NOT TO BE CITED WITHOUT PRIOR
REFERENCE TO THE AUTHOR(S)

Northwest Atlantic Fisheries Organization

Serial No. N4023 NAFO SCR Doc. 98/114

SCIENTIFIC COUNCIL MEETING - NOVEMBER 1998

A Review of the Trawl Survey of the Shrimp Stock off West Greenland

by

Dan Carlsson[1], Ole Folmer[1], Carsten Hvingel[1], Per Kanneworff[1],
Michael Pennington[2] and Helle Siegstad[1]

[1]Pinngortitaleriffik – Greenland Institute of Natural Resources
Box 570, DK-3900 Nuuk, Greenland
[2]Institute of Marine Research
PO Box 1870 Nordnes 5024 Bergen, Norway

Introduction

Since 1988 the Greenland Institute of Natural Resources has conducted an annual stratified-random bottom trawl survey of the shrimp stock (*Pandalus borealis*) off West Greenland (Carlsson and Kanneworff, 1997). The surveys cover the offshore shrimp distribution in NAFO Subarea 1 and a small part of Div. 0A. The purpose of the surveys is to assess the abundance of the stock and to gather biological information on the resource. The advantage scientific surveys have over catch based techniques, such as the commercial CPUE abundance index for shrimp (Anon.,1997), for assessing a stock is that the uncertainty associated with survey estimates of population characteristics can be quantified. Given the nature of commercial catch data, the uncertainty associated with catch based assessments is difficult to measure and often ignored with sometimes disastrous consequences (Pennington, 1998).

Now that ten years of survey data are available, it was decided that a panel should be formed to evaluate the design and efficiency of the survey. The charge to the panel was to assess the precision of the survey estimates, the effectiveness of the present stratification, the allocation of effort within the survey area, the appropriate tow duration and the suitability of two-stage (adaptive) sampling. Because of time constraints, the currently used methods for collecting and analyzing biological data, such as length measurements were not examined. Based on their findings, the panel was asked to make recommendations on future survey design and analysis.

Stratification and effort allocation

The total survey area extents from 59°30'N to 72°30'N along the West coast down to a depth of 600m. The southern areas were not covered in the first years of the time series (Carlsson and Kanneworff, 1997). The survey catch of shrimp in the northern part of the survey region and in shallow water areas was a small proportion of the total catch during the last ten years. Thus it was determined that survey effort in the north and in shallow water areas should be reduced and redirected to the western part of the survey region. The north would be monitored by taking a few transects of stations in the future and sampling intensity enhanced when and if abundance in the north increases from its current low level.

In this review, survey data from the western areas (W1 through W5 and C1 and C3), which contain the bulk of the survey catch and effort, were examined in detail (figure 1). The areas contain three or four strata based on depth. The depth stratification is 150-200m, 200-300m, 300-400m and 400-600m. In total the area is divided into 25 strata. To determine the efficiency of the stratification semivariograms were constructed (Figure 2). Mean density and standard deviation were calculated for latitude and depth intervals. The delta value of the semivariogram were calculated as the squared difference in density for neighbor intervals, intervals two steps apart and so forth up to six. If the semivariogram shows an increasing trend, the intervals chosen reflect differences in the mean between intervals.

The spatial distribution of the shrimp appears to be strongly related to depth with little correlation with latitude. Thus four "super" strata were formed in the western area based only on depth (see Table 1).

There are basically two advantages for having fewer and larger strata; 1) analyses based on the resulting larger sample sizes within a stratum are more stable and more varied analytical techniques can be used (Pennington, 1996), and 2) effort can be more efficiently allocated among the strata (Gavaris and Smith, 1987; Smith and Gavaris 1993). Furthermore, usually little is gained in terms of precision by increasing the number of strata beyond six (Cochran, 1977). Since sampling effort is currently allocated approximately proportional to stratum area, the stations within the super strata can be treated as approximately a random sample from each new stratum (Cochran, 1977).

In Figure 3a is a plot of the estimated mean density of shrimp by super stratum and year. It is apparent that the stratification is fairly effective. The average density of shrimp was generally highest in stratum C (depth 300-400m) and consistently extremely low in stratum A (150-200m) during the survey period (Figure 3a).

The stratified estimator of mean shrimp density in the entire area is given by (Cochran, 1977; eq. 5.1, p. 91)

$$\bar{y}_{st} = \sum_{i=1}^{L} W_i \bar{y}_i , \qquad (1)$$

where L is the number of strata,
n_i is the number of tows in the i^{th} stratum,
$y_{i,k}$ is the catch by the k^{th} tow in stratum i,

$\bar{y}_i = \dfrac{\sum_{k=1}^{n_i} y_{i,k}}{n_i}$ is the average catch in the i^{th} stratum,

and

W_i the proportion of the survey area in the i^{th} stratum.

The estimated variance of the stratified mean, $\bar{y}_{st}$, is

$$\mathrm{var}(\bar{y}_{st}) = \sum_{i=1}^{L} W_i^2 \frac{s_i^2}{n_i} , \qquad (2)$$

where

$$s_i^2 = \frac{\sum_{k=1}^{n_i} (y_{i,k} - \bar{y}_i)^2}{n_i - 1} . \qquad (3)$$

One way to measure the usefulness of a stratification scheme is to compare the variance of the density estimates based on the stratification with those from a simple random sample from the entire area (Gavaris and Smith, 1987). Sampling effort was allocated approximately proportional to stratum area therefore an estimate of the variance if there were no stratification (*i.e.* simple random sampling in the entire area) is given approximately by s^2/N, where s^2 is the estimated variance ignoring stratification and N is the total number of tows (Cochran, 1977; eq. 5A.51, p. 137). The relative precision of a stratification scheme versus simple random sampling may be measured by

$$\frac{\mathrm{var}(\bar{y}_{ran})}{\mathrm{var}(\bar{y}_{st})} ,$$

where $\mathrm{var}(\bar{y}_{ran}) = s^2 / N$ (Cochran, 1977, p. 103). In Table 2, column 3, is the estimated relative precision of allocating effort proportional to stratum area (the current design) versus allocating effort randomly in the entire survey region. On average, the precision increases by 20% using the stratified design or equivalently, the variance is reduced by around 17%. Put another way, if there were no stratification, sample size would need to be increased by 17%, on average, to generate estimates that are as precise as the stratified estimates.

Since only a small proportion of the total biomass was observed in stratum A, little was gained in terms of the precision of the abundance estimates by allocating effort proportional to the area of stratum A. It was decided to determine the possible gain in precision to be had by reallocating 50% of the effort from stratum A and 25% from D (the smallest stratum) to strata B and C. The result of this reallocation was an estimated gain in precision of 42% on average as compared with simple random sampling (Table 2, last column).

The final allocation of stations will be determined by the total number of stations that can be taken in the western Subarea. This number should increase significantly with the decrease in sampling effort in the north and in shallow water areas (stratum A).

Two stage adaptive sampling

For the years 1994 through 1997 additional stations, based on the method proposed by Francis (1984), were taken in strata when the variance of the first-stage observations was relatively large. There are two problems associated with this technique The first is that the sampling scheme may introduce a fairly large negative bias (Folmer, 1997). Since the distribution of the shrimp catches is highly skewed to the right, the bias is caused by a tendency for the additional catches to be smaller than the first stage catches in strata where large catches occurred during the first stage. The second problem is the additional travel time it takes to collect the second stage samples, which, on occasion, causes considerable back tracking during a cruise. This time may be more efficiently used by increasing the number of stations sampled during the first stage. It was concluded that using all the effort on first stage sampling would produce more precise estimates since bias would be eliminated and a larger total number of stations could be sampled than in a two-stage design.

