowly and by less, reaching by 2005 a level 46% higher than in 2001; but then did not follow the survey series in decreasing, but stayed at that higher level. The series crossed over in 2006–07.

The response of the model was to abandon the survey series and to pin its faith on the CPUE series. In the 2011 model run it has estimated the error CV of the survey at 23%, but that of the CPUE series at 4.3%. And because the CPUE behaves more orderly, the process variability can be estimated at 8.4%. The modelled biomass trajectory closely follows the trajectory of the CPUE series. And CPUE staying high, the model remains optimistic about the present status and future prospects for the stock.

There are concerns about this. The first is that the model is making the wrong decision in setting the survey index so completely aside. The survey is well designed and carefully executed; all aspects of its design and execution have been thoroughly thought over and it draws on long experience; as trawl surveys go, it is comparable to the best. The strong serial correlation in its results is convincing evidence that it is not simply producing random results. The second concern is that the CPUE index could well be deceptive. It is true that it is based on several thousand hauls a year, where the survey is based on a couple of hundred; but the several thousand are not independent, whereas the couple of hundred are. CPUE measures density in fished areas, and there is no doubt that the fished area has been contracting even while CPUEs have stayed at their present high level. Trawlers now use navigational aids that allow them, having found a good fishing spot for shrimps, to trawl repeatedly and with great accuracy in the same place, and we know that *P. borealis* does have a clumped distribution. At the present time it seems that the industry, while recognising that catch rates are staying high, also recognises that the stock distribution is shrinking and that its biomass is probably much less than it was a few years ago.

A first-order autoregressive model of the survey series of fishable biomass had a residual standard deviation of 20½%, and it ought to be possible to take this as an upper bound on the random error of the survey[7]. In which case, the model is overestimating the survey error in order to justify abandoning it. It is true that the survey, by fixing the position of a proportion of stations from each year to the next, seeks to induce serial correlation into its results, but this has only a small effect. We should therefore be justified in taking 20% as a limit on the error CV of the survey.

The next step is to say that the CPUE is not to be considered any more reliable as a linear index of fishable biomass than the survey. It might be less reliable, but not more.

These thoughts were then implemented in the assessment model by changing the priors on the variances of the components of the model. Before, there were uninformative gamma-distributed priors on all the ‘precisions’ (i.e. reciprocals of variances). Instead, an informative prior, uniform from 0.1 to 0.2, was given to the c.v. of the survey index as a measure of biomass. The c.v. of the CPUE index was defined to be a multiple of the survey c.v.; the multiplier was given a prior uniform from 1 to 10, so that the c.v. of the CPUE must be greater than that of the survey. Other variance terms were given uninformative priors.

The reformulated model was run with 30 years’ data from 1982 to 2011. The shorter series has the practical advantage that it runs faster and with less autocorrelation in the MCMC chains, so results are available much more quickly. It has the theoretical advantage that it does not require assuming that the underlying mechanisms, and the

[7] in general, if x is an indicator of an autoregressive process y, and the scatter of x about y is serially uncorrelated and independent of y, then the scatter about an autoregressive model of x must be at least as big as the scatter of x about y.

associated ecosystem parameters, have been the same for nearly 60 years, but the disadvantage of reducing the range in the data[8]. This meant that two significant changes had been made in the model coding. However results were also available from running the original model, with its uninformative priors, reduced to a 30-year series, so we could compare them.

