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A Bayesian Gear Change: estimating and using a correction factor for gear catchability

by

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Abstract

A research trawl survey, carried out since 1988, contributes to the assessment of the stock of *Pandalus borealis* on the West Greenland shelf. The *Skjervøy 3000* trawl used since 1988 has been replaced by a *Cosmos 2000*. In order to be able to compare old data with new, calibration experiments were carried out in 2004 and 2005 by trawling twice consecutively on the same track, using either the same gear twice or the two different gears in one order or the other. Data were analysed with likelihood models and by using Bayesian methods to fit model parameters to data. Disturbance effects, i.e. reduction in second catch relative to the first, were found to depend on density, second catches being a smaller proportion of first catches when densities were high. The *Cosmos* trawl was estimated to fish with about 85–86% (s.e. 6%) of the catchability of the *Skjervøy* trawl.

The assessment of northern shrimp in West Greenland waters is carried out using a stock-production model, including a term for predation by cod. The model is fitted to the data series by Bayesian methods. The results of the present study include a probability distribution for the catchability change. This facilitates using the result in the assessment model, as the gear change can be written into the model as a shift of catchability parameter, and the probability distribution of the catchability ratio can be specified as a Bayesian prior in the assessment model.

Introduction

A trawl survey, carried out by the 722-GRT trawler 'Paamiut', has been a component of the monitoring and assessment of the stock of *Pandalus borealis* on the West Greenland shelf since 1988. The trawl used has been a *Skjervøy 3000,* with steel-bobbin ground gear. It was recently decided to change to a *Cosmos 2000* with rubber-disk rock-hopper ground gear, in order to be able to survey effectively on a wider range of bottoms. However, it was foreseen that this switch would pose a problem in using the entire series of survey data in assessments, so a calibration study was undertaken to be able to compare the existing series of data obtained with the *Skjervøy* with the data now to be obtained with the *Cosmos*. The fishing effectiveness (catchability) of the two trawls was compared in a calibration study carried out in 2004 and 2005. The results are presented here.

The series of survey biomass indices is one of the data series input to a stock-production model that forms the basis of the assessment of northern shrimp in West Greenland. The model is fitted to the data series by Bayesian methods (Hvingel and Kingsley 2006). The output from the Bayesian analysis of the calibration experiment includes a probability distribution for the relative catchabilities of the two gears. Therefore, it is possible to insert the catchability ratio as a parameter in the assessment model, with its posterior probability distribution from the calibration experiment as a prior distribution in the assessment model. This easily allows an exact modelling of the state of our knowledge about the catchability ratio, that would have been much more difficult, if at all possible, had the existing data simply been converted to conform to the new data using a single estimate of the catchability ratio.

Methods

Field Methods

Calibration stations were selected as a part of the routine annual survey for northern shrimp carried out on the West Greenland shrimp-fishing grounds, which surveys the West Greenland shelf between 150 and 600 m depth; it has a stratified random design with a partly systematic placing of stations. The fishing conditions were the normal ones for that survey (see e.g. Wieland and Bergström 2005), fishing only between 7 am and 5 pm local time. Both trawls used had a 20-mm stretched-mesh liner in the cod-end. 7.5 sq.m *Injector International* trawl doors installed for use with the *Cosmos* trawl were also used with the *Skjervøy* trawl during the calibration study.

The study design followed Levy et al. (2004), and attempted to avoid the problem of spatial variation in density by fishing at calibration stations twice consecutively over the same trawl track. Sets were consequently of four kinds: either the same trawl was fished twice on the same track, or the two different gears were fished consecutively in one order or the other. The two hauls at each station lasted for the same time, either 15 minutes or 30.

A sample of about 2–8 kg, depending on how big the shrimps caught were (the 'deck sample') was taken from the cod-end on deck when the trawl was boarded and before the catch was dropped into the ship's holding tank. The whole catch was usually processed, and the shrimp was weighed wet off a sorting belt. However, for some large catches only one cod-end was processed, and the other was assumed to weigh the same. The deck sample was sorted, and oblique carapace lengths (CL) measured for individuals of the target species *Pandalus borealis*.

The catches were divided by swept areas as provided in the available data set (see Wieland and Bergström (2005) for details on the calculation), to give a first and a second density estimate for each station. For one station for which no swept area was available in the data set, the mean swept area for that gear and haul duration was used.