Though the additional stations would negatively bias estimates based on the original stratification, they would cause a positive bias if included in the super strata, since the second stage samples would tend to be larger, on average, than those in the expanded stratum. In addition, the second stage samples would cause sampling to be far from proportional to stratum area. Therefore they were not included in the analyses based on the super strata.

Tow duration

Based on numerous experiments, it has been observed that little is gained in terms of precision by towing longer than about 15 minutes at a station (Godø et al., 1990; Pennington and Vølstad, 1991,1994; Gunderson, 1993; Goddard, 1997). At present, one-hour tows are taken during the offshore shrimp survey and there is some evidence that little is achieved by towing that long. The inshore shrimp survey uses 30-minute tows and the precision of the inshore estimates (as measured by the coefficient of variation) is the same as that for the offshore estimates. Experimental towing along transects for shrimp off Western Greenland indicates that there is a relatively high positive correlation in catch between stations that are close together (Carlsson, 1997) and when this is the case, little is gained by taking tows of long duration.

By reducing tow duration, the number of stations that can be sampled during the survey will increase and thus the resulting density estimates will be more precise. Decreasing tow duration not only saves survey time but also reduces operating costs since total towing time for a survey will be significantly reduced. Gear and equipment wear is a function of tow length, and less fuel will be consumed while dragging the trawl. An additional benefit of reducing tow duration is the resultant smaller catches that will require less sorting time and allow more time for taking other biological measurements. The total shrimp catch will be less if tow duration is reduced but estimates of biological characteristics, such as length frequencies, will be more precise because the number of stations at which samples are taken will be larger (Pennington and Vølstad, 1994).

Precision of the estimates of mean density

Estimates based on the sample mean

The estimated mean density of shrimp for each super stratum and year are in Table 3, column 3. The estimate of the standard error for each stratum mean (column 4) is given by

$$se(\bar{y}_i) = \sqrt{\frac{s_i^2}{n_i}},$$

where s_i^2 is from equation (3). The estimate of the yearly stratified mean using equation (1) is in the last row in each panel along with its standard error. The standard error (i.e. the square root of the variance of $\bar{y}_{st}$, see equation 2) is calculated as

$$se(\bar{y}_{st}) = \sqrt{var(\bar{y}_{st})},$$

where $var(\bar{y}_{st})$ is defined by equation (2).

Figure 4a is a plot of the yearly stratified estimates of average shrimp density. The solid line is the average density (2354 kg/km^2) over the ten year survey period. It appears that density has fluctuated about its mean level during the last ten years. In order to judge the significance of the movements of the estimates from year to year, we need a measurement of how far the estimates may likely be from the true values. If the sample size is "large" enough, then the Central Limit Theorem states that each time a survey is conducted there is a 95% chance that the true mean lies in the interval (see Cochran, 1977, pp. 39-44)

$$\bar{y}_{st} \pm 2se(\bar{y}_{st}). \tag{4}$$

In Figure 5a is a plot of the survey series along with each estimate's 95% confidence interval. Again, the series appears to be fairly stable except for, perhaps, the 1991 value may be low.

Since abundance data from marine surveys usually have a large variance and are highly skewed to the right, the sample sizes are typically not large enough so that equation (2) is a valid 95% confidence interval. In fact, the confidence associated with the interval given by equation (4) is usually much lower than 95% (McConnaughey and Conquest, 1992; Conquest *et al.*, 1996; Pennington, 1996).

Estimates of the mean based on lognormal theory

One way to generate more precise estimates of the mean and more accurate confidence statements for skewed marine data is to base the estimators on the lognormal distribution (Pennington, 1983, 1996; Conquest *et al.*, 1996). For the shrimp data it was found that the density values larger than 40 kg/km^2 were well approximated by a lognormal distribution (*i.e.* the logged values were normally distributed). Then a more precise estimator of mean density within each stratum, $\hat{\mu}_i$, is given by (modified from Pennington, 1983, 1996)

$$\hat{\mu}_i = \frac{(n_i - m_i)}{n_i}\bar{y}_i' + \frac{m_i}{n_i}\exp(\bar{x}_i)G_{m_i}(s_{x,i}^2/2), \tag{5}$$

where m_i is the number of sample values greater than 40 in stratum i; $\bar{y}_i'$ denotes the mean of the values less than 40 and $\bar{x}_i$ and $s_{x,i}^2$ are the mean and variance, respectively, of the logged values of catches greater than 40 and $G_m(t)$ is a function of m and t [for example, $m = m_i$ and $t = s_{x,i}^2/2$ in equation (5)] defined by

$$G_m(t) = 1 + \frac{m-1}{m}t + \sum_{j=2}^{\infty}\frac{(m-1)^{2j-1}t^j}{m^j(m+1)(m+3)\cdots(m+2j-3)j!}. \tag{6}$$

It can be shown that an estimator of the variance of $\hat{\mu}_i$ is given by

$$var(\hat{\mu}_i) =$$

$$var(c_i) + \left(\frac{n_i - m_i - 1}{n_i(n_i-1)}\right)s_i'^2 + \left(\frac{m_i(n_i - m_i)}{n_i^2(n_i-1)}\right)\bar{y}_i'^2 - 2\left(\frac{n_i - m_i}{n_i(n_i-1)}\right)\bar{y}_i' \times c_i, \tag{7}$$

where $s_i'^2$ is the variance of the values less than 40,

$$c_i = \frac{m_i}{n_i} \exp(\bar{x}_i) G_{m_i}(s_{x,i}^2/2)$$

and

$$\mathrm{var}(c_i) = \frac{m_i}{n_i} \exp(2\bar{x}_i) \left\{ \frac{m_i}{n_i} G_{m_i}^2\left(s_{x,i}^2/2\right) - \frac{(m_i-1)}{(n_i-1)} G_{m_i}\left(\frac{m_i-2}{m_i-1} s_{x,i}^2 \right) \right\}.$$

A computer program is available for calculating the equations (5), (6) and (7).

In Table 2 are the estimates of the mean density of shrimp and their standard errors, $\sqrt{\mathrm{var}(\hat{\mu}_i)}$, based on equations (5) and (7) for each stratum and year and in Figure 3b are yearly plots of the means for each super stratum. The stratified estimate of mean density (denoted by $\hat{\mu}_{st}$) in the entire area is calculated by replacing $\bar{y}_i$ with $\hat{\mu}_i$ for each stratum in equation (1). The standard error of $\hat{\mu}_{st}$ is obtained by substituting var($\hat{\mu}_i$) for s_i^2/n_i (which equals var($\bar{y}_i$)) in equation (2) and then

$$\mathrm{se}(\hat{\mu}_{st}) = \sqrt{\mathrm{var}(\hat{\mu}_{st})}.$$

The estimates of the yearly average density of shrimp based on the lognormal model also appear to fluctuate about the overall mean which is equal to 2862 (Figure 4b). The estimated ten-year average based on the $\hat{\mu}_{st}$-estimator is higher than the one based on the sample mean (Figure 4). This is because, given the sample sizes typical for marine surveys, the sample mean tends to underestimate the true mean most of the time for these highly skewed distributions (Pennington, 1983, 1996; Conquest *et al.*, 1996).