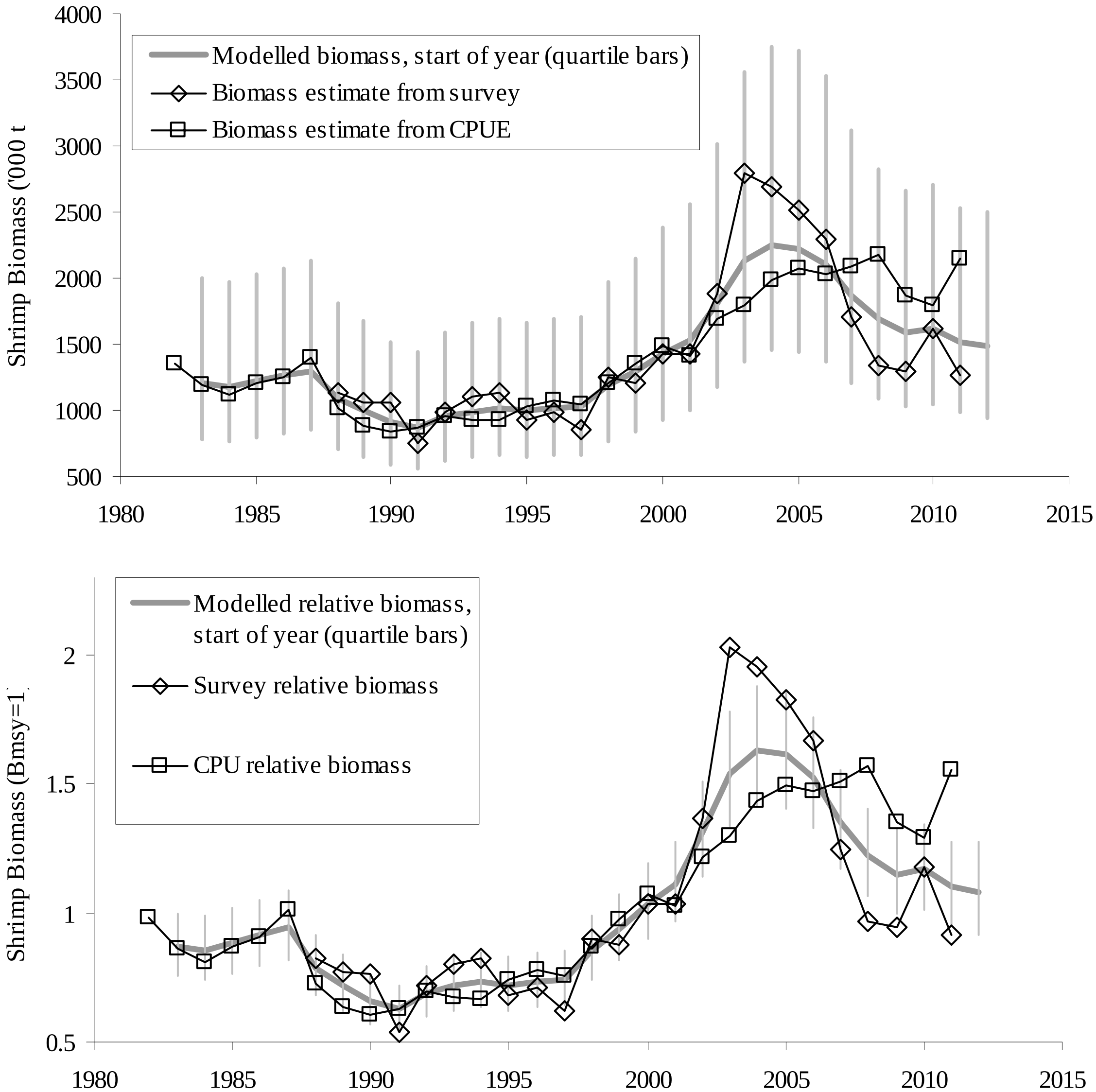
	Original standard model	30-year series, uninformative priors on CVs	30-year series, informative priors on CVs
MSY	155	157.6	135.1
B/B_{msy}, end 2011	1.22	1.21	1.08
Z/Z_{msy}, 2011	0.87	0.89	1.11
CV-CPUE (%)	4.3	3.7	15.0
CV-survey (%)	23.0	23.0	13.1
CV-process (%)	8.4	6.6	11.1
CV-predation (%)	53.8	25.9	94.6

Taking 30 years' data with uninformative priors allows the model to fit the data series more closely. All the CVs are less, except for the survey; the predation term especially is able to fit better. The estimates of MSY and of stock status in 2011 are not different from those with the full series of data. Shortening the data series, on its own, does not make a big difference.