The principle behind the analysis was that a 'disturbance effect' could be calculated from the results of fishing twice with the same gear, and used to correct the difference in catch when different gears were used, to end up with a calibration factor—catchability ratio—between the two different gears. All analyses were carried out on density statistics, expressed as weight of shrimps caught per unit of swept area.

The catches were also disaggregated by size class on the basis of the size composition of the deck sample, so that catchability ratios could be estimated for different groups of size classes. A power-law relationship was fitted to a set of 4195 values of CL measured to 0.01 mm and weight to 0.1 g (Wieland and Bergström (2005), data from different years pooled), and used to assign a mean weight to each half-mm size class.

Catchability-ratio analyses.

Second density (at each station) was first plotted against first density on a log-log plot. (Two) first-level outliers, both of which had second catches that were orders of magnitude less than their first catches, were marked, discussed with survey biologists, and discarded (Fig. 1).

The effect of two second-level outliers, both with second catches several times smaller than their first catches, was evaluated by analysing the data with and without them. One had large catches (3700 and 370 kg), but the second catch was only 10% of the first; the other had small catches (0.4 and 0.1 kg) with a 4:1 ratio. They were both eventually discarded because it was thought that the difference between the first and second catches was dominated by variability in the occurrence of shrimp rather than by the catchability of the gear. However, both were of type Co–Sk (i.e. Cosmos followed by Skjervøy), so removing them affected the results for that type of set considerably, and with them, the calibration factor estimated from that type of set. A fifth data point that was also discarded had very small catches in both hauls—a couple of orders of magnitude smaller than the next smallest (Fig. 1). Catches of that size are not very relevant to calibration of the gear for the purposes of biomass estimation, and there were concerns that this point would have an excessive influence on the analysis. The final data set comprised 61 sets—11 Co–Co, 17 Co–Sk, 18 Sk–Co, and 15 Sk–Sk—that gave a homogeneous data set (Fig. 2).

Size classes were aggregated into three groups: 5–12.5 mm, 13–17 mm, and over 17 mm. The composition of each catch was estimated from the counts of different length classes in the deck samples. An estimated weight in the deck sample was calculated for each size group from the numbers and weights of the individual size classes and multiplied up so that the sum of the group weights equaled the recorded total catch weight. Analyses were then carried out for the data on the three size groups separately, as well as on the total catch weight.

1. Exploratory Spread-sheet Analysis

Initial analyses were linear regressions in log-log space fitted using Excel® Solver®. The density[1] in the second haul was regressed on the density in the first haul. Data from all set types was analysed simultaneously, and constraints were applied to regression parameters to fit parallel or coincident models. The fit criterion was maximum likelihood, assuming that the scatter about the lines was Normal and homoscedastic in log-log space. For most analyses the scatter about the lines was assumed to be the same for all. Standard errors were estimated by finding parameter values that reduced the likelihood by 0.5.

Regressions were first fitted as one line to all data, as independent lines to the four set types, and as parallel lines.

2. Spreadsheet Likelihood model.

The log-log regressions above were not completely satisfactory, as the first catch at each set could not properly be regarded as an independent variable, but as depending itself on the true independent variable, which was the local density. So a slightly more complex model was built in which both catches at each station were considered a reflection of an underlying density and a gear-specific catchability[2]. The model that was deduced from the regression analyses, i.e. density-dependent disturbance factors and a density-independent catchability ratio, was rebuilt as a log-likelihood model. All quantities were translated into log space and catches were predicted in log space as:

First.catch – First.swept.area = Density + Catchability(First.Trawl)

---

[1] swept areas were measured in sq. km. In order to have convenient-sized numbers, catches in kg were divided by 100. Densities analysed were therefore expressed in kg/ha.

[2] this model was in fact first built as a check on the results from the Bayesian model, about which I was in some doubt.

and

Second.catch – Second.swept.area = Density + Disturbance.Factor(First.Trawl) + Catchability(Second.Trawl)

where

Disturbance.Factor(Trawl) = Base.Factor(Trawl) + Density.Effect x Density

The observed catches were then assumed normally distributed (still in log space) about the predictions with uniform variance and the log likelihood of the observed catches was maximised (using Excel Solver) by fitting a density for each station, a catchability ratio, a base factor for each gear, and a common power (‘Density.Effect’) for the effect of density on the disturbance factor.