An approximate 95% confidence interval for $\hat{\mu}_{st}$ is given by

$$\hat{\mu}_{st} \pm 2\mathrm{se}(\hat{\mu}_{st}).$$

In Figure 5b is a plot of the estimated average density, $\hat{\mu}_{st}$, of shrimp for each year along with 95% confidence intervals. The confidence intervals based on the lognormal distribution are larger and have a tendency to be more accurate than those (see Figure 5a) based on the sample mean and variance (McConnaughey and Conquest, 1992; Conquest *et al.*, 1996). Again it appears that the mean density of shrimp has been fairly stable over the past ten years.

Using the entire survey series to estimate abundance

Information on the present status of the shrimp stock is contained in the current survey data and also in previous surveys. Since each point in a survey series is not an isolated event, time-series techniques can be used to estimate more precisely the relative or absolute abundance of a stock over time. The basic idea is that the previous values of the series are used to forecast the current level of abundance. Just as one would use previous and subsequent points to fit a trend line by eye, the entire series can be used to estimate each individual point.

Briefly, a more precise index of abundance can be derived as follows (for details, see Pennington, 1985, 1986; Pennington and Godø, 1995; Pennington and Strømme, 1998). Suppose the population size of shrimp, p_t, can be described by the autoregressive integrated moving average (ARIMA) process (Box and Jenkins, 1976):

$$\phi(B)p_t' = \theta(B)a_t \qquad (8)$$

where $\phi(B)$ and $\theta(B)$ are polynomials in B, the backward shift operator (i.e., $B^m x_t = x_{t-m}$); $p_t' = p_t - \mu$, μ a constant; the a_ts are independent and identically distributed (iid) $N(0,\sigma_a^2)$; and the zeros of $\phi(B)$ lie on or outside the unit circle and those of $\theta(B)$ lie outside the unit circle. Thus p_t is a linear function of a finite number of previous values of the series and of a finite number of previous random shocks (the a_ts).

It is further assumed that the expected value of the survey series, y_t, is proportional to p_t, that is:

$$y_t = qp_t + e_t, \tag{9}$$

where the e_ts are iid $N(0, \sigma_e^2)$ and independent of the a_ts. It follows that y_t is represented by the process:

$$\phi(B)y'_t = \theta(B)c_t \tag{10}$$

where $y'_t = y_t - \mu'$, the c_ts are iid $N(0, \sigma_c^2)$ and the zeros of $\theta(B)$ lie outside the unit circle.

Thus the signal generated by the changes in population size (model 8) is corrupted by random noise (equation 9) and the problem is to estimate each qp_t given the observed series (model 10).

One way to estimate qp_t is to fit an ARIMA model (see Box and Jenkins, 1976) to the observed series to obtain an estimate of model 10 and use the fitted model along with equation 9 to estimate qp_t. For example, suppose y_t follows model 10. Then the information on the level of the current survey index, y_T, contained in the previous values of the series is given by the one-step-ahead forecast of y_T at time T-1, denoted by $\hat{y}_{T-1}(1)$, based on model 10 (Box and Jenkins, 1976, Chap. 5). The estimator $\hat{y}_{T-1}(1)$ is an unbiased estimator of $E(y_T)$ and hence by equation (9) of qp_T. The current survey value, y_T, is an unbiased estimator of qp_T. Therefore for any k,

$$\hat{z}_T = (1 - k)y_T + k\,\hat{y}_{T-1}(1) \tag{11}$$

is an unbiased estimator of qp_T. Since $\hat{y}_{T-1}(1)$, as an estimator of qp_T, is independent of y_T with variance equal to $\sigma_c^2 - \sigma_e^2$ (Pennington, 1985) and the variance of the original index y_T is σ_e^2, it follows that:

$$\mathrm{Var}(\hat{z}_T) = (1 - k)^2\, \sigma_e^2 + k^2(\sigma_c^2 - \sigma_e^2). \tag{12}$$

The minimum value of $\mathrm{Var}(\hat{z}_T)$ is obtained from equation (12) when $k = \sigma_e^2/\sigma_c^2$ and is equal to $\sigma_e^2(1 - \sigma_e^2/\sigma_c^2)$. For all k between 0 and $2\sigma_e^2/\sigma_c^2$, the variance of the unbiased estimator $\hat{z}_T$ (equation 11) will be less than the variance of the original survey index, y_T.

The shrimp survey series is relatively short and thus the *a priory* model (Pennington, 1985, 1986; Helser and Hayes, 1995)

$$y_t = y_{t-1} + c_t - \theta c_{t-1} \tag{13}$$

was used to model the observed series, where $\theta = \sigma_e^2/\sigma_c^2$ and $|\theta| < 1$. From model (13), it follows that the forecast of stock size at time T based on the previous values of the series is given by (Pennington, 1985)

$$\hat{y}_{T-1}(1) = (1 - \theta)y_{T-1} + \theta(1 - \theta)y_{T-2} + \theta^2(1 - \theta)y_{T-3} + \ldots \tag{14}$$

Since θ $(= \sigma_e^2/\sigma_c^2)$ minimizes the variance of the estimator defined by equation (11), k is set equal to θ. Thus from equations (11) and (14), the estimator the abundance of the shrimp stock at time T can be written as

$$\hat{z}_T = (1 - \theta)y_T + \theta(1 - \theta)y_{T-1} + \theta^2(1 - \theta)y_{T-2} + \ldots, \tag{15}$$

and the variance of $\hat{z}_T$ is given approximately by (Pennington, 1985)

$$\mathrm{var}(\hat{z}_T) \approx \theta(1 - \theta)\sigma_c^2. \tag{16}$$

For the shrimp survey series, the estimate of θ equals 0.8 and that of σ_ε equals 700 for both the abundance series based on the mean and for the series using the lognormal estimator (Figure 4). In Figure 6 are plots of the original series and the abundance estimates from estimator (15). An approximate 95% confidence intervals for $\hat{z}_T$ is given by

$$\hat{z}_T = \pm 2\sqrt{\mathrm{var}(\hat{z}_T)}\ .$$

Plots of the estimated yearly abundance of shrimp based on the entire series are in Figure 7 along with 95% confidence intervals. The confidence intervals are considerably smaller than those based only on the individual values (compare Figures 5 and 7) but the conclusion is the same: it appears as if the abundance of shrimp has been fairly stable over the past ten years.

Conclusions and Discussion Points

- The spatial distribution of shrimp is fairly strongly correlated with depth. Forming four super strata based on depth in the western survey area provides more flexibility for analyzing and interpreting the survey data. In particular, larger samples in each stratum enable alternative estimators, such as the estimator based on the lognormal distribution, to be efficiently applied. With larger strata, effort can be allocated more efficiently among the strata, which would result in more precise estimates.

- Sampling effort should be reduced in the North and in super stratum A and reallocated to the three deepest strata, B, C and D. This reallocation of effort would increase considerably the number of stations that could be sampled and thus increase the precision of the abundance estimates.

- The adaptive sampling scheme employed since 1994 introduces bias and the effort spent collecting the second stage samples would be more efficiently employed by increasing the number of primary stations. It was decided to discontinue using the adaptive sampling scheme.

- It appears that a tow duration of 15 minutes instead of the hour tow currently taken would increase the precision of the abundance estimates (since more stations could be sampled in the same amount of survey time) and improve overall survey efficiency.

- Time-series techniques, which utilize the information contained in the entire survey series, can be used to estimate density for each year. Such estimates are more precise than density estimates for each year based only on survey data from that year.