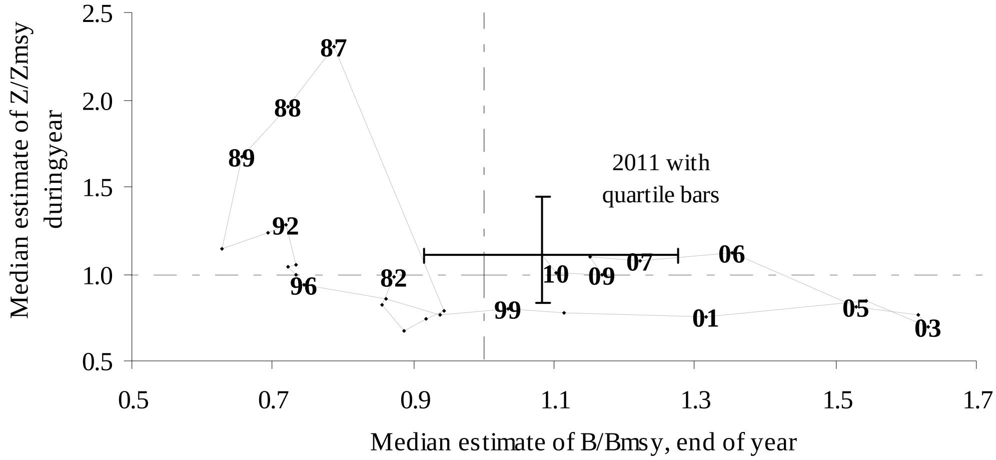
When the model is told to take more notice of the survey, the estimates change quite a lot. Now that the stock size is compelled to go down under the influence of the 150 Kt catches of 2004–2008 instead of staying the same, the MSY estimate is lower by about 20 Kt and the estimate of the stock status in 2011 becomes also correspondingly worse. The fit CVs of the two biomass-index series behave as instructed: the CPUE CV is larger than the survey CV, so the biomass trajectory doesn't fit the CPUE so closely, and so gets closer to the survey index, which is thereby enabled to get its CV down to 13%. But the resulting contortions in the biomass trajectory increase both the process variability and, especially, the fit CV of the predation term. The critical change was not limiting the CV of the survey series to be less than 20%—that constraint is in the end ineffective—but requiring the CV of the CPUE series to exceed it.

The CV of the CPUE increases to about 15%. The scatter about a first-order autoregressive model of the CPUE similar to that for the survey results is about 11¼%. In the case of the survey, we argued that the scatter about the autoregressive model should be an upper bound for the scatter of the indicator about the process, which would imply that the model is now overestimating the error of the CPUE. One counter-argument is that the CPUE series is (presumably?) built to have serially correlated errors, so it is possible for the scatter of the indicator about the process to be bigger than the scatter about the autoregressive model of the indicator; another is that the CPUE is an indicator of a different process.

[8] the model became much less able to estimate absolute levels of biomass and the absolute value of B_{msy}



Biomass and biomass-index trajectories from a model with informative priors on CVs.



Joint trajectory of biomass and mortality, model with informative priors on CVs.

Table: risk table for first future year.

20 000 t cod	Catch option ('000 tons)				
Risk of:	80	90	100	110	120
falling below B_{msy} end 2012 (%)	35.9	36.7	38.2	39.0	40.0
falling below B_{lim} end 2012 (%)	0.9	0.9	0.9	0.8	0.8
exceeding Z_{msy} during 2012 (%)	23.5	30.3	38.9	47.0	54.5

Table: Risks at the end of 5 years, 20 and 30 Kt cod.

Catch (Kt/yr)	Prob. biomass < B_{MSY} (%)		Prob. biomass < B_{lim} (%)		Prob. mort > Z_{msy} (%)	
	20 Kt	30 Kt	20 Kt	30 Kt	20 Kt	30 Kt
80	31.1	35.8	2.6	3.4	24.2	30.7
90	35.3	39.6	2.8	4.1	31.6	39.2
100	39.5	43.2	3.1	4.2	40.0	47.1
110	43.4	48.4	3.2	4.7	49.1	56.1
120	47.2	51.9	3.7	5.0	56.4	63.4

Risks of all kinds increase with the revision of the model: not only is the stock estimated to be in worse condition, but also the uncertainty about the process is bigger than it was and the future trajectory of the stock is therefore more uncertain.

The model is premised on the assumptions that two measures of biomass are both reasonably reliable linear indices of the fishable stock, that the stock dynamics follows a Pella-Tomlinson model closely enough for that model to predict future stock trajectory with usable precision, and that the model fitting can indicate how accurately each index series reflects the biomass. On present experience, it looks as though the two index series diverge too much for both to be considered reliable, as though the one that would best fit the stock-dynamic model is therefore plausible, but not necessarily trustworthy, and as though the stock dynamics has enough uncertainty associated with it to make predicting biomass trajectory from the model uncertain.