The two catches at each station were therefore not linearly related (in real space), as the predicted second catch would be affected by the parameter Density.Effect.

As a check on the results from the model, the catchability ratio was turned upside down to check that the resulting estimate of the catchability of the *Skjervøy* relative to the *Cosmos* was really the reciprocal of that of the *Cosmos* relative to the *Skjervøy*. It was.

3. Bayesian Inference.

A similar model in which parameters were fitted to the data by Bayesian methods,using the WinBUGS[3] platform, was also built.

Catch(1, Station) = Density(Station) . Catchability(Geartype(1,Station)) . SweptArea(1, Station)

while the second catch was also considered to reflect the disturbance due to the first gear:

Catch(2, Station) = Density(Station) . Catchability(Geartype(2, Station)) . SweptArea(2, Station) . Disturbance(Geartype(1, Station))

The two catches at each station were therefore considered to be linearly related, the factor between them being compounded of the Catchability ratio and the disturbance factor of the first gear.

The model was fitted by Bayesian methods using MCMC sampling with the Bugs software. Two catchabilities were fitted, with priors selected by trial and error to be only informative enough to prevent catchabilities and densities from wandering off into regions that would hinder the MCMC sampling process. The catchability ratio had no assigned prior, but for comparison with its posterior distribution its effective prior was obtained by sampling from the prior distributions of the two catchabilities and calculating the ratios of the sampled values.

A model in which a catchability ratio calculated from the results of the Co-Co and Co-Sk trials was compared with one calculated from the Sk-Sk and Sk-Co trials was also run.

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[3] ‘Bayesian inference using Gibbs sampling, under Windows’. See http://www.mrc-bsu.cam.ac.uk/bugs/.

Results

Analysis by weight classes.

The fitted relationship between weight (W; kg) and oblique carapace length (L; mm)was:

W_{pred} = -1.174E-5 + 0.3228E-5 x (L – 2.2315) ^ 2.5358.

The standard deviation about the fitted function was given by:

SD (W) = 1.12 x W_{pred} ^ 0.6184.

A plot of cumulative sums of residuals showed regions where this fitted function systematically over- or under-estimated weights. Between about 15.6 and 17.4 mm CL it overestimated weights by about 7.3226E-5 kg on average (roughly 2.6% of predicted weight), between about 19.4 and 21.7 mm CL it underestimated weights by 8.6502E-5 kg (1.7%), between 23 and 27.2 mm CL it overestimated weights by 6.8774E-5 kg (0.80%), and between 27.2 and 29.7 mm CL it underestimated weights by 31.002E-5 kg (2.6%). (For comparison, the CV of weight is estimated at 12.7% at 15 mm CL and 7.3% at 25 mm CL.) These corrections were, however, not applied in converting the deck-sample length-class counts to the length-group composition of the catch by weight.

A few stations had no length data for the second haul; they were omitted from all the length-group analyses. Quite a lot more had no catch in one or both of the smaller length groups in one haul or the other. Stations with zero catch in a length group in either haul were omitted from the analysis for the group. The resulting data sets contained 40 sets for shrimp up to 12.5 mm cpl, 50 for shrimp from 13 through 17 mm, and 57 for shrimp over 17 mm. All analyses were carried out on density data (kg/ha), even though densities expressed in this way are very small for the smallest size classes.

Calibration Analyses

The *Cosmos* trawl had a wingspread about one-third larger than the *Skjervøy*. It was nonetheless necessary to assume that the disturbance factor allowed for in predicting the second catch at a station depended only on the first gear type (i.e. was the same regardless of the following gear), otherwise it was too difficult to fit predictive models of catches and estimate calibration factors.

1. Log-log Regression model

Plotting first density against second density in log-log space the aggregate data set had a linear appearance (Fig. 2). When a single line was fitted to the data, a quadratic term was very small (significant at 95%), and was ignored. Separate straight lines were fitted to the four types of set; their slopes were not significantly different (p=14.3%.) Parallel lines were fitted, and their common slope, 0.884, was very significantly different from unity (p=1.68E-6). This implies an average ratio of second to first density estimate decreasing with increasing catch. Inspection showed that n the highest-density areas second catches averaged little over 60% of first catches, while in the lowest-density areas second catches were 70 to 80% *higher* than first catches. These effects are quite consistent between the catches made at these density levels. The data really says that there is a straight-line relationship in log space, and it isn’t at 45 degrees.