- Confidence intervals for the abundance estimates should be provided so that the uncertainty associated with changes in the yearly estimates can be assessed. In contrast to scientific surveys, it is difficult or impossible to assess the uncertainty associated with catch based estimates such as the commercial CPUE index (Anon., 1997) for the Greendlandic shrimp stock.

- Given the present precision of the survey estimates, it appears that the abundance of shrimp has been fairly stable over the past ten years. After the 1998 survey is completed, it should become clearer whether or not the abundance of the shrimp stock declined significantly in 1997.

- Only the shrimp density data were examined. It would be useful to determine the precision of survey based estimates of biological characteristics such as population length distributions.

References

Anonymous, 1997. Report of Scientific Council. Special NAFO meeting, 14-17 November 1997. Box, G.E.P. and Jenkins, G.M., 1976. Time Series Analysis: Forecasting and Control, revised edn. Holden-Day, San Francisco, 575 pp.

Carlsson, D. M., 1997. A first report on a special study on variations in catch of shrimp (*Pandalus borealis*) by depth in West Greenland (NAFO Subarea 1) in 1997. NAFO SCR Doc. 97/108.

Carlsson, D. M. and P. Kanneworff, P., 1997. Offshore stratified-random trawl survey for shrimp (*Pandalus borealis*) in NAFO Subarea 0+1, in 1997. NAFO SCR Doc. 97/101.

Cochran, W. G., 1977. Sampling Techniques, 3rd ed. John Wiley and Sons, New York, NY, 428 pp.

Conquest, L., Burr, R., Donnelly, J., Chavarria, J. and Gallucci, V., 1996. Sampling methods for stock assessment for small-scale fisheries in developing countries. In: V. F. Gallucci, S. B. Salia, D. J. Gustafson and B. J. Rothschild (Editors), Stock Assessment: Quantitative Methods and Applications for Small Scale Fisheries, p. 179-225. CRC Press, New York, NY.

Folmer, O., 1997. A discussion note about the Greenland trawl survey. ms. Francis, R. I. C. C., 1984. An adaptive strategy for stratified random trawl surveys. N.Z. J. Mar. Freshwater Res. 18:59-71.

Gavaris, S. and Smith, S. J., 1987. Effect of allocation and stratification strategies on precision of survey abundance estimates for Atlantic cod (*Gadus morhua*) on the eastern Scotian Shelf. J. Northwest Alt. Fish. Sci., 7:137-144.

Goddard, P. D., 1997. The effects of tow duration and subsampling on CPUE, species composition and length distributions of bottom trawl survey catches. MS Thesis, University of Washington, Seattle, Washington, 119 pp.

Godø, O. R., Pennington, M. and Vølstad, J. H., 1990. Effect of tow duration on length composition of trawl catches. Fish. Res., 9:165-179.

Gunderson, D. R., 1993. Surveys of Fisheries Resources. John Wiley and Sons, New York, NY, 248 p.

Helser, T. E. and Hayes, D. B., 1995. Providing quantitative management advice from stock abundance indices based on research surveys. Fish. Bull., 93:290-298.

McConnaughey, R. A. and Conquest, L. L., 1992. Trawl survey estimation using a comparative approach based on lognormal theory. Fish. Bull., 91:107-118.

Pennington, M., 1983. Efficient estimators of abundance, for fish and plankton surveys. Biometrics, 39:281-286.

Pennington, M., 1985. Estimating the relative abundance of fish from a series of trawl surveys. Biometrics, 41:197-202.

Pennington, M., 1986. Some statistical techniques for estimating abundance indices from trawl surveys. Fish. Bull., 84:519-526.

Pennington, M., 1996. Estimating the mean and variance from highly skewed marine data. Fish. Bull. 94:498-505.

Pennington, M. and Godø, O. R., 1995. Measuring the effect of changes in catchability on the variance of marine survey abundance indices. Fish. Res. 23:301-310.

Pennington, M. and Strømme, T., 1998. Surveys as a research tool for managing dynamic stocks. Fish. Res. (in press).

Pennington, M. and Vølstad, J. H., 1991. Optimum size of sampling unit for estimating the density of marine populations. Biometrics 47:717-723.

Pennington, M. and Vølstad, J. H., 1994. Assessing the effect of intra-haul correlation and variable density on estimates of population characteristics from marine surveys. Biometrics 50:725-732.

Smith, S. J. and Gavaris, S., 1993. Improving the precision of abundance estimates of eastern Scotian Shelf Atlantic cod from bottom trawl surveys. N. Am. J. Fish. Man., 13:35-47.

Table 1. Definition of four super strata in the western area for the Greenlandic shrimp survey.

Super stratum	Depth (meter)	Substrata	Area (square km)	Stratum weight, W_i
[illegible]	150-200	w1-1,w2-1,w3-1, w4-1, w5-1	14002	0.2252
[illegible]	200-300	w1-2, w2-2, w3-2, w4-2, w5-2, c3-2	19036	0.3061
[illegible]	300-400	w1-3, w2-3, w3-3, w4-3, w5-3, c1-3, c3-3	17912	0.2881
[illegible]	400-600	w1-4, w2-4, w3-4, w4-4, w5-4, c1-4, c3-4	11232	0.1806

Table 2. Relative precision for proportional stratified sampling and for a reallocation of effort to strata B and C as compared with simple random sampling in the entire survey area.

Year	no. Of stations	Relative precision: Proportional (%)	Relative precision: Reallocation (%)
88	102	96	104
89	100	100	121
90	179	124	126
91	113	90	105
92	79	138	158
93	80	141	160
94	85	149	203
95	86	130	185
96	78	128	146
97	87	103	116
Average relative precision		120%	142%

Table 3. Summary statistics for estimating the mean density and its standard error for each stratum and for the entire survey area based on the sample mean, $\bar{y}_i$, and on the lognormal model, $\hat{\mu}_i$.

1988

Stratum	n_i	$\bar{y}_i$	$se(\bar{y}_i)$	$\hat{\mu}_i$	$se(\hat{\mu}_i)$
A	22	1010	1000	655	628
B	32	2400	631	3332	1532
C	29	3969	714	4534	1223
D	20	2118	511	2730	1069
Stratified estimates for total area		2488	372	2966	634

1989

Stratum	n_i	$\bar{y}_i$	$se(\bar{y}_i)$	$\hat{\mu}_i$	$se(\hat{\mu}_i)$
A	22	887	572	740	473
B	29	6523	2104	6105	2229
C	29	3733	1045	3914	1256
D	20	1170	382	1301	570
Stratified estimates for total area		3483	726	3398	786

1990

Stratum	n_i	$\bar{y}_i$	$se(\bar{y}_i)$	$\hat{\mu}_i$	$se(\hat{\mu}_i)$
A	33	13.2	4.6	7.5	4.4
B	55	2018	671	2498	1034
C	54	4934	904	5210	1150
D	37	3912	1306	5326	2618
Stratified estimates for total area		2749	407	3230	658

Table 3 (cont.).

1991 Stratum	n_i	$\bar{y}_i$	$se(\bar{y}_i)$	$\hat{\mu}_i$	$se(\hat{\mu}_i)$
A	35	6.6	5.6	6.6	5.6
B	37	398	141	454	216
C	25	3314	647	4032	1226
D	16	1626	604	2859	1921
Stratified estimates for total area		1372	220	1819	500

1992 Stratum	n_i	$\bar{y}_i$	$se(\bar{y}_i)$	$\hat{\mu}_i$	$se(\hat{\mu}_i)$
A	14	0.6	0.5	0.6	0.5
B	24	1476	869	2095	1546
C	24	5507	1005	7224	2326
D	17	1800	771	2505	1535
Stratified estimates for total area		2363	417	3175	866

1993 Stratum	n_i	$\bar{y}_i$	$se(\bar{y}_i)$	$\hat{\mu}_i$	$se(\hat{\mu}_i)$
A	15	1.2	0.7	1.2	0.7
B	23	1674	797	2179	1311
C	26	5453	1060	7873	3038
D	16	2378	755	2467	923
Stratified estimates for total area		2513	414	3381	977

Table 3 (cont.).

1994 Stratum	n_i	$\bar{y}_i$	$se(\bar{y}_i)$	$\hat{\mu}_i$	$se(\hat{\mu}_i)$
A	15	1.6	1.6	1.6	1.6
B	24	1178	550	1181	642
C	28	7582	2351	8285	2530
D	18	1599	369	1892	690
Stratified estimates for total area		2834	701	3090	754

1995 Stratum	n_i	$\bar{y}_i$	$se(\bar{y}_i)$	$\hat{\mu}_i$	$se(\hat{\mu}_i)$
A	17	5.7	4.3	5.7	4.3
B	25	1124	627	1802	1420
C	26	5032	1208	5814	1959
D	18	1679	699	2412	1538
Stratified estimates for total area		2098	417	2664	768

1996 Stratum	n_i	$\bar{y}_i$	$se(\bar{y}_i)$	$\hat{\mu}_i$	$se(\hat{\mu}_i)$
A	14	0.1	0.09	0.1	0.09
B	28	1390	1195	1408	1272
C	21	4069	749	6843	3020
D	15	3162	1591	3813	2177
Stratified estimates for total area		2168	513	3091	1031

Table 3 (cont.).

1997 Stratum	n_i	$\bar{y}_i$	$se(\bar{y}_i)$	$\hat{\mu}_i$	$se(\hat{\mu}_i)$
A	16	34.5	19.9	30.5	20.4
B	26	1588	1142	1412	1008
C	26	2446	808	3464	1746
D	19	1756	602	1835	710
Stratified estimates for total area		1516	434	1766	604

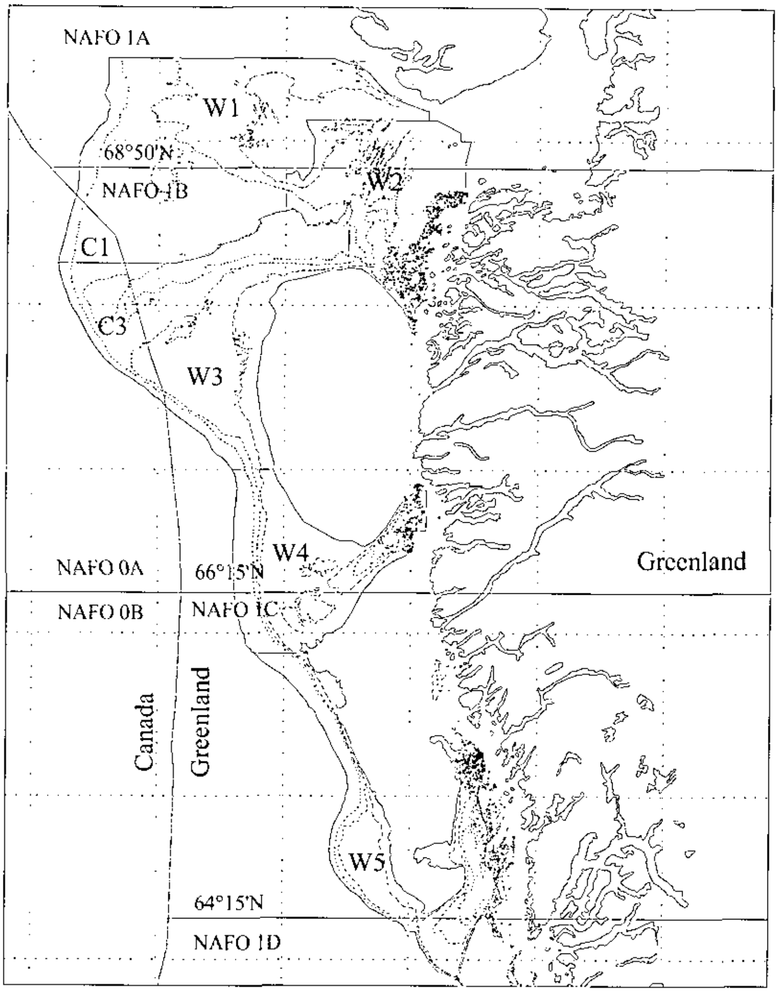


Figure 1. Map of survey area.