A model that would explain this effect is easy to arrive at: disturbance effects depend on density. To explain why this should be so is more difficult. But perhaps, for example, in high density areas the first haul fishes out a significant proportion of the shrimp initially present and reduces the remaining density so that the second catch is lower, while this effect does not occur at low densities, either because catches then depend more on chance encounters with small clusters of shrimps or because shrimp move around more in the time between the two hauls.

However, since parallel lines could be fitted, it appeared that a satisfactory model might have both disturbance factors depending on density in the same way, and a catchability ratio independent of density. Accepting a model of density-dependent disturbance factors had some effect on the estimates of catchability ratio.

The intercepts of the log-log regression of second density on first density were:

Co-Co	Sk-Sk	SkCo	Co-Sk
0.0800	0.3090	0.2275	0.3345

From Co–Co and Co–Sk sets the disturbance factor of the *Cosmos* trawl was estimated as:

Density.Estimate.2 = 1.083 * Density.Estimate.1 ^ 0.884

while from Sk-Sk and Sk-Co sets, that for the *Skjervøy* is

Density.Estimate.2 = 1.362 * Density.Estimate.1 ^ 0.884.

The catchability of the *Cosmos* trawl relative to that of the *Skjervøy*, estimated from Co-Co and Co-Sk sets, was 77.5%, while from Sk-Sk and Sk-Co sets it was 92.2%. When the regression model was constrained to give a single calibration factor, it was estimated at 85.2%, with std error about 8.6%.

2. Spreadsheet Likelihood model.

The density effect on disturbance factors was estimated at 0.893, significantly different from 1 ($p \approx 9E-10$). The disturbance factor for the *Cosmos* trawl was estimated at 1.14 * Density ^ 0.893, and that for the *Skjervøy* at 1.386 * Density ^ 0.893. This model confirmed the results from the regression analyses that the disturbance effects—i.e. the reduction in second catch relative to the first—are greater at high densities.

A single overall estimate of the catchability ratio (*Cosmos* relative to *Skjervøy*) was estimated at 85.4% with a standard error of 6.3%.

The log-likelihood spreadsheet model was also run on each of the size groups separately, with these results:

Size group	No. of stations	Calibration factor (%) (S.E.)	Disturbance factor (%)		Exponent of density-dependence
			Cosmos	*Skjervøy*	
< 13 mm	40	75.4 (11.9)	84	85	0.794
13–17 mm	50	69.8 (8.2)	89	95	0.894
> 17 mm	57	86.3 (6.6)	112	138	0.894
All sizes	61	85.4 (6.1)	114	139	0.893

Note: all results are maximum likelihood estimates, assuming log-Normal distribution of catches about predictions.

3. Bayesian model

The Bayesian fitting process with the BUGS platform ran smoothly to stable and consistent results. Estimates of the catchabilities of the separate gears and of the densities at the different stations were imprecise and highly correlated, but the estimate of the catchability ratio—calibration factor—was stable and not highly dependent on other estimates. Its prior was strongly updated to a narrow and fairly symmetrical posterior distribution.

Results from the Bayesian fitting of the model of App. 1 to the data were similar to those of the likelihood model. The power of density entering into the disturbance factors was estimated at 0.896 with s.e. 0.022—precisely estimated, and clearly different from unity—while the multiplier was estimated at 1.03 for the *Cosmos* trawl and 1.24 for the *Skjervøy*.

The catchability ratio was estimated at 86.3% with s.e. 0.085.
When the Bayesian model was run on the size groups separately, the following results were obtained:

Size group	No. of stations	Calibration factor (%) (S.E.)	Disturbance factor (%)[4]		Exponent of density-dependence
			Cosmos	*Skjervøy*	
< 13 mm	40	72.8 (15.3)	90	93	0.811
13–17 mm	50	69.7 (11.4)	89	98	0.898
> 17 mm	57	87.0 (9.2)	115	140	0.894
All sizes	61	86.3 (8.5)	116	140	0.894

Note: all results are mean (not median) estimates from MCMC output.

When the overall catchability ratio was disaggregated and separate ratios calculated from the two pairs of station types (for all-size data) the two ratios were 80.1% (s.e. 12.1%) from comparing Co-Co stations with Co-Sk stations, and 92.3% (s.e. 12.8%) when Sk-Sk stations were compared with Sk-Co. However, the standard errors were so large that the *statistical* significance of this difference was small.