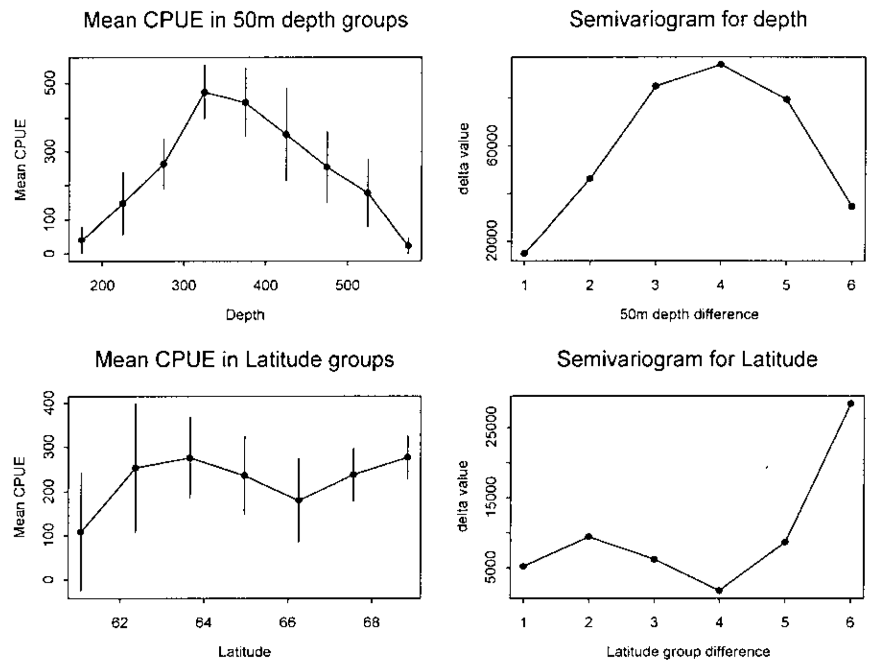
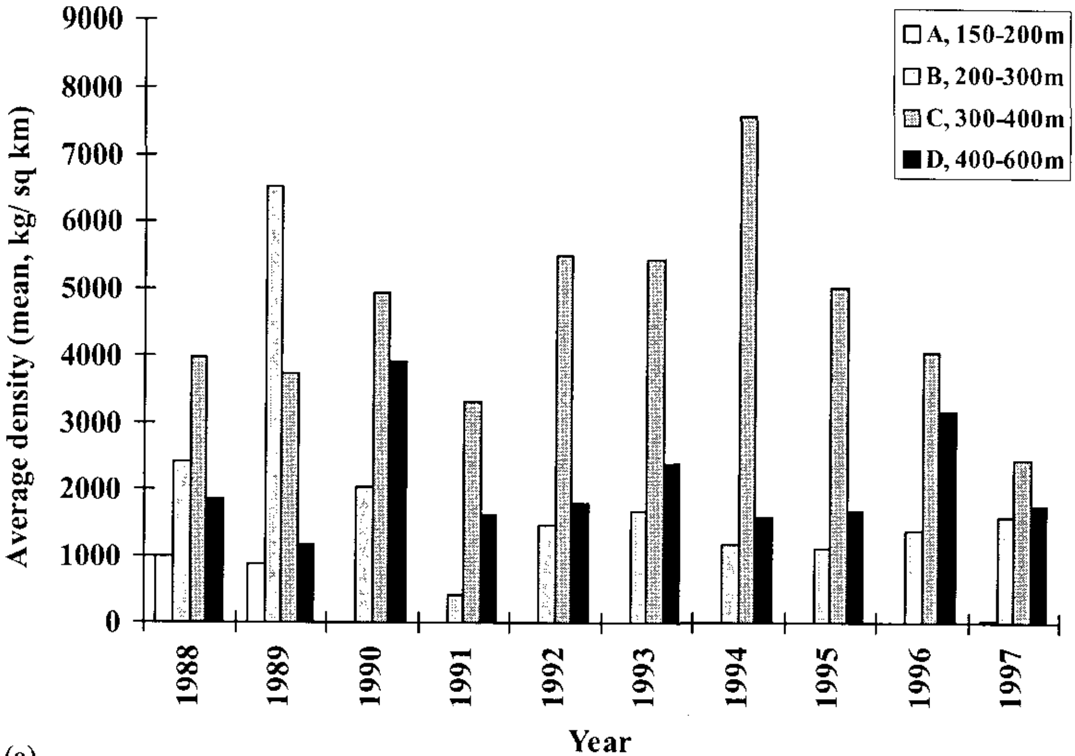
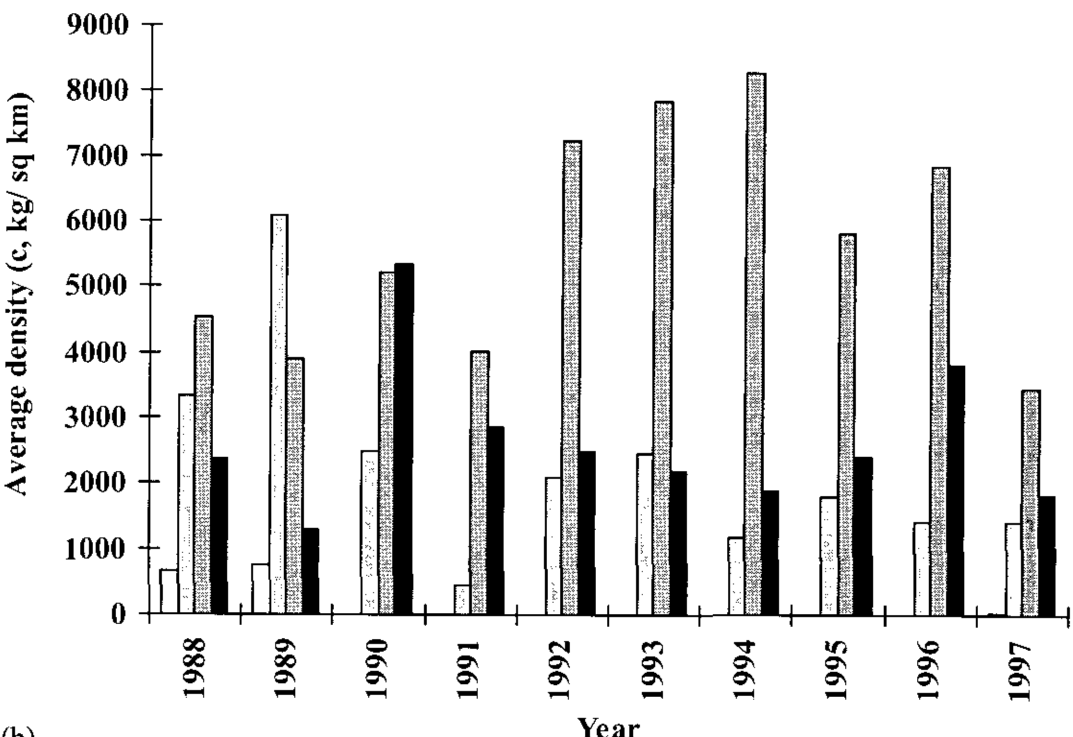


Figure 2. Mean CPUE with two times standard deviation for depth and latitude groups of station taken from 1988 to 1997. The Semivariogram for depth groups have a clear increasing trend whereas the semivariogram for latitude groups has no obvious trend

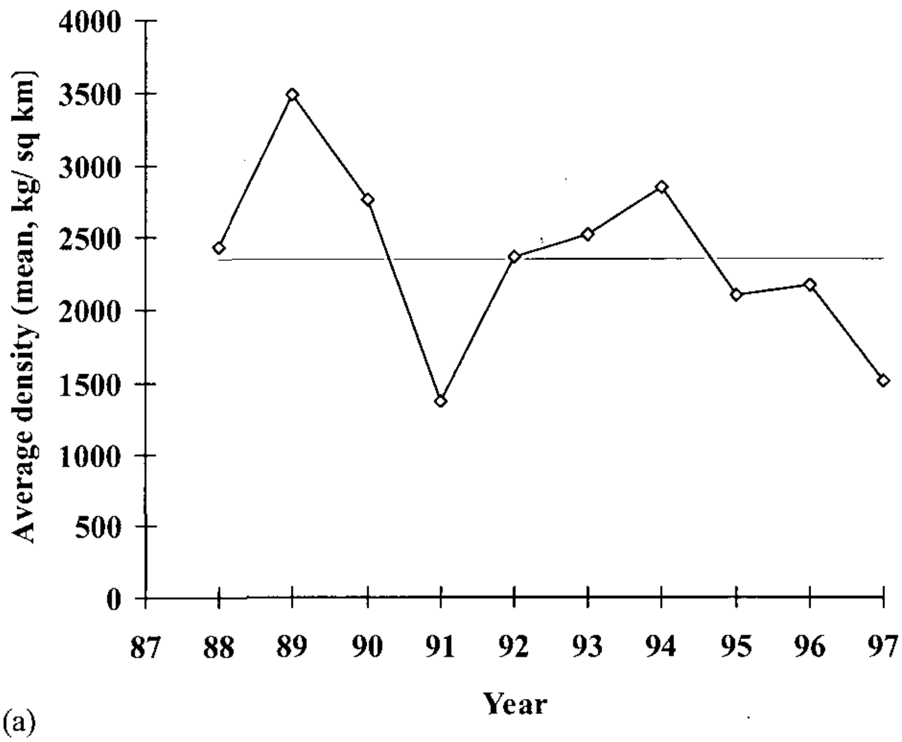


(a)

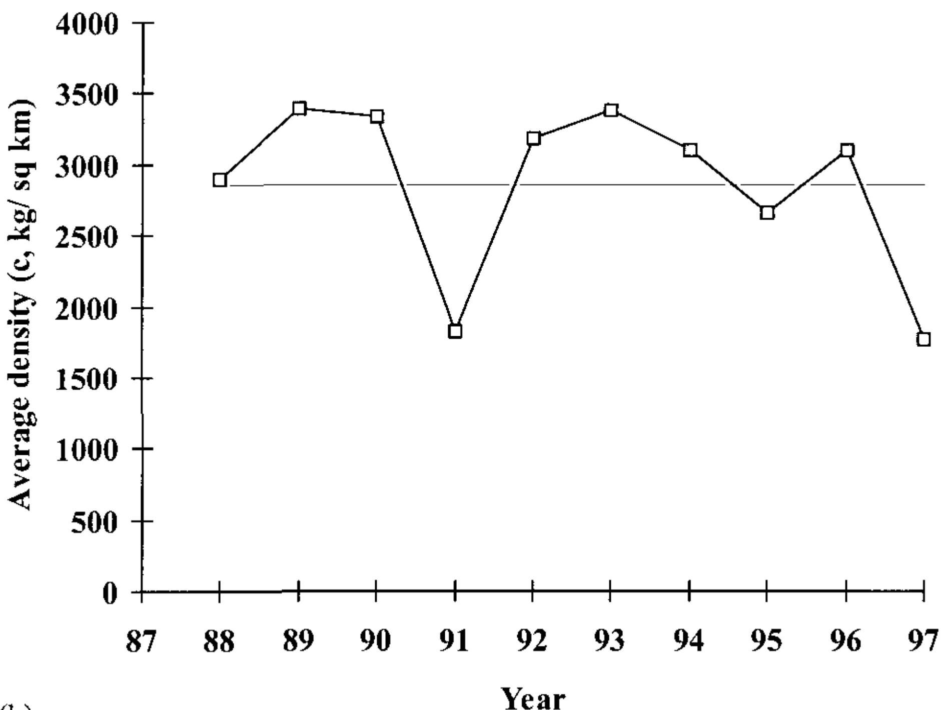


(b)

Figure 3. The estimated mean density of shrimp by year and stratum based on the sample mean (a) and the lognormal model (b).

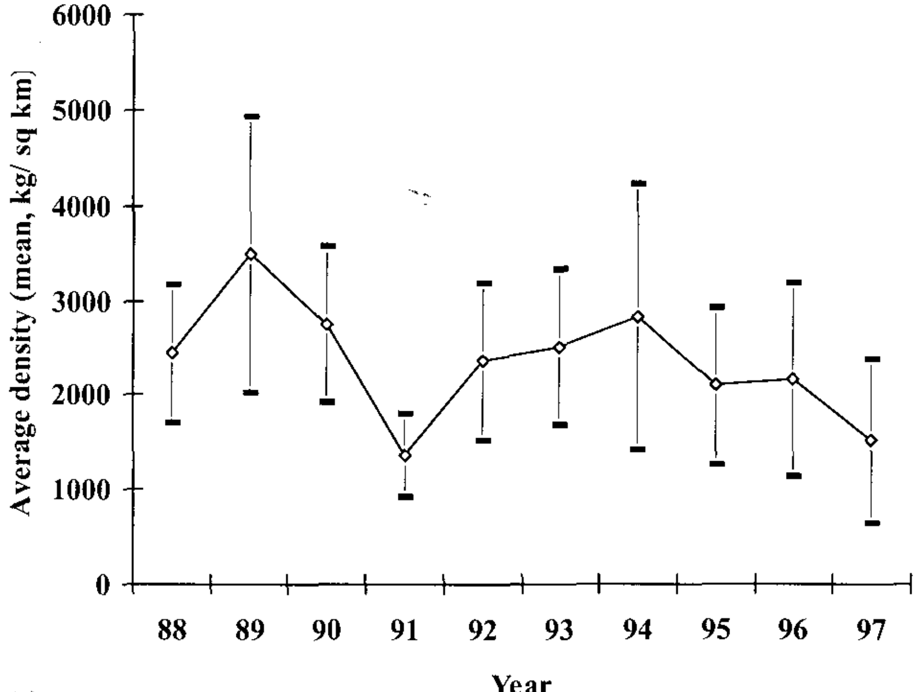


(a)

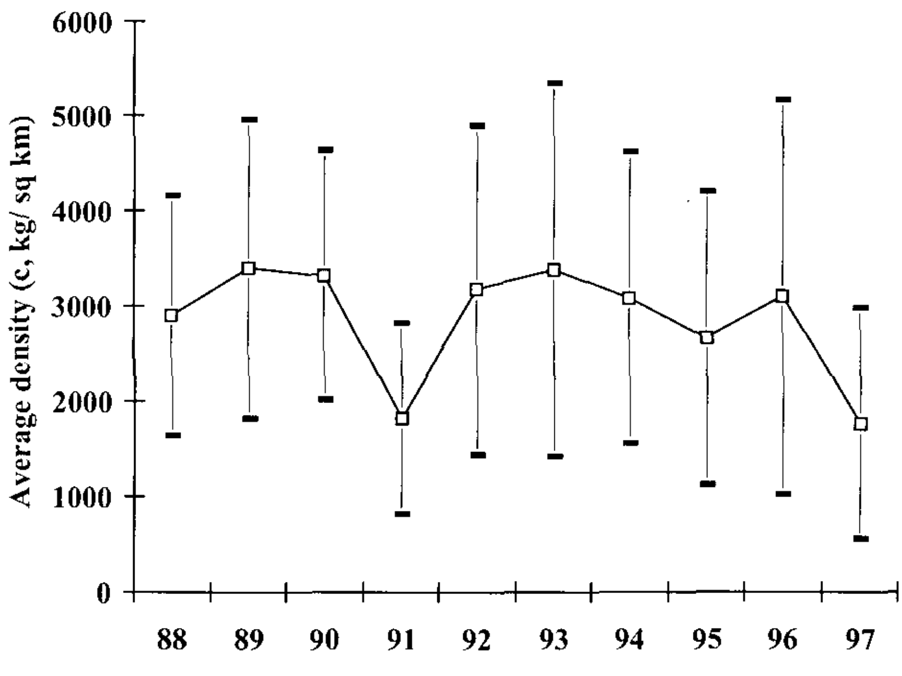


(b)

Figure 4. Estimated average density of shrimp versus year based on the sample mean (a) and the lognormal model (b). The solid lines are the average values for the ten-year survey period.



(a)



(b)

Figure 5. Estimated yearly average density of shrimp along with 95% confidence intervals for the sample mean (a) and the estimates based on the lognormal model (b).