Discussion

[4] these Disturbance Factors are not immediately comparable with those from the spreadsheet likelihood model. That model assigned the *Skjervøy* trawl unit catchability and estimated the catchability of the *Cosmos* under that constraint; the Bayesian model assigned both gears the same prior distribution for catchability and estimated the difference in catchabilities. This different treatment of catchability affects the estimates of Disturbance Factor.

It is not clear that the basic design of the study is fully appropriate to the objective. This design estimates a calibration factor that can relate the catches from two trawls fished one after the other in the same place, but that is not the solution to the current problem. What is needed is a calibration factor to relate the catches if one gear had been fished once on a track *instead* of the other being fished once on that track. And it is not entirely clear that the results of the one kind of experiment can replace the other.

The analysis methods proposed by Lewy et al. (2004) assume—require—that the disturbance factor is independent of density. The catches we obtained on the West Greenland shrimp grounds are not consistent with this assumption; second catch is not proportional to the first. So we had to construct analysis methods that would deal with the data we had. Lewy et al. assumed CPUE to be Poisson-distributed and the ratio of second catch to sum of first and second catches therefore a binomial; they then used the logit of this ratio in analyses. This logit is, however, simply the log of the ratio of CPUEs, or the difference in the logarithms of the CPUEs, which is a heuristically reasonable starting point. The general linear model of logits of Lewy et al. is a linear model of logarithm of CPUE, which is basically the same as what has been used here, except for the extra term inserted to take care of the non-linear relationship between first catches and second catches.

Weight analysis. The data set was an unselected sample of shrimp from survey trawling. The length-weight analysis was fitted unweighted[5]. Different length classes therefore received a weighting in the fitting that was proportional to their number in the sample, not to their total weight. The line fits best in the length regions where shrimp are most *numerous* in survey catches, not necessarily where they contribute most to catch *weight* either in the survey or in the commercial fishery.

Using a Bayesian result for the gear change in a Bayesian assessment model would then be relatively simple. The existing model (Hvingel and Kingsley 2006) considers the survey catchability as a single parameter, which is coded in the following lines in the specification of the Bayesian model:

```
for (i in 1:N) {
            survmed[i] <- log(max(1.E-3,qs*Bmsy*P[i]))
            surv[i] ~ dlnorm(survmed[i],precsurv)
}           }
```

which is interpreted as stating that the median for the probability distribution of the survey estimate of biomass is a catchability (*qs*) times the true biomass. The realized result of the survey then has a log-normal distribution with a precision parameter *precsurv* and the already stated median. The precision parameter itself has an uninformative gamma-distributed prior.

The catchability has an uninformative prior distribution, wide and uniform in log. space:

```
            logqs ~ dunif(-10,0.4)
            qs <- exp(logqs)
```

This set of lines could be replaced by, for example:

```
for (i in 1:n) {
            survmed[i] <- log(max(1.E-3,qSkj*Bmsy*P[i]))
            surv[i] ~ dlnorm(survmed[i],precsurv)
}
```

[5] disregarding the automatic weighting implied by fitting a power-law standard deviation—which is a different kind of weighting.

```
for (i in (n+1):N) {
            survmed[i] <- log(max(1.E-3,qCos*Bmsy*P[i]))
            surv[i] ~ dlnorm(survmed[i],precsurv)
}
```

giving different catchabilites to two parts of the survey series; and then relating the two catchabilities by:

```
            qCos <- qSkj * calibfact
            calibfact ~ dnorm(calibmu, calibprec)
            calibmu  <- 0.863
            calibprec <- pow(1/0.085,2)
```

where the prior probability distribution for *calibfact*, the catchability ratio, is given to the assessment model as the (presumed Normal) posterior from the Bayesian fitting from the calibration experiment. This model modification introduces into the assessment model the alteration in survey catchability due to the gear change, and its associated uncertainty.

The catchability of the Skjervøy trawl would be given the same uninformative prior as before:

```
            log.qSkj ~ dunif(-10,0.4)
            qSkj <- exp(log.Skj)
```

This modification to the assessment model will be used as a candidate model for the northern shrimp assessment in autumn 2006.

Conclusions

The *Cosmos 2000* fished with about 85% of the efficiency of the *Skjervøy* trawl for all sizes combined and slightly more—about 86%—for large shrimp over 17 mm CL. The *Cosmos* appeared to be relatively even less efficient for shrimp below 17 mm, with a relative catchability nearer to 70%. Relative catchabilities for finer subdivisions of the size spectrum will be investigated, but it is difficult to predict that they would be accurately estimated.

Acknowledgements

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References

Hvingel, C. and M.C.S. Kingsley. 2006. A framework to model shrimp (*Pandalus borealis*) stock dynamics and quantify risk associated with alternative management options, using Bayesian methods. ICES J. Marine Sci. 63: 63–82.

Lewy, P., J.R. Nielsen and H. Hovgård. 2004. Survey gear calibration independent of spatial fish distribution. Can. J. Fish. Aquat. Sci. 61: 636–647.

Wieland, K. and B. Bergström (2005): Results of the Greenland bottom trawl survey for northern shrimp (*Pandalus borealis*) off West Greenland (NAFO Subarea 1 and Division 0A), 1988-2005. NAFO SCR Doc. 05/74.

Appendix:

BUGS[6] Coding for a Bayesian model for catchability analysis.

```
for (j in 1:sets) {
for ( i in 1:1)  {  l.exp.catch[i,j] <- log(SWA[i,j]*Dens[j]*Catchability[Trawl[i,j]])
        Catch[i,j]  ~  dlnorm(l.exp.catch[i,j], preccatch)  }
        for ( i in 2:2)    {  l.exp.catch[i,j] <-
        log(SWA[i,j]*Dens[j]*Catchability[Trawl[i,j]]*Dfact[Trawl[1,j]]*pow(Dens[j],Dens.Effect))
        Catch[i,j]~dlnorm(l.exp.catch[i,j], preccatch)  }  }

Catchability.Ratio  <- Catchability[1]/Catchability[2]

#Prior distributions:
for (i in 1:2) { Catchability[i]   ~  dlnorm(0,1)
Dfact[i]  ~  dunif(0,2) }
Dens.Effect   ~  dunif(-2,2)

for (j in 1:sets)  {          Dens[j]  ~  dlnorm(meandens, precdens)  }

meandens ~ dunif(-8,12.5)
precdens ~ dgamma(3,.004)
preccatch ~ dgamma(3,.004)
}
```

[6] ‘Bayesian inference using Gibbs sampling’. See http://www.mrc-bsu.cam.ac.uk/bugs/.

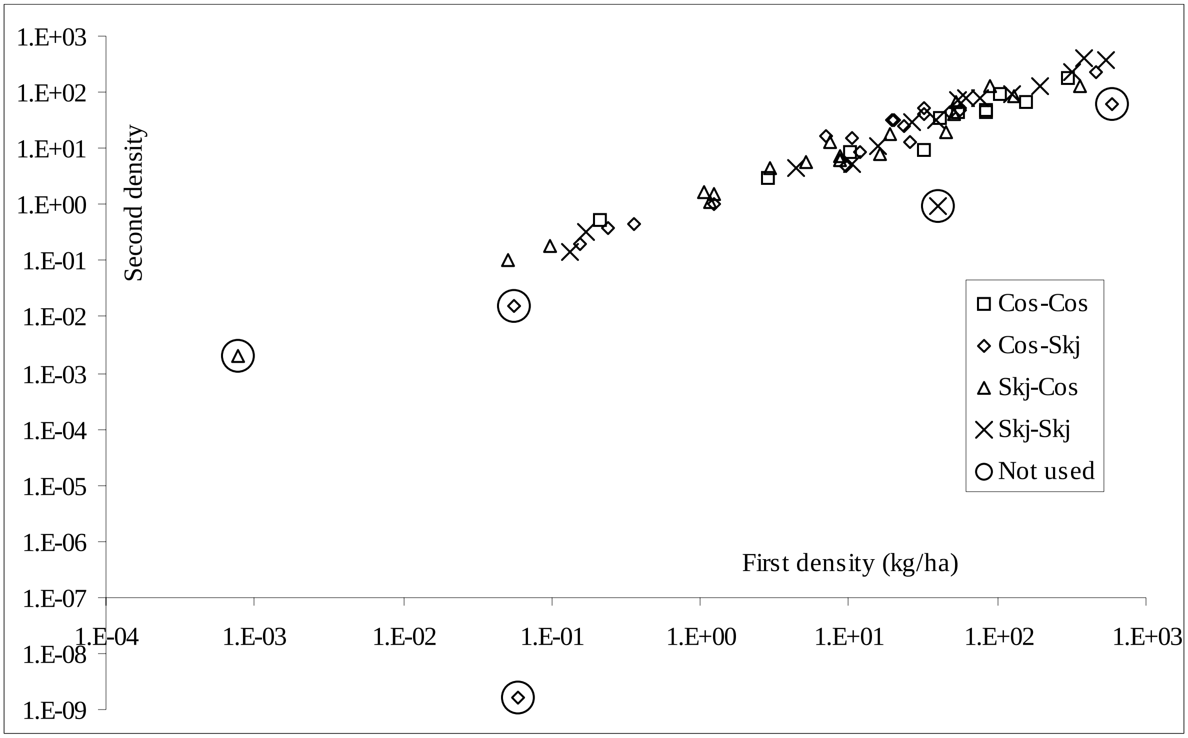

Fig. 1 Densities of shrimp in calibration experiments with a *Cosmos* and a *Skjervøy* trawl on the West Greenland shrimp grounds.

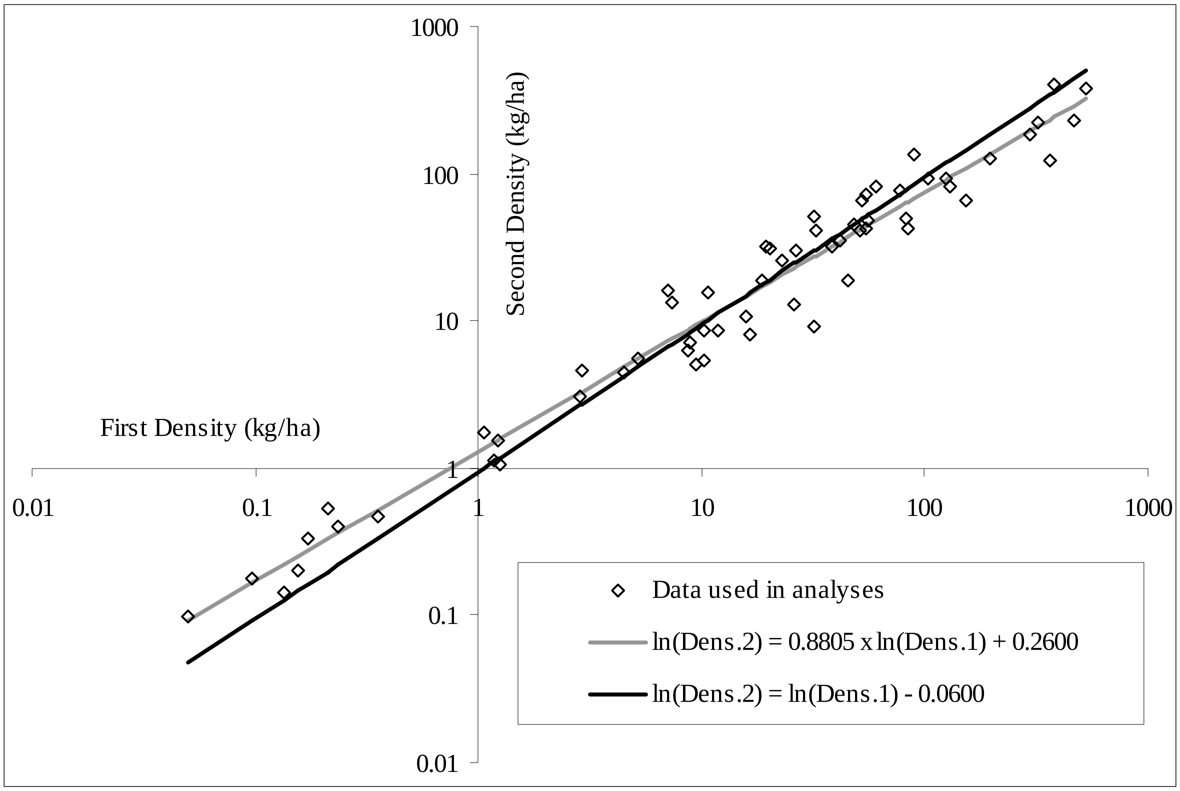

Fig. 2. Linear relationships between the logarithms of first and second densities in paired hauls with *Cosmos* and *Skjervøy* trawls on the West Greenland shrimp grounds