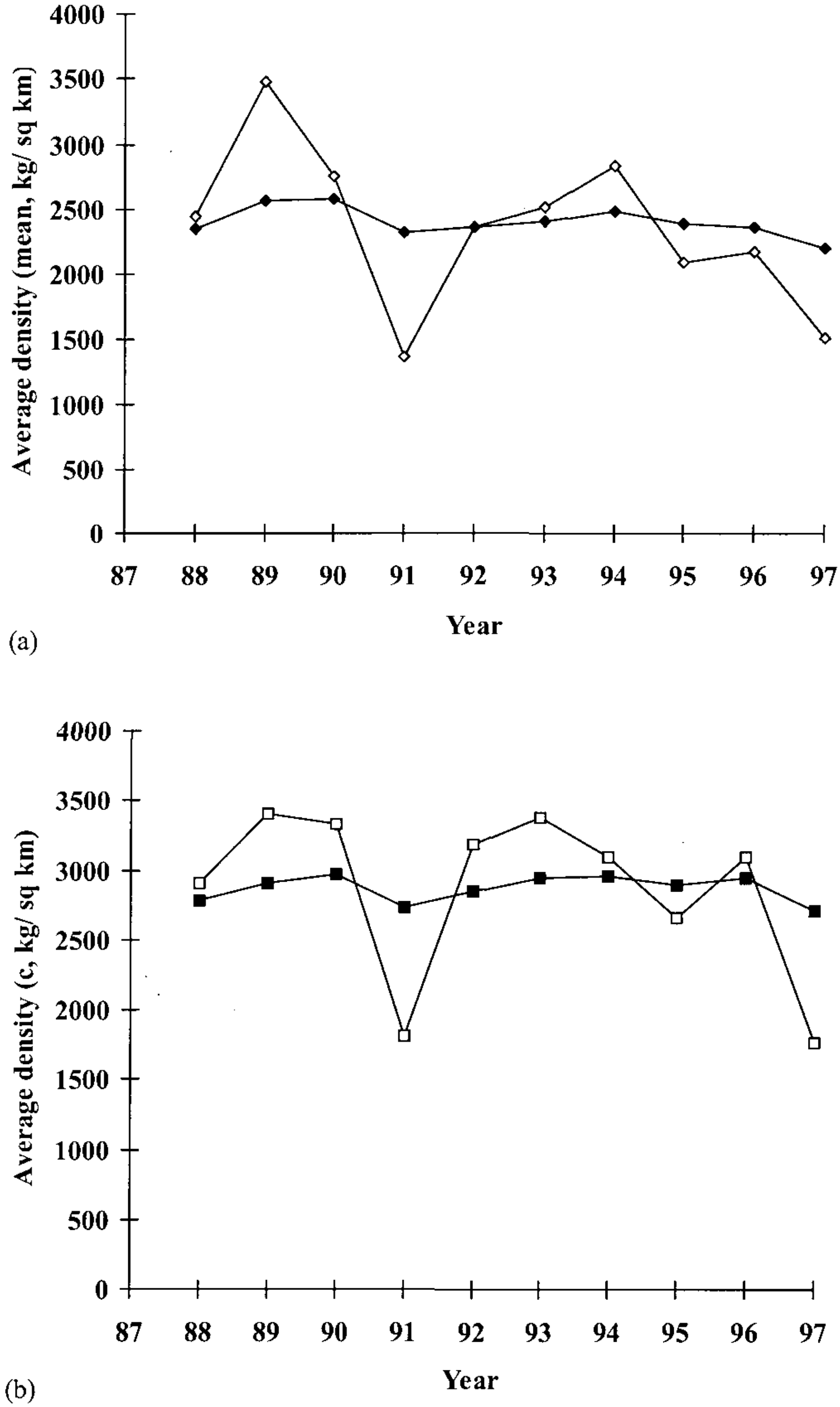
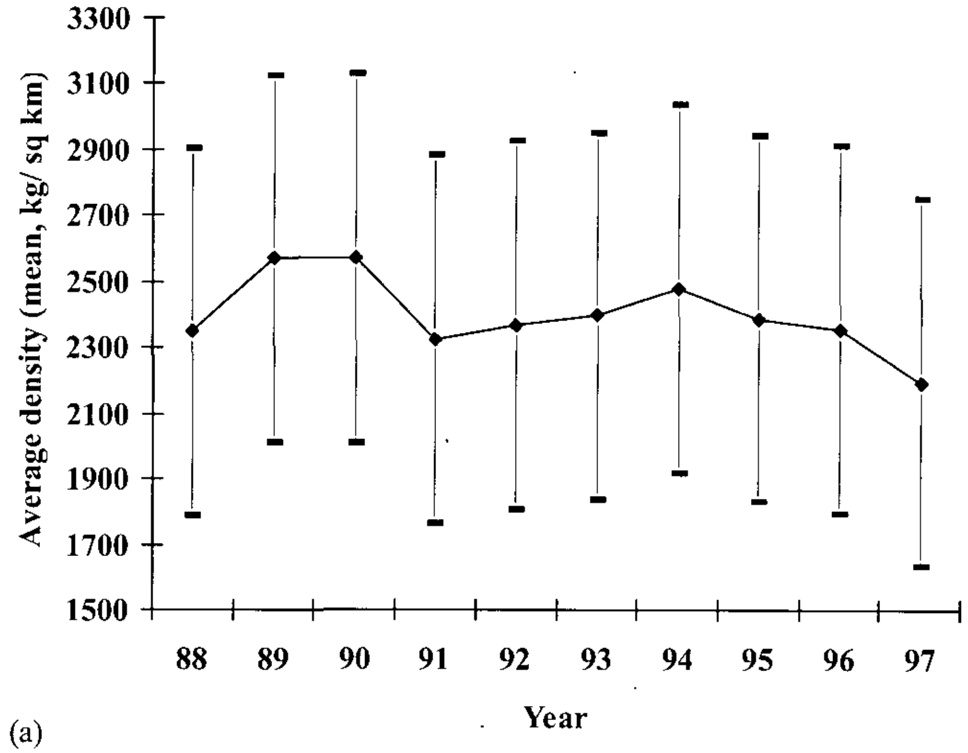


Figure 6. Original survey estimates of shrimp density (open symbols) and the estimates using the entire time series (solid symbols) based on sample mean (a) and lognormal model (b).



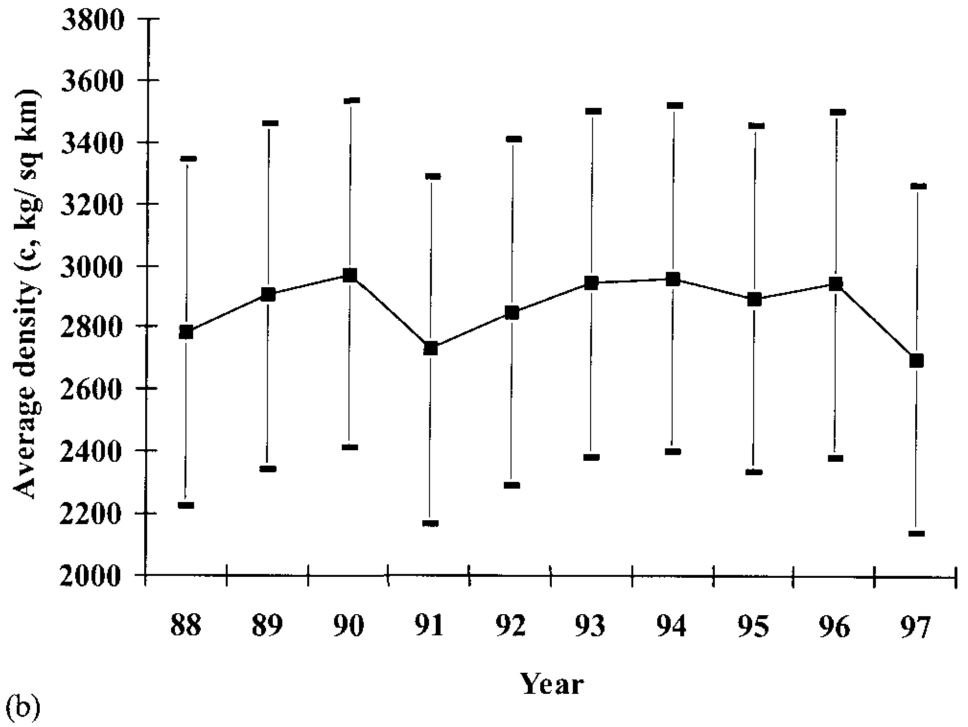


Figure 7. Estimated density of shrimp generated using the entire time series along with their associated 95% confidence limits based on the sample mean (a) and the lognormal model (